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Chronology of deposition and alteration in the Mawrth Vallis region, Mars

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A R T I C L E I N F O

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A B S T R A C T

The Mawrth Vallis area displays some of the largest phyllosilicate-rich outcrops of Mars, on Noachian highlands. The Mawrth Vallis region is located just at the dichotomy boundary between the Noachian highlands and the younger, northern lowlands. A large, thick, layered clay-rich unit is present throughout the inter-crater plateaus. Clay-rich layers have also been identified in parts of the Mawrth Vallis and Oyama crater floors. The age of the alteration and its relationships with other processes such as fluvial activity is fundamental for estimating the timing of aqueous activity and habitability in this region, and on Mars. We have investigated the relative stratigraphy and ages of the regional plateau, of key surfaces of the inter-crater plateau, of Oyama crater's floor and of Chryse Planitia deposits in Mawrth Vallis' mouth to constrain the age of the clay unit and its alteration. According to the cratering model results, the main layered unit may have started forming prior to ~4.0 Ga ago, was largely deposited by ~3.9 Ga ago, and suffered erosion and redeposition up to ~3.8 Ga ago, as indicated by the latest age of the deposits on the floor of Oyama crater. Surface aqueous alteration stopped no later than 3.7–3.6 Ga ago, corresponding to the age of the dark, non-altered material capping the region, and of the dark deposits in Mawrth Vallis' mouth. This work provides useful boundaries for constraining the time period of surface or shallow sub-surface water activity in this region. This preserved window into early phases of aqueous activity on Mars gives us a unique opportunity to study an aqueous environment of exobiological interest in the early solar system.

1. Introduction

The Mawrth Vallis area (Fig. 1) contains some of the largest outcrops of phyllosilicate-rich rocks on Mars (Poulet et al., 2005; Bibring et al., 2006). The plateaus of this region include numerous exposures of thick (>150 m), finely layered (layer thickness <10 m), light-toned clay-rich units (Loizeau et al., 2007; Michalski and Noe Dobrea, 2007). Fe/Mg–smectites, Al–smectites (Poulet et al., 2005; Loizeau et al., 2007), kaolinite, hydrated silica (Bishop et al., 2008; McKeown et al., 2009), and sulfates (Farrand et al., 2009; Wray et al., 2010) have been detected associated with this layered unit by the Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité (OMEGA, on board Mars Express) and the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM, on board Mars Reconnaissance Orbiter). A large fraction of clay minerals in the composition of this layered unit has been inferred from OMEGA's near infrared (IR) spectral imagery datasets: unmixing modeling estimates clay mineral abundances as high as 50% for many outcrops (Poulet et al., 2008). The clay-rich rocks at Mawrth Vallis exhibit the highest degree of aqueous alteration identified on Mars so far, from the orbit (Poulet et al., 2008), providing an intriguing and unique window into early Mars hydrogeologic history.

The potential for habitability and preservation of the different minerals and rocks identified in the region is addressed in Bishop et al. (in this issue).

Mawrth Vallis also constitutes an important target for missions seeking to investigate past habitable environments and searching for biomarkers. It figured among the four final candidate landing sites for the 2011 Mars Science Laboratory mission (Michalski et al., 2010; Grant et al., 2012), and in this respect, a better knowledge of the timeframe of the stability of liquid water in the region is also critical for future *in situ* investigations on Mars.

Michalski and Noe Dobrea (2007) have estimated the age of the rock units around Mawrth Vallis to the middle to early Noachian age, with a major resurfacing in the early Hesperian age. In this study we will better constrain the age and the time span of water activity in the region. We first need to establish the relative distribution and stratigraphic ordering of the different units, and then constrain their ages of formation and alteration.

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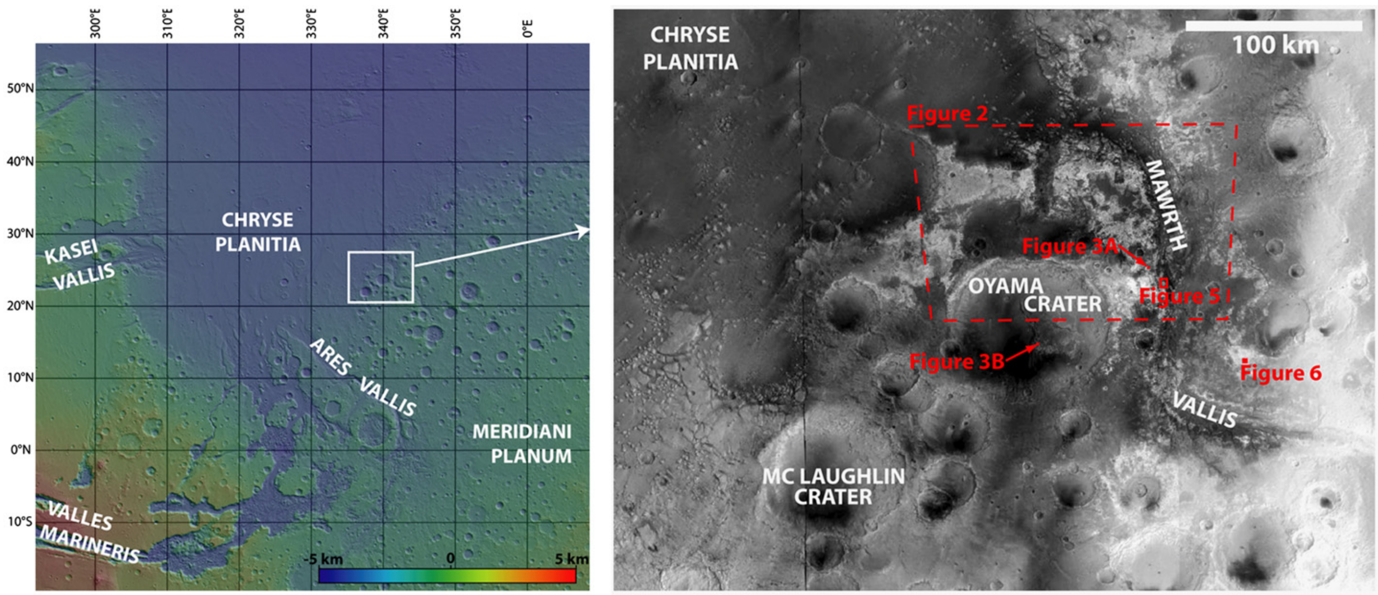

Fig. 1. Left: MOLA shaded relief of the Chryse Planitia region, surrounded by outflow channels. The box shows the location of Mawrth Vallis. Right: HRSC mosaic of the Mawrth Vallis region, centered on the Oyama crater. The light-toned outcrops in the central part correspond to exposures of clay-rich rocks, except on the eastern border of the image where dust is predominant, as in most of the adjacent Arabia Terra. The red boxes show the location of images in following figures. Note that HiRISE close-ups in Figs. 3 and 6 can only be represented as small red squares at this scale, indicated by red arrows for Fig. 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

After establishing the overall stratigraphy, we have tried to evaluate ages by dating the surface of several units of the region by crater counts. This method evaluates the crater retention age of these surfaces by comparing the surface crater population with model crater populations.

2. Datasets and dating method

2.1. Thermal and visible imagery

In order to retrieve the crater size distribution, we have used image sets providing full coverage of the Mawrth Vallis region and of the more local surfaces we investigated. The topography needs to be easily pictured in order to detect and measure the size of craters with poor surface expression.

For the regional crater count, the daytime temperature mosaic from the THermal EMission Imaging Spectrometer (THEMIS, on board Mars Odyssey (Christensen et al., 2004)) was used. This dataset has an image resolution of ~100 m/pixel and provides very good topographic contrast: the slopes facing the sun have a higher temperature than the opposite slopes.

For local crater counts we needed higher-resolution images. For this reason we have utilized mosaics from the context CTX camera on board MRO (Malin et al., 2007), which has an image resolution around 6 m/pixel.

Geological context is shown using images from the High Resolution Stereo Camera (HRSC, onboard Mars Express (Jaumann et al., 2007)) and the High Resolution Imaging Science Experiment (HiRISE, onboard MRO (McEwen et al., 2007)), and topography from the Mars Orbiter Laser Altimeter (MOLA, onboard Mars Global Surveyor (Smith et al., 2001)).

2.2. Cratering model ages, resurfacing ages

We have used the "craterstats2" software developed and described by Michael and Neukum (2010) in order to estimate cratering retention ages from the measured crater size-frequency distributions on the chosen areas. Ages have been derived by fitting a crater production function from Ivanov (2001) and by using the chronology function from Hartmann and Neukum (2001) to translate relative crater frequencies into absolute model ages. All ages given in the following sections are estimated based on this model. For the smaller diameter crater where we have observed a deviation of the crater size-frequency distribution from the expected isochron, we tested resurfacing scenarios. This evaluation has been performed with "craterstats2" as well. The observed crater measurements are given in Figs. 8–10 (solid squares). Possible resurfacing events are plotted with open-squares in the cumulative plots: this new crater population takes into account the fact that the original cumulative distribution includes craters formed before the resurfacing event (the larger ones were not erased by the resurfacing), overestimating the age of the resurfacing event when directly fitting an isochron to the original distribution. Hence, a new post-resurfacing distribution is estimated, and the isochron is fitted to this new distribution (Michael and Neukum, 2010).

3. Geological context and stratigraphy

3.1. Main units

Fig. 2 illustrates the stratigraphic relationships between the main units of the region: the clay layered deposits of the plateaus, partly covered by a capping unit; Mawrth Vallis' channel and small valleys on Oyama crater's rim, and floor deposits inside Oyama. In the background, Mawrth Vallis' mouth and part of Chryse Planitia are filled with dark material.

The main clay-bearing unit (indicated as "clay layered deposits" in Fig. 2) has an extent of at least 300 km by 400 km around Mawrth Vallis (see Fig. 1). It corresponds to light toned layers with a minimum thickness of 200 m as observed in some crater walls and inferred from some outcrops (Loizeau et al., 2007, 2010) and could reach a thickness of >1 km (Michalski and Noe Dobrea, 2007). When exposed at the surface, the clay-rich unit

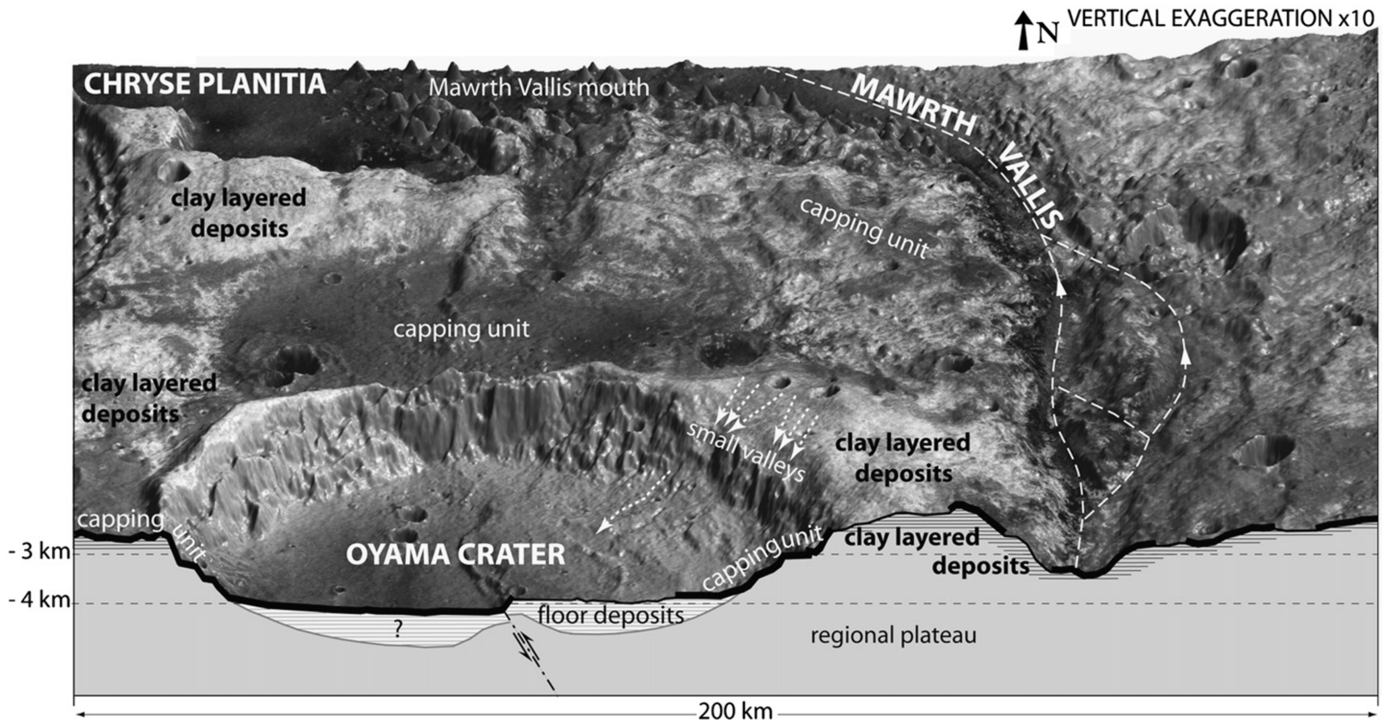

Fig. 2. Perspective view of the central Mawrth Vallis region derived from HRSC images and HRSC topography—please note the 10X vertical exaggeration. The schematic cross-section, at the bottom, depicts the layout of the clay-rich layered deposits, the clay-rich Oyama crater floor deposits, and the dark capping unit. Elevation figures are given with respect to the MOLA reference geoid. A north–south trending thrust fault crosscuts Oyama crater and surrounding terrain. Layers have been represented as horizontal strata for simplification. They have been drawn where they are observed, although, layered deposits are only seen on the eastern half of Oyama's floor, as the western part is covered by dark material. Fluvial erosion is visible on many outcrops on the region's plateau, as for example indicated on the eastern wall of Oyama (white arrows). A dark capping unit is partially eroded, revealing the clay-rich rocks. Figs. 8–10 help to constrain the ages of these events.

is much eroded and shows very few small craters (e.g. Loizeau et al., 2007).

Massive crustal bedrock is not detected in Mawrth Vallis plateaus from hyperspectral data nor observed from visible imagery; this is why it is difficult to evaluate the maximum thickness of the clay-bearing unit. In contrast, at Nili Fossae and Tyrrhena Terra, outcrops of massive or brecciated material exhumed by craters or wind erosion display variable mineralogy including low-temperature alteration phases (e.g., smectites), high-temperature alteration phases (e.g. chlorite, serpentine), and non-altered phases (low calcium pyroxene (LCP) or high calcium pyroxene (HCP)) signatures (e.g., Mustard et al., 2007, 2009; Mangold et al., 2007; Loizeau et al., 2012). This mineralogical diversity is representative of the crustal bedrock (Ehlmann et al., 2011; Loizeau et al., submitted for publication). At Mawrth Vallis, no sign of this primitive crust is visible; all hydrated minerals are part of light-toned layered deposits.

A dark capping unit drapes part of the clay-bearing unit (see Fig. 2); it may have been deposited over the entire region in the past, and partly removed and reworked today by wind erosion. It is estimated to be around 10 m thick (Loizeau et al., 2007, 2010). This dark cap shows no detected alteration on spectral datasets (e.g. Loizeau et al., 2007; Michalski and Fergason, 2009), but a weak pyroxene signature in OMEGA data (Loizeau et al., 2007). Clay-rich rocks are typically observed where this dark capping unit was eroded by wind and on small crater walls.

Fig. 3A shows a typical example of the first tens of meters of the clay unit from the top layers (overlaid by the dark cap), on the walls of a small crater on the plateau between Oyama crater and Mawrth Vallis.

In the center of the region, the large Oyama crater (100 km in diameter, see Figs. 1 and 2) has impacted into the main clay-bearing unit (Loizeau et al., 2007). However, on the floor of Oyama crater, clay-rich layered rocks were also identified (Loizeau et al., 2007), indicated as "floor deposits" in Fig. 2. When compared with the clay-rich layered rocks of the plateaus surrounding Oyama crater (Fig. 3A), the Oyama floor's strata (Fig. 3B) appear more contrasted between each other in visible and color images (bright strata are often separated by thin dark layers), and less fractured in small blocks or polygons, so that one can track more easily single layers over long distances. Thus, we infer that these are two different units (plateau unit vs. Oyama floor unit) , which were deposited at different time periods.

Chryse Planitia is a smooth plain lying to the northwest of the Mawrth Vallis region. The transition from the clay layered unit to adjacent units of Chryse Planitia is abrupt, forming cliffs and buttes, as can be seen in the northern part of Fig. 2 (a close-up is presented in Figures 6 and 9 of Loizeau et al., 2010). The mouth of Mawrth Vallis is filled by the same smooth dark material as in Chryse Planitia. This area of Chryse Planitia was dated to the Late Hesperian (Chryse Planitia 2 unit), while the Chryse Planitia plain just south of Mawrth Vallis mouth (Chryse Planitia 1 unit) was dated to a period from Late Noachian to Early Hesperian (Tanaka et al., 2005). These flat smooth plains show no aqueous alteration but contain pyroxene in spectral datasets, suggesting predominantly basaltic material (Loizeau et al., 2007). Chryse Planitia is stratigraphically younger than the plateaus around Mawrth Vallis, and may contain material transported from Mawrth Vallis, although these sediments must have been overlain by the dark material observed at the surface. The latter seems to be of volcanic origin, either emplaced by ancient lava flows, or volcanic airfall deposits.

Parts of the surface display dark sand beds and sand dunes; thus it has been eroded by wind. Also many small craters are filled by sand, indicating that resurfacing took place after the Chryse Planitia infilling.

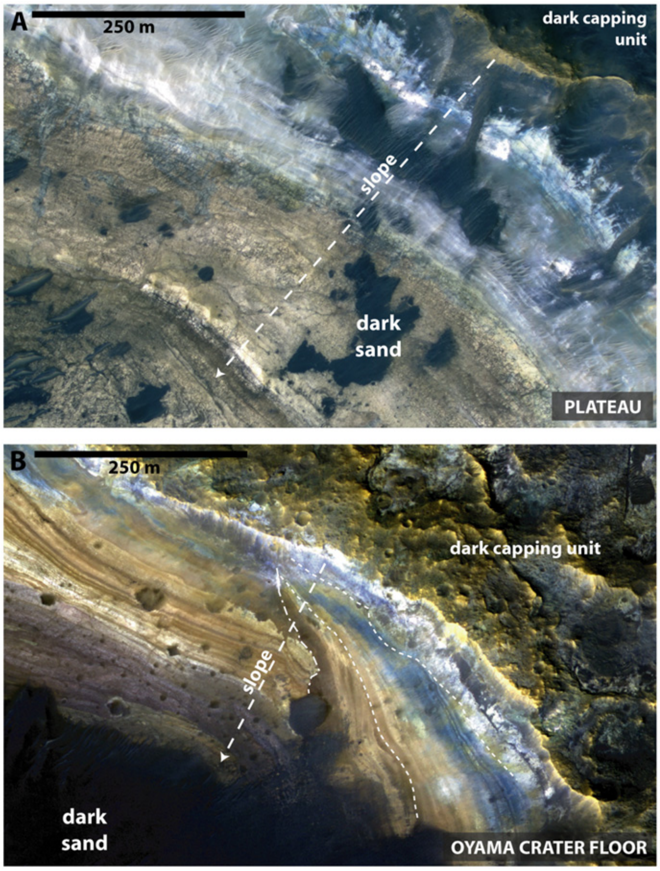

Fig. 3. Examples of layered outcrops on the plateau and on Oyama crater floor. Both images show the northeastern inner wall of small craters. The scale is the same for both images. The main directions of slope are indicated by thick dashed arrows. (A) HiRISE image ESP_20297_2045_COLOR, on the wall of a 3.0 km-diameter crater on the plateau near Mawrth Vallis (centered 341.27°E, 24.28°N). A topmost bluer sub-unit overlies a tan sub-unit, as observed in many locations across the region. (B) ESP_022354_2035_COLOR, on the wall of a 2.0 km-diameter crater on the floor of Oyama crater (centered 339.99°E, 23.40°N). The thin mixed line outlines a truncation of the layers through the different color units, indicating some deformation events after the deposition of the layers. Two thin dashed lines indicate possible unconformities inside sediments by erosion events of the layers below. Individual strata in Oyama crater floor deposits are generally more easily distinguishable than those on the plateaus: strongly contrasting beds can be followed over kilometers in Oyama crater, while beds are less contrasted, more fractured, and generally less horizontally extensive on the plateaus. The bluer, upper part of the layered units, generally associated with Al–clay composition (Loizeau et al., 2010; Wray et al., 2008; McKeown et al., 2009), is significantly thicker on the plateau near Mawrth Vallis than on the crater floor. The tan sub-unit is associated to Fe-bearing smectites like nontronite. Dark sand, possibly coming from the dark cap degradation, partly fills the floor of these small craters, and covers part of their walls, forming local small dunes and ripples. Brighter fine material seems also to cover the upper part of the walls; it may originate from the erosion of the upper clay-rich layers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3.2. *Distribution of hydrated minerals and implications for alteration*

In most outcrops of the clay-bearing unit, the clay mineralogy varies with depth from Fe/Mg–smectites in the lower layers (seen as various tan-tones in the HiRISE images of Fig. 3) to Al–phyllosilicates and hydrated silica in the upper layers (seen as blue to white in the HiRISE images of Fig. 3) (Bishop et al., 2008; Wray et al., 2008; Loizeau et al., 2010), with a possible ferrous component at the transition (Bishop et al., 2008, in this issue; McKeown et al., 2009). Local sulfate-rich outcrops were also detected at CRISM scale (Farrand et al., 2009; Wray et al., 2010), not excluding possibly more extended sulfate-rich buried layers. The plateaus' stratigraphy is later schematized in Fig. 7.

Either the clay-bearing unit has not likely suffered any long, deep burial, or water availability in the unit has been very limited since its formation, as no mineral diagnostic of diagenesis has been identified (e.g. illite or chlorite).

While the largest exposures of phyllosilicate-rich rocks are spread over a region of ~300 km × 400 km, similar stratigraphy (Al-phyllosilicates on top of Fe-smectites) can be found in smaller outcrops over a larger region extended towards south and east over a ~1000 km × ~1000 km region (Noe Dobrea et al., 2010). This compositional stratigraphy, Al over Fe/Mg phyllosilicates, has been found in other regions of Mars, like Nili Fossae (Ehlmann et al., 2009), Valles Marineris (Le Deit et al., 2012), Noachis Terra (Wray et al., 2009), or Terra Sirenum (Wray et al., 2011), and could reveal a larger, maybe global scale event, triggering a weathering process (pedo-diagenetic processes) related to surface conditions (Gaudin et al., 2011).

The fact that the Al–clay unit follows the eroded topography (Wray et al., 2008; Loizeau et al., 2010) over a large region demonstrates that the alteration forming the Al–clay minerals occurred close to the surface, in agreement with pedo-diagenetic processes, and that this alteration has occurred after the layered unit deposition and its major erosion. In general, there is an agreement consistent scenario that the layered Fe/Mg–clay rich unit could have been formed by deposition, followed by alteration that may have included acid leaching close to the surface, forming the Al–clay upper zone (e.g. Michalski et al., 2010). Thus, the alteration was likely pre-existent or ongoing during the main layered unit deposition (forming Fe/Mg–smectites), and continued subsequently, forming Al–phyllosilicates and hydrated silica by *in situ* alteration.

Also the layered unit on the Oyama floor displays a bluer, upper portion, as seen on the plateau (see the two comparable outcrops of Fig. 3). This bluer zone is generally associated with Al–clay composition on the plateau (Loizeau et al., 2010; Wray et al., 2008; McKeown et al., 2009); similarly, this zone of the Oyama floor shows an Al–phyllosilicate spectral signature (Carter, 2011). This observation shows that the layered unit there experienced similar late leaching as on the plateau, and hence has been active after the deposition of the layers in Oyama.

The bluer zone is significantly thinner on the Oyama floor than on the plateau, which could be explained by a lateral difference in the leaching due to a difference in the physical properties of the rocks.

Later, the dark material of the capping unit was deposited, mantling the Al–clay bearing layers. The fact that this dark cap is unaltered shows that surface alteration stopped before the dark material deposition.

3.3. *Erosional landforms*

Numerous km-long to tens-of-km-long fluvial valleys incise the surface of the clay-bearing unit, generally indicating ancient flows towards Mawrth Vallis (or a former valley pre-existent to the outflow channel) and towards Oyama crater (some are indicated in Fig. 2, and more precisely in Fig. 4). They are all more or less filled by the dark capping unit, hence they were deposited after the end of the fluvial activity. Many of them are strongly eroded and often appear as inverted relief (Loizeau et al., 2007; Mangold et al., 2010; Ehlmann et al., submitted for publication). This fluvial erosion may have transported and deposited clays inside Oyama crater (although the fluvial link between the walls and the floor of Oyama crater is not visible, perhaps it was degraded by subsequent erosion).

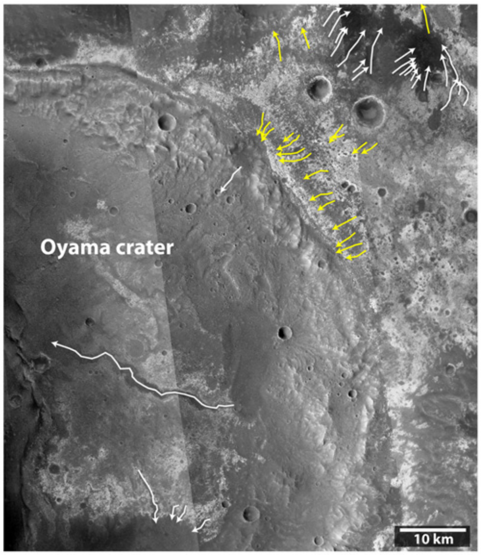

Fig. 4. CTX mosaic on the northeastern side of Oyama crater. A few fluvial valleys are highlighted by arrows indicating the direction of flow. Some valleys cross Oyama's crater rim and some others cut its floor. Inverted channels, indicated in yellow, are observed mainly on the north-eastern wall of Oyama crater. Subsequent erosion and filling have likely erased some valleys and filled others. Outside the rim of Oyama, valleys incise the plateau with flow direction toward the north, in agreement with local topography, as observed in the upper-right of the image, with partial inversion due to erosion. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The most obvious aqueous erosion feature of the region is the outflow that formed the Mawrth Vallis channel. Images from the Mawrth Vallis walls and floor suggest that the outflow has cut into the clay-bearing layered unit (Loizeau et al., 2007, 2010; Michalski and Noe Dobrea, 2007). Fig. 5 shows HiRISE close-ups on the lowest part of the western wall of Mawrth Vallis, with anaglyphs images to estimate the topography qualitatively. Layers there have been strongly eroded and they dip more steeply than the local slope of the valley wall, as revealed by some remnant buttes. This image shows that layers there were dipping before the outflow, or at least before the last outflow episode in Mawrth Vallis. A valley pre-existed the last outflow episode: layers either draped the pre-existing valley, or were deformed during the formation of a tectonic valley.

Wray et al. (2008) showed that the uppermost blue-color section was dipping towards the channel center, therefore suggesting a draping over the channel. Dips were extracted from the compositional boundary between the Al–phyllosilicate sub-unit and the Fe/Mg-smectite sub-unit, and not from the deposited layers: this is one of the observations that suggested that this uppermost section was created by an alteration front from the surface. Bishop et al. (in this issue) also show the presence of Al–phyllosilicates on the floor of Mawrth Vallis, showing that the formation of this sub-unit post-dates the last outflow.

Thus, a view consistent with the observations is that Mawrth Vallis has cut inside the clay-bearing layered deposits but that the last phase of alteration occurred after the outflow.

The surface of the smooth plain at the mouth of Mawrth Vallis and Chryse Planitia shows no outflow erosion features. Thus, the outflow activity in Mawrth Vallis ended before the emplacement of this unit.

3.4. Water circulation in fractures

The clay unit of the plateaus around Mawrth Vallis is crossed by numerous fractures, up to >10 km long. Many of the large fractures appear in positive relief; this could be an indication of higher cementation of a halo of rocks around the fractures, due to groundwater circulation in the fracture and in the contiguous rocks. Other, much smaller bright-rimmed fractures have been observed in this region (Wray et al., 2008), and also elsewhere on Mars, in west Candor Chasma (Okubo and McEwen, 2007), or Meridiani Planum (Okubo et al., 2009) for example, they could be explained by a similar process.

One fracture in particular shows an exceptional structure with a $\sim$150 m-wide, high-standing halo around a $\sim$15 km-long fracture that shows very bright rocks in some places (Fig. 6). These 15–20 m-wide bright spots in the fracture may have been formed by water–rock interaction, and possible mineral precipitation in the fracture. This observation may confirm the hypothesis of localized alteration by subsurface fluids in the smaller bright-rimmed fractures of the region (Wray et al., 2008). This aqueous activity in the region is more localized than the large surface alteration described before and may have happened only underground, but it opens the possibility of late alteration by groundwater circulation or hydrothermal circulation.

3.5. Summary: stratigraphic column

Fig. 7 summarizes the stratigraphy of the main clay-bearing layered unit of the plateaus around Mawrth Vallis. The dark cap overlays the two main clay-rich zones: Al–phyllosilicates and hydrated silica over Fe/Mg–smectites, with ferrous material at the transition. Some sulfate outcrops have been detected in particular outcrops, possibly indicating a larger sulfate layer. Some of the layers may be due to ejecta, and some dark beds are interbedded between clay layers (some were identified in Loizeau et al., 2010). Some fractures have also seen water–rock interaction after the layers' deposition. Fluvial valleys dissected the surface of the clay unit before being covered by the dark cap. This does not exclude earlier fluvial activity during the layers' deposition.

The rims of Oyama have cut layered deposits, and are eroded by fluvial activity, so that the layered unit in Oyama is expected to have formed after the deposition of the main layered unit on the plateau (Loizeau et al., 2007), but before the end of the alteration phase.

4. Regional and local crater counts

Large craters, up to the 100 km-diameter Oyama crater, are frequent in highlands of the study region. Where exposed, the clay-rich unit appears strongly eroded, and contains only few small craters. The dark capping unit, on the other hand, preserves craters much better, and presents high crater densities in some places (e.g. Loizeau et al., 2007). We have investigated the cratering retention ages of some of the Mawrth Vallis units to derive age constrains for the region's stratigraphy. In the following, derived ages are rounded to nearest 0.05 Ga of model crater distribution fit age.

4.1. Age of the regional plateau

The first count aims to date the mean age of formation of the regional plateau, rather than the uppermost units of the region. To be reliable, the age estimation must be performed on the biggest craters (>2 km in diameter), as some of the smaller craters have been infilled or eroded since the formation of the regional plateau. The area evaluated (Fig. 8) was chosen to include the main clay-rich outcrops, but excludes the younger Chryse Planitia to the northwest and also the mouth of Mawrth Vallis.

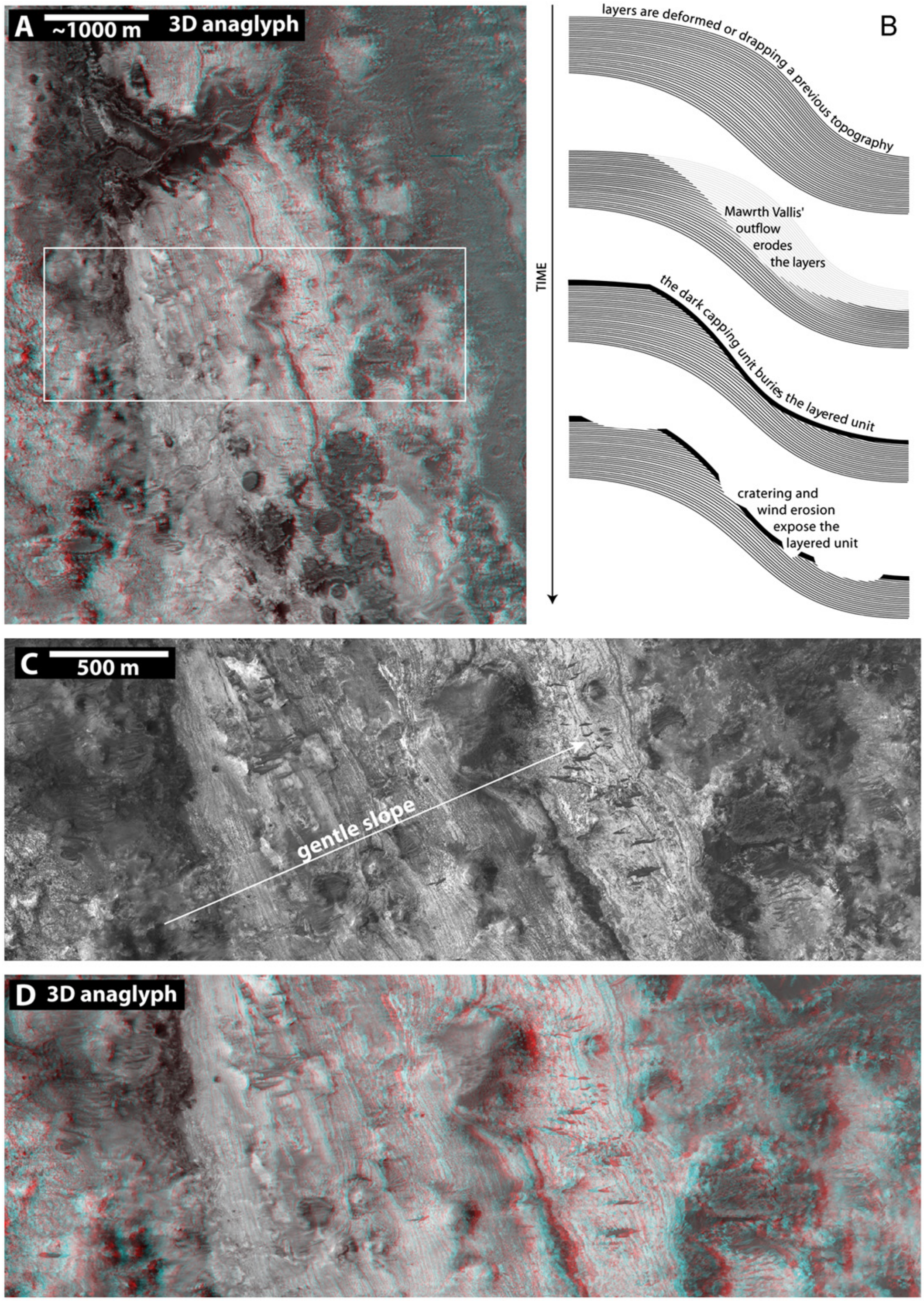

Fig. 5. Close-ups on the layers exposed on the western wall and floor of Mawrth Vallis, near the candidate landing ellipse for MSL (Michalski et al., 2010), around 341.46°E, 24.11°N, see Fig. 1 for location. (A) 3D anaglyph close-up of image ESP_018530_2045_ESP_017897_2045_RED, the dark capping unit covers part of the layered unit. Where exposed, the latter shows a series of exposed layers in the north–south direction. The anaglyph shows the slope of the valley wall from west to east where the valley floor is covered with the dark capping unit. The white box indicates the location of close-ups (C) and (D). (B) Hypothesis on the series of events on this Mawrth Vallis wall (vertical relief is exaggerated): deposited layers are deformed through the formation of a tectonic valley or are deposited over a previous topography, and then eroded by the outflow. The dark capping unit covers the layered unit, and is then eroded to expose the layered unit. Note that the continuous link between the nearly horizontal layers on the plateau west of Mawrth Vallis and the steeply dipping layers on the floor of the valley cannot easily be made with the existing data and that it is an hypothesis in this sketch. (C) and (D) Close-up on some remnant buttes on the wall of Mawrth Vallis (ESP_017897_2045_RED and ESP_018530_2045_ESP_017897_2045_RED). The exposed layers circle around the buttes going up the wall slope, showing that they dip more steeply that the wall slope. (For interpretation of the anaglyph images, the reader is referred to the web version of this article.)

The cumulative crater size-frequency distribution (Fig. 8) follows the ~4.0 Ga (3.98 ± 0.02 Ga) model isochron for craters > 20 km in diameter, suggesting this corresponds to the age of the upper crust at this location. The deviation of the cumulative crater distribution for smaller craters is indicative of resurfacing of the plateau, responsible for erasing some craters < 20 km in

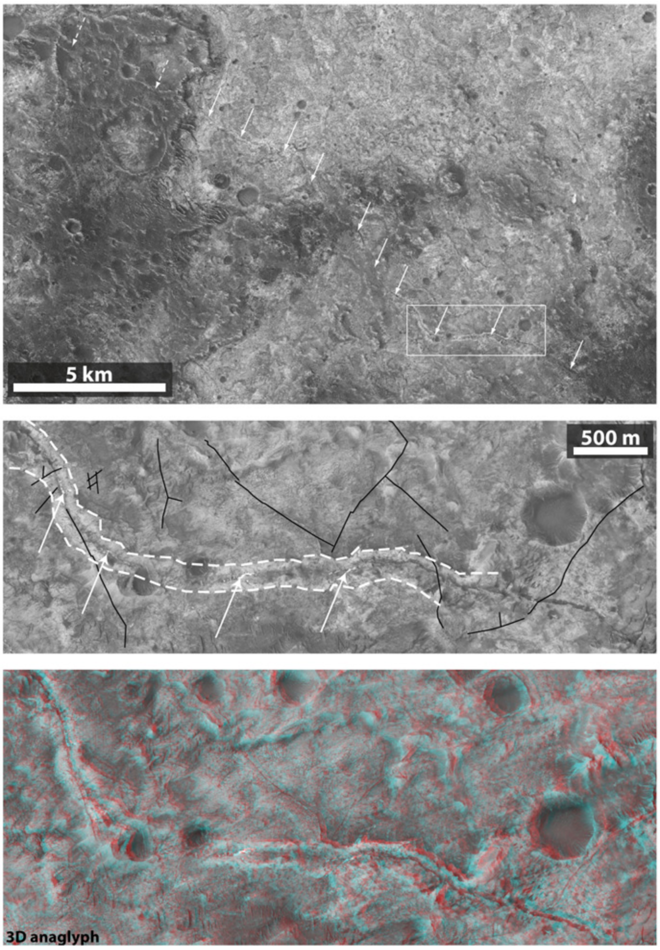

Fig. 6. Close-ups on a long halo-bounded fracture on HiRISE image PSP_006610_2035_RED, and on the anaglyph made from this image and PSP_008179_2035_RED. The image is centered around 342.43°E, 23.09°N, see Fig. 1 for location. Top: the full visible fracture is shown by white arrows. A linear trough on the dark cap (indicated by dashed arrows) may indicate that the fracture was active/re-activated after the dark cap deposition. Middle: HiRISE close-up as indicated by the white box in the top image. The central fracture is surrounded by a ~90-m-wide halo on each side, mapped with white dashed lines. The central part is generally dark, but sometimes very bright spots (15–20 m wide, indicated by white arrows) fill the fracture: they may be due to precipitation, due to ancient fluid circulation in this fracture. Also the halo may be due to a change in the composition or cementation of the rocks around the fracture. Thin black lines show the longest apparent younger fractures of the close-up. Bottom: Anaglyph view of the same image (the orientation of the anaglyph is different as it was not georeferenced). One can see that the halo appears high standing, and thus likely is more resistant to erosion than the surrounding rocks (For interpretation of the anaglyph images, the reader is referred to the web version of this article.)

diameter, in agreement with crater counts from Michalski and Noe Dobrea (2007). This has been observed for many highland units (Tanaka et al., 1992). This resurfacing effect could be fitted by a model isochron at ~3.9 Ga (3.89 ± 0.01 Ga), extending down to a crater diameter of 3 km. This resurfacing period may be associated with a major erosion episode for the highland, as expected by fluvial erosion (Craddock et al., 1997) and/or an important deposition process on the highland plateau (e.g. the clay-rich layered unit deposition). Because it is mainly craters of diameters < 10 km which have been erased by this event at ~3.9 Ga, we can evaluate around 1 km of vertical erosion and/or deposition. Further resurfacing may have also occurred, as suggested by the more local measurements in the following sections; however, this remains unresolved in the present count because craters smaller than about 2 km were not considered to evaluate the age of the regional plateau only—although the image resolution of 100 m/pixel would permit the confident detection of smaller craters.

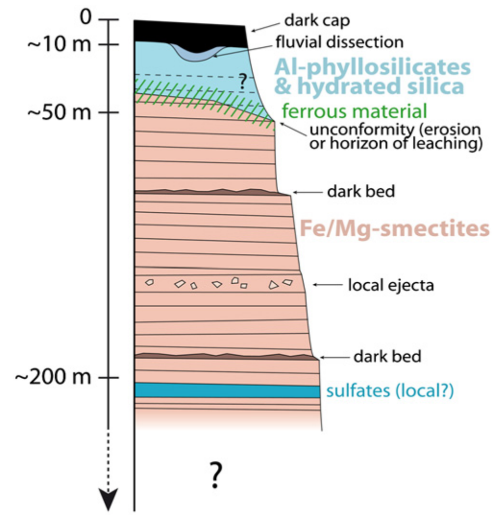

Fig. 7. Schematic stratigraphic column of the main clay-bearing layered unit on the plateau around Mawrth Vallis. The thickness of individual layers is not drawn to scale. Dark beds correspond sometimes to cratered surfaces (perhaps hiatuses of deposition) as discussed in Loizeau et al. (2010); their number and position are not well defined. The total thickness of the layered unit is also unknown but reaches 200 m at single outcrops on crater walls (Loizeau et al., 2010). Sulfates (spectrally similar to bassanite) were detected by Wray et al. (2010) below Fe/Mg clay bearing layers. Farrand et al. (2009) also detected jarosite in a less clear setting. The Al–phyllosilicate zone in blue is sometimes seen to truncate the Fe/Mg-smectite zone in red (e.g. Loizeau et al., 2010), probably due to variations of a horizon of leaching (Michalski et al., 2010). Some fluid circulation may also have mineralized some fractures going through the clay-rich layers after their deposition. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.2. *Age of the Oyama crater floor*

Following the formation of the main clay-rich layered unit in the Mawrth Vallis plateau region, some remobilization of the clay-rich rocks took place. Wind and/or water-related activity reworked clay-rich rocks, creating new deposits in local depressions, such as the floors of Mawrth Vallis and of Oyama crater (e.g. Loizeau et al., 2007), as illustrated in Fig. 2. The floor infill in the Oyama crater (diameter ~100 km) offers a relatively large area for crater counting. The area that has been investigated covers most of the crater floor, but excludes the walls and some impact ejecta on the western side (Fig. 8). The largest craters were considered, as we wanted to estimate the age of the crater infilling, and not that of later resurfacing events. By using crater with diameters > 1 km, effects from the dark cap on the age estimation are avoided. The cumulative crater size-frequency distribution (Fig. 8) follows the ~3.8 Ga model isochron (3.78 + 0.03/ − 0.04 Ga) for craters above this limit and we attribute the layered deposits on the floor of Oyama crater to have formed at that model age.

4.3. *Age of the capping unit*

Major portions of the dark capping unit material have been eroded—often completely removed. This has allowed us to detect the underlying clay-rich rocks. On the other hand, the remaining capping unit patches available for study present relatively small areas, with small craters often filled by dark sand due to this erosion in the region, which are difficult to assess. The largest remaining dark cap patches have been chosen for estimating the age of the capping unit. Crater counts have been made for two

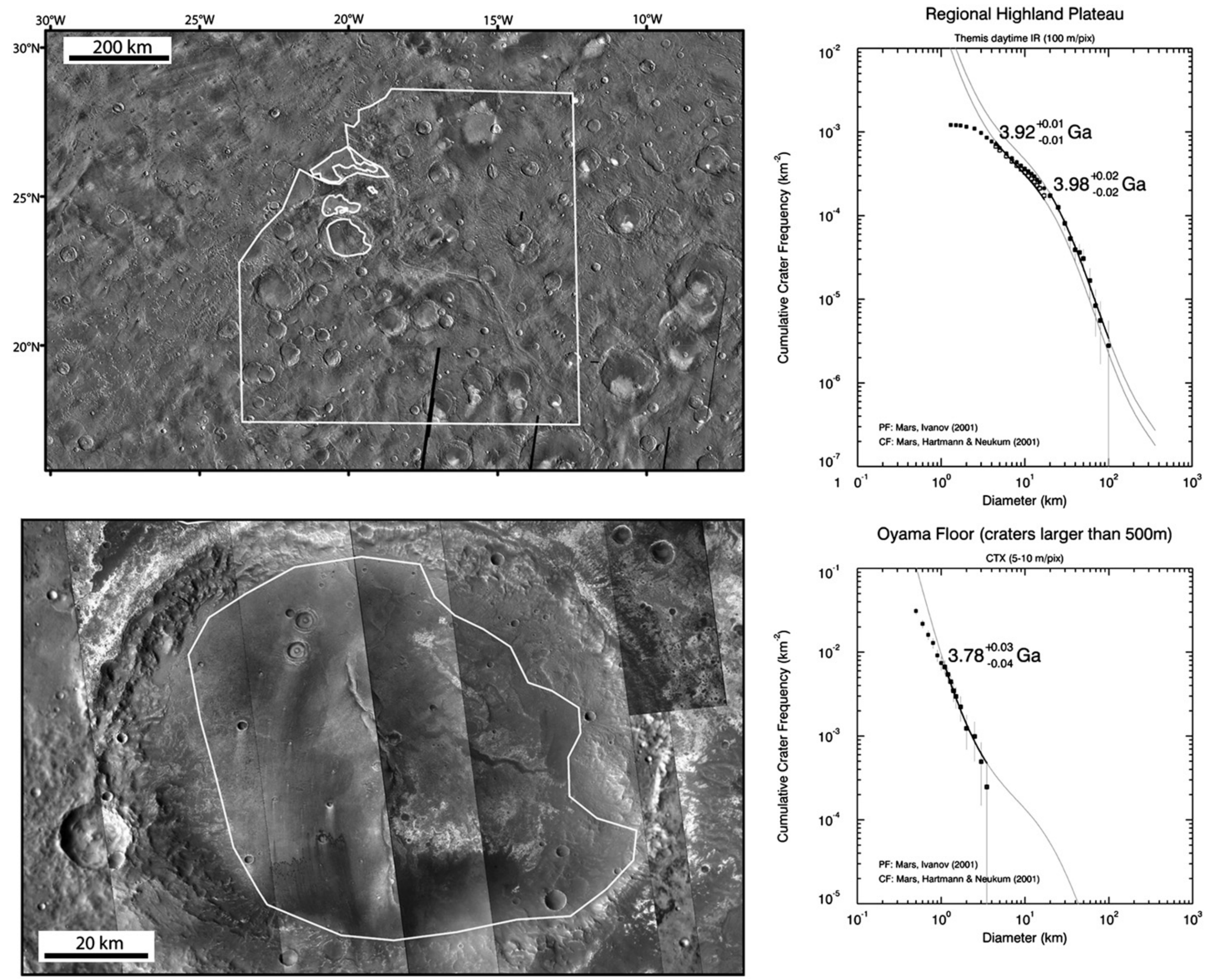

Fig. 8. Top Left: counting areas over the region of Mawrth Vallis (THEMIS IR daytime mosaic). The largest delimited area corresponds to the "regional plateau", while the four smaller delimited areas correspond to the lower image and to Figs. 8 and 9. Top Right: resulting formation and resurfacing cumulative crater size distribution (filled-squares and open-squares respectively) and fitted isochrons for formation and resurfacing: the plateau formed ~4.0 Ga ago, a first resurfacing event is dated to ~3.9 Ga. Bottom Left: Oyama crater floor (CTX mosaic) and delimited area of the crater count. Bottom Right: resulting cumulative crater size-frequency distribution and fitted isochron at ~3.8 Ga. Note that the two similar, strangely shaped craters in the northwestern part of the enclosed area were not counted in the crater size distribution, as their morphology does not correspond to usual impact craters of this size.

relatively close capping unit areas (Fig. 9): (a) a larger one, area 1, just to the north of Oyama crater, and (b) a smaller one, area 2, south of the Mawrth Vallis mouth.

Area 1 contains big craters; however, the largest (~12-km diameter) crater, towards the north, has not been included in the count, as it is completely filled and thus obviously older than the capping unit. For the few craters >2 km in diameter, the cumulative crater distribution indicates a model age of ~3.95 Ga (3.97+0.05/−0.08 Ga). These large craters could not be erased by the ~10 m thick capping unit: this age likely corresponds to the clay-unit surface below the dark capping unit, as also seen in the regional count (Fig. 8). For smaller craters, the deviating cumulative distribution section can best be modeled by a resurfacing age at ~3.75 Ga (3.73+0.04/−0.05 Ga). This age could indicate the capping unit formation, but may also simply indicate the last major erosion event of the underlying clay-rich unit. Area 1 has suffered further resurfacing, as indicated by the shallow crater size-frequency distribution when compared to the isochron.

Area 2, the second, smaller cap unit portion, has just one crater of diameter >1 km, but this crater is filled by the capping unit, thus it is likely older than the capping unit. The five largest craters (possibly also present before the capping unit deposition) follow a model isochron at ~3.85 Ga (3.83+0.06/−0.10 Ga) that may reveal the resurfacing of the underlying clay-rich surface. However, this value is less well constrained than other ages, due to the low number of craters. The crater distribution for diameters between 500 m and 250 m follows a model isochron at ~3.65 Ga (3.66+0.04/−0.06 Ga) with resurfacing correction. This value is more likely to indicate the age of formation of the capping unit. Given the model's uncertainty, this age can be considered similar to or slightly younger than the ~3.75 Ga resurfacing age derived from the area 1. Finally, for smaller craters, the crater curve suggests that the capping unit material of area 2 has suffered further erosion.

The exposed position of area 2, on a local high elevation, suggests that it was mostly modified due to material removed by

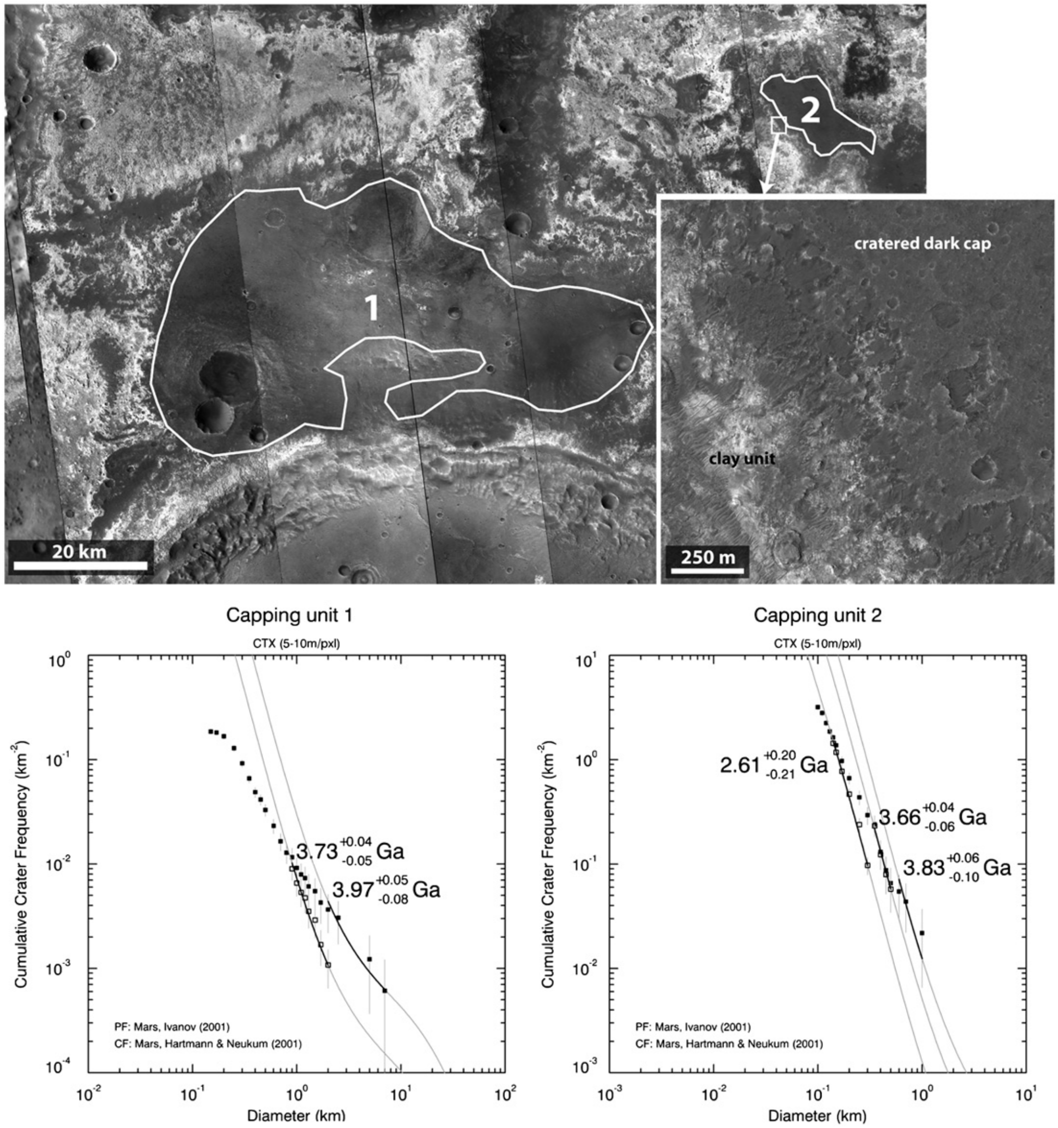

Fig. 9. Count areas over the dark capping unit in areas 1 and 2, north of Oyama crater (top), with a close-up at the border of the dark cap (HiRISE image PSP_002351_2050_RED), and resulting formation and resurfacing cumulative crater size frequency distributions (filled-squares and open-squares respectively), and fitted isochrons with model ages (bottom). The oldest age for area 2 is only determined using five craters, and hence is less well constrained than the other ages. The dark capping unit being quite thin (~10 m thick), the largest craters in these counts were probably only draped by the cap, preexisting its deposition. Also small craters are filled, as observed on the HiRISE close-up. The deposition of the dark capping unit is interpreted to be no older than the first resurfacing event in these two areas, about 3.7 Ga ago.

erosion, while area 1, in a local basin, was likely a place where material would have accumulated.

The interpretation of the formation age for the dark capping unit is difficult. First, since wind erosion has clearly reworked its surface, small craters could have been erased. Even though surfaces have been carefully chosen to exhibit limited erosion, the resulting estimated ages could be younger than the real age for capping unit formation if we look at small craters (~100 m in diameter). Second, the capping unit is only ~10 m thick in most places where vertical extent could be evaluated from HRSC DEMs (e.g. Loizeau et al., 2010). Large craters present before the capping unit deposition would have been simply draped, but remain visible today. Thus, an age older than the capping unit could be estimated through the largest craters of the distribution. Hence, the crater size frequency distribution of the capping unit surfaces may both show the ages of the older underlying surface and of resurfacing events younger than the dark cap deposition.

Given the crater size distributions of areas 1 and 2 in Fig. 9, we can conclude that a last resurfacing of craters >400 m in diameter on the plateau clay-bearing unit, which may correspond to the deposition of the dark cap, occurred ~3.7 Ga ago.

4.4. Age of the deposits in the mouth of Mawrth Vallis and Chryse Planitia

Non-altered deposits in Chryse Planitia, extending into Mawrth Vallis' mouth, have filled the plain northwest of the Mawrth Vallis plateau, extending around clay-rich buttes, and reaching the clay-rich cliffs north of the plateau (see Figs. 1, 2 and 10).

A large area from Mawrth Vallis to Chryse Planitia has been investigated to determine the age of these deposits. Fig. 10 shows the region studied and its crater size-frequency distribution. The model deposition age is ~3.55 Ga, but the surface suffered more recent resurfacing, likely around 1.15 Ga ago.

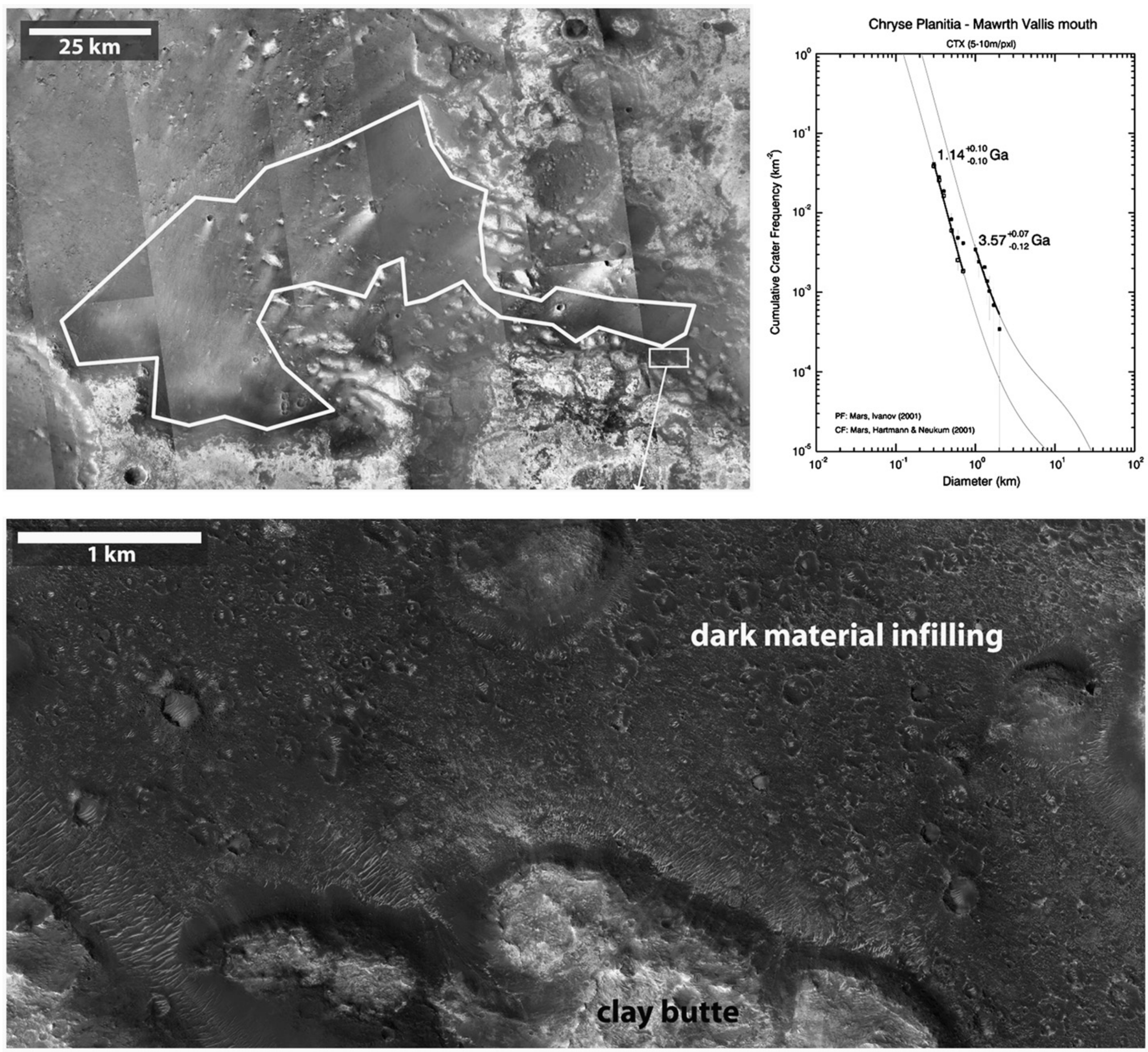

Fig. 10. Top: count area over the mouth of Mawrth Vallis and Chryse Planitia (left), and resulting formation and resurfacing cumulative crater size frequency distribution (filled-squares and open-squares respectively), and fitted isochrons with model age (bottom). The dark deposits in Mawrth Vallis' mouth are between 3.45 and 3.65 Ga old, and suffered resurfacing about 1.15 Ga ago. Bottom: HiRISE close-up (PSP_22011_2060_RED) just outside of the count area, displaying the dark material infilling of Mawrth Vallis' mouth and emerging clay buttes. The clay buttes are much eroded while the flat dark material retains craters.

The age of these deposits is an additional constraint to the end of the surface alteration process in the region and also to the activity of the outflow in Mawrth Vallis.

5. History of the clay layered unit of the region

The regional crater distribution shows that a large part of the region's highland plateau should have been formed by ~4.0 Ga ago, as indicated by the retention age of the biggest craters (diameter >20 km). From our work it is not possible to establish if the layered unit was entirely formed at that time, if major alteration had already begun, or indeed, if it was extensive. However, since crater walls and stratigraphical studies indicate a thickness >200 m for the layered-unit around Mawrth Vallis, and possibly >500 m, depending on the stratigraphy of the unit (Loizeau et al., 2007), a significant part of the clay-bearing layered unit may have been deposited by ~4.0 Ga ago.

The same regional crater count also shows a regional resurfacing age at ~3.9 Ga for crater diameters <20 km, indicating a major resurfacing event, eroding or infilling these craters. The local crater counts on the capping unit also indicate an age for the largest craters (diameter >1 km) of around ~3.8 to ~4.0 Ga. This can be explained by the presence of a surface of this age just under the ~10 m-thick dark capping unit. Hence, the surface of the clay-rich layered unit would be from ~3.8 to ~4.0 years old. This represents either the age of the end of the deposition, or a major erosion of the surface (for example by intensive fluvial erosion, as many small valleys are observed in the top layers of the clay-rich unit (Loizeau et al., 2007; Mangold et al., 2010)).

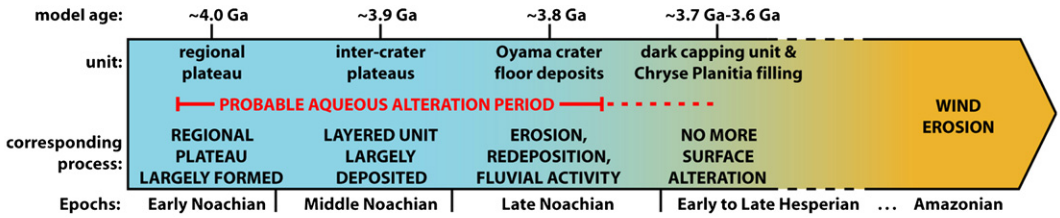

Fig. 11. Approximate model ages of the different counted units in the Mawrth Vallis region (top) and corresponding formation/alteration processes (bottom). The beginning of the layered unit deposition and alteration cannot be directly dated, but it is estimated that the unit was emplaced, at the latest, between 4.0 and 3.9 Ga ago. The cratering record indicates that all major alteration of the surface would have stopped ~3.7 Ga ago the latest to account for the lack of alteration of the dark cap. The major part of (if not all) the alteration would have occurred during the Noachian Epoch (based on the chronology and production function from Ivanov (2001)).

The crater count on the floor of Oyama shows that the impact happened prior to 3.8 Gy, and it also happened after the formation of the main layered unit as shown by stratigraphic relationships (illustrated in Fig. 2), hence after 4.0 Ga. This count also shows that the clay-rich deposits of the floor of Oyama were emplaced ~3.8 Ga ago. This deposition may be related to the fluvial dissection of the surrounding plateaus and rim of the Oyama crater. Ejecta of Oyama have not been found around the crater, suggesting they were deposited above the former deposits and subsequently removed by erosion before the dark cap deposition.

Concerning the dark capping unit, its unaltered composition as seen from orbit indicates that this unit records the end of surface alteration in the region, as well as the end of the deposition of the clay-rich layered unit and of fluvial dissection of the plateaus. The estimated model age of the last resurfacing of the plateau clay unit, and possibly of the dark cap, in between 3.7 Ga and 3.6 Ga, is the youngest possible age for the last surface alteration at Mawrth Vallis.

Chryse Planitia and Mawrth Vallis mouth infilling occurred around 3.55–3.6 Ga ago, possibly linked to the dark cap deposition. It also marks the end of the surface alteration in the region and of any outflow activity in Mawrth Vallis.

These ages can also be translated into the classical stratigraphic epochs, using the new scale given by Werner and Tanaka (2011), to enable comparison with other regions on Mars.

The probable age of the dark cap is between 3.7 and 3.6 Ga, which gives a major transition from altered to unaltered surface units. This can be translated as being Early Hesperian, a period during which major transitions occurred on Mars. Indeed, this period marks the end of the activity of valley networks (Fassett and Head, 2008). The age of the fluvial valleys observed in Mawrth Vallis fits with this global study. This age is also consistent with a change in crater degradation, as obtained from the transition between heavily degraded craters in the period before 3.7 Ga, towards less intensely degraded craters after 3.7 Gy (Craddock et al., 1997; Mangold et al., 2012).

The Al–clay, from the alteration of the uppermost section of layers, should have formed between 3.8 and 3.7 Ga, inside the Late Noachian to beginning of the Early Hesperian Epochs. Such an age is similar to that found for the same Al- over Fe/Mg–phyllosilicates sections in other regions: in Valles Marineris, it postdates the Noachian lava flows but is confined below fresher Early Hesperian lava flows (Le Deit et al., 2012); in Nili Fossae, it is superimposed at the top of the Noachian crust (e.g. Ehlmann et al., 2009; Gaudin et al., 2011).

The deposition of clay-bearing material on Mawrth Vallis' plateau is older than ~3.8 Gy, with a beginning probably before ~3.9 Ga, in the Early and/or Middle Noachian Epochs. This period is poorly understood on Mars, and therefore these deposits are some of the best-preserved, oldest sedimentary records of the planet.

6. Habitability and preservation

Liquid water was present at the surface and in the shallow subsurface in the Mawrth Vallis region during the Noachian Period over large areas, and during a significant length of time to allow alteration of large amounts of rocks. Liquid water was also present during multiple periods and environments, as revealed by the different chemical conditions of alteration that formed several types of clays and sulfates in the region, in distinct geological units. These correspond to many different environments of exobiological interest.

Furthermore, clay-rich sediments are known as a favorable environment for the preservation of biosignatures (Farmer and Des Marais, 1999). Also, the mineralogy of the clay-rich unit does not indicate any deep burial diagenesis, which could have damaged potential biosignatures (see Bishop et al., in this issue).

Finally, the freshness of the clay-rich outcrops, protected by the dark cap and more recently eroded by wind, gives also access to rocks which have been preserved from long exposure to the sterilizing atmosphere and cosmic rays.

Hence, any biosignature that may have been present in the layers in the plateaus around Mawrth Vallis would have been buried with the clay-rich sediments before 3.8 Ga. Some of these biosignatures may have been transported and redeposited in layers on the floor of Oyama crater, together with possible new biosignatures formed during this episode, about 3.8 Ga ago. New biological activity may also have occurred when the topmost Al–phyllosilicate-rich rocks formed before 3.7 Ga, as well as in groundwater, circulating in fractures for example, as revealed by the halo-bounded fractures throughout the region.

7. Conclusion

The surfaces for which the ages were evaluated in Mawrth Vallis are ancient and have suffered episodes of erosion and deposition. Hence, crater size frequency distributions always show resurfacing ages. Under these conditions, to provide a precise age of formation is not straightforward, but formation and erosion ages can be constrained and evaluated by examining the region's stratigraphy (see Figs. 2 and 7), and dating key surfaces in this stratigraphy. The chronology of the Mawrth Vallis region, based on these observations, is summarized in Fig. 11.

The crater size frequency distribution of the plateau coupled to relative stratigraphy allowed us to better constrain the age of the dominant geological episodes in the Mawrth Vallis region. From bottom to top, we infer:

(i) The main clay-rich layered-unit was deposited in the Noachian Period, between 4.0 Ga, and 3.8 Ga ago. Fe/Mg–smectites inside these sediments formed during deposition or predate this period.

(ii) The Oyama crater formed before ~3.8 Gy during the Middle to Late Noachian, followed by deposition on the crater floor of reworked clay-bearing layered material.
(iii) Fluvial incision by small valleys occurred until ~3.7 Gy ago (Late Noachian–Early Hesperian), as well as the incision by the Mawrth Vallis outflow.
(iv) The leaching observed regionally in the top layers, characterized by the Al–phyllosilicate outcrops, occurred between ~3.8 and ~3.7 Ga. This episode may be coeval to the fluvial incision. Some large fractures indicate groundwater circulation after the deposition and fracturing of the layers, opening the possibility of local underground alteration along these fractures, which is more difficult to date.
(v) The dark capping unit was deposited unconformably over an eroded substratum of clay-bearing deposits probably 3.7–3.6 Ga ago during the Hesperian, marking the end of any surface alteration.
(vi) The Chryse Planitia episode of infilling around 3.6 Ga ago during the Late Hesperian postdates all episodes of surface water alteration inside the Mawrth Vallis plateau.

Since then, wind erosion has removed large parts of the capping unit, exposing the underlying clay-rich rocks, further eroding them so that the clay-rich outcrops appear very young when compared to the age of the surrounding regional units. Aeolian activity can also explain the absence of dust around Mawrth Vallis, an important factor that has enabled orbital imaging spectrometers to unambiguously identify the clay minerals.

The chronology of deposition and alteration in the Mawrth Vallis region points to complex aqueous activity at the surface of Mars, revealing many potentially habitable environments > 3.7 Ga ago. The lack of detection of extended aqueous alteration in geologic units formed later on Mars indicates that a global change occurred at that time, and that the presence of liquid water was either too short-lived or too local after 3.7 Ga to alter any significant amount of rocks. Younger, Hesperian clay-bearing deposits such as the bottom layers of the central mound in Gale crater (Thomson et al., 2011) are either reworked rocks altered beforehand, or characteristic of only local and short-lived aqueous environments. Mawrth Vallis offers us a unique opportunity to investigate a well-preserved record of sediments formed at the surface/shallow sub-surface during the most active period of surface alteration on Mars. Hence this region provides an exceptional access to the time when Mars was the most likely habitable on a large scale.

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