Geology of Aeolis Dorsa alluvial sedimentary basin, Mars

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ABSTRACT

Aeolis Dorsa is a topographic depression, ~800 km east of Gale Crater, located along the Mars’ dichotomy boundary. This area hosts a set of fluvial sedimentary rocks displaying an exceptional record of depositional environments and fluvial channels patterns that suggest the presence of a large amount of surface and/or subsurface water. We interpreted the plain as an ancient waterlogged environment, a sedimentary basin passing into distal depositional environments. Regional mapping of the area revealed the presence of a large-scale fluvial system that points to a long-term and extensive hydrological cycle. A significant wet period with changing environmental conditions in Hesperian/Amazonian occurred in the study area diverging from the present-day climate. Our map (Main Map) contributes to the understanding of past climatic conditions on Mars. Moreover, it provides an interesting perspective for future missions looking for evidence of present-day and/or past extraterrestrial organisms as the life as we know it needs liquid water.

1. Introduction

The Aeolis Dorsa region (centered at 151°E 3°S; Figure 1(A–B)) is a broad depression located along Mars’ highland-lowland boundary, ~ 800 km east of Gale Crater. This region records several geological events, but also eroded morphologies. The identification of the stratigraphy of the studied region is challenging owing to the difficulty in discriminating between multiple fluvial and alluvial events within heavily eroded surfaces. The Aeolis region was deeply investigated by several authors, who identified different fluvial and alluvial morphologies: a dense cluster of sinuous ridges (e.g. Burr et al., 2009; DiBiase et al., 2013; Pain et al., 2007), recently interpreted as exhumed fluvial channels (also mentioned as inverted in Burr et al. (2009, 2010)) in which differential eolian erosion has removed fine sediments and exposed remnants of more resistant and coarser channels as sinuous ridges or meander belts.

Aeolis Dorsa basin fluvial deposits are stacked within the two westernmost lobes of the formal Medusae Fossae Formation (MFF) (Tanaka, Robbins, Fortezzo, Skinner, & Hare, 2014), an extensive light-toned and friable layered unit. The origin of the MFF is still debated, although terrestrial ignimbrites seem to be the best analog (Mandt, de Silva, Zimbelman, & Crown, 2008; Scott, 1982; Scott & Tanaka, 1986; Zimbelman, Crown, Grant, & Hooper, 1997). The MFF onlaps the dichotomy boundary from 140°E to 230°E, locally reaching a thickness of 2–3 km (Greeley & Guest, 1987; Scott & Tanaka, 1986). Though previous studies suggested that MFF is one of the youngest Martian deposits (Amazonian, Head & Kreslavskky, 2001, 2004; Schultz & Lutz-Garihan, 1981; Scott & Tanaka, 1986; Werner, 2006), and fluvial activity during the Amazonian period was recently confirmed (Adeli et al., 2016; Salese, Di Achille, Neesemann, Ori, & Hauber, 2016; Wilson, Howard, Moore, & Grant, 2016), recent findings stated MFF is partly Hesperian-aged (Kerber & Head, 2010; Tanaka et al., 2014; Zimbelman & Scheidt, 2012).

With the main aim, firstly, to provide a detailed cartographic base and, secondly, to bind the geographic distribution, the stratigraphic relations and ultimately the evolution of the sedimentary deposits of the Aeolis Dorsa region, we produced a geological map (Main Map) at the 1:430,000 scale, using multiple datasets including altimetry and visible images at various spatial resolutions (e.g. from 50 m pixel−1 to 25 cm pixel−1). Our mapping partly matches the Kite et al. (2015) division, but – in order to reflect Journal of Map’s spirit – here we present a Main Map that shows the geological framework of Aeolis Dorsa attempting a ‘two-scales analysis approach’, e.g. the association of a greater cartographic detail to a wide regional context analysis. The discussion focuses on the implications of these observations and their genetic interpretations on the Hesperian and Amazonian evolution of Aeolis Dorsa.
2. Datasets and software

2.1. Datasets

Visible imagery at different scale was used to reconstruct the stratigraphy of the studied region. High Resolution Stereoscopic Camera (HRSC) images (12.5–25 m pixel\(^{-1}\)) (Jaumann et al., 2007; Neukum & Jaumann, 2004) were used for morphological interpretations at a regional scale. The Context (CTX) camera (6 m pixel\(^{-1}\)) (Malin et al., 2007) and the High Resolution Imaging Science Experiment (HiRISE) camera (25 cm pixel\(^{-1}\)) (McEwen et al., 2007) provided detailed images which were useful to reconstruct stratigraphic relationships. Visible images were used in association with altimetry data at different scales, such as the Mars Orbiter Laser Altimeter (MOLA) dataset (Smith et al., 1999) at \(\sim\)463 m pixel\(^{-1}\), digital elevation models (DEMs) constructed from HRSC stereo images at \(\sim\)50–150 m pixel\(^{-1}\), and CTX and HiRISE DEMs with the minimum gridding of 6 and 1 m pixel\(^{-1}\), respectively.

2.2. Software

CTX and HiRISE DEMs were processed to produce stereo pairs using the NASA Ames Stereo Pipeline (Broxton & Edwards, 2008; Moratto, Broxton, Beyer, Lundy, & Husmann, 2010); CTX stereo pair images were then radiometrically corrected and projected using the USGS software ISIS (Integrated Software for Imagers and Spectrometers).

All data were integrated into the Arc-GIS platform (v. 10.2.2) and co-registered in the geographic coordinate system for Mars with a sinusoidal map projection (central meridian 155\(^\circ\)).

3. Description of the units

We grouped all the pre-fluvial units in a single unit because they were not the focus of our study. Embayed by younger alluvial deposits in onlap, it includes an eroded paleotopography at east, plateaus at south and deep inliers in the central part of the basin. We indicated these sub-units as ‘early materials (E)’ that may be mostly considered volcanic (and impacts?) materials.
even though other depositional processes cannot be excluded. Fluvial unit 1 (F1) hosts Aeolis Serpens, the Martian longest known channel (about 500 km (Williams, Irwin, Burr, Harrison, & McClelland, 2013)) and its deposits. F1 unit at HiRISE resolution consists of faintly bedded light-toned deposits disrupted into meters-scale up to tens of meter polygonal surfaces. Unit F1, rough at CTX-scale, includes: (1) up to \( \approx 2 \) km-wide exhumed meander belt deposits, and (2) adjacent sedimentary materials related to earlier floodplain deposits (Figure 2(A–C)). The former deposits are topped by isolated meandering ridges that are well exposed in the easternmost part of the basin.

![Figure 2.](image)
The latter deposits, located beside the channels, show planar bedding at HiRISE scale (Figure 2(C)) and appear more eroded than the channels. Small yardangs (hundreds meters scale) affect the surface of the unit with an orientation varying from NW-SE in the central part of the basin to N-S in the southern region.

Unit F1 is fairly constant in elevation trending to a horizontal geometry northward. Unit F1 rests non-conformably on top of the underlying pre-fluvial materials.

Fluvial unit 2 is present only in the south-western part of the study area (F2; Figure 2(D)). Unit F2 consists of a light-toned deposit with polygonal pattern fractures at HiRISE scale; while it is rough at CTX-scale. HiRISE images analysis show boulder-sized objects along unit F2 scarp (Figure 2(E)). Channels deposits are generally NE-SW trending and are characterized by flat tops. Small yardangs are present and mostly N-S oriented. F2 unit outcrops at higher elevations (> −2000 m) than the other fluvial units (F1, F3 and Fal). We will discuss the stratigraphic position of F2 in the next section.

Fluvial unit 3 consists of broad domes superposed on unit F1 in southeast Aeolis Dorsa region (F3; Figure 2(F)). Unit F3 is slightly darker-toned compared to F1 and F2 at HiRISE scale; it is covered by recent (loose?) dust and appears smooth at CTX-scale except for the km-scale knobs. Small-scale channels (generally <10 km in length) are found preserved both in negative and positive (exhumed – inverted) relief. Recent eolian dune forms, small craters and km-scale knobs are widespread, while yardangs are absent. F3 deposits rest disconformably on top of F1 materials and their contact varies around fairly constant −2250 m.

Fan-shaped deposits (unit Fal) branch downslope from both high-standing Aeolis and Zephyria Planum plateaus. This unit rests in possible disconformity on top of both F1 and F3. Channels are exhumed, suggesting that the surrounding lobes materials have been removed most probably by wind action after their deposition (Figure 2(G)).

An ‘undefined unit’ has been established in order to indicate some light-toned, rough deposits, at CTX-scale, that are difficult to assign based on our assignment criteria. These deposits might likely be part of units F1 or F2, or be a transition unit, but as they lack of the most significant fluvial morphologies and show pervasive eolian bedforms, we prefer to indicate them as unclassified.

Two post-fluvial units were also defined: Unit G (Figure 3(A)) and H (Figure 3(B)). The former is represented by Aeolis and Zephyria Plana materials and consists of rough and slightly darker-toned materials compared to the fluvial units at CTX-scale. Unit G shows morphologies reflecting eolian erosion (erosionally resistant 100 m-scale knobs) and no fluvial or other water-related landforms. It crops out roughly at elevation >−2100 m and superposes fluvial units; the nature of the limit with the fluvial units is uncertain. Unit H outcrops in the easternmost part of the basin and on Zephyria Planum plateau. This unit is represented by horizontal indurated thin-layered and dark-toned materials that are densely and heavily grooved by deflation, forming pervasive yardangs dissection. Unit H drapes disconformably all the older units and represents the youngest unit of the Aeolis Dorsa stratigraphic succession.

The geological mapping allowed us to reconstruct the stratigraphic framework of the area and to
characterize the putative ancient river network of Aeolis Serpens that flowed in Aeolis Dorsa and extended over a large portion of the basin (Figure 1(B)).

4. Discussion

We suggest an alluvial origin for Aeolis Dorsa basin deposits because of the presence of morphologies such as meander belts (Figure 2(A,B)), alluvial fans (Figure 2(G)) and straight rivers and network type (Figure 1(B)). The areal channel pattern shows remarkable analogies with alluvial basins on Earth with tributary rivers flowing into a trunk that stretches longitudinally. Some of these channels have been interpreted as distributary by DiBiase, Limaye, Scheingross, Fischer, and Lamb (2013); this interpretation cannot be excluded; however, we prefer the north-going system interpretation because it is more consistent within a regional context. The presence of low-standing areas between and adjacent to meander belts showing flat-lying bedding and probably consisting of relatively easily erodible finer-grained deposits is consistent with flood plain deposition (Pondrelli et al., 2011) due to a lower cementation grade. The geological mapping and derived stratigraphic framework outline four main geologic events in Aeolis Dorsa: (1) pre-fluvial materials deposition and erosion prior to (2) a wet period in which water was stable on the surface for a geologically significant amount of time, (3) post-fluvial erosion and (4) deposition of post-fluvial materials. The sketch shown in Figure 4 sums up the geological evolution of the basin. Pre-fluvial materials (E) have been eroded before fluvial materials embayed them; Unit E shows no association with fluvial- or alluvial-related morphologies.

The widespread identification of channels suggests a relatively long-lasting fluvial activity, too long to be explained by a single short-lived wet episode; in fact, a variety of ages have been proposed for these fluvial deposits (Kite, Williams, Lucas, & Aharonson, 2014). Three different fluvial units, F1, F2 and F3, have been recognized based on channel morphologies and textures, channel-deposit ratio, stratigraphic relations, presence of post-fluvial features such as yardangs and dune forms. Even though small yardangs in F1 could mark a later period of erosion/non-deposition, we assume that some fluvial erosion should have occurred between the different fluvial episodes and, hence, units, but it was not significant, since the contacts run fairly constant in elevation (≈200–250 m elevation gap) all over the study area at the scale of our analysis. Furthermore, paleo-channels orientation trend in unit F1 and unit F3 is mostly concordant; slight differences are expected considering possible post-formation modification (Lefort, Burr, Beyer, & Howard, 2012). As erosion has heavily affected the region after the deposition of the fluvial materials, it is likely that unit F3 was more extended once and, hence, present-day domes may be part of a previous and continuous outcrop. The fact that channels embedded in F3 deposits show the same trend in different outcrops is consistent with this interpretation. The stratigraphic position of unit F2 is ambiguous: Kite et al. (2015) noted that F2 deposits outcrop both above and beneath unit F3 in different locations. It may: (1) postdate both unit F1 and unit F2 or (2) it may be heteropic and, hence, in lateral transition with the other fluvial units. We prefer the latter hypothesis due to the foresaid ambiguous presence of F2 outcrops concurrently with unit F3, but the stratigraphic succession is still uncertain.

We analyzed qualitatively the mutual proportion of channel versus deposit (and their type) among units in order to better characterize the nature of the alluvial systems. As eolian bedforms cover most of F3 surface, interpretation is more difficult in this unit, but some considerations can nevertheless be made. The proportion of channels versus deposits appears to be higher in F1 and F2 than F3. Accordingly, it may be assumed that unit F3 contains a higher percentage of floodplain deposits compared to F1 and F2, which instead host a greater presence of channel deposits. Well-preserved meander belts, point bars and individual meandering channels within unit F1 (Figure 2(A, B)) attest a relatively long-term water activity as meanders and related environments require a significant geological time to develop. The presence of boulder-sized objects in F2 unit scarp (Figure 2(E)) might imply increasing transport energy or anisotropic geochemical cementation conditions. This in turn implies a change in the controls on the deposition, possibly

Figure 4. Time-space geological sketch of Aeolis Dorsa basin. Thicknesses of some units are exaggerated for a better understanding and view.
reflecting climatic fluctuations of the system at regional scale and, hence, differential erosion of the unit. Unit Fal has been interpreted as alluvial fan deposits preserved in inverted relief that may superpose unit F1 and also unit F3 in the east. This depicts a complex scenario with different, laterally interfingering, depositional elements. An extensive region-wide period of erosion followed the fluvial deposits emplacement resulting in an exhumation of the older geomorphological features (meander belts and singular sinuous channel), which – due to the geochemical cementation – were more resistant to weathering and erosion before post-fluvial materials deposition. In fact, part of the unit H deposits lies unconformably in the more topographically depressed zones between both inverted exhumed F3 channels and F1 alluvial fan channels (Figure 5). This gap has been estimated as >10⁸ years using the population of craters embedded at the unconformity limit by Kite et al. (2015).

5. Conclusions

The geological mapping emphasized the presence, distribution and evolution of a large exhumed river system in Aeolis Dorsa during the elapsing time between the Hesperian and Amazonian.

A trunk river (or river system) stretched longitudinally and alluvial fans, distributary systems and tributary rivers flowed perpendicularly to the basin axis. Several time (and deposition) gaps have been noticed between observed deposits, so the whole stratigraphic sequence points to several deposition-erosion cycles controlled by the amount of available water provided by rain or snowmelt. We discard groundwater contribution because of (1) the lack of evident sapping channels and springs and (2) the articulated and well-distributed areal pattern. The presence of three types of fluvial deposits in Aeolis Dorsa points to different amounts of available water, different regime flows and amount of transported sediments. Accordingly, at least three main wet phases are recognizable, corresponding to three main different fluvial units. In conclusion, Aeolis Dorsa region deposits record a regional climate that differs from the present-day Martian environmental conditions. In those periods, the water supply had to exceed infiltration and evaporation processes in order to transport sediments. This implies that water was stable on the Martian’s surface for a significant geological interval of time, putting an important clue in the planet’s past climatic history and evolution.

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No potential conflict of interest was reported by the authors.

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