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Equatorial Layered Deposits in Arabia Terra, Mars: facies and process variability

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Abstract:	We investigated the Equatorial Layered Deposits (ELDs) of Arabia Terra in Firsoff crater and on the adjacent plateau. We produced a detailed geological map that included a survey of the relative stratigraphic relations and crater count dating. We reconstructed the geometry of the layered deposits and inferred some compositional constraints. ELDs drape and onlap the plateau materials of Late Noachian age while they are unconformably covered by Early and Middle Amazonian units. ELDs show the presence of polyhydrated sulfates. The bulge morphology of the Firsoff crater ELDs appears to be largely depositional. The ELDs on the plateau display a sheet-drape geometry. ELDs show different characteristics between the crater and the plateau occurrences. In the crater they consist of mounds made of breccia sometimes displaying an apical orifice laterally grading into a light-toned layered unit disrupted in a meter-scale polygonal pattern. These units are frequently associated with fissure ridges suggestive of subsurface sources. We interpret the ELDs inside the craters as spring deposits, originated by fluid upwelling through the pathways likely provided by the fractures related to the crater formations, and debouching at the surface through the fissure ridges and the mounds leading to evaporite precipitation. On the plateau, ELDs consist of rare mounds, flat-lying deposits and cross-bedded dune-fields. We interpret these mounds as possible smaller spring deposits, the flat-lying deposits as playa deposits, and the cross-bedded dune-fields as aeolian deposits. Groundwater fluctuations appear to be the major factor controlling ELDs deposition.
Suggested Reviewers:	Dorothy Z. Oehler, Ph.D Research Scientist, JETS/ LZ Technology dorothy.z.oehler@nasa.gov Described similar deposits in Vernal crater (Allen and Oehler, 2008)
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Equatorial Layered Deposits in Arabia Terra, Mars: facies and process variability

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ABSTRACT

We investigated the Equatorial Layered Deposits (ELDs) of Arabia Terra in Firsoff crater and on the adjacent plateau. We produced a detailed geological map that included a survey of the relative stratigraphic relations and crater count dating. We reconstructed the geometry of the layered deposits and inferred some compositional constraints. ELDs drape and onlap the plateau materials of Late Noachian age while they are unconformably covered by Early and Middle Amazonian units. ELDs show the presence of polyhydrated sulfates. The bulge morphology of the Firsoff crater ELDs appears to be largely depositional. The ELDs on the plateau display a sheet-drape geometry. ELDs show different characteristics between the crater and the plateau occurrences. In the crater they consist of mounds made of breccia sometimes displaying an apical orifice laterally grading into a light-toned layered unit disrupted in a meter-scale polygonal pattern. These units are frequently associated with fissure ridges suggestive of subsurface sources. We interpret the ELDs inside the craters as spring deposits, originated by fluid upwelling through the pathways likely provided by the fractures related to the crater formations, and debouching at the surface through the fissure ridges and the mounds leading to evaporite precipitation. On the plateau, ELDs consist of rare mounds, flat-lying deposits and cross-bedded dune-fields. We interpret these mounds as possible smaller spring deposits, the flat-lying deposits as playa deposits, and the cross-bedded dune-fields as aeolian deposits. Groundwater fluctuations appear to be the major factor controlling ELDs deposition.

INTRODUCTION

Layered deposits are very common on Mars at all scales (Thomas et al., 1992; Chapman and Tanaka, 2001; Malin and Edgett, 2000; Williams et al., 2003). Among them, light-toned layered deposits are diffuse in various locations in the equatorial regions of Mars, including the Valles Marineris and the chaotic terrains (Lucchitta et al., 1992; Chapman and Tanaka, 2002), crater bulges (such as Gale and Becquerel craters) (Lewis et al., 2008; Kite et al., 2013a, 2013b; Le Deit et al., 2013) and Meridiani Planum (Grotzinger et al., 2005; McLennan et al., 2005), and are grouped under the informal name of Equatorial Layered Deposits (ELDs) (Hynek et al., 2002; Okubo et al., 2009). However, those light-toned layered deposits that can be confidently interpreted as fluvio-deltaic systems are excluded from this definition (e.g. Pondrelli et al., 2011b).

The genesis of the ELDs has been attributed to many different depositional processes and environments, including lacustrine (Lucchitta et al., 1992; Newsom et al., 2003), sub-ice volcanism (Chapman and Tanaka, 2001; Komatsu et al., 2004), weathering of basalts (Madden et al., 2004), pyroclastic (Scott and Tanaka, 1982; Hynek et al., 2003; Kerber et al., 2012), and dust airfall (Tanaka, 2000; Michalski and Niles, 2012). Interplay between airfall and aeolian processes with groundwater fluctuations, leading to episodes of evaporite precipitation, have been proposed by Grotzinger et al. (2005), Andrews-Hanna et al. (2007, 2010), Murchie et al. (2009a), Andrews-Hanna and Lewis (2011) and Zabrusky et al. (2012). Ori and Baliva (1999) discussed the possibility of an interaction between lacustrine deposition and hydrothermal vents or large mud volcanoes. Groundwater upwelling leading to spring deposits precipitation and/or mud volcanoes deposition has been proposed by Rossi et al. (2008), Allen and Oehler (2008), Oehler and Allen (2010), Pondrelli et al. (2011a) and Franchi et al. (2014).

A compositional constraint was provided by the spectral data coming from OMEGA (Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité) (e.g. Bibring et al., 2005), on board the ESA Mars Express mission and from CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) on board the NASA MRO (Mars Reconnaissance Orbiter) (Murchie et al., 2007). Monohydrated and/or polyhydrated sulfates, suggestive of acidic conditions, have been in fact detected at several ELDs (Gendrin et al., 2005; Bibring et al., 2006; Mangold et al., 2008; Murchie et al., 2009b).

This work focuses on the ELDs located in Arabia Terra (Fig. 1A) and in particular on the area of Firsoff crater and the adjacent plateau (Fig. 1B).

Arabia Terra consists of heavily cratered Noachian plains partially covered by Hesperian material interpreted as low viscosity lava (Scott and Tanaka, 1986). It connects the highlands and the lowlands of Mars with relatively low slopes (less than 3° with the exception of the crater-related slopes) over a wide area (approximately 2500 X 3600 km) (Smith et al., 1999).

Here ELDs formation has been related to a groundwater-dominated hydrological system (Andrews-Hanna et al. 2007, 2010; Andrews-Hanna and Lewis 2011; Zabrusky et al., 2012).

Additionally, fluid expulsion-related processes have been increasingly invoked to explain the formation of some pitted cones and mounds within the light toned deposits in Arabia Terra (Allen and Oehler, 2008; Rossi et al., 2008; Pondrelli et al., 2011a; Franchi et al., 2014). Light-toned deposits in McLaughlin crater analyzed with CRISM data, in the topographically most depressed part of Arabia Terra, show evidence of Fe–Mg–smectite and possibly serpentine and carbonates (Michalski et al., 2013a). Michalski et al. (2013a) interpret these deposits as formed by alkaline fluids in a lake fed by groundwater upwelling. They claim that groundwater activity might have occurred at a small scale, locally heterogeneous, rather than as a global or regional processes (Andrews-Hanna et al. 2007, 2010; Andrews-Hanna and Lewis 2011) that have been invoked to explain overall “sulfate-ELDs” deposition.

In the adjacent Terra Meridiani, the fluid chemistry has been inferred to have been acidic (Tosca et al., 2005); however, the presence of smectites in the lower portions of the stratigraphic column (Arvidson et al., 2014) suggests at least partial formation under higher pH conditions (Wiseman et al., 2010). A hydrological cycle that drives groundwater upwelling requires surface temperatures to be above freezing for long periods of time in order to facilitate precipitation-induced recharge of the aquifers and subsequent evaporation.

Hydrothermal activity that may be associated with volcanic activity interacting with groundwaters, cryosphere or related to impact crater formation has also been invoked as a possible control to explain ELDs composition (e.g., Bishop et al., 2009).

Moreover, ELDs in Arabia Terra are particularly intriguing because they are documented both as crater bulges (Newsom et al., 2003; Allen and Oehler, 2008; Lewis et al., 2008; Pondrelli et al., 2011a) and in the plateau (Edgett and Malin, 2002), which may imply a complex geological history and a significant process variability.

We selected the study area (longitude 7.1°W-10.7°W, latitude 3.9°N-0.9°S) of Firsoff crater and the surrounding plateau (Figs. 1A, 1B) because here ELDs can be observed and are well exposed both in the craters and in the plateau (Edgett and Malin, 2002; Pondrelli et al., 2011a). Moreover, according to Scott and Tanaka (1986), this displays the geological context required to reconstruct the stratigraphic framework spanning a significant part of Mars geological history (Fig. 1C). The Noachian Cratered unit (Npl1) and Subdued cratered unit (Npl2) of the Plateau Sequence that represent the base of the stratigraphic sequence, result covered by the Hesperian Ridged Plains Material (Hr) (Scott and Tanaka, 1986). These units might help to consider the ELDs in a wider stratigraphic context.

In addition, this area has good data set coverage with a fully HRSC (High Resolution Stereo Camera on board of Mars Express, Neukum et al., 2004) and CTX (Context Camera on board of Mars Reconnaissance Orbiter, MRO, Malin et al., 2007) coverage, and a good CRISM and HiRISE (High Resolution Imaging Science Experiment on board of Mars Reconnaissance Orbiter, MRO, McEwen et al., 2007) coverage, including several stereo pairs (Fig. 1D).

We reconstructed the stratigraphic framework of the study area and constrained the depositional age of the ELDs. Subsequently, we evaluated the depositional geometries of the ELDs inside and outside of the craters. The morphologies, textures, sedimentary structures and compositional characters of the ELDs were analyzed to infer the depositional processes and emplacement environments. The resulting interpretation is discussed in the context of the regional geology and with regard to the possible implications in terms of habitability.

DATA AND METHODS

Mars Express (Mex) High Resolution Stereo Camera data (HRSC; Neukum et al., 2004;

Jaumann et al., 2007), data of the Mars Reconnaissance Orbiter (MRO) Context Camera (CTX; Malin et al., 2007) and MRO High Resolution Imaging Science Experiment data (HiRISE; McEwen et al., 2007) data have been processed using the JPL/DLR Video Image Communication and Retrieval (VICAR) environment software for HRSC data and Integrated Software for Imagers and Spectrometers (ISIS) provided by the United States Geological Survey (USGS, Anderson et al., 2004) for CTX and HiRISE data. All data were integrated in the software ESRI ArcGIS Geographic Information System (GIS).

We produced a detailed geological map at a mapping scale of 1:50000 in order to constrain ELDs' vertical and lateral stratigraphic framework and depositional geometries. In order to provide timelines to our reconstructions, we derived absolute ages using crater-size frequency analyses. Craters were counted using the CraterTools extension for ESRI ArcGIS software (Kneissl et al., 2011). Absolute model ages were determined using the software Craterstats (Michael and Neukum, 2010) applying the Mars production function of Ivanov (2001) and the chronology function of Hartmann and Neukum (2001).

CTX and HiRISE-based digital elevation models (DEMs) were computed using the NASA Ames Stereo Pipeline (ASP) suite (Moratto et al., 2010, Broxton and Edwards, 2008). 3D visualization and analyses have been made using the software QPS Fledermaus. Layer attitudes were measured using the software Orion from Pangaea Scientific.

MRO's instrument Compact Reconnaissance Imaging Spectrometer for Mars (CRISM; Murchie et al., 2007) provided hyperspectral data that were processed using the software CAT (CRISM Analysis Toolkit; Morgan et al., 2009), produced by the CRISM Science Team, which runs as extension to ENVI (ITT VIS). The spectral parameter maps were computed using the spectral parameter summary products described in Pelkey et al. (2007).

The geological map has been made using the available dataset, but mapping at CTX scale (i.e., 1:50000), with the aim to integrate geological and a geomorphological approaches. Accordingly, in defining the units, we tried to merge the information on the characteristics of the deposits (e.g., layered/non layered, albedo, texture, sedimentary structures, hints on composition where possible) together with their morphological characters both at regional (e.g., depositional geometries such as crater bulges, etc.) and more detailed (e.g., dunes, raised rims, etc.) scale. The position within the stratigraphic succession, defined using relative stratigraphy and constrained by crater counting analysis, has also been a key to distinguish the units. All these information were listed in the attribute table, so that a unit is defined by common deposits (e.g., high albedo, medium rough texture, layering, meter-scale polygonal pattern) showing the same morphologies at a regional (e.g., located within a crater bulge) and at a local scale (e.g., raised rims, circular depressions) and located in the same stratigraphic position within the succession (e.g., nonconformably on top of the Plateau Sequence and disconformably below the Hummocky Material).

No genetic interpretations on the units have been included in the units identification in order to make the geological map as objective as possible.

GEOLOGICAL SETTING

Our geological map of the study area (Fig. 2) enabled us to identify the lateral and vertical relations between the geological units and allowed us to eventually reconstruct the stratigraphic framework (Fig. 3).

The bases of the stratigraphic succession of the area are the Cratered and Subdued crater units of the Plateau Sequence (Scott and Tanaka, 1986). The Cratered unit consists of massive, although frequently fractured, medium albedo material. Locally it shows sharp edges which suggest a strong resistance to weathering; it can appear locally as smooth or rugged, thus suggesting a variety of emplacement processes. The Cratered unit is primarily found at the craters rims (Fig. 2).

According to Scott and Tanaka (1986), these materials formed during the period of high impact flux and are thus heavily cratered. They represent a mixture of lava flows, pyroclastic material and impact breccia.

This unit is nonconformably covered by the Subdued crater unit, which shows similar characteristics as the Cratered Unit, although darker-toned and smoother. This unit embays the older Cratered unit. Scott and Tanaka (1986) interpreted the Subdued crater unit as interbedded lava flows and aeolian deposits that partly bury the underlying Cratered unit.

ELDs rest nonconformably on top of both units of the Plateau Sequence (Figs. 2 and 3). Within craters, ELDs tend to drape and onlap the Cratered unit (Fig. 4A), whereas outside craters they drape both the Cratered and the Subdued crater units.

ELDs consists of distinctly to faintly layered light-toned deposits locally interlayered with layers of dark-toned material. In general, they show the characteristic pattern of the etched terrains as described in Meridiani Planum (e.g., Hynek et al., 2002). More in detail, their characteristics change substantially from the craters to the plateau (Table 1).

The depositional architecture in the craters consists of bulges which reach thicknesses of up to more than two thousand meters. In the plateau, instead, ELDs form sheet drapes. Locally, inside as well as outside the craters, mounds with diameters of a few hundred meters are associated with the well bedded ELDs. These differences in morphologies, detailed below, were used to distinguish sub-units among ELDs (Fig. 2).

ELDs are unconformably overlain, both inside and outside of craters, by a unit that we informally named ‘Hummocky material’ (Fig. 4B). This unit consists of dark-toned and relatively smooth material forming slightly irregular undulated surfaces at all scales but mostly characterized by high wavelengths (up to kilometers). This unit appears to be resistant to weathering and erosion showing at places sharp edges and boundaries. Where eroded, the resulting material appears to be reworked by wind to form aeolian dunes. The Hummocky material covers the previously deposited Plateau sequence and ELDs, preferentially, but not exclusively, occupying topographic lows. Although more detailed analyses would be necessary to properly interpret the genesis of the Hummocky material, the general character appears to be consistent with a deposition through pyroclastic processes, in particular pyroclastic surges.

In the southernmost part of the study area in the plateau the ELDs and the Hummocky material are unconformably covered by the Ridged Plains Material. The Ridged Plains Material consists of broad flat and rough surfaces very resistant to weathering and erosion with flow lobes visible in places and long, parallel, linear to sinuous wrinkle ridges. On the basis of such characters and due to its widespread geographical distribution, it has been interpreted as extensive flows of low-viscosity lava erupted from several sources at high eruption rates (Scott and Tanaka, 1986).

The youngest deposits of the area consist of mass wasting materials along the slopes and aeolian dust and dunes made up of dark-toned sediments draping the older parts of the succession.

Aeolian processes also produced erosional features, forming yardangs through incision of the ELDs both inside and outside of craters (Fig. 2).

In some areas the exposed surface has weathered to form a level of regolith. This material is indistinguishable from and probably mixed with later dust deposition, and has been mapped as the generic unit ‘mantling’ (Fig. 2).

The deposition age of the Cratered unit has been estimated by performing crater counts on the Firsoff crater ejecta (Fig. 5A). For an area of $2.62x10^3$ km we counted 174 craters in the diameter range of 0.1–7.2 km. This data yielded an estimated emplacement model age of $3.67^{+0.06}/_{-0.10}$ Ga or even earlier (Fig. 5B), corresponding to Late Noachian age, according to the size-frequency distribution of Hartmann (2005) and Werner and Tanaka (2011) (Fig. 3). The size-frequency distribution bends over at diameters of 300 m and less and shows a pronounced kink in the distribution indicating that the Cratered unit has undergone a resurfacing event up to $2.82^{+0.32}/_{-0.46}$ Ga (Fig. 5B), which corresponds to the Early Amazonian age (Hartmann, 2005; Werner and Tanaka, 2011) (Fig. 3).

The Hummocky material disconformably covers the ELDs inside (Fig. 6B) and outside (Fig. 6A) Firsoff crater. Both ELDs and Hummocky material drape the older deposits of the Plateau Sequence, possibly concealing some craters, likely representing the cause of the resurfacing events up to $2.82^{+0.32}/_{-0.46}$ Ga (Fig. 5B). Our data do not allow to distinguish the probably various phases of resurfacing events but the $2.82^{+0.32}/_{-0.46}$ Ga would mark the last event (emplacement of the last deposits of the Hummocky material) and thus postdate ELDs deposition.

The deposition age of the units on the plateau, in the southernmost part of the study area, has been estimated using crater-size frequency analyses in the area outlined in Fig. 5C. We counted 3495 impact craters in the diameter range of 0.04–4.0 km on a counting area of 12,734 km^2. Data were fitted up to a diameter size of 300 m where the distribution bends over towards smaller craters. The distribution does not show pronounced kinks but a general flattening near the 1 km diameter size indicating continuous erosion. Analyses resulted in a well-constrained emplacement age of $3.39^{+0.08}/_{-0.14}$ Ga and a resurfacing age of $1.07^{+0.05}/_{-0.05}$ Ga (Fig. 5D). In these zones, the Subdued crater unit is covered by the Ridged Plains Material (Figs. 2, 4B) which embays and partially conceal the older deposits. Accordingly, we interpret the $3.39^{+0.08}/_{-0.14}$ Ga as the depositional age of the Subdued crater unit and the $1.07^{+0.05}/_{-0.05}$ Ga as the depositional age of the uppermost portion of the Ridged Plains Material.

Relative stratigraphy and crater counting data are summarized in the space-time diagram of Fig. 3. According to these data, the Plateau Sequence would have been deposited until the Late Noachian (with an evident, although unquantifiable, nonconformity between the Cratered unit and the Subdued crater unit). ELDs deposition would be constrained between the Noachian-Hesperian transition and the lower part of the Early Amazonian, postdated by the Hummocky material deposition. The Ridged Plains Material was deposited until the Middle Amazonian, closing the stratigraphic succession of the study area with the exception of the most recent aeolian dust and dunes deposition and regolith formation.

EQUATORIAL LAYERED DEPOSITS: GEOMETRIES

ELDs mapped inside and outside craters (Fig. 2) show the same basic characters: faint to well-developed layering and high albedo. However, ELDs exhibit different depositional geometries depending on their location (Fig. 7A, Tab. 1). ELDs form a km-thick crater bulge inside Firsoff but exists as patches on the plateau (sheet drape shape) where they are irregular and rough at the 100s m scale but relatively flat at regional scale (Fig. 7B).

On the inner rim side of Firsoff, ELDs reach and cover the terraces related to the crater formation, located 400 m above the crater floor (Fig. 4A). No ELDs are found above that level. Using equations derived by Garvin and colleagues (Garvin et al., 2003) and assuming a simple ballistic impact, the geometry of the impact crater and therefore of the thickness of the sedimentary infilling can be (indirectly) estimated (Franchi et al., 2014; Lucchetti et al., 2014). In this case, the greatest thickness of the crater infill reaches about 2 km roughly on top of the central peak, whereas the thickness of sedimentary infill relative to the bulk of the crater floor, was estimated to reach up to 1.2 km (Franchi et al., 2014; Lucchetti et al., 2014). We acknowledge that these numbers are approximations since it is neither possible to quantify the effects of erosion nor the amount of materials (e.g., aeolian dust or dunes) deposited below the ELDs. Our aim is merely to infer the order of magnitude of the scale of the sedimentary body and its geometry as a whole.

On the plateaus next to Firsoff crater, ELDs do not form kilometer-thick mounds. They appear to drape the older plateau more or less homogeneously as a sheet drape, although irregularities exist at smaller scales (Figs. 7A, 7B). No complete section allows us to estimate the overall thickness of ELDs on the plateau, but the available exposures reach at maximum the ten meter-scale on the base of the available CTX-based DTM.

ELDS WITHIN CRATERS

ELDs are heavily eroded by aeolian activity as shown by the widespread presence of yardangs which occur especially, although not exclusively, in the topmost part of the bulge of ELDs in Firsoff Crater. Here, the depositional morphology of ELDs is obscured by the younger erosional landforms (Fig. 8A). The presence of such features implies that ELDs are made of relatively easily erodible material and that the original depositional geometry is at least partly destroyed by the erosion. However, especially on the crater floors most of the ELDs appear to be largely unaffected by aeolian erosional overprinting (Figs. 8A, 8B). In these locations, ELDs layers show rounded shapes or occasionally raised (Fig. 8C) margins, and lengthen irregularly in directions that are not consistent with a formation as erosional remnant resulting from wind action (Figs. 8B, 8C). Moreover, their orientation is unrelated to wind direction as inferred from yardangs (Fig. 8B). ELDs here are sinuous, rounded, locally showing quasi-circular depressions sometimes bounded by elevated rims.

Figure 8D shows a NW-SE-trending depression which is lens-shaped in plan view and displays a regularity and trend that seems to be unrelated to wind erosion as inferred from yardangs. Moreover, this depression is characterized by mounds (10s to 100s meters large) aligned along elevated lineaments (Fig. 8D, possible fissure ridges) both indicating a depositional origin.

On the basis of these observations we suggest that at least part of the ELDs morphologies are depositional or at least that they cannot be attributed to aeolian erosion alone.

In order to preserve depositional morphologies in the bulge of ELDs in Firsoff, the bulge must either represent the product of differential erosion that was able to exhume older preserved landforms, or it must be the original depositional landform with the exception of the post-depositional erosion emphasized by the yardangs. Desiccated fine-grained materials (i.e., clay- and/or silt-sized) might be relatively easily eroded by wind action. This has been considered as a likely process leading to the exhumation of clay-embayed bodies such as channels in Miyamoto (Newsom et al., 2010) and Eberswalde craters (Pondrelli et al., 2011b). Nevertheless, in our study area there is no evidence which might support the presence of different lithologies (i.e., fine-grained materials easily eroded by wind) that could explain differential erosion and exhumation of older preserved morphologies. Yardangs do not appear to selectively affect some particular stratigraphic levels. ELDs show, at the available resolution, common characteristics that do not support the hypothesis of a significant difference in the lithological composition.

As a consequence, we suggest that the ELDs never filled the crater entirely and that the current bulge morphology, although affected by some post-depositional erosion, represents the remnant of a depositional geometry.

ELDs in Firsoff and other craters consist of two informal units, which potentially might be formalized as Formations: layered unit and mounds (Figs. 2, 9A, 10A). These units are defined on the basis of their sedimentological (texture and structure at the scale of the available resolution) and morphological characters.

The layered unit consists of light-toned meter-scale layered material sometimes probably interlayered with dark-toned layers, disrupted in a polygonal pattern (Fig. 10B). The polygons are on average about three to four meters in diameter. Polygons of this scale and morphology (i.e., where a periglacial origin can be excluded both by the morphology of the features themselves and by the lack of associated periglacial landforms) are very widespread on Mars and have been associated to potential desiccation cracks (Schieber, 2007; El-Maarry et al., 2013, 2014), to post-depositional cementation in sulfate sand followed by contraction due to dehydration (Chavdarian and Sumner, 2006) or to post-depositional weathering (Chan et al., 2008). Whatever their genesis, the polygonal features overprint the original sedimentary structures.

Layers generally gently dip (less than 10°) and drape the older crater deposits (Figs 4B, 9A, 9B). Higher dip values (still not exceeding 20°including possible measurement errors) are found in correspondence to the steeper parts close to the crater rim (Figs. 9A, 9B, 9C). At the scale of the available resolution (25 cm/pixel) there is no observable evidence of cross stratification or other sedimentary structures, apart from the polygonal pattern, within the layered unit (Figs. 9C, 10B). Layers appear to possess a good lateral continuity although their irregularities make it difficult to trace individual layers (Figs. 10D, 10E). Layer irregularities take the form of dish-shaped depressions, raised rims, bowl-shaped appearances and serrated layer morphology (Figs. 10D, 10E, 11A, 11C). As a consequence, though there is no evidence of major unconformities, it is not possible to exclude the presence of some subtle disconformities and/or paraconformities.

Layer morphologies may represent depositional or alternatively syn- or post-depositional erosional characters. We argued that post-depositional aeolian erosion is unlikely. Layers often show slightly vertical or sub-vertical synform-like geometries (Fig. 11C), sometimes similar to the ones found in Crommelin crater (“ridge-and-trough”: Franchi et al., 2014). However, no antiform-like, recumbent, chevron or in general tight folds are present, which is against a slump or tectonic origin for these features.

The rounded margins and shape (Figs. 8B, 8C, 10E) and the dish-shaped depressions (Figs. 8B, 8C, 10D, 10E, 11C) are very similar to dissolution-related morphologies such as solution pans (Murana and Kneissl, 2014). These morphologies would suggest a possible combination between a depositional control (e.g., higher vs lower depositional rate) and/or syn- to post-depositional water-related chemical etching.

Exposures of stratigraphic successions in the study area are never thick enough to consistently evaluate the possible presence of a cyclic depositional pattern such as the one investigated in nearby Becquerel crater (Lewis et al., 2008).

ELDs within craters show the presence of rectilinear, probably fracture-controlled, elevated lineaments (Figs. 8D, 11A, 11B). These lineaments are made of the layered unit (Fig. 11A). Their scale is quite variable, ranging from few hundreds of meters to several kilometers in length while their height in CTX and/or HiRISE DEMs can be estimated to be some tens of meters. We interpret these features as possible fissure ridges. The presence of fissure ridges would imply sourcing from the subsurface.

Putative fissure ridges are often associated to the presence of mounds (Figs. 8D, 11B). The mounds consist of both simple and coalescing conical features. Simple mounds are conical features 100–300 m in diameter with subcircular shapes in plan view, while composite mounds can reach up to 500 m in diameter (Figs. 2, 10A, 10C, 12A, 12B). In HiRISE-based DEMs the height of these edifices ranges from approximately 30 m to 120 m for the simple mounds, but can reach up to several 100s m for the composite mounds (Figs. 12B, 13B, 13C) (Pondrelli et al., 2011a). The mounds are made of either matrix or clast-supported boulder-sized material, with high-albedo clasts and darker matrix (Fig. 10C) (Pondrelli et al., 2011a).

Mounds in Firsoff crater have been described by Pondrelli et al. (2011a). The mounds are particularly abundant and form clusters of mounds (Fig. 12A) close to the outermost margin of the craters (Figs. 2, 3), especially in the southern margin (Franchi et al., 2014) where rim-related faults and fractures are abundant (Schultz et al., 1982). Mounds are also found, although rarer and scattered, both within and outside the craters (Figs. 2, 3). Mounds are commonly aligned with putative fissure ridges (Figs. 8D, 11B, 13A). The relation between mounds and fissure ridges suggests a possible genetic linkage between the presence of assumed preferential pathways for groundwater upwelling and mound formation.

Some of the mounds display an apical orifice (Fig. 12B). Pondrelli et al. (2011a) calculated that within the HiRISE image PSP_003788_1820, approximately 35% of the mounds possess an orifice and further argued that the orifices represent depositional morphologies within the mounds, suggestive of a formation related to fluid and/or gas expulsion. It is also possible that some mounds may be erosional remnants of layered deposits, produced by aeolian erosion, in which case the extent of the mound-covered area in the geological map is overestimated (Fig. 2). However, erosional remnants resulting from aeolian processes show morphologies generally elongated along the wind direction, whereas the mounds display a sub-circular outline in plan view (Pondrelli et al., 2011a). Furthermore, the layered unit contains layers disrupted in a polygonal pattern whereas the mounds have a brecciated texture. These features are distinguishable at HiRISE scale and make a misidentification unlikely.

Mounds are always associated with the layered unit (Figs. 12A, 12B) but unambiguous stratigraphic relations are difficult to establish. In some cases, mounds are on top of the layered unit (e.g., Fig. 12B) (Pondrelli et al., 2011a). Locally, layers appear to be up-warped at the flank of the mounds (Fig. 13B), which may suggest either a lateral transition between coeval units or post-depositional bending related to the mounds formation. The mound imaged in Fig. 13C shows a well-bedded mound about 250 m in diameter and 120 m in height, with exceptionally well-exposed internal geometries. Layers appear to continue, with some irregularities, from the mounds to the embedding layered unit. This observation suggests a possible facies heteropy, i.e., lateral transition, which in turn implies temporal and genetic association between the two units.

ELDs within Firsoff and in the unnamed crater located immediately east of Firsoff contain hydrated phases (Figs. 14). CRISM spectra display a large shoulder between 2.3 and 2.4 μm, a large absorption band at ~1.9 μm, and a faintly visible band at ~1.4 μm (Fig. 14B). These characteristics are due to bound water (Clark et al., 1990) and may be attributed to polyhydrated sulfates and zeolites spectra. As previously mentioned in Carter et al. (2013), distinction between those two mineral groups is not trivial using remote NIR spectroscopy. However, zeolites have only been detected in fines in Meridiani Planum by the Mini-TES instrument on board Opportunity (Glotch et al., 2006). Since ELDs in our study area likely correspond to similar formations as those in Meridiani Planum, we infer that the hydrated minerals detected in our study area correspond to polyhydrated sulfates rather than zeolites.

ELDS ON THE PLATEAU

ELDs on the plateau share some of the basic textural and albedo characteristics of ELDs within craters: they are high-albedo, layered deposits disrupted in a polygonal pattern (Fig. 15A). These characteristics led us to include these deposits with ELDs (Le Deit et al., 2010).

Still, other elements allow us to distinguish the ELDs in the craters from those on the plateau. Such elements include their geometry as depositional bodies (Fig. 7), and some textures and morphologies that can be identified at HiRISE scale. In particular, ELDs on the plateau consist of 1. mounds; 2. flat-lying bedded to faintly bedded deposits; 3. bedded deposits associated with dune-fields.

Mounds, although widespread on the plateau, are generally poorly exposed due to dust coverage or erosion. It is not possible to clearly observe their texture and exclude that they represent erosional remnants produced by post-depositional aeolian erosion on previously deposited ELDs. Still, their scale and shape are as those of the mounds in the craters and in places they seem to possess an apical orifice. This suggests that at least some of them might represent the equivalent of the features observed in the craters (Pozzobon et al., 2013).

Flat-lying bedded to faintly bedded deposits represent an approximately horizontal flat unit (Fig. 15A), showing rectilinear troughs and ridges sculpted by differential aeolian erosion possibly emphasizing pre-existing more resistant features (Edgett and Malin, 2000). ELDs are disrupted in a polygonal pattern and in places show smaller-scale ridges (probably not more than 10s m in height according to CTX-based DEM) which may possibly resemble eroded dune crests (Fig. 15B). Disconformities are locally visible. At places they separate levels with ridges and levels made up of planar beds (Fig. 15B).

The bedded deposits associated with dune-fields represent the best exposed ELDs unit on the plateau (Fig. 15C). The dunes are present at different scales, although erosion as well as later depositional cover complicate a detailed reconstruction of their morphologies and stratigraphy, and make it difficult to infer regional flow direction(s). However, erosional cuts display locally the presence of cross stratification (Figs. 15C, 15D). Metric to decametric thick cross beds can be irregular, suggesting the presence of flows of different directions and partial reworking of previously deposited beds. To illustrate the similarity to a terrestrial analogue, Figure 15E is a satellite view (i.e. the same viewpoint and comparable scale of Mars images) of cross stratification in the Early Jurassic Navajo Sandstone (southern Utah, USA).

The scale of the cross stratification and the lack of association with water-related landforms such as fluvial channels, suggests a formation in an aeolian depositional environment.

ELDs on the plateau possibly contain hydrated minerals (i.e., sulfates, phyllosilicates). The occurrence of barely visible signatures of hydrated minerals in two CRISM observations do not ensure their detection from orbit (Fig. 14A).

DISCUSSION

The stratigraphic position of ELDs can be constrained between the Cratered unit and the

Subdued crater unit of the Plateau Sequence at their base, and the Hummocky material and the Ridged Plains Material at their top (Fig. 3B). Crater count data constrain this to the Noachian-Hesperian transition and the lower part of the Early Amazonian (Figs. 5A, 5B).

ELDs were found to contain polyhydrated sulfates in 3 CRISM observations in Firsoff crater and in the crater east of Firsoff (Fig. 14). Because of the similarity with ELDs located elsewhere in the study area we suggest that most if not all ELDs might represent polyhydrated sulfates-bearing deposits. Sulfate-bearing high albedo layered deposits present elsewhere on Mars have been interpreted to span the age range from the Noachian-Hesperian transition to the Early Hesperian (e.g., Gendrin et al., 2005; Poulet et al., 2008; Bibring et al., 2006; Le Deit et al., 2008) and these share the same basic morphologic and spectral characteristics of the ELDs in the study area. Layer morphologies, albedo, structure, composition and stratigraphic setting enable us to include the ELDs in Firsoff crater and the surrounding plateau in the wider frame of the sulfate-bearing layered deposits seen elsewhere on Mars.

ELDs found in craters and in the plateau (Fig. 2) can be distinguished from each other on the basis of: 1. basin-scale morphologies (kilometers-thick crater bulges vs 100s meter-thick sheet drape deposits), 2. local-scale morphologies (rounded shape, sub-circular depressions, raised rims, bowl-shaped appearance and serrated layer vs flat-topped bodies or dune fields with cross stratification). These morphologic differences suggest that genetic processes might at least partly be different, too.

Aeolian erosion was one of the main processes that shaped the morphology of the ELDs architecture inside and outside craters. This demonstrates that ELDs are easily erodible by wind

(Figs. 2, 8A, 8D). Still, most of the morphologies within craters do not show the typical characters (yardangs, preferential elongation, differential erosion) associated with wind erosion. These are mostly concentrated in the topmost part of the Firsoff crater bulge.

Most ELDs display rounded shapes, sub-circular depressions, raised rims, bowl-shaped appearance and serrated layers (Figs. 8B, 8C, 8D, 10D, 10E). These morphologies are consistent with syn- to post-depositional chemical etching processes leading to partial solution (Murana and Kneissl, 2014), but may also result from locally different depositional rates resulting in changes in layer thickness. These characteristics appear to be consistent with a depositional or water-related weathering origin rather than with an aeolian erosional product.

A depositional origin of a crater bulge has been proposed also by Kite et al. (2013a) and Le Deit et al. (2013) in Gale crater, while according to most authors (e.g., Malin and Edgett, 2000; Andrews-Hanna et al., 2010; Michalski and Niles, 2013), craters were originally filled with sediments and only after post-depositional aeolian erosion, bulges in their current form were shaped as erosional remnants. Our data are consistent with Kite et al. (2013a) and Le Deit et al.'s (2013) interpretation, but we are cautious not to extend automatically our inferences over the whole range of crater bulges. Although a common origin appears likely, solid evidence based on geological observations must be sought and evaluated separately in each locale before reaching regional interpretations and models.

The presence of polyhydrated sulfates within the rock component has been associated and is potentially consistent with a formation through evaporitic processes (e.g., Grotzinger et al., 2005) either as cement or main constituent. The polygonal pattern which extensively disrupts the

ELDs inside and outside craters (Fig. 10B), might reflect desiccation cracks in evaporites (e.g., Grotzinger et al., 2005), possibly occurred during later diagenesis in the phreatic zone or capillary fringe of a groundwater table (McLennan et al., 2005). Polygonal patterns of comparable scale have been alternatively suggested to form as a consequence of post-depositional weathering, although still in the presence of salts (Chan et al., 2008).

Morphologies such as the rounded shapes, the sinuous margins and the quasi circular depressions are typical, although not exclusive, of evaporite deposits (e.g., Bruthans et al., 2009). On Earth such landforms develop by dissolution thus implying the presence of water, which in turn implies that such erosion occurred or at the same time of deposition or in any case before the establishment of dry conditions. Bowl-shaped feature and raised rims might represent erosional products of originally more uniform layers or result from laterally inhomogeneous deposition rates.

Although no single observation can point exclusively to an evaporite composition of the ELDs located in the craters, all data are consistent with this interpretation.

Putative fissure ridges and mounds may be indicative of fluid expulsion thus suggesting that the source area of the ELDs was in the subsurface (Figs. 8D, 11A, 11B, 12A, 12B, 13A, 13B, 13C). Although fissure ridges may have originated on faults and/or fractures as suggested by their generally straight shape, no evidence of offset has been found. Moreover, they are wedge-shaped (Fig. 11A), which suggest either a higher deposition rate or a better cementation than the ELDs distant from the fissure ridges, and frequently associated with mounds developing at their top (Figs. 8D, 11B). These prominent morphologies suggest fluid expulsion of sulfate-rich fluids which started to precipitate evaporites after their expulsion.

Mounds consist of layered to non-layered, either clast- or matrix-supported breccia (Pondrelli et al., 2011a) or, more rarely, of layered deposits (Figs. 10C, 12B). Even if some mounds are the erosional remnants of the layered unit produced by aeolian activity, their generally different texture (observable at HiRISE scale), and the common presence of an apical orifice (Fig. 12B) point toward a depositional origin for at least a part of the mounds (see discussion in Pondrelli et al., 2011a). The lateral gradual transition between the layered unit and the mounds (Fig. 13C) suggests that these units are coeval, and thus reflect adjacent depositional environments. Like the fissure ridges of the layered units, the orifices on the mounds are suggestive of fluid expulsion processes (Pondrelli et al., 2011a). Sourcing from the subsurface is also suggested by layers which were up-warped at the flanks of some mounds (Fig. 13B).

The available image resolution does not permit to distinguish whether the boulders forming the mounds actually represent clastic material or crystalline materials. Hence, the term breccia is used simply to describe the unit. This distinction is entirely descriptive because it implies a different genetic mechanism. Fluid expulsion can lead to the formation of mounds such as the ones observed in the study area, in fact, either by mud volcanism (Pondrelli et al., 2011a), a clastic process, or spring precipitation, a chemical process. The lateral transition between the mounds and the layered unit is a transition between the mounds and a unit characterized by the presence of fissure ridges. Both morphologies are suggestive of an evaporitic composition, possibly with polyhydrated sulfates as components. This appears to be consistent with a spring deposit formation, whereas the mud volcanism process seems less likely. Under such a scenario, the boulders found in the mounds would represent crystallized masses and/or better cemented blocks formed during fluid upwelling and transported toward the surface. Thus, the use of the terms clasts or breccia is not entirely inappropriate.

On the basis of these evidences at all scales, we suggest a spring deposit scenario for the ELDs deposited in the craters (Fig. 16). The bulge morphology (Fig. 7B) might have resulted from chemical precipitation following water upwelling similar in processes, though not in composition, to that of the terrestrial travertines. Fluid upwelling and expulsion might have been favored by pre-existing fractures formed during crater formation (Pondrelli et al., 2011a). Fissure ridges and mounds would represent the pathways that would have allowed the actual expulsion (Figs. 8D, 11A, 11B, 12A, 12B, 13A, 13B). The polyhydrated sulfates detected among the components (Fig. 14), the presence of the polygonal pattern (Fig. 10B) as well as morphologies such as the rounded shapes, the sub-circular depressions and the serrated pattern (Figs. 8B, 8C, 10D, 10E) are consistent with such a scenario. The polygonal pattern might have resulted from syn- to post-depositional desiccation while the rounded shapes, the sub-circular depressions and the serrated pattern may be the result of syn- to post-depositional dissolution. The raised rims, locally associated with bowl-shaped depressions (Figs. 11A, 11C), may be the equivalent of the pool-and-dam system typical of terrestrial travertines and the “ridge-and-trough” observed in the nearby Crommelin crater (Franchi et al., 2014). The geometry of the layers, which drape and onlap the older deposits, is also consistent with a formation by evaporite precipitation in probably mixed ephemeral lake and subaerial conditions.

Such a scenario is challenged by different interpretations proposed in other similar crater bulges.

According to Kite et al. (2013b) on the basis of models developed for Gale crater, the crater bulge morphology might be explained by airfall deposition because slope winds are expected to peak on the steep crater wall and mound slopes, thus preventing sediments to settle in these zones. However, airfall dust deposition in Firsoff and adjacent craters, even if it can explain the different depositional geometries within the craters and between craters and plateau, would not explain the extensive presence of fluid expulsion features such as fissure ridges and mounds. Moreover, a formation of ELDs by air fall dust deposition would imply the same depositional process in the craters and in the plateau. But on the plateau we documented the differences in morphologies and sedimentary structures such as cross-bedded deposits (Figs. 15C, 15D), which imply a granulometric range (medium sands to granules) inconsistent with airfall settling. Aeolian deposition might have occurred with a variety of processes including settling of fine-grained materials and turbulent transport of coarser-grained (sands to granules) deposits. Still, no cross-bedding was found inside the craters despite the extensive HiRISE coverage. Settling of fine-grained materials later cemented by upwelling groundwater flows might instead explain the observed morphologies and it cannot be excluded that such processes contributed to the Firsoff stratigraphic column. Still, cementation by groundwater fluctuations, associated to the following aeolian reworking of loose sediments, produces sharp flat-lying unconformable surfaces (Stokes surface) (Stokes, 1968; Fryberger et al., 1988) that should be visible at HiRISE scale, but that have not been detected. Hence we think it unlikely that aeolian deposition and reworking can explain the observed complexity.

Some authors have proposed that ELD deposition might have been driven by pyroclastic processes (Scott and Tanaka, 1982; Hynek et al., 2003; Kerber et al., 2012; Michalski and Bleacher, 2013). Pyroclastic processes are characterized by deposition in an upper flow regime where antidunes develop, while the dunes on the plateau are typical of lower flow regime. Moreover, pyroclastic processes alone cannot explain the different characters of ELDs between craters and plateau and also cannot explain the presence of the proposed fluid-expulsion features. However, we cannot exclude that some pyroclastic deposits contributed to the geological history of the area.

Kite et al. (2013a) focused their observation on the Gale crater bulge where they described a depositional geometry similar to what observed in Firsoff crater. They described uniform outward dipping layers and the absence of clear identifiable unconformities. These authors suggest that such geometry might be inconsistent with a formation by spring deposits because such deposits are typically fed from different spring sources and are precipitated soon after the fluid emergence, hence tend to form lenticular coalescent bodies rather than uniform dipping strata (Kite et al., 2013a). In the study area, the lateral transition between layers and mounds indicates a more complex scenario. The lateral extension of layers and the continuity of spring deposits depend on water chemistry, temperature and flow discharge. Low-energy environments might favor the formation of layers with a sub-horizontal attitude (De Filippis et al., 2013). This geometry would contribute to conceal eventual unconformities, especially if image resolution limits, the observed disruption by the polygonal pattern and the dust coverage are considered. In addition, layers formed during even short-lived lacustrine stages may exhibit extensive lateral continuity.

Pitted cones similar to the mounds observed in our study area can form as pingos in periglacial environments as hypothesized in several locations on Mars (e.g., Burr et al., 2009; Balme and Gallagher, 2009). The presence of a polygonal pattern is a potential analogy with thermal contraction cracks in periglacial environments as well. Ice-related weathering has been shown to explain sulfur formation (e.g., Szynkiewicz et al., 2013).

The mounds in the study area lack the fracture patterns typical of pingos (Müller, 1959; Gurney, 1998; French, 2007; Burr et al., 2009). Most important, other possible periglacial morphologies such as scarps with cuspate niches and associated debris apron or “Swiss Cheese Terrain” (MacClune et al., 2003) were not found.

ELDs on the plateau are associated with dune-fields, here interpreted as the result of aeolian deposition. We further suggest that the flat-lying deposits formed as playa deposits during stages of a rising groundwater table (Fig. 16). Mounds may be small spring deposits, possibly formed where water upwelling was favored by the presence of fractures in the basement (Rossi et al., 2009). A rising groundwater table might also have caused cementation of the aeolian dunes, thus preserving them from aeolian erosion. Groundwater protects the material below the water table from erosion. Material above the water table is preferentially eroded, thus defining the horizontal Stokes surface (Stokes, 1968; Fryberger et al., 1988). Such a depositional geometry might be consistent with the observed flat-lying, horizontal limit between cross stratified sets in the plateau, but more extensive data are necessary to test this hypothesis.

The overall geological setting in the plateau appears to be very similar to the one depicted in Meridiani (e.g., Grotzinger et al., 2005) with alternating playa and aeolian deposits. The critical role of groundwater in controlling sedimentation on one side and the preservation of sedimentary deposits on the other side has been proposed by, e.g., Grotzinger et al. (2005).

We suggest that the groundwater presence and its fluctuations might have been the main control on the geological evolution of the study area (Fig. 17). The importance of groundwater for the formation of ELDs in Arabia Terra has been modeled by Andrews-Hanna et al. (2007, 2010) and Andrews-Hanna and Lewis (2011). Based on different data it has also been supported to different extents by others (e.g., Rossi et al., 2008; Pondrelli et al., 2011a; Zabrusky et al., 2012; Franchi et al., 2014). Others have challenged the existence of groundwater (e.g., Michalski and Niles, 2012; Michalski et al., 2013b) or suggested that it is of limited importance (Michalski et al., 2013a). According to these authors, the existence of groundwater would require amounts of sulfur too high and high erosion rates (Michalski and Niles, 2012). In Mawrth Vallis the stratigraphic position of sulfur- and clay-bearing deposits is more consistent with an origin of atmospheric leaching rather than due to groundwater activity (Michalski et al., 2013b).

According to Michalski et al. (2013b), the formation of the Mawrth Vallis and possibly similar nearby layered deposits might have been caused by ice/snow-mediated weathering.

Our observations do not support an extension of such a scenario in the study area. We suggest that the bulge is a largely a depositional and not an erosional geometry, so we do not expect particularly high erosion rates. Although hampered by the paucity of compositional data, there is no evidence for different characteristics in the stratigraphy of ELDs which would suggest differences in mineral composition within the unit.

We observe a widespread distribution of fissure ridges and mounds suggestive of fluid expulsion, which suggests sourcing from the subsurface, but we found no evidence of glacial and/or periglacial deposits and/or snow-related morphologies.

Differences in the nature of the Noachian units of the Plateau Sequence, which have been interpreted as a mixture of lava flows, pyroclastic material and impact breccia for the Cratered unit, and interbedded lava flows and eolian deposits for the Subdued crater unit (Scott and Tanaka, 1986), would result in differences in their permeability. These differences would control the geometry and behavior of any aquifer and associated fluid flows. As a consequence, the aquifer or aquifers were probably characterized by irregular geometries and differences in their lateral extents. Parnell et al. (2010) performed measurements in impact breccia and showed that their permeability is low, which favors fluid circulation to occur mainly through fracture systems.

Groundwater fluctuations might have controlled playa deposition and the preservation of aeolian dunes in the plateau. Upwelling through the fracture systems might have led to spring deposit precipitation in the craters and locally in the plateau.

Spring deposits and playa deposits are potentially suitable targets when searching for life or traces of life (e.g., Walter and Des Marais, 1993; Cady and Farmer, 2007; Glamoclija et al., 2011, 2012).

The presence of spring and playa deposits imply the presence of hydrological cycle that drives groundwater upwelling at surface temperatures above freezing. For formation of playas the temperatures should had been above freezing for long periods of time in order to facilitate precipitation-induced recharge of the aquifers and subsequent evaporation. The climate supporting such a cycle was likely arid by terrestrial standards and such surface conditions in mineralogically similar terrestrial environment would have been conducive for microbial colonization (e.g., Dong et al. 2007; Glamoclija et al. 2011, 2012). On Earth playa environments host taxonomically diverse microbial communities adapted to high salt concentrations and dehydration stress due to exposure to long periods of drought (Ventosa et al. 2008; Hollister et al. 2010, Glamoclija et al. 2011).

Besides the fact that the presence of sulfates (whether associated or not to hydrothermal conditions) indicates the potential existence of habitable conditions (e.g., Mustard et al., 2008), sulfates are characterized by a good potential to preserve life traces (Panieri et al., 2010), making these deposits appealing targets for astrobiology and exploration of habitability of the red planet.

CONCLUSIVE REMARKS AND INTERPRETATIVE SCENARIO

The geological succession of the study area begins with the emplacement of the Cratered unit and the Subdued crater unit, both part of the Plateau Sequence (Scott and Tanaka, 1986) (Fig. 17). According to crater count results, these two units would have been emplaced during the Late Noachian. ELDs are found to rest nonconformably on top of the Plateau Sequence. In particular, they lie on top of the Cratered unit in the craters and of both Cratered and Subdued crater units on the plateau. ELDs are themselves unconformably overlain by the Hummocky Material in the craters as well as on the plateau, and by the Ridged Plains Material on the plateau. Crater count data constrain ELDs deposition between the Noachian-Hesperian transition and the Early Amazonian.

We hypothesize that during this interval, a confined aquifer entered in contact with the fault/fractures related to crater formation as well as with fault/fractures possibly related to normal regional faulting. This aquifer led to fluid upwelling and spring deposits precipitation ("Spring ELDs"). The extensive and interconnected fractures associated with craters possibly favored upwelling in the craters which ultimately resulted in the formation of bulges.

We hypothesize that local upwelling along faults led to mounds formation on the plateau. This setting was associated with evaporative pumping and/or possibly ephemeral lake formation leading to playa deposition ("Playa ELDs"), although we find no evidence for lacustrine stages within the craters. Aeolian processes ("Aeolian ELDs") were always present, but were likely geologically more significant when the fluid upwelling processes were of lower intensity or simply stopped. During these phases some ELDs might have been deposited by dust airfall or even aeolian dunes.

It is not possible to estimate the duration and the continuity of such evolution. On Earth spring deposits show sedimentation rates ranging from less than a millimeter to several centimeters per year (Anderson and Wells, 2003; Pentecost, 2005), which implies that potentially the spring ELDs might have been emplaced in a geologically short period. Since it is not possible to identify the controls on the deposition of the spring deposits these parameters cannot be quantified. The absence of extensive unconformities suggests that spring deposits growth was a relatively continuous process. This does not imply that other processes, including aeolian airfall or pyroclastic deposition, might have not been present at times.

The study area lacks sufficient exposure to better constrain the presence of a cyclic depositional pattern such as the one documented in Becquerel crater (Lewis et al., 2008). Nevertheless, the change of texture, resistance to weathering, and locally albedo, suggests a fluctuation of the relative intensity and/or distribution of the different controls through time leading to different deposition rates although in a context of a continuous process. Fluctuation of the water table, which depends on the climatic conditions, most probably was prominent among these controls.

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Figure captions

Figure 1. (A) Location map of the study area on MOLA-based shaded relief map. Topographic contours (1000 m spacing) are indicated. (B) HRSC mosaic of the mapped area. Topographic contours (500 m spacing) are indicated. (C) Excerpt of the geological map by Scott and Tanaka (1986) on HRSC mosaic. Npl1: Noachian 'Cratered unit' of the 'Plateau Sequence', Npl2: Noachian 'Cratered unit' of the 'Plateau Sequence', Hr: 'Hesperian Ridged Plains Material'; see text for more details. (D) Footprints of HiRISE coverage on HRSC mosaic. The white filling indicate the stereo pairs. The area is fully covered by CTX imagery. CRISM scenes used in this study are recognizable by the hourglass shape.

Figure 2. Geological map of the study area. AA" represents the trace of the geological section shown in Fig. 3.

Figure 3. (A) Geological section through the study area (see figure 2 for location). (B) Interpretative space-time diagram sketching the relative stratigraphic relations among the units. Line pattern represents period of erosion and/or non-deposition.

Figure 4. Stratigraphic relations of the ELDs. (A) 3D image showing ELDs layers that drape and onlap the deposits of the Plateau Sequence (Cratered unit). Location of the image is indicated in the top right HRSC mosaic. Stratigraphic relations and geometries are sketched in A'. (B) ELDs

covered by younger Hummocky Material and Ridged Plains Material. Location of the image is indicated in the top right HRSC mosaic. Stratigraphic relations and geometries are sketched in B'.

Figure 5. Crater size-frequency distribution results. (A) Excerpt of the geological map with outlined in dark grey the area where crater size frequency measurements have been performed in the HPl1 unit (see the down left HRSC mosaic for location). (B) Crater size frequency measurements of the area shown in (A). Isochrones plot based upon crater chronology model by Hartmann and Neukum [2001] and production function coefficients by Ivanov [2001]. See text for discussion. (C) Excerpt of the geological map with outlined in dark grey the area where crater size frequency measurements have been performed in the plains (see the down left HRSC mosaic for location). (D) Crater size frequency measurements of the area shown in (C). Isochrones plot based upon crater chronology model by Hartmann and Neukum [2001] and production function coefficients by Ivanov [2001]. See text for discussion.

Figure 6. Stratigraphic relations. (A) CTX image showing the stratigraphic relations between the Cratered unit, the ELDs and the Hummocky material north of Firsoff crater (see the HRSC-based mosaic located at the center-right for location). The Hummocky material stays in nonconformity on top of the Cratered unit and in disconformity on top of the ELDs. Stratigraphic relations and geometries are sketched at the upper right of the image. (B) HiRISE image showing the stratigraphic relations between the ELDs and the Hummocky material inside Firsoff crater (see

the HRSC-based mosaic located at the center-right for location). ELDs consist of layers and mounds and are covered in disconformity by the Hummocky material. Stratigraphic relations and geometries are sketched in the block diagram at the lower right of the image.

Figure 7. Geometries of the basins. (A) CTX-based 3D view across part of the study area with the trace of the profiles shown in B. (B) HRSC-derived profile XX' though Firsoff crater and CTX-derived profile YY' in the plateau. In the profile XX', the inferred approximate morphology of the crater devoid of ELDs and other possible deposits (Garvin et al., 2003) is reconstructed in light grey. See text for description.

Figure 8. Erosional vs depositional morphologies. (A) Example of aeolian erosion with yardangs on ELDs. (B) ELDs irregularly shaped layers. ELDs show rounded shaped edges and lengthen in a direction and with geometries not consistent with a formation by aeolian erosion. Main wind direction as inferred by yardangs alignment is indicated top left in the figure. (C) ELDs irregularly shaped layers. Some of the layers are characterized by the presence of rims. (D) NW-SE trending depression. Its regularity and trend do not seem consistent with an erosional formation by wind action. Main wind direction as inferred by yardangs alignment is located to the bottom left of the figure. Inside the depression, elevated lineaments (fissure ridges?) emphasized by mounds, are present. The location of the images is indicated in the top right HRSC mosaic.

Figure 9. Layer attitude in the ELDs layered unit located in the south-eastern part of Firsoff crater. (A) HiRISE based map with the measured layer attitudes. The location of the image is indicated in the HRSC mosaic shown in the lower left inset. The white-transparent box in the lower left part of the figure represents the location of C. (B) Stereonet representing attitude values. The diagram shows a tight cluster but a definite preferred orientation. (C) Layered unit material draping Crater rim deposits. Note the absence of cross stratification at the scale of the available resolution. See A for location.

Figure 10. ELDs units. (A) HiRISE image showing the two units which make the ELDs: layered high albedo deposits disrupted in polygonal pattern and mounds made of either matrix- or clast-supported boulder-sized material. The two white polygons represent the approximate location of B and C. (B) Example of the layered unit. (C) Example of mounds. (D) Layered unit showing layer morphologies. (E) Depressions, raised rims and layer morphologies. The location of the image is indicated in the top right HRSC mosaic.

Figure 11. ELDs morphologies. (A) CTX image showing an example of elevated lineament (possible fissure ridge). Material appears to source from the subsurface in correspondence of a tectonically-controlled fracture. ELDs layers appear to be bounded by a rim. (B) Example of an elevated lineament (possible fissure ridge) with mounds developing on the top. (C) Example of ELDs layers which seem to be bounded by a rim. The location of the images in (A), (B) and (C) is indicated in the top right HRSC mosaic.

Figure 12. Mounds. (A) Field of simple and complex mounds in the southern part of Firsoff crater (see inset for location). Location of B is shown by the white-bounded polygon. (B) HiRISE-derived 3D view of simple mounds.

Figure 13. (A) Example of mounds aligned along fractures and not (redrawn after Franchi et al., 2014). (B) Layers up-warped at the flanks of the mounds. (C) Depositional geometry of a mound and relation with the layered unit. Layers continue from the mounds to the layered unit, suggesting facies heteropy between the units. The location of the images is indicated in the HRSC mosaic shown in the lower right corner.

Figure 14. Sulfate-rich deposits in the study area. (A) Subset of HRSC nadir mosaic overlain by CRISM footprints of observations showing sulfates in craters. Observations on plateaus possibly display hydrated minerals. (B) CRISM ratioed spectra compared to laboratory spectra of zeolites and polyhydrated sulfates (RELAB library spectrum). The ratioed spectrum of the CRISM observation FRT C384 corresponds to an average of 30 pixels divided by an average of 35 pixels of a neutral region. It corresponds to an average of 32 pixels divided by 25 pixels for the observation FRT 236DE, and of 4677 by 356 for the observation FRT 2437E. (C) False color image of the CRISM observation FRT C384. (D) Spectral parameter map of the same observation (red, SINDEX; blue, BD1900R). Displayed values: red, 0.037–0.054; blue, 0.014–0.024. Pink tones indicate occurrence of polyhydrated sulfates, and blue tones of hydrated

phases. (E) False color image of the CRISM observation FRT 236DE. (F) Spectral parameter map of the same observation (BD1900R). Displayed values: 0.002–0.010. White tones indicate occurrence of hydrated phases. (G) False color image of the CRISM observation FRT 2437E. (H) Spectral parameter map of the same observation (BD1900R). Displayed values: 0.003–0.010. White tones indicate occurrence of hydrated phases.

Figure 15. Example of ELDs on the plateau. The location of the images is indicated in the left HRSC mosaic. (A) Flat-lying bedded to faintly bedded deposits. The boxed area represents the location of B. (B) ELDs on the plateau are characterized by high albedo and are disrupted in polygonal pattern as in the craters. Possible dune deposits are covered in disconformity by flat-lying bedded deposits. (C) Bedded deposits associated with dune-fields. The boxed area represents the location of D. (D) Meter-scale cross-stratification (see text for discussion). (E) Example of meter-scale cross-stratification from the Early Jurassic Navajo Sandstone (southern Utah, USA). Google Earth image (centered lat. 37°11'22.81"N, long. 112°57'16.73"W), used with permission.

Figure 16. Processes inferred to have caused ELDs formation. ELDs inside craters (in yellow) are interpreted as formed by fluid expulsion and spring deposits precipitation. In blue areas possibly submerged by waters are indicated. ELDs outside craters were probably subjected in part to aeolian reworking (light brown) and in part to playa deposition (white).