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Geological, geomorphological, facies and allostratigraphic maps of the Eberswalde fan delta

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ABSTRACT

Geological, facies, geomorphological and allostratigraphic map of the Eberswalde fan delta area are presented. The Eberswalde fan delta is proposed as a sort of prototype area to map sedimentary deposits, because of its excellent data coverage and its variability in depositional as well as erosional morphologies and sedimentary facies.

We present a report to distinguish different cartographic products implying an increasing level of interpretation.

The geological map – in association with the facies map – represents the most objective mapping product. Formations are distinguished on the basis of objectively observable parameters: texture, color, sedimentary structures and geographic distribution. Stratigraphic relations are evaluated using Steno's principles. Formations can be interpreted in terms of depositional environment, but an eventual change of the genetic interpretation would not lead to a change in the geological map.

The geomorphological map is based on the data represented in the geological map plus the association of the morphological elements, in order to infer the depositional sub-environments. As a consequence, it is an interpretative map focused on the genetic reconstruction.

The allostratigraphic map is based on the morphofacies analysis – expressed by the geomorphological map – and by the recognition of surfaces which reflect allogenic controls, such as water level fluctuations: unconformities, erosional truncations and flooding surfaces. As a consequence, this is an even more interpretative map than the geomorphological one, since it focuses on the control on the sedimentary systems.

Geological maps represent the most suitable cartographic product for a systematic mapping, which can serve as a prerequisite for scientific or landing site analyses. Geomorphological and allostratographic maps are suitable tools to broaden scientific analysis or to provide scientific background to landing site selection.

1. Introduction

Geological mapping of planetary surfaces is different in many instances from the one commonly performed on Earth, because ground truth is limited to robotic exploration – at least on Mars – and bulk rock composition is largely unknown, except for some hyperspectrally inferred minerals, while on Earth geological maps are based on units defined by lithology or lithological association. Instead, morphologies are usually relatively pristine, depending on the limited effectiveness of weathering on Mars. Moreover spatial resolution of Viking images at the time in which the efforts of preparing geological maps of the Martian surface started, in the 1980s, allowed observing the morphologies down to decametric scale, but not the textural and the geometrical characteristics of the different deposits.

As a consequence, geological mapping on Mars has been actually a geomorphologic mapping with superposed crater frequency based absolute dating to estimate the age of the different units (i.e., Scott and Tanaka, 1986; Greeley and Guest, 1987).

The increasing amount of new high-resolution imagery available for the last ten years allows to describe in much better detail the textural characteristics as well as the morphologies of the deposits, while hyperspectral data provide at least some compositional hints.

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This implies on one side that it highly improved the possibility to interpret the morphologies in terms of their genetic processes and depositional environments. In terms of mapping, this leads to more interpretative geomorphological maps, while on Earth geological maps are intended to be the most objective cartographic products. On the other side, the new available database allows, at least in some selected areas in which high-resolution data are present, to distinguish and map the deposits regardless of their morphological association, which means to realize an almost 'sensu strictu' geological maps, with the obvious and not subordinate concern of the limited compositional knowledge.

With these premises, we tried to differentiate distinct geological, geomorphological and allostratigraphy-based maps in order to provide increasingly interpretative information on the kind and distribution of deposits, on their genetic origin and on units divided by the surfaces with temporal implication reflecting allogenic controls.

The Eberswalde crater (centered 33°W–24°S) is located in the Margaritifer Sinus region, along the putative valley network connecting Argyre with the Ares Vallis (Grant and Parker, 2002; Parker, 1985) (Fig. 1a). The discovery of a spectacular water-related landform within the crater (Malin and Edgett, 2003) represented the most unambiguous evidence that water has been present and stable on Mars surface during some part of the Early Martian history.

The water-related delta-like landform, characterized above all by the presence of pristine mainly meandering channels displaying a distributary pattern, has been the object of many geomorphological analyses, in which its significance in terms of depositional environment has been discussed in order to understand whether the development of such a feature implied the presence of a standing body of water as well. Even if some authors do not agree with the interpretation of the mender bens as meandering channels (Kraal and Postma, 2008), most of the authors claim that the feature

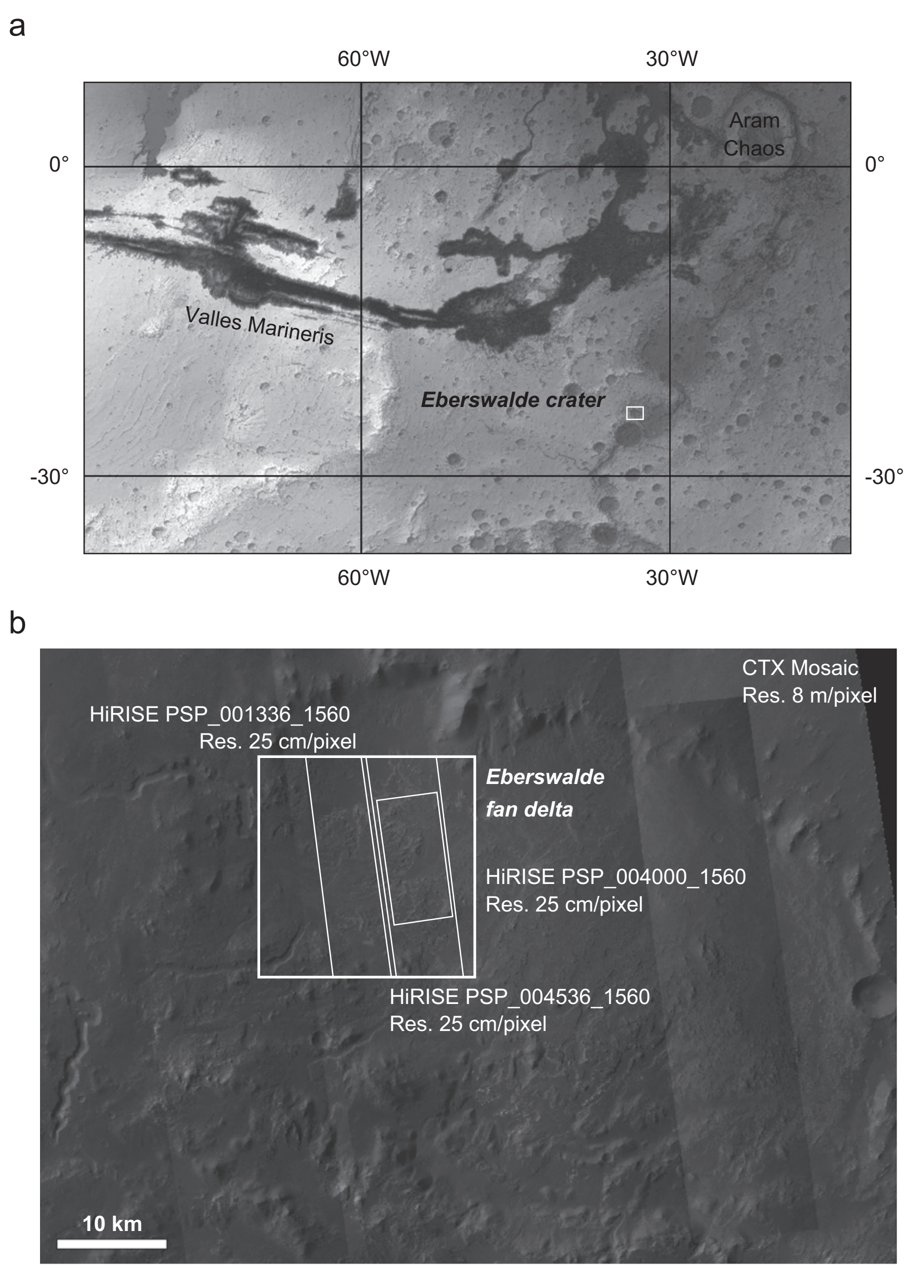

Fig. 1. (a) Location map of the Eberswalde crater on topographic map based on altimetry data, acquired by the Mars Global Surveyor MOLA instrument and (b) data sets used for this study.

formed as a fan delta thus entailing that a standing body of water filled the crater (Moore et al., 2003; Bhattacharya et al., 2005; Lewis and Aharonson, 2006; Wood, 2006; Pondrelli et al., 2008). Moreover the depositional sub-environments within the fan delta and the surrounding deposits, both in the crater and in the putative drainage basin have been described (Pondrelli et al., 2008).

The investigations have been supported by the excellent available data set, including very high resolution and hyperspectral data, also because this crater has been selected as possible landing site for the future robotic missions.

The combination of interesting scientific topics, pristine morphologies, large exposures and excellent available data set,

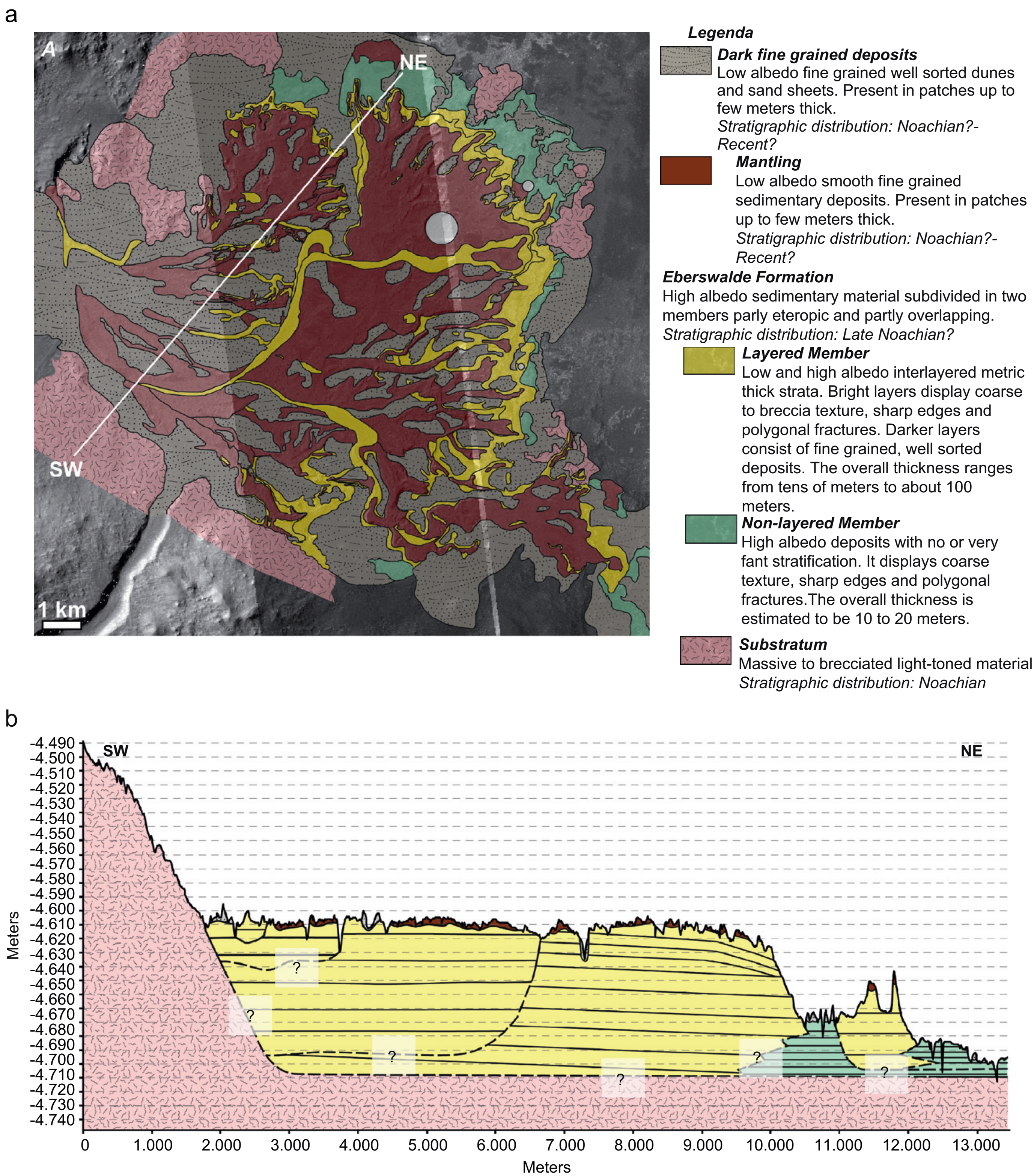

Fig. 2. (a) Geological map of the Eberswalde fan delta and (b) geological section across the trace represented in (a).

makes this area an ideal setting to use it as a prototype area to try to distinguish geological from geomorphological maps and to introduce the concept of facies and allostratigraphic maps in planetary sedimentary settings.

2. Data and methods

The Eberswalde fan delta has been an object of much interest since its first discovery thanks to MOC narrow angle images (Malin and Edgett, 2003), because it represents probably the best preserved example of water-related landform that has been discovered on Mars so far.

As a consequence, the fan delta is fully covered by CTX and HiRISE imagery (Fig. 1b).

In this work, we have utilized data from the CTX camera in order to derive digital elevation models (DEM) from images targeted as stereo pairs (Ivanov and Rossi, 2009). CTX data varies in resolution and stereo pairs analyzed in this work can be derived at approximately 10 m scale. We employed stereo matching technique (Ivanov and Lorre, 2002), in conjunction with radiometric and geometric image processing in an ISIS3. This technique is capable of deriving tiepoint co-registration at the subpixel precision.

3. Geological map

The geological map is based on and modified from the one presented by Pondrelli et al. (2008). The units are distinguished on the base of their texture, color, sedimentary structure, stratigraphic relations and, where present, compositional hints provided by hyperspectral data (Milliken et al., 2007, 2009) (Fig. 2a).

3.1. Substratum

The base of the stratigraphic succession is represented here by a unit informally named Substratum that is part of the unit CS (impact crater material) by Scott and Tanaka (1986) of Noachian age. It consists of massive to brecciated light toned material. When not brecciated, the texture appears smooth, with sharp ridges and jagged peaks suggesting a competent behavior of this material (Pondrelli et al., 2008).

According to Scott and Tanaka (1986), this unit represents ejecta deposits – most probably derived by the Holden impact – reworking volcanic successions.

3.2. Eberswalde Formation

We propose to formalize the Eberswalde Formation that crops out nonconformably on top of the Substratum (Fig. 3). Its geological features, as well as its internal subdivision, are very similar to the ones shown by Grant et al. (2008) in the nearby Holden crater. It consists of layered to faintly layered and non-layered high albedo sedimentary deposits that are present in correspondence of the fan delta (Fig. 2a). This Formation stays on top of the Substratum and partly onlaps against it (Figs. 2b, 3a).

Within this Formation, two members can be recognized, the element of distinction being the presence of interlayered low albedo deposits or the absence of stratification, accordingly named Layered Member and Non-layered Member (Fig. 2). The two members are eteropic (Figs. 3b, c).

3.2.1. Layered member

The Layered Member crops out in correspondence of the proximal part of the fan delta (Figs. 2, 3) and consists of low and high albedo few meters thick interlayered strata (Fig. 3b, c). Dark layers consists of fine-grained well sorted deposits that are at places reworked by aeolian dunes, thus suggesting a granulometric range roughly between 0.5 and 5 mm (Jerolmack et al., 2006). Bright layers are more resistant to weathering and erosion than the dark ones and consist of three facies: (1) medium rough texture; (2) breccia and (3) polygonal pattern (Fig. 4).

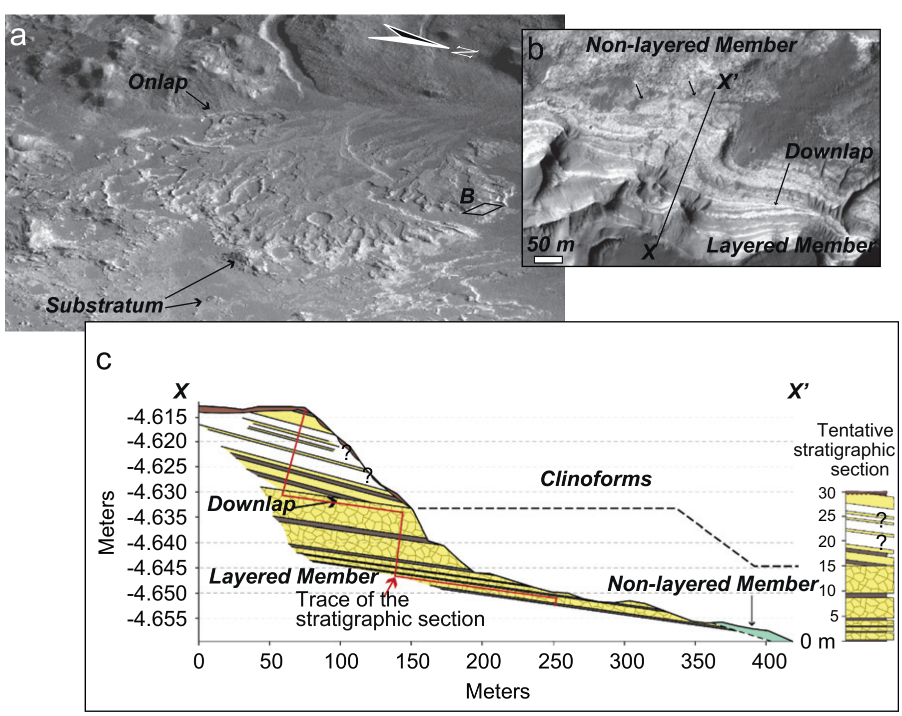

Fig. 3. (a) 3D representation of the study area: CTX mosaic draped on CTX-based DEM. Vertical exaggeration. (b) HiRISE image of the outcrop shown in (a). A downlap surface is visible. *X–X′* represents the trace of the geological section of (c). (c) Geological section through the trace *X–X′*. Interlayering between low (brown) and high albedo (yellow) layers has been emphasized and roughly measured in the stratigraphic section to the right.

The 'medium rough texture' facies crops out everywhere in the studied area; its grain size is not detectable at the available scale, but its textural characteristics allows to hypothesize either an uneven degree of erosion or the presence of relatively coarse material within or not a finer matrix. At places, it is characterized by the presence of sedimentary structures, which we interpret as fossil dunes (Fig. 4b). Their scale and morphology is very similar to the ones shown by recent aeolian dark dunes cropping out nearby, except for the rounded crest which suggest a certain degree of erosion. These possible fossil dunes are locally sutured by younger high albedo layers, which exclude a more recent formation through an aeolian reworking of eroded bright deposits.

'Breccia' facies have been mapped in the most proximal part of the deltaic form (Fig. 4). It consists of boulders up to a couple of meters in diameter – although locally their size can reach even 4 m – in a darker matrix. Where the clasts are larger and their textural characteristics can be evaluated at the available resolution, they show a very low roundness, an irregular shape and they are poorly sorted. The texture is prevalently but not exclusively clast supported. In terms of textural maturity, they are immature; nevertheless, these deposits show a certain degree of organization. Locally, they display a very clear erosional surface at their base (Fig. 4b).

Most of the bright layers are disrupted into polygons from a couple of meters and up to 4 m in size. This facies is by far the most widespread being especially dominant in the most distal part of the delta and in the basin (Fig. 4). Each limit of the polygons is mirrored by the limit of the adjacent polygon, which implies that this unit has not been deposited as a breccia, but it has been deposited and then disrupted into polygons, which accordingly are post-depositional structures. At places, the fractures limiting the polygons appear to be associated with faults and/or fractures, but in most cases there are no relations between polygonal features and tectonic features (Fig. 4b).

Polygonal fractures 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 almost syn-sedimentary thermal contraction (Schieber, 2007), to post-depositional cementation of dump gypsum sand followed by contraction due to dehydration (Chavdarian and Sumner, 2006) or to post-depositional weathering (Chan et al., 2008). Post-depositional weathering is the most constrained hypothesis in the study area, because of the lack of evaporite signature detection through OMEGA and CRISM data (Milliken et al., 2009) and also because polygonal pattern appears to be more abundant on relatively flat areas, where weathering is supposed to be more effective. Whatever their genesis, the polygonal features overprint the original sedimentary structures.

Most of the strata are gently inclined toward the basin. A rough estimate of the dip using CTX-based DEM provides values from 2° to maximum 6°. At places, in correspondence of the frontal p art of the delta front, strata dip can be higher, up to 15° (Fig. 3a) to again ecome sub-horizontal going towards the basin. This overall geometry is typical of fan deltas (Pondrelli et al., 2008), the more inclined strata corroborating the hypothesis of an interaction with a standing body of water.

The maximum thickness of the Layered Member can be estimated at about 120 m (Fig. 2b).

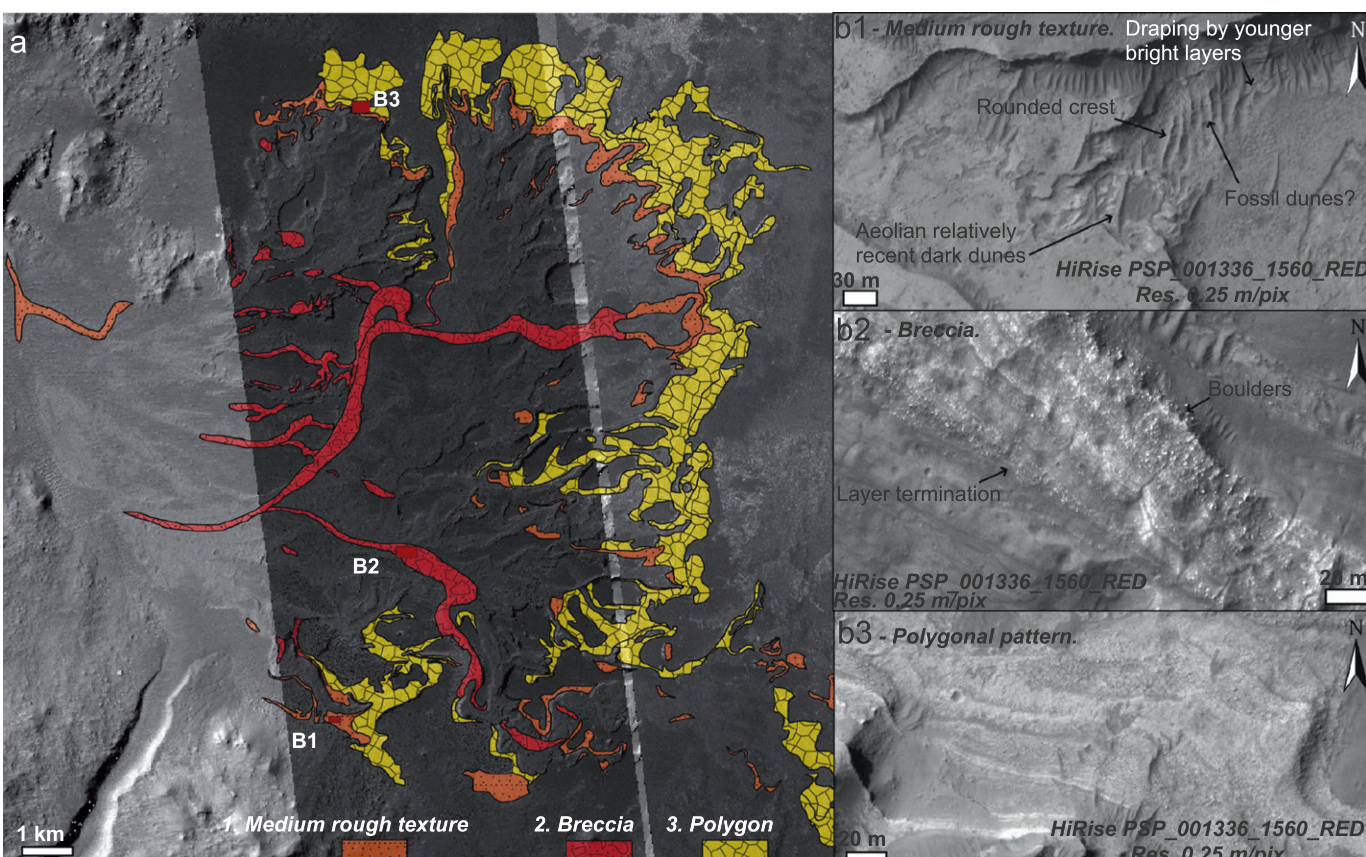

Fig. 4. (a) Map of the facies distribution in the bright layers of the study area. (b) Examples of the three facies: (1) medium rough texture, with possible fossil dunes similar in scale and morphology to the dark recent one; (2) Breccia, with up to metric sized boulders organized in few metric-thick layers; some of these layers display a clear erosional base; and (3) polygonal pattern, with polygons up to 4 m in size.

3.2.2. Non-layered member

The Non-layered Member crops out in the most distal part of the deltaic feature, in correspondence of what it has been interpreted as prodelta deposits (Bhattacharya et al., 2005; Wood, 2006; Pondrelli et al., 2008) (Fig. 2a). It mostly consist of non- to faintly layered high albedo deposits displaying a polygonal pattern and, more rarely, medium rough texture facies.

CRISM data have been acquired in order to get some compositional hints of the deltaic feature. While no evidence of sulfates or other evaporitic mineral have been detected (Milliken et al., 2009), clay signature is present in correspondence of the prodelta bottomset layers, but not in the more proximal part of the fan delta (Milliken et al., 2007, 2009).

The maximum thickness can be estimated at approximately 60 m (Fig. 2b).

The minimum age of the Eberswalde Formation has been estimated using crater count analyses.

According to Scott and Tanaka (1986), the impact creating Eberswalde crater occurred in the Noachian. In order to estimate the age of Eberswalde crater, a counting area was defined roughly along the crater rim. Although it does not conform with our usual procedure to exclude steep scope ($>10^{\circ}$), due to erosive processes and subsequent easy erasure of impact craters, the inner crater wall and crater rim had to be included because larger impact craters are located directly on the rim postdating the Eberswalde impact (cf. Fig. 1b, large 4 km diameter crater on the eastern rim). It is therefore essential to include those craters in the measurement. Using the production function and chronology function of Ivanov (2001) and Hartmann and Neukum (2001), respectively, an age of 3.72 Ga for the crater results (Fig. 5d). Since sediments filled the crater, and therefore, buried and/or eroded larger craters on the floor, this age is regarded as a minimum. The formation age of Eberswalde crater is likely be older than 3.72 Ga.

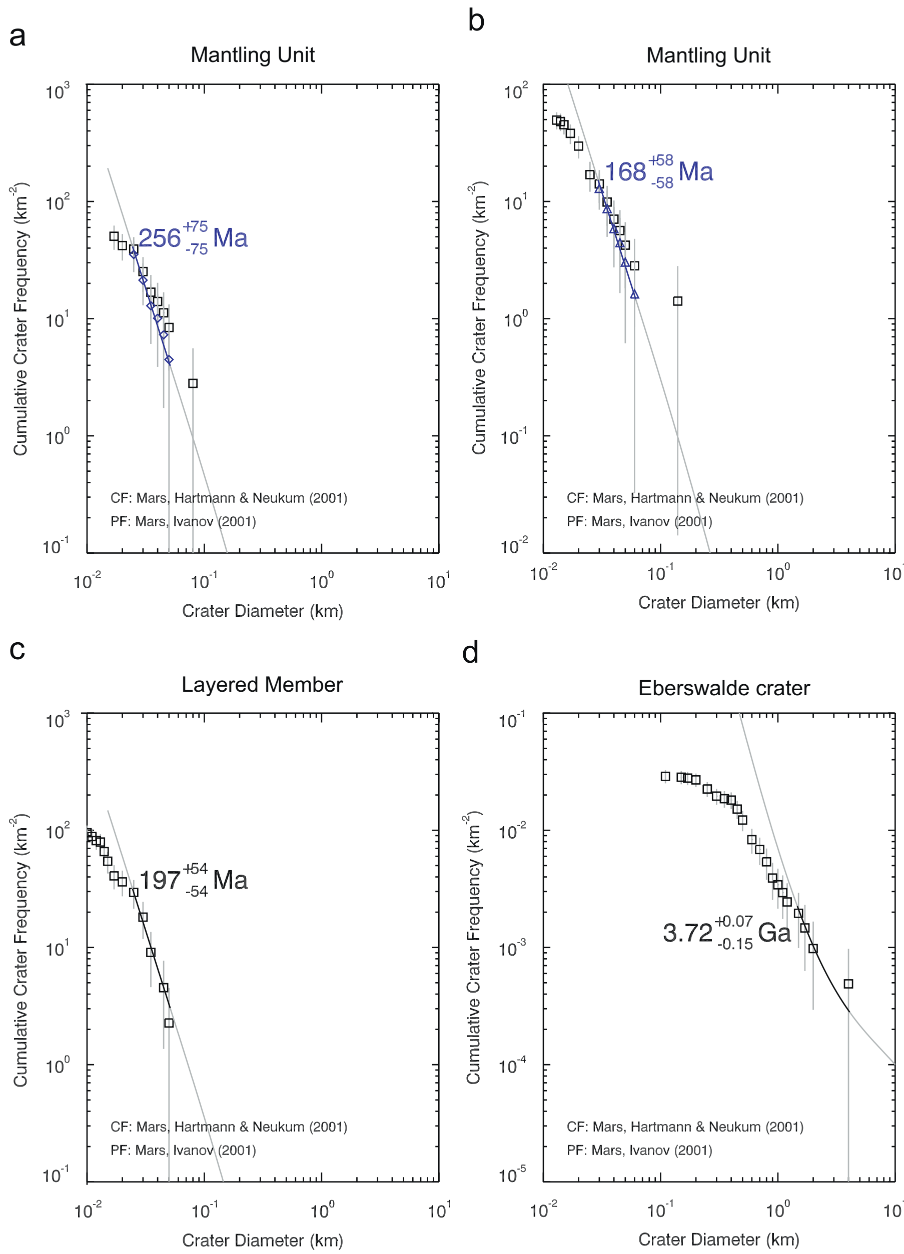

Fig. 5. Crater size-frequency distributions of the Mantling (a and b), the Layered Member (c), and Eberswalde crater (d). Craters in (d) were counted on HRSC images h2013_0000 and h4310_0000; all remaining craters were measured on HiRISE image PSP_001336_1560. In (a) and (b) a resurfacing correction had to be applied, because craters in the largest bin are partially buried crater belonging to the underlying surface.

Crater size-frequency distributions were also obtained on the Mantling and the Layered Member units using the HiRISE imagery. Crater diameters up to 15 m were measured with the software Cratertools (Kneissl et al., this volume). Using craterstats software (Michael and Neukum, 2010) modeling ages in the range of about 170–260 Ma were obtained (Fig. 5a–c). These ages reflect the termination of major erosive/degradational processes in this region, and therefore, do not represent the ages of formation of these units.

3.3. Mantling, dunes and sand sheets

The Eberswalde Formation and the Substratum are at places disconformably covered by a unit named informally Mantling (Figs. 2 and 3). It consists of low albedo fine-grained sedimentary deposits, in which thickness can be very roughly estimated to few meters. On the basis of its geographical distribution and its textural characteristics, the depositional process can be inferred as airfall, but in consideration of the limited extension of the study area, no more specific interpretation is possible.

The youngest deposits mapped in the study area consist of low albedo well sorted dunes and sand sheets (Fig. 2). These deposits locally drape disconformally all the previously described units and their thickness can be estimated around few meters at maximum. Their geographical distribution, textural characteristics and sedimentary structures allow to interpret these units as related to different episodes of aeolian deposition.

4. Geomorphological map

The geomorphological map has been presented and described by Pondrelli et al. (2008) (Fig. 5), so we refer to that paper for a detailed description of the units.

Unlike Viking data based geomorphological maps, morphological elements are not used as descriptive and non-interpretative terms, but units are recognized and distinguished on the basis of what it is interpreted to be their genetic origin. Lateral relations between coeval units are very important to reconstruct the association between different morphological elements and straighten the genetic interpretation: this can be performed only through mapping.

The Eberswalde fan delta can be roughly divided in three parts depending on the topographic slope values. The most proximal part of the fan delta lobes display slope value lower than 22° – but mostly less than 10° and often less than 2°–3° – while the distal part reaches average slope values of about 40°and then towards the basin slope again become lower than 22°, on an average less than 10° (Fig. 6).

According to Malin and Edgett (2003), Moore et al. (2003), Bhattacharya et al. (2005), Wood (2006) and Pondrelli et al. (2008), these different physiographies correspond to different deltaic sub-environments: delta plain, delta front and prodelta. Distributary channels – rectilinear, maybe braided, to meandering – have been recognized and mapped (Bhattacharya et al., 2005; Wood, 2006; Pondrelli et al., 2008). Low to moderate channel sinuosity of the meandering systems (channel sinuosity index between 1.2 and 1.8)

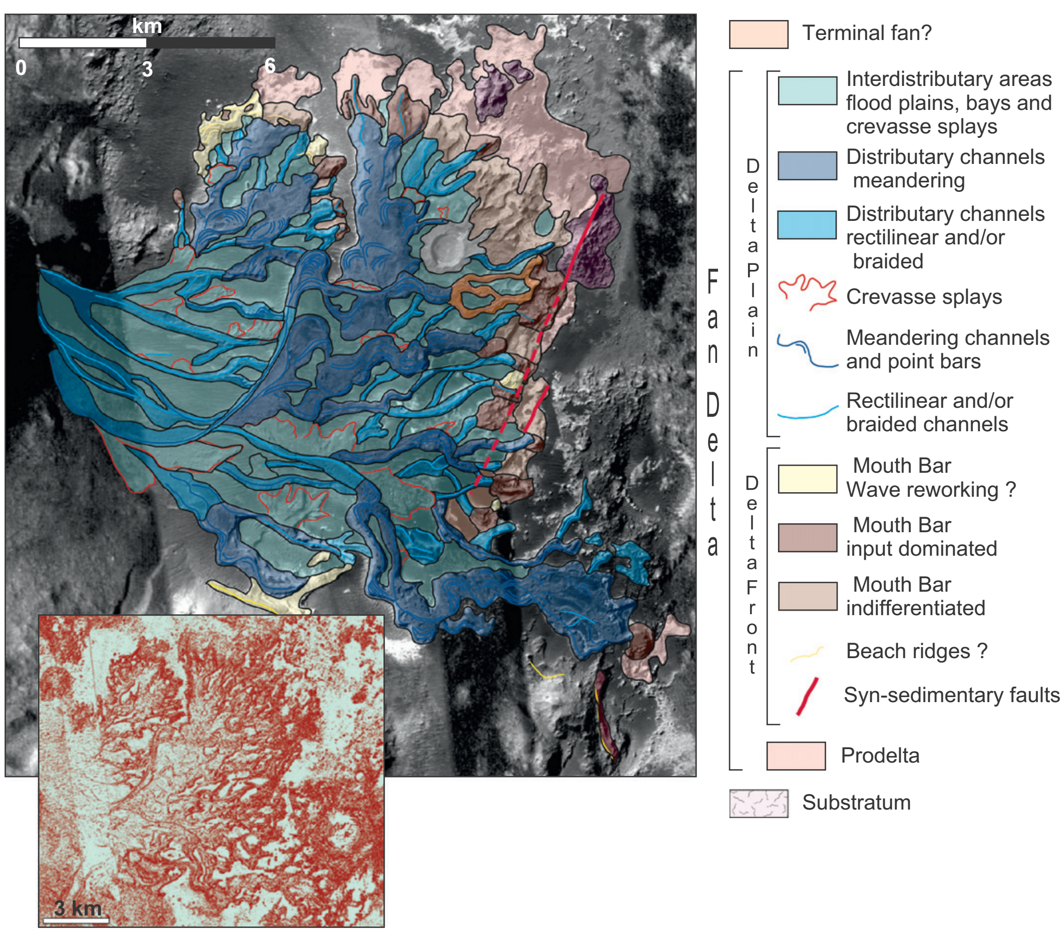

Fig. 6. Geomorphological map of the Eberswalde fan delta (modified after Pondrelli et al., 2008). Delta plain is indicated in shades of blue (distributary channels) and green (interdistributary areas), delta front in shades of brown (input-dominated) and yellow (wave-reworking), while prodelta in light red. Note how meandering channels tend to develop more distally than the non-sinuous ones. The small box at the bottom left represents the slope map, where the light blue color correspond to slope values lower than 22° and the red color values from 22° up to 84°.

imply a bedload to mixed-load sedimentary transport (Wood, 2006). This is consistent with the presence of chute cut-off and not meander cut-off mechanism of avulsion (Wood, 2006; Pondrelli et al., 2008). In correspondence to the distributary channels, the light-tone deposits appear to consist mostly of breccia (Fig. 4). Kraal and Postma (2008) queried whether such boulders could have been transported by a normal turbulent flow and argued against the interpretations of these features as channels, also in consideration that layering in correspondence of the putative meanders appear to be horizontal and not slightly inclined as it would be expected in correspondence of point bar accretion. Accordingly, they proposed a debris flow process of formation (Kraal and Postma, 2008), implying a debris flow dominated alluvial fan genetic interpretation for the structure as a whole.

We favor the hypothesis that these deposits represent distributary channels of the delta plain for two reasons: pertaining to the sedimentology of the breccia facies and the geological–geomorphological context. Breccia facies – where they crop out in situ and not as eroded blocks mixed with aeolian or mass wasting-related deposits – display erosional bases, organized deposits with mostly clast supported layers showing some internal stratification, interlayered with finer grained darker material (Fig. 4b). Debris flows possess a severe erosional capability, including removal of bedrock material, in the source areas (i.e., Enos, 1977; Takahashi, 1981; Mangold et al., 2003), but in the depositional lobes – such as the one that would crop out in the Eberswalde crater – have in general little erosive effect (i.e., Enos, 1977; Takahashi, 1981). Moreover debris flows consist of poorly organized mostly mud-supported to clast-supported deposits. If textural characteristics at the available resolution, cannot be observed in such detail to prevent from any doubt of misinterpretation, the very clear and deep erosional incision documented for example in Fig. 4b point toward a fluvial channel origin for these deposits.

Debris flow dominated alluvial fan is in general quite uniform depositional bodies. The presence of exhumed bodies – regardless of their genetical interpretation – implies different competence among the materials forming the deltaic structure, which in turn implies a variability of the deposits which is not consistent with the debris flow interpretation. We interpret the depressed areas between the exhumed channels as interdistributary areas. Interdistributary areas represent a low energy depositional environment, in which clays would have been deposited. Clays would have provided the necessary cohesion to allow meandering to develop. Then, after desiccation, they would have been eroded by an aeolian activity (Malin and Edgett, 2003). This succession of processes would explain the reason why phyllosilicate spectral signature is almost absent from the putative delta plain (Milliken et al., 2007). Moreover the 'depressed areas' are at places occupied by fan shaped lobes connected with the channels, which we interpret as crevasse splays (Pondrelli et al., 2008). Regardless of genetic interpretation, in general, debris flow dominated alluvial fans do not present such a morphological diversity. We hypothesize that an epsilon cross stratification is not observable – unlike in Jezero crater (Mustard et al., 2008) – because of lack of resolution and disruption of the original sedimentary structures by the post-depositional polygonal fractures.

In the delta front zone – in correspondence of the steepest part of the deltaic structure – the main morphological and architectural characters are bifurcating channels, ridges or terraces and slightly inclined foresets (Pondrelli et al., 2008).

The significance of the frontal scarp to enforce the deltaic interpretations has been discussed in detail by several authors (see for example discussions in Lewis and Aharonson (2006) and Pondrelli et al. (2008)).

Bifurcating channels typically form in the delta front, where friction-related processes are dominant, which means that the fluvial channel is entering a very shallow basin (Pondrelli et al., 2008). Shallow waters are consistent with the sub-horizontal attitude of most of the layers of the delta front (Pondrelli et al., 2008). Instead, at places some layers appear to be more inclined. It is difficult to evaluate layer internal geometries with confidence, excluding data-dependant artifacts. Nevertheless, at least in the area represented in Fig. 3b, layers of the upper part of the outcrop appear to dip more – even if just few degrees more (estimates 9–15°) – than the layers of the lower part (estimates 2–6°). The layers exhibiting greater dip appear to prograde and rest upon the less dip ones thus originating a downlap surface; this depositional architecture suggests a water level rise with sediment supply first exceeded and then exceeding the accommodation space (Pondrelli et al., 2008).

At places, ridges roughly parallel to the deltaic lobes – although not as clear as the ones present in Shalbatana Vallis (Di Achille et al., 2009) – and in some cases with crescentic shape suggest a limited amount of wave-reworking even if the overall lobes morphology, ranging from digitate to lobate, is consistent with an input-dominated system (Bhattacharya et al., 2005; Wood, 2006; Pondrelli et al., 2008).

Delta front deposits consist of either medium rough texture or polygonal pattern. Post-depositional polygonal pattern conceals the original depositional texture and structures, but the putative fossil dunes present among the medium rough texture facies represented in Fig. 4b allow some considerations. These dunes appear not to be constrained in a channel, thus neglecting the possibility to have been formed through river processes. They are located close to a ridge located roughly parallel to the lobe margin, which have been tentatively interpreted as produced by wave-reworking using the geomorphological analysis alone (Pondrelli et al., 2008). A wave-related formation is unrealistic, because they appear too big and because none of the other features, which should be associated with them (i.e., bars, rip channels) are present.

We interpret them as an aeolian dune formed on the landward side of the beach such that it normally happens in such context on Earth.

Prodelta mostly consists of polygonal pattern (Figs. 4 and 6). In correspondence of these zones, phyllosilicate spectral signature has been detected (Milliken et al., 2007) and this is consistent with the interpretation of such areas as the lower energy of the whole system (Milliken et al., 2007).

The youngest channel with its deposits (Lobe E of Fig. 7) does not seem to fit this overall frame. It consists of a relatively high-energy low sinuosity channel made of breccia cutting previously deposited meanders and distally developing a distributary pattern (Figs. 4, 6, 7a). No extensive frontal scarp or internal layering to support a deltaic interpretation can be detected. Distributaries seem to die out without evidences of delivering sediments to a standing body of water. As a consequence, we tentatively interpret the distal part of Lobe E as a terminal fan (Fig. 6).

5. Allostratigraphic map

The transition between delta plain and delta front occurs in correspondence of the slope break, in which formation is the direct consequence of the interaction between fluvial and basin related processes. As a consequence, the elevation at which this slope break occurs corresponds at least roughly to the water level of the lake at the moment of formation of that particular part of the lobe.

The Eberswalde fan delta consists of five lobes (four deltaic), in which relative stratigraphy can be easily unraveled through simple cross-cutting relations (Pondrelli et al., 2008). The maximum elevation of the slope break of the four deltaic lobes – and so the level of the water table during their formation – can be estimated

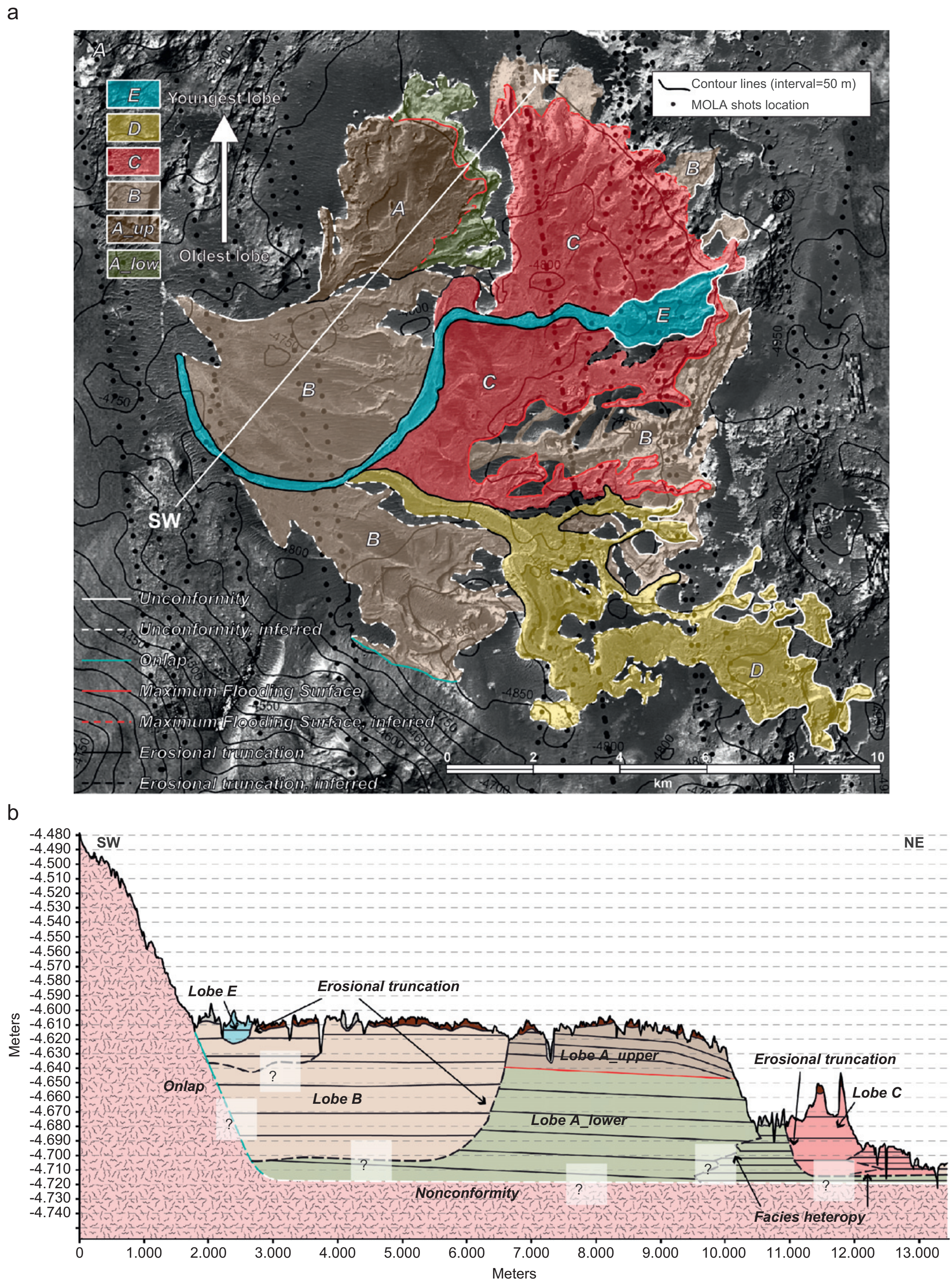

Fig. 7. (a) Allostratigraphic-based map of the studied area. Units are distinguished on the base of unconformities, erosional truncations and flooding surfaces. A progressive prograding trend, possibly driven by the decreasing water level, inside the basin, is visible. (b) Allostratigraphic-based section across the same trace as Fig. 2b. Erosional truncations formed by channels avulsion in response of intrinsic processes do not represent an allostratigraphic boundary.

using CTX DEM and the elevations are different from lobe to lobe (Fig. 8). Lobe A would have been formed in correspondence of a water table located at roughly −4605/−4610 m below the Martian datum, Lobe B at −4720, Lobe C at −4680 and finally Lobe D at −4730. Different elevations correspond also to different degree of progradation of the lobes in the basin (Fig. 7a).

Different levels of the water table imply an allogenic control – most probably climatic – on deposition. While channel switching within the

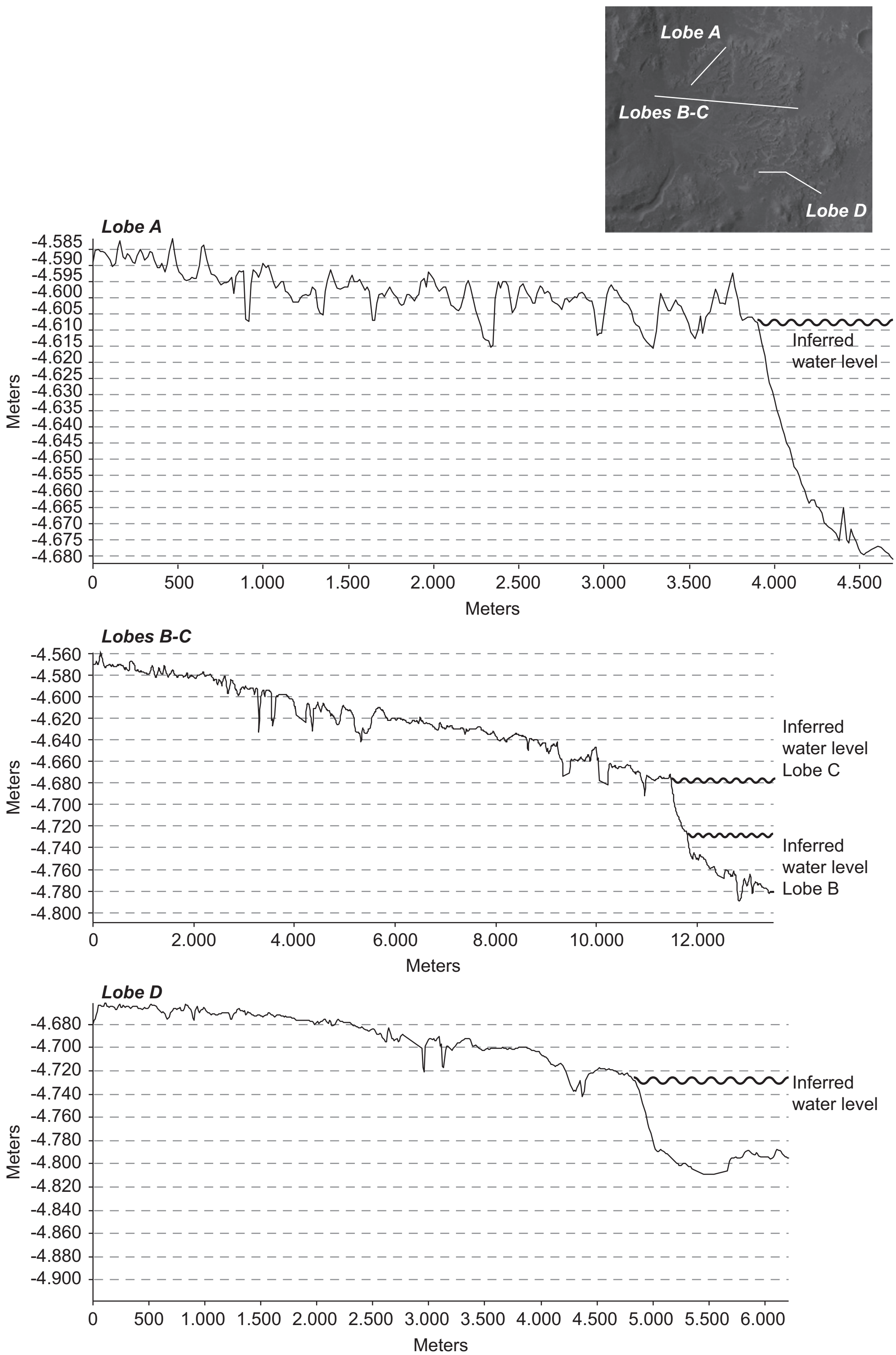

Fig. 8. CTX DEM based profiles through the deltaic lobes A, B–C and D. Location of the profile is shown in the box at the top right. Note how the water level fluctuates, but with a longer term trend towards a water level fall.

single lobes (Fig. 6) appears to be related to intrinsic processes, the switching between the different lobes is inferred to be controlled by the water table fluctuation (Pondrelli et al., 2008).

Allostratigraphic units are divided by surfaces which reflect this allogenic control: unconformable surfaces (here not further distinguished in nonconformity and disconformity), erosional truncations and flooding surfaces (Fig. 7). As they reflect an allogenic control, these surfaces divide the units on the basis of the timing of their accumulation.

Some of these units and surfaces have been described by Pondrelli et al. (2008) and we refer there for a detailed description and the implications in terms of sequence stratigraphy. Here, we concentrate on mapping the allostratigraphy-derived units (Fig. 7).

Lobe A is the oldest one and its succession is divided in two stacking pattern, the uppermost one (Lobe A_upper) prograding on top of the lowermost one (Lobe A_lower) emphasized by a downlap surface (Figs. 3b and c, 7b). This surface has been interpreted accordingly as a Maximum Flooding Surface (Pondrelli et al., 2008). The presence only in the stratigraphically lower unit of a nice example of bifurcating channel is consistent with a context of water level rise.

Lobe B finds its way by eroding previously deposited lobe A; it develops more distally (Fig. 7a) and its transition between delta plain and delta front occurs at a deeper position than lobe A (Fig. 8), which means that the water table of the lake was in a deeper position. Moreover the distributary channels sinuosity passes from high at the top of lobe A to low at the top of lobe B (Fig. 6). All these elements concur to infer a water level drop (Pondrelli et al., 2008)—which can be quantified of about 80 m.

Lobe B is partly covered by Lobe C which delta plain-delta front transition can be estimated to be at about −4680 m (Fig. 8). Distributary channels on top of this lobe are mostly meandering (Fig. 6), suggesting a decreasing of transport energy, which is consistent with a water level rise (Pondrelli et al., 2008).

Lobe D cuts through the previously deposited deltaic lobes (Figs. 6, 7a and b), it represents the most distal lobe of the whole system (Fig. 7a) and the delta plain-delta front position is located at about −4730 m. These data concur to hypothesize another water level drop (Pondrelli et al., 2008).

Bounding discontinuities such as unconformable surfaces, erosional truncations and flooding surfaces define lobe A_lower, lobe A_upper, lobe B, lobe C, lobe D and lobe E units. These units consist of different members, different materials, different depositional subenvironments, but they have time-stratigraphic significance. The boundaries between them correspond to fluctuations of the water table implying an external control on deposition and most probably a climatic forcing.

6. Conclusion

The Eberswalde fan delta area has been chosen as a test area to apply different approaches of mapping sedimentary systems on Mars (i.e., Moore and Howard, 2005). The area is characterized by an excellent data set and by a very well expressed variability of sedimentary systems and so it could represent a sort of prototype area to test some of the procedures for a systematic and standardized mapping. In particular, we focus on the

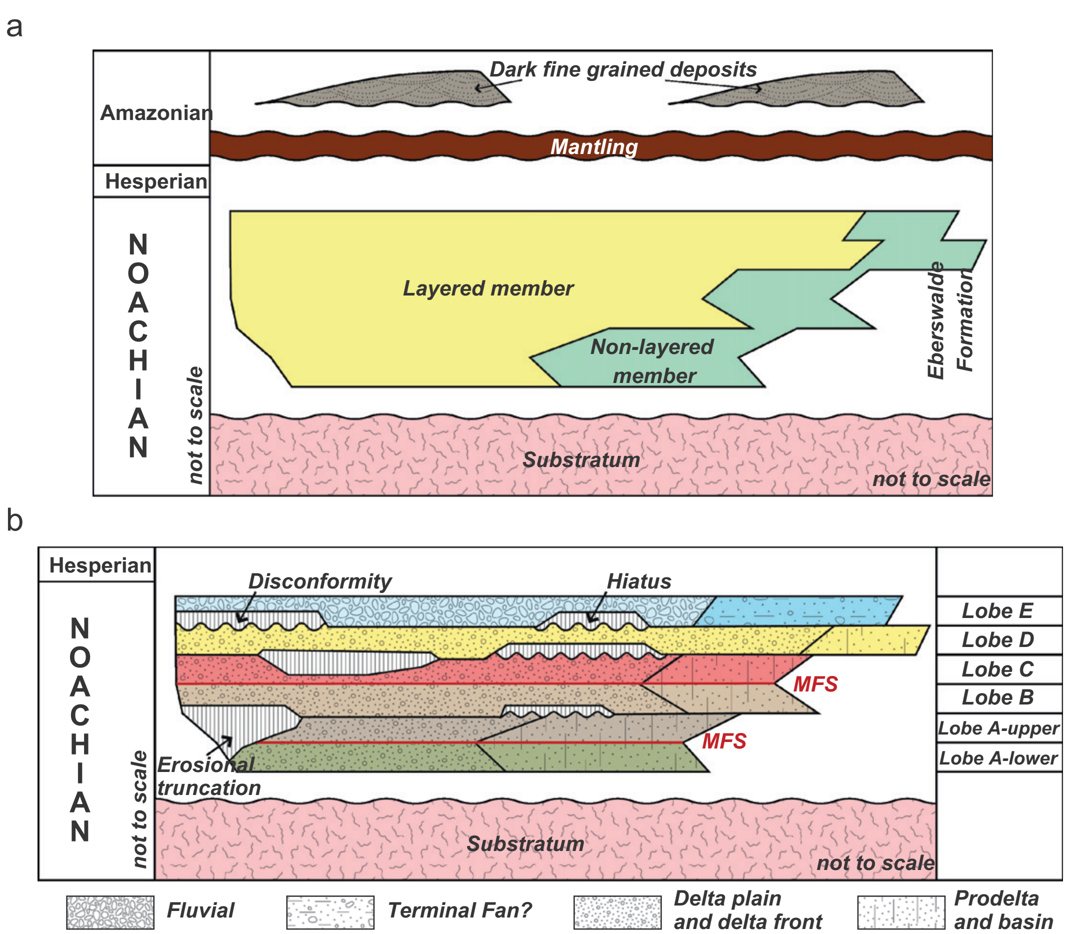

Fig. 9. Stratigraphic schemes derived from (a) the geological map, where the limits between the units are heteropic and eterocronous and (b) the geomorphological and allostratigraphic maps. Intra-formational hiata can be emphasized by such a scheme.

differences between geological, facies, geomorphological and allostratographic maps.

Geological maps are intended to be the most objective mapping product. Substratum, Eberswalde Formation (with two members), Mantling and Dark fine-grained deposits are divided on the base of their objectively observable characteristics, such as texture, color, sedimentary structures and geographic distribution (Fig. 2a). Compositional hints – where present – contribute to the description of the unit, but it should be avoided, their use as unique distinction element, since they do not represent the overall lithological composition, but only some minerals. Moreover lithological composition alone is not sufficient to distinguish units on Earth as well (i.e., formation consisting of polimictic conglomerate is generally distinguished by a formation consisting of litharenites with similar composition).

We tentatively tried to formalize the institution of the Eberswalde Formation by describing its geographical distribution, its various characteristics also drawing a stratigraphic log of a significant outcrop (Fig. 3), defining its stratigraphic relations (Fig. 2b) and their crater count derived age.

In order to better describe the textural characteristics of the different deposits of the Eberswalde Formation, a facies map has been also realized (Fig. 4a). The facies map represents an objective map as well, where different facies are mapped on the base of observable parameters (Fig. 4).

Within the Eberswalde Formation minor differences are present. In particular, layering is present only in the proximal part of the basin, while in the distal one it is faint to absent. On the basis of such difference, we introduced the distinction in two members: layered member and non-layered member. These members are partly heteropic, while partly the layered member stays on top of the non-layered member (Fig. 2).

Stratigraphic relations are inferred using Steno's principles and recognizing possible discontinuities, while crater count statistics are necessary to provide quantitative dating. According to the International Stratigraphic Guide (Salvador, 1994), the association between composition and stratigraphic subdivision for any unit and rank should be avoided. Even if Mars geology lacks the enormous complexity of the Earth geology, the use of interpretative terms to define stratigraphic units should be discouraged. In some cases, on Earth composition is used to define Formation – i.e., Freikofel Limestones – but these terminologies are maintained for historical reasons and should not be perpetuated, all the more so on Mars. Phyllosilicates are present – even if in localized outcrops – within the Eberswalde Formation (Milliken et al., 2007), but we prefer not to use the term 'phyllosian' era (Bibring et al., 2006) to respect the Stratigraphic code and to avoid to put interpretative terms (which could, maybe, prove inadequate with more data in the future) in the terminology.

In the geomorphological map, units are distinguished and mapped on the base of the interpreted depositional environment. The interpretation is based on the facies characteristics of the deposits (provided through the geological and facies maps) plus the geomorphological assemblage (Fig. 6). As a consequence, it represents an interpretative map focused on depositional environment reconstruction and evolution.

The allostratigraphic map is based on a morphofacies analysis (provided through the geomorphological map) plus the recognition of time-significant surfaces: unconformities, erosional truncations and flooding surfaces. Accordingly, the allostratigraphic map is an interpretative map, which divides units on the base of the time of their accumulation and it is focused on the recognition of the allogenic controls on sedimentation.

The stratigraphic schemes derived from the geological map and the geomorphological plus allostratigraphic maps reflect the different mapping approaches (Fig. 9).

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