An application of sequence stratigraphy to Mars: the Eberswalde fan delta

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Abstract

We present a review of our work on an intriguing feature on Mars, the Eberswalde delta-like feature, based on detailed geological analyses aimed to recognize and map the depositional environments and to infer their evolution through time. The topset-foreset-bottomset geometry, typical of delta progradation, has been observed in the Eberswalde outcrops allowing to interpret this feature as a fan delta. We distinguished delta plain, delta front and prodelta depositional sub-environments in the exposed stratigraphic succession. The delta plain is made of distributary channels and interdistributary areas, in which crevasse splays delivered coarser sediments from the channels. Polygonal shrinkage cracks formed probably after exposure in the interdistributary areas. At places the polygons have been reworked by more recent distributary channels causing the formation of intrabasinal breccia. In the delta front inertia and friction-related processes appear to be dominant in different phases of the fan delta evolution, suggesting fluctuations of the controls on sedimentation through time.

The dynamics of the recognized depositional environments has been evaluated in terms of sequence stratigraphy, recognizing geometries such as offlap and downlap, erosional truncations and stacking patterns, entering them in a stratigraphic framework. The sedimentary architecture of the fan delta appears to be organized in three cycles, which we tentatively interpreted as depositional sequences. The evolution of these sequences would have been controlled by relative water level fluctuations showing a longer term trend toward decreasing water content inside the basin.

The evolution of the Eberswalde fan delta appears to be controlled by autogenic processes within the single discharge lobes. Allogenic processes, such as tectonic activity and/or climatic forcing, would have instead caused fluctuations of the level of the water table in the lake, consequently driving the switching among the deltaic lobes.

Keywords: Mars surface geology, Fan delta, Sequence stratigraphy

Introduction

The continuously growing number of imaging, hyperspectral, topographic and subsurface data from Mars missions in recent years is deeply changing the way we try to unravel the geological evolution of the planet. In particular, the presence of water related landforms, neglected by several authors until last decade and hypothesized among the others by Baker and Milton (1974), Carr (1987), Baker et al. (1991), Parker et al. (1993), Ori et al. (2000), and Baker (2001), is now accepted by most of the scientific community, particularly after evidences such as the one provided by Malin and Edgett (2003) in the Eberswalde crater (provisionally named Holden NE crater at the time). Since then new satellite data with higher spatial resolution allowed detailed analysis not only to prove that liquid water was present on Mars surface during its geological past, but also to try and recognize the processes which were active and to infer the depositional environments and their evolution. Some attempt to develop these data into a sequence-stratigraphic approach have been outlined by Ori et al. (2006) and Thaisen and Schieber (2006).

We present here a review of our work on the Eberswalde crater and in particular on the delta-like feature located in this crater (Pondrelli et al., 2005; 2006a, b; in press).

The Eberswalde crater (centered 33W-24S) is located to the north-east of the Holden crater (Fig. 1a) along a well developed fluvial network connecting the Argyre impact basin to Ares Vallis (Parker, 1985; Scott and Tanaka, 1986; Grant and Parker, 2002), one of the largest outflow channel resulting from catastrophic floods. Thus, the Eberswalde area represents an ideal location for hunting water-related landforms as confirmed by the spectacular delta-like feature (Fig. 1b) discovered (Malin and Edgett, 2003).

Our aim is to infer the sedimentary processes

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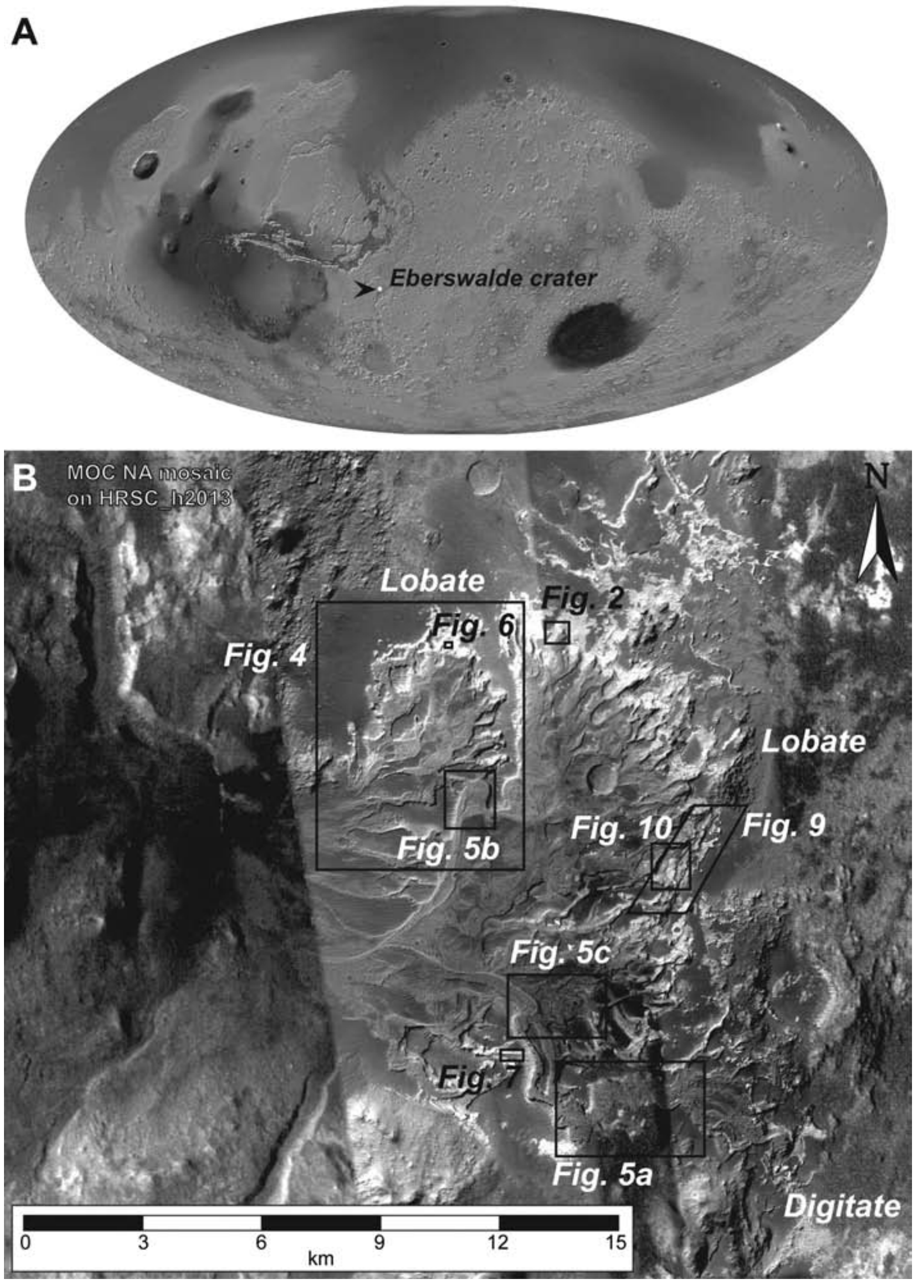

Fig. 1 - A. Location of the Eberswalde crater on a global map of Mars (Mollweide Projection). B. The Eberswalde fan delta. The deltaic lobes display lobate to digitate morphologies, suggesting dominating input-related processes. Location of Figs. 2, 4, 5a, 5b, 5c, 6, 7, 9 and 10 is shown.

characterizing the potential fan delta and to distinguish the recognizable depositional environments. The different morphologies have been mapped and the depositional environments inferred. Ultimately, we want to understand how this system evolved through time and which factors controlled its evolution. The dynamics of the recognized depositional environments have been evaluated in terms of sequence stratigraphy trying to recognize depositional geometries, erosional truncations and possible stacking patterns within a stratigraphic framework.

Our analyses took advantage of the remarkable data coverage available in this area. Mars Orbiter

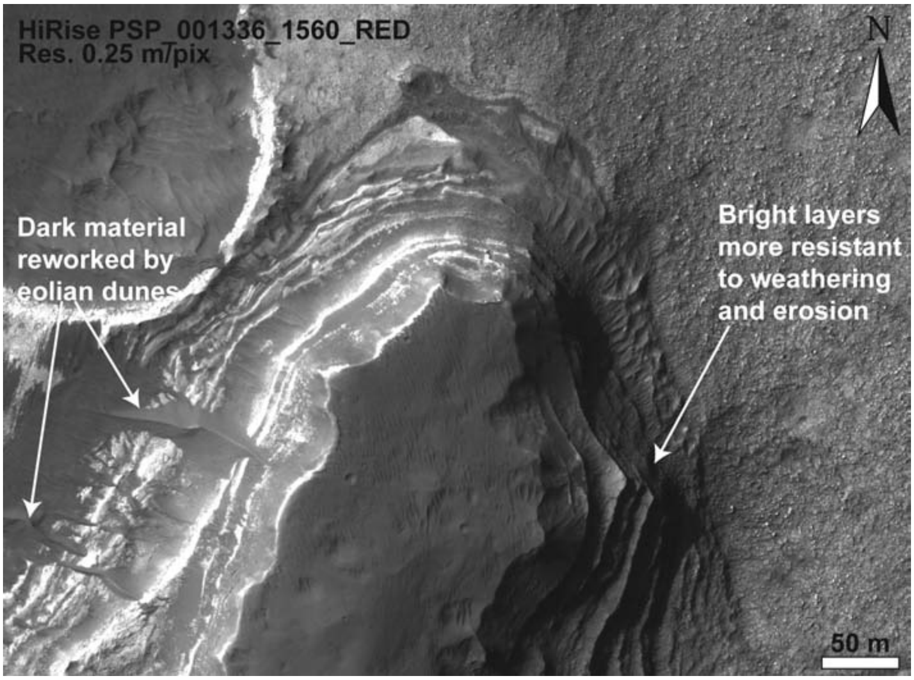

Fig.2 - Bright layered deposits cropping out in correspondence of the Eberswalde delta-like feature (see Fig. 1b for location). Unlike bright material, detritus originated by the dark layers is reworked by aeolian dunes, suggesting that the darker layers consist of finer clasts.

Camera (MOC) narrow angle (NA) images with an average spatial resolution of about 3 meters/pixel have been used for this study. Moreover, a recently released High Resolution Imaging Science Experiment (HiRise) image (spatial resolution of 25 cm/pixel) covers part of the delta-like feature. Topographic reconstruction has been highly improved by the High Resolution Stereo Camera (HRSC) Digital Terrain Model (DTM), with tridimensional reconstruction, which allows an almost Earth-like approach.

Morphofacies analysis

The Eberswalde delta-like feature consists of bright and dark interlayered deposits displaying a cyclic depositional pattern (Fig. 2). The bright layers appear to be more resistant to weathering and erosion than the darker ones which, unlike the bright ones, are reworked into aeolian dunes. On Earth, clasts transported by aeolian dunes suggest a granulometric range comprised between middle sands and granules. Due to the different gravity and atmospheric conditions it is not possible to define a precise granulometric range for the bright and dark layers, but it is possible to infer that the bright layers are coarser or better cemented than the darker ones.

The bright-dark thickness ratio varies, but usually the bright portion is thicker than the darker one. The average thickness of each bright-dark couplet has been estimated by dividing the total thickness of the succession in one profile by the number of cycles. In order to have the best possible estimations, we co-registered different topographic data: altimetry from MOLA PEDR (Mars Orbiter Laser Altimeter – Precision Experiment Data Records) single profiles, HRSC DTM data and MOC NA images. We measured an average thickness roughly ranging from 2 to 8 meters. These values do not aim to be precise, but they are just intended to provide a rough scale.

The overall thickness of the delta-like feature deposits ranges from some tens of meters to about 100 m, estimated on the basis of the HRSC as well as MOLA DTMs.

The delta-like feature consists of a low-dipping proximal area (dip value can be measured using HRSC DTM in 0^{o}-2.7^{o}), a distal relatively high-dipping area (2.7^{o}-8^{o}) and an even more distal low-dipping area (0^{o}-2.7^{o}), which gradually connects to the crater floor (Fig. 3).

The presence of a morphological step in the

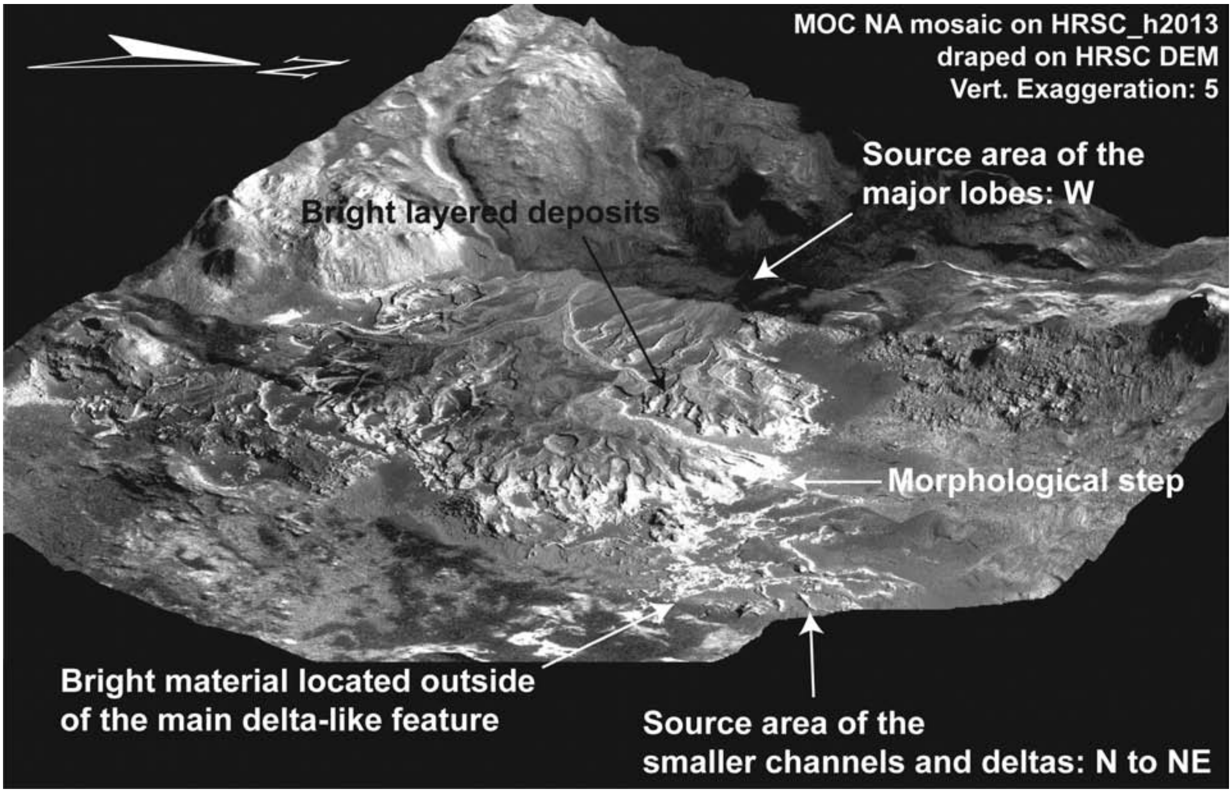

Fig. 3 - 3d image of the Eberswalde delta-like feature emphasizing the presence of a morphological step in the frontal part of the lobes. The bright material located outside of the main fan delta consists of fluvial channels and delta-like feature whose source area is totally different from that of the major fan delta.

frontal part of the structure suggests a possible interaction with a standing body of water (Malin and Edgett, 2003; Moore et al., 2003), but Jerolmack et al. (2004) considered that this step could have been produced by aeolian erosion. The latter constrained their interpretation observing the bright levels in areas located far away from the delta-like feature (Fig. 3), and concluded that the delta-like feature could have been originated as an alluvial fan which was originally much more extended into the crater and was later partially eroded by the wind.

Nevertheless, at a closer look, the bright material located out of the delta-like feature consists of smaller channels and delta-like features, the source area of which is completely different from that of the major deltaic body (Fig. 3). Thus, this is inconsistent with a common origin of the bright materials in these distant outcrops, as parts of a single, very large alluvial fan.

Based on these elements and according to the discussions on the morphometric parameters of the distributary channels drainage pattern done by Bhattacharya et al. (2005) and Wood (2006), we interpret the Eberswalde delta-like feature as a fan delta depositional environment.

The delta consists of five different lobes displaying either a lobate or a digitate geometry (Fig. 1b), suggesting the dominance of input-related processes.

The proximal gently-dipping part of each lobe consists of exhumed channels showing a distributary pattern (Fig. 4). According to Malin and Edgett (2003), this "inverted" topography presumably formed because of aeolian deflation of the finer materials.

The morphology of the distributary channels ranges from rectilinear, possibly braided, to mainly meandering (Bhattacharya et al., 2005) (Figs. 4, 5a, 5b).

The point bar assemblage reflects the lateral accretion of the meandering distributary channels and represents in fact the most distinctive feature of the proximal gently-dipping part of the fan delta (Fig. 4, 5a, 5b). The sinuosity index of the meanders has been calculated by Wood (2006) to

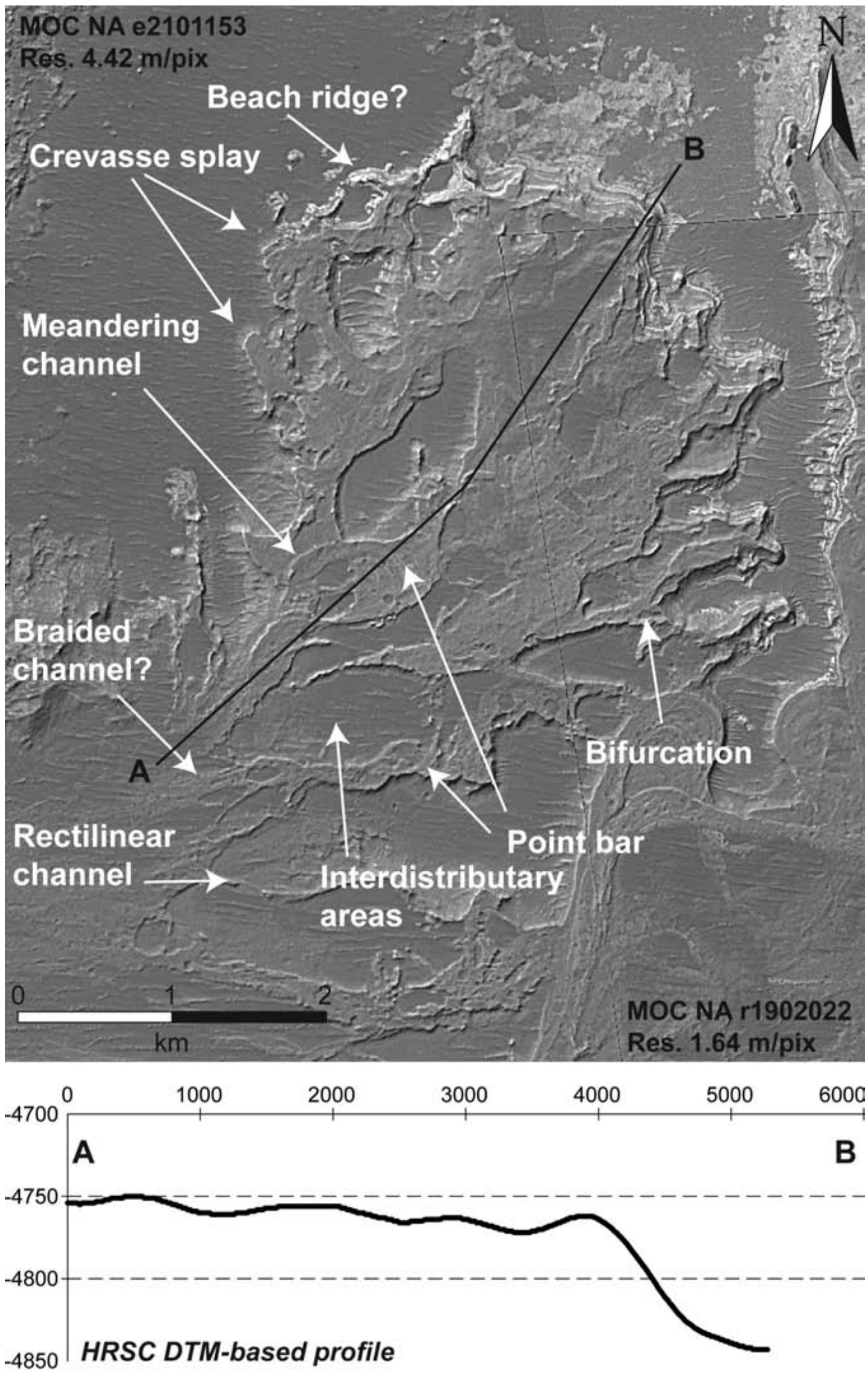

Fig. 4 - Deltaic lobe in correspondence of the Eberswalde fan delta. The proximal low-dipping part of the lobe (see the A-B topographic profile) consists of distributary channels and interdistributary areas. Exhumed distributary channels are made of coalescing point bars, but rectilinear, sometimes possibly braided, channels, are also present. Crevasse splays formed as a result of large flooding breaching the levees and delivering coarser sediments in the interdistributary areas. The frontal part of the lobe is steeper as it is shown in the A-B topographic profile. In correspondence of this dipper part, some features elongated parallel to the lobe margins might have been formed as beach ridges following wave reworking (see Fig. 1b for location).

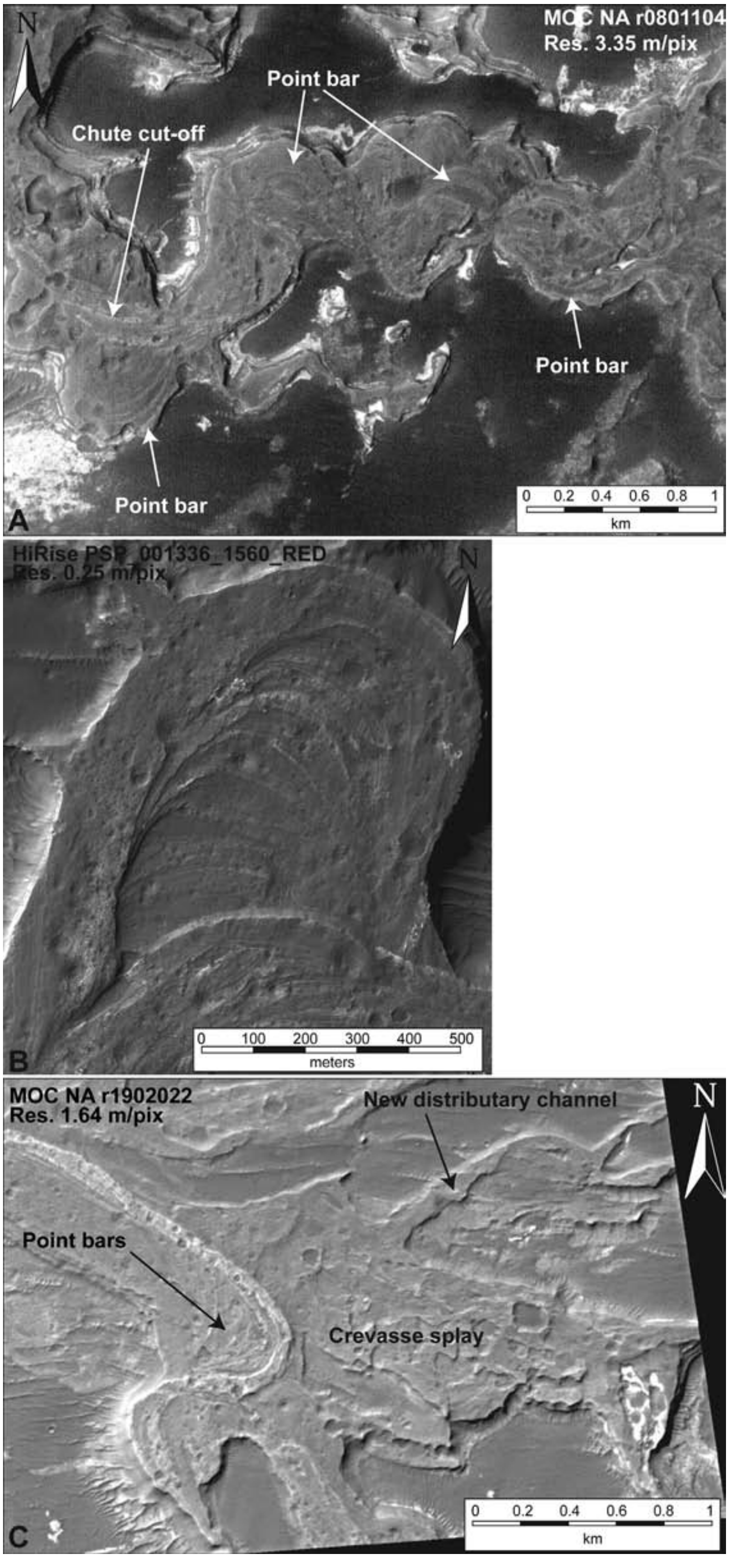

Fig. 5 – A. Distributary channels mostly consist of coalescent point bars formed following lateral accretion. A chute cut-off marks a phase in the evolution of the meander (see Fig. 1b for location). B. Detail of a meandering channel characterized by a point bars assemblage. A chute cut-off is recognizable (see Fig. 1b for location). C. Sinuous channel with point bars following its lateral accretion. A crevasse splay suggesting flooding of the interdistributary areas after breaking the channel levees is preserved. The crevasse splay originates new distributary channels (see Fig. 1b for location).

be between 1.1 and 1.8, which is consistent with bedload to mixed-load sediments. Some chute cutoff, the most spectacular of them discovered by Malin and Edgett (2003) (Fig. 5b), are formed following the abandonment of the sinuous channels in favour of chute channels (Figs. 5a, 5b). The presence of chute cutoff and not meander cutoff confirms that the meanders did not reach the highly sinuous stage which would be indicative of fine grained systems (Wood, 2006).

At places, roughly fan-shaped tongues of bright deposits are located beside the channels developing into the surrounding deeper areas, suggesting the infilling of coarser material in an area usually subjected to low energy and finer sedimentation (Fig. 5c). The morphology of these deposits and their association with distributary channels suggest a formation as crevasse splays formed during episodes of high flooding, with levee breach and consequent infilling of the flooding plain with coarser sediments. New distributary channels can originate from these crevasse splay (Fig. 5c), a typical mechanism of avulsion on Earth. Channel avulsion has been observed along the whole delta-like feature (Bhattacharya et al., 2005).

The extensive presence in the whole delta of a polygonal pattern affecting the bright layers has been reported by Schieber (2007) using HiRise images. The dimensions of the single polygons range roughly from 1 to 4 metres (Fig. 6). As noted by Schieber (2007) such features on Earth develop in sandstones subjected to thermal contraction on evaporite-encrusted surface (Kocurek and Hunter, 1986). This would imply that the polygonal areas underwent frequent exposure (Schieber, 2007).

Howard et al. (2007) and Schieber (2007) recognized the widespread distribution of boulders exceeding 1 m size, wondering if a normal turbulent flow can transport such materials. According to Schieber (2007) the presence of these boulders would suggest the importance of brief pulses of high energetic discharge rather than sustained flow over long periods.

A sequence of a very low sinuosity channel has been observed in recently released HiRise image (Fig. 7). The channel consists of few meters thick superposed lenticular bodies. Each of them is made of gravels up to few meters of diameter grading up to sediments fine enough to be reworked by aeolian dunes. The gravels consist of polygonal blocks showing the same geometry and

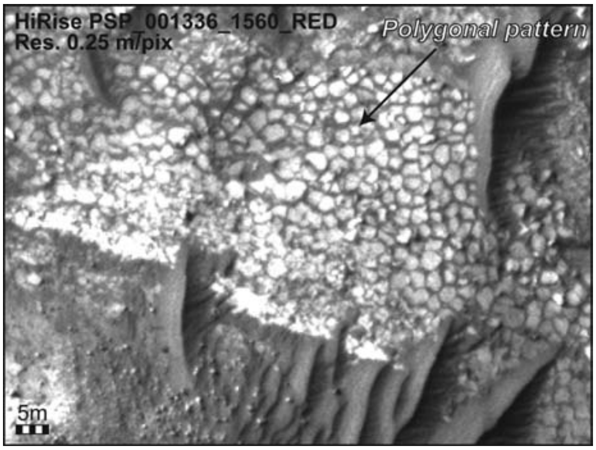

Fig. 6 - Detail representing the polygonal pattern affecting the bright layers (see Fig. 1b for location). Each polygon roughly measures from 1 to 4 meters.

scale of the polygonal pattern shown in Figure 6. At places these clasts seems to show a consistent inclination which might correspond to up-current imbrications.

These lenticular bodies are very poorly sorted and rich in matrix, even if clast-supported, thus suggesting a very low textural maturity. A fining-upward trend is recognizable and evidenced by the upward transition to much finer sediments (Fig. 7).

In braided channels on Earth comparable fining-upward cycles are caused by the abandonment of channels related to lateral migrations or avulsions and subsequent channel fill by finer sediments. Such evolution causes the formation of autocyclic sequences. Accordingly, we interpret the bright-dark deposits of Fig. 7 as coarse grained braid bars interlayered with finer materials representing cycles of filling and abandonment of channels. Moreover, we hypothesize that the polygonal clasts originally formed following thermal contraction on evaporite-encrusted surface in an area subjected to exposure (Schieber, 2007), were then eroded and reworked by the fluvial channel. The breccia cropping out in this channel and possibly also part of the breccia deposits recorded in other parts of the delta (Howard et al., 2007; Schieber, 2007) would thus represent an intrabasinal breccia, the provenance of which is likely located inside the depositional basin.

On the basis of the described morphologies, we interpret the low dipping proximal part of the fan delta as formed in a delta-plain depositional en-

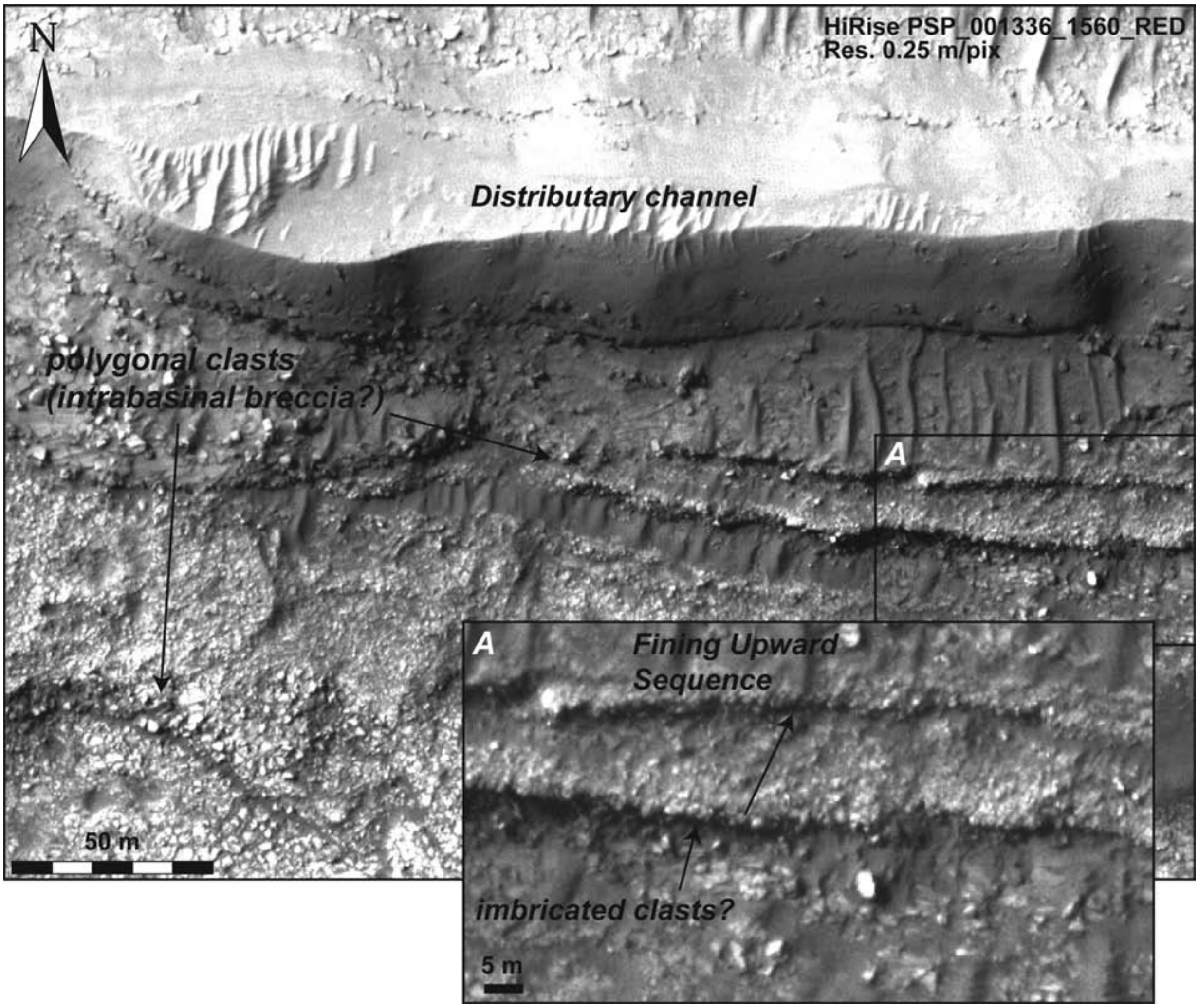

Fig. 7 - Erosional cut in correspondence of a low-sinuosity distributary channel (see Fig. 1b for location). Several lenticular bodies made of gravels up to few meters of diameter grading into finer sediments crop out. Gravels are made of very poorly sorted reworked polygonal clasts possibly showing at places up current imbrication. Each lenticular body displays a fining-upward sequence.

vironment, in which distributary channels and interdistributary areas are distinguishable (Fig. 8).

The presence of systems such as point bars or crevasse splays strongly suggests that "normal" traction processes have been dominant in the delta plain. The presence of polygonal shrinkage cracks and of boulders does not seem to be in contrast with such scenario.

In correspondence of the high-dipping part of the fan delta, layers which are gently dipping in the delta plain become more inclined and then again sub-horizontal to connect with the crater floor (Fig. 9). This topset-foreset-bottomset geometry is typical of some kind of fan deltas and gives even more consistent evidence that this delta-like feature has been indeed deposited as a fan delta, which implies that during its formation the Eberswalde crater was filled by a standing body of water.

We interpret this area as the delta front (Fig. 8).

In correspondence of the delta front, at places, some levels displaying very poorly sorted texture with boulders up to 10 m of diameter floating in finer sediments are observable, suggesting mass flow as depositional process (Fig. 10). This putative mass flow might imply either inertia-dominated homopycnal flows or hyperpycnal flows, conditions which might correspond to periods of the deltaic evolution where river discharge was the dominant process.

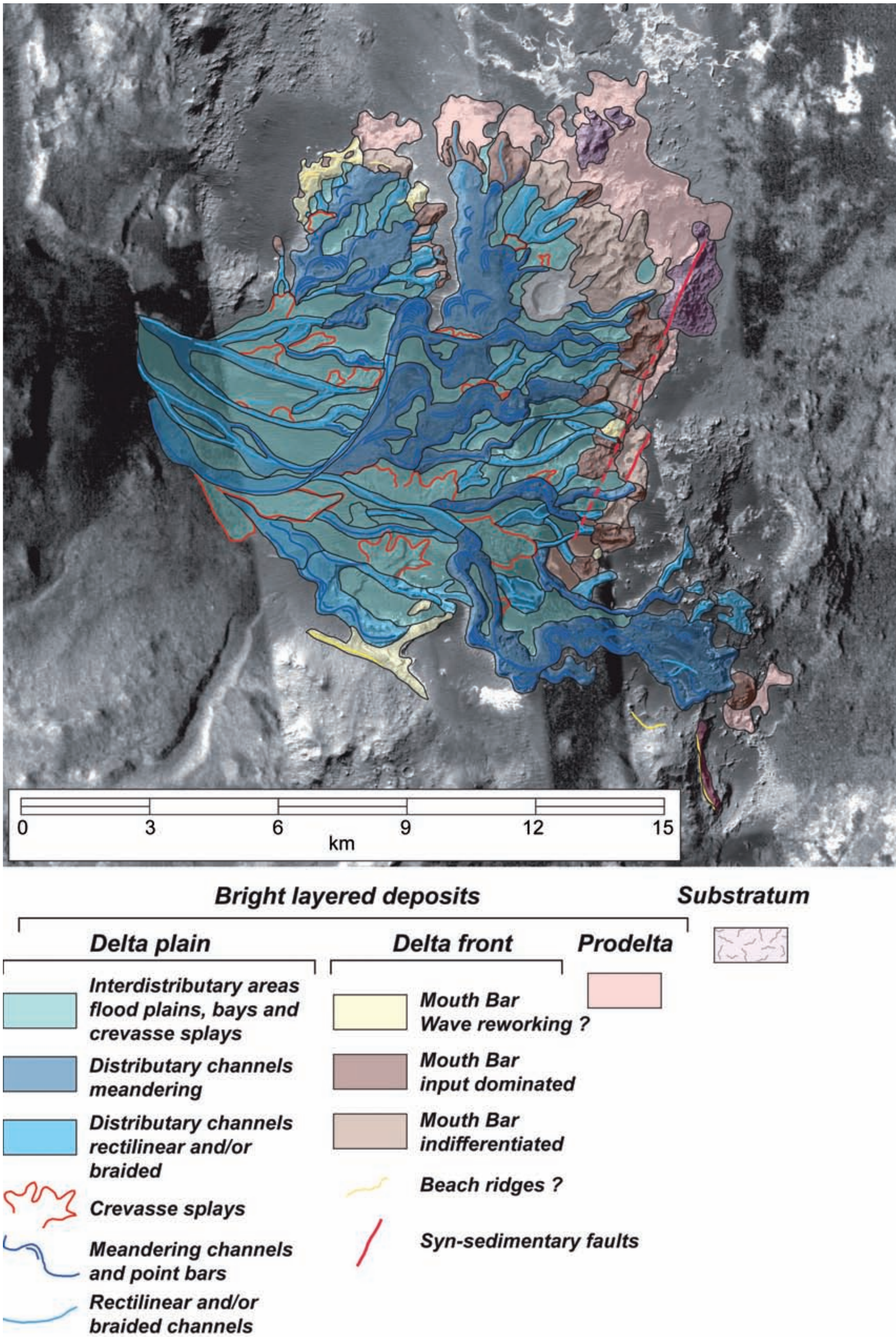

Fig. 8 - Interpretative morphofacies map of the Eberswalde fan delta.

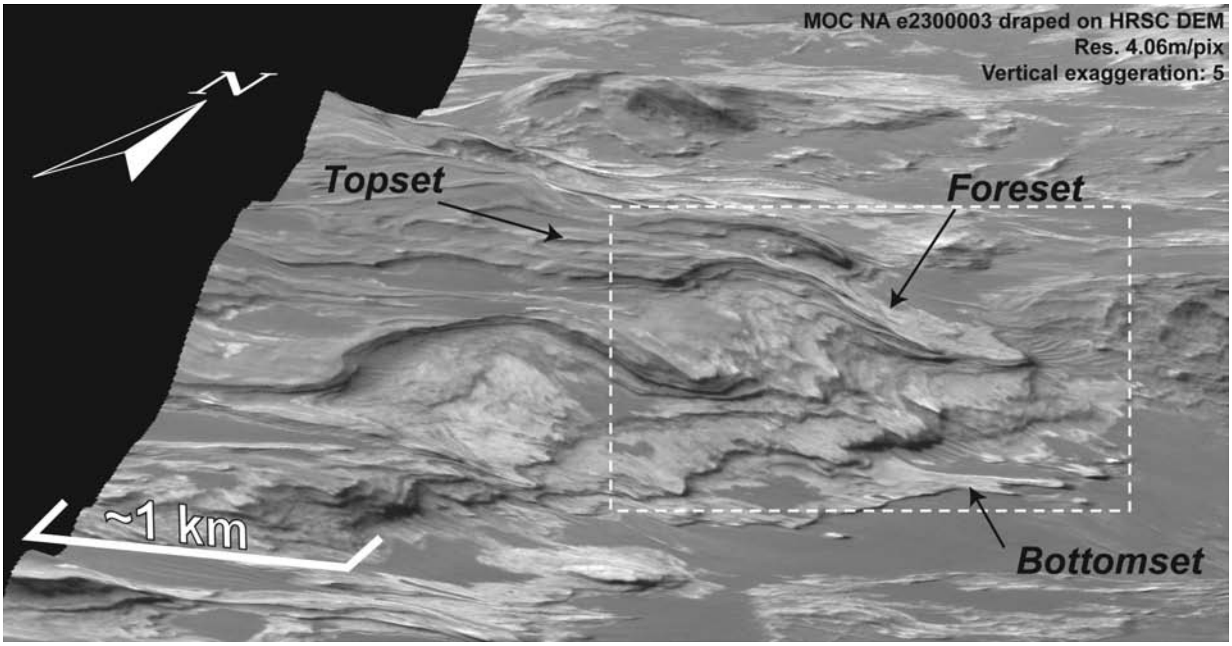

Fig. 9 - Topset-foreset-bottomset geometry in correspondence of the high-dipping part of the fan delta (see Fig. 1b for location). This pattern represents the most striking evidence that the Eberswalde delta-like feature has been deposited as a fan delta. White box represents the location of Fig. 15.

At places, again in the high-dipping part of the delta, channels tend to bifurcate (Fig. 4).

Channels may bifurcate when enter very shallow basins, and frictional interaction between the flow and the sediment surface leads to the deceleration of the incoming flux, with consequent deposition of part of the sedimentary load in a bar that force the channel to bifurcate. The presence of such geometries might thus suggest the dominance of friction-related processes at the river mouth possibly associated with a shallow-water basin.

In some limited locations of the delta front, bright layers form bodies distributing parallel to the lobe margins. This morphology might represent beach ridges, which would suggest re-

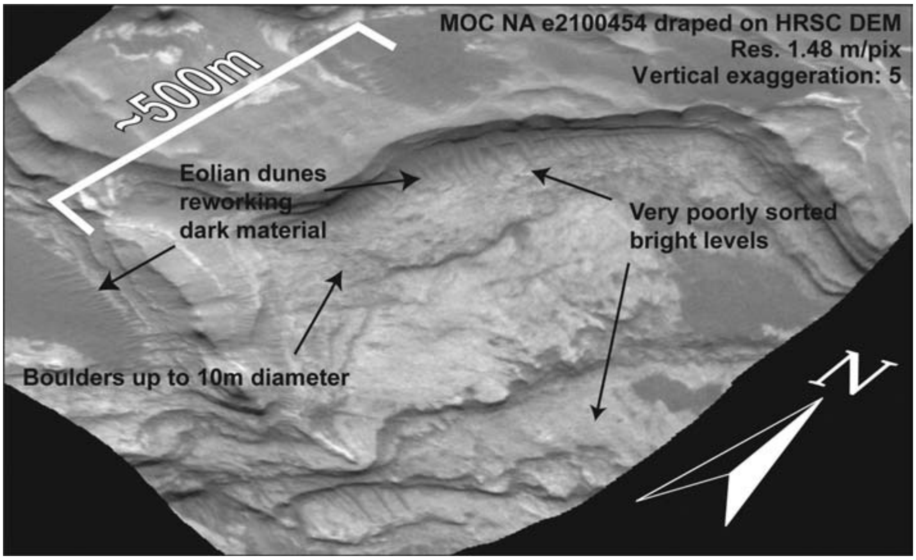

Fig. 10 - Sedimentary deposits cropping out in correspondence of the delta front (see Fig. 1b for location). Some layers are very poorly sorted with boulders up to 10 m of diameters floating in a finer matrix.

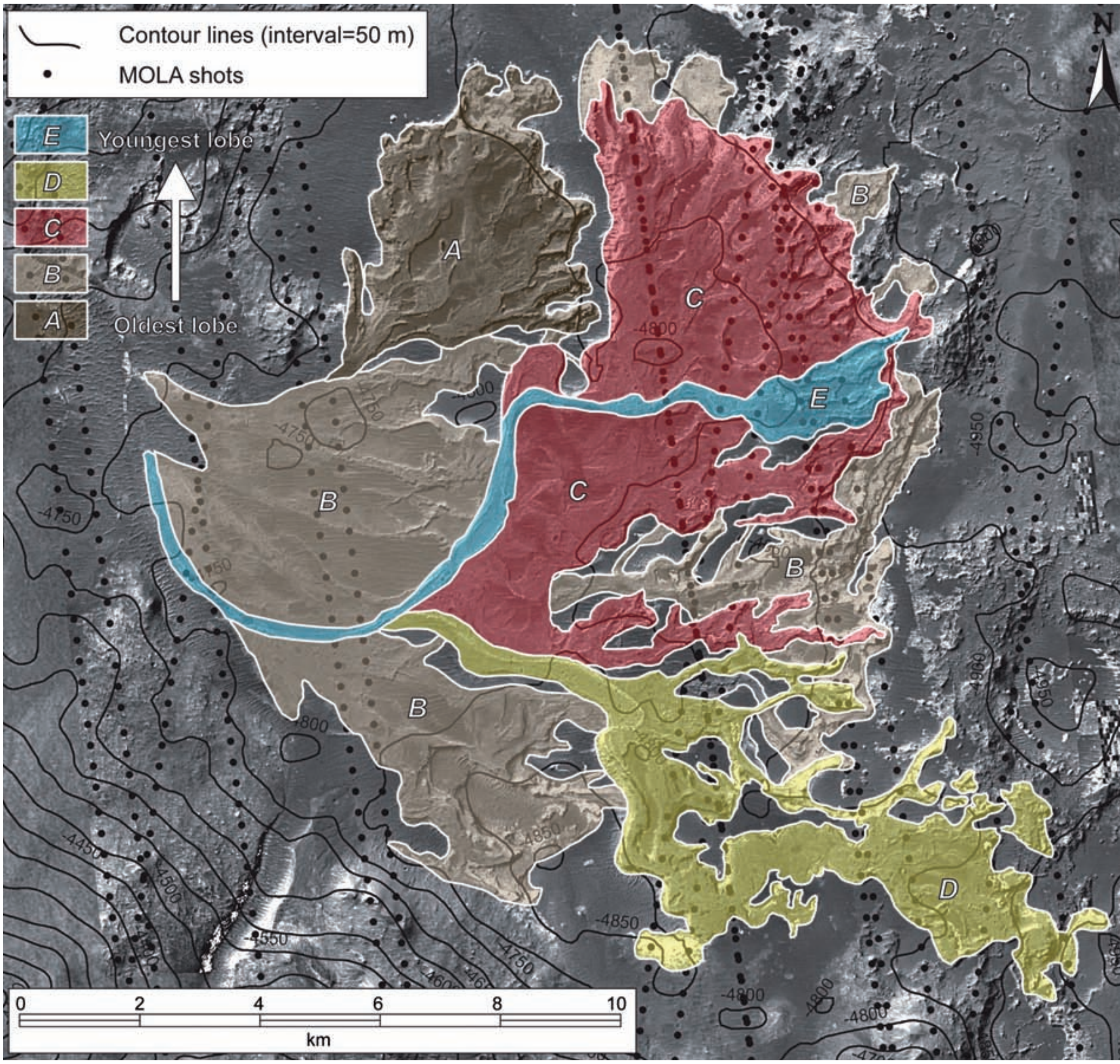

Fig. 11 - Relative stratigraphy of the different lobes of the Eberswalde fan delta, recognized using cross-cutting relationships. Each lobe represent a different stage of the evolution of the delta, corresponding to different levels of the water table. Contour lines have been obtained through HRSC based DTM. MOLA shots are shown.

working by wave action (Fig. 4). Even if these features cannot be unambiguously interpreted, a slight degree of wave reworking is consistent with the lobate morphology recorded in some lobes (Fig. 1b). Accordingly, we tried tentatively to distinguish wave-dominated delta front areas (Fig. 8).

The recognition of different processes dominant in different periods of the evolution of the delta, suggests fluctuations of the discharge conditions and of the level of the water table through time.

Dynamic of the deltaic system

Our aim has been to reconstruct the evolution of the fan delta and to try and infer by which factors it has been controlled and in particular if these factors were simply related to the normal dynamic intrinsic of a deltaic system, or if some external control (*i.e.* climatic or tectonic) has been present. Of course, it is very difficult to evaluate the depositional architecture only from remote sensing analyses, in an area in which the boundaries between the different lobes at places can be

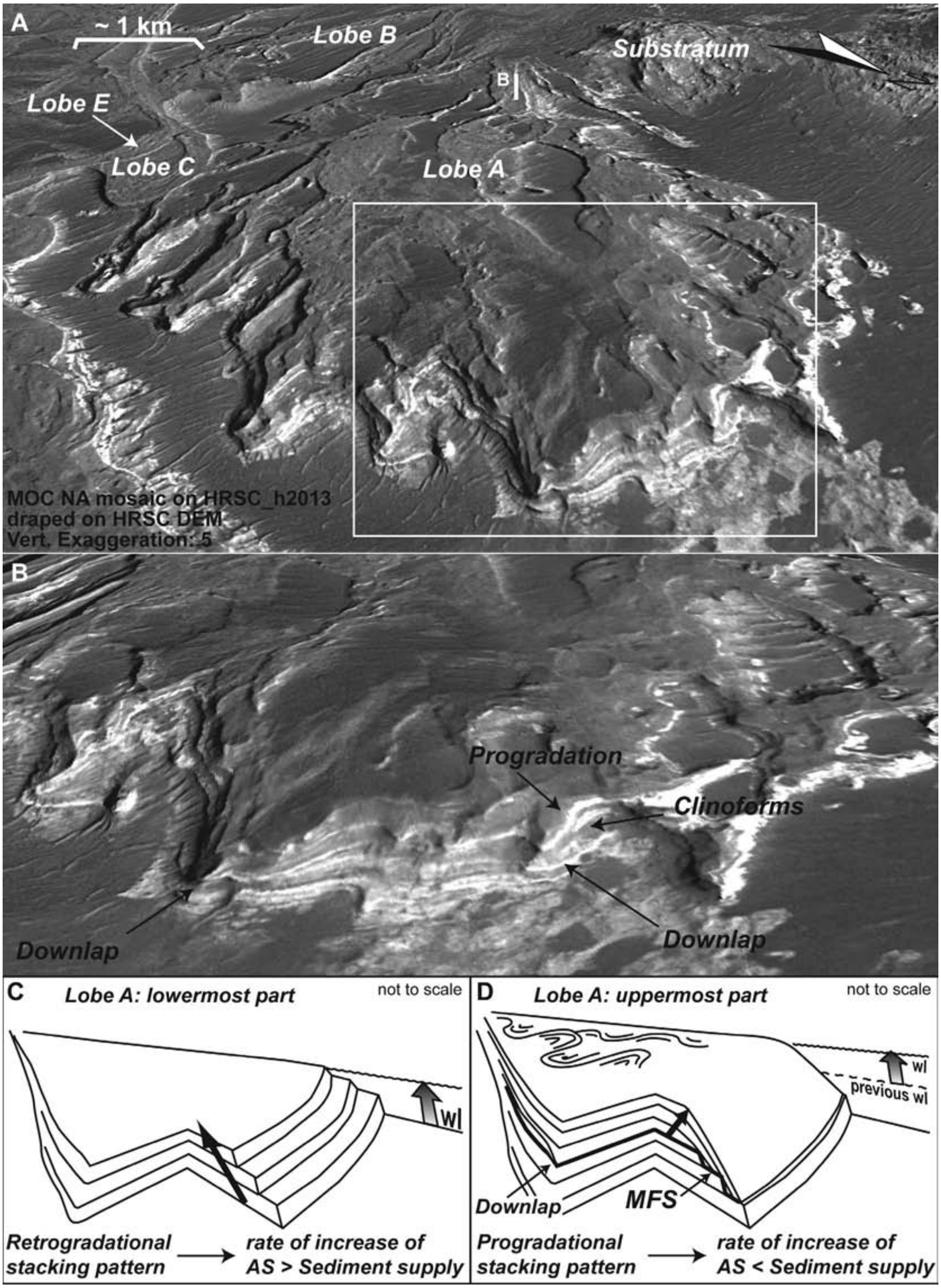

Fig. 12 - A. 3d view of lobe A in which the cross-cutting relationships with lobes B, C and E are visible. The white box corresponds to the location of b. B. Geometrical features recognized in the delta front of lobe A. We distinguish a lower part where layers display an almost horizontal attitude and an upper part in which they are more inclined. Progradation of clinoforms is present in the upper part of the succession. Clinoforms terminate on top of the older low-inclined layers of the lower part of the succession, originating a downlap geometry. C. Interpretative sketch relative to the lowermost part of the succession. wl = water level. D. Interpretative sketch relative to the uppermost part of the succession. The almost horizontal layers deposited in the previous phase are superposed by clinoforms prograding on top of them. The distributary channels are mainly meandering. We speculate that the lower part might represent a retrogradating stacking pattern, while the upper part would correspond to a progradational stacking pattern. These stacking patterns would be separated by a Maximum Flooding Surface emphasized by the downlap. wl = water level; previous wl = water level corresponding to the MFS.

only tentatively inferred and in which the hierarchy of the different depositional cycles cannot be properly evaluated. On the other hand, the erosion of the fossil fan delta (e.g. with aeolian removal of fine-grained material from interdistributary areas) greatly enhanced its features, making possible to distinguish its geometrical and stratigraphic characteristics.

The relative stratigraphy to define the stratigraphic framework within the five different lobes has been inferred using simple cross-cutting relationships (Fig. 11).

We named the oldest recognizable lobe of the fan delta, which is also the most proximal and the one reaching the highest elevations, lobe A (Figs. 11, 12a). The erosional cut characterizing the delta front exposes the sedimentary architecture (Fig. 12b).

In the lowermost part of the succession the layers are sub-horizontal and just gently inclined toward the basin (Figs. 12b, c). Some of these layers seem to thin going distally. Whereas, the upper layers which are sub-horizontal in the delta plain, become more inclined in the delta front. We interpret them as clinoforms prograding toward the basin, where they terminate on top of the lowermost sub-horizontal layers they develop a downlap surface (Figs. 12b, 12d).

We thus interpret this depositional architecture as a transgressive-regressive cycle (Figs. 12c, d). The layers of the lower part of the succession seem organized in a retrogradational stacking pattern (Fig. 12c), while in the upper part the stacking pattern appear to be progradational (Fig. 12d). We interpret the dividing surface, emphasized by the downlap, as a Maximum Flooding Surface (MFS), the surface corresponding to the most proximal level reached by the water level during transgression.

In this putative scenario the succession below the MFS would have been formed in correspondence of a relative rise of the water table during which the sediment supply could not fill the continuously forming accommodation space. The succession above the MFS would have been formed from of an excess of sediment supply respect to the rate of creation of accommodation space. Accordingly, we speculate that the lowermost part of the succession represent a Transgressive Systems Tract, while the uppermost part a Highstand Systems Tract (Fig. 13).

In the lower part of the succession delta-front layers just gently dip toward the basin, thus suggesting that the lower part of lobe A could have been formed as a shallow-water type fan delta (Galloway, 1976). Foresets are present in the upper part of the succession, roughly 6° to 8° inclined according to HRSC DTM based measurements. This inclination angle is too small to interpret this fan delta as a Gilbert-type fan delta (Gilbert, 1885).

The transition to lobe B is marked by the erosion of the most proximal parts of lobe A by lobe B distributary channels (Figs. 11, 12a). Even if lobe B is partly covered by the younger lobe C, it is possible to observe that this lobe extends more distally in the basin and that the transition between delta plain and delta front occurs at deeper elevations (Fig. 11), which suggests that during its deposition lobe A underwent subaerial exposure. Moreover, while the distributary channels in lobe A are mostly meandering, in the proximal part of lobe B they appear rectilinear, possibly braided, suggesting higher discharge and higher channel gradients (Figs. 8, 11, 12a).

The concurrency of erosional truncation of part of lobe A together with the increasing channel energy, the distal shifting of the delta front and the deeper elevation at which the transition between delta plain and delta front occur, suggest a drop of the base level of the erosion, which would correspond to a drop of the water table (Fig. 14).

We thus hypothesize that the transition between lobes A and B might have been caused by a forced regression. The dividing surface would thus represent a Sequence Boundary. Lobe B would have thus prograded into the basin following the drop of the water level, continuing to prograde as far as the water level continued to fall and then slowly to rise, with a rate too low to exceed the sedimentary input. We interpret this progradational phase as a Falling-Stage Systems Tract and Lowstand Systems Tract (Figs. 13, 14). We do not have elements to distinguish among the two systems tracts.

Lobe C developed on top of lobe B with no evidence of erosional episodes (Fig. 11). The distributary channels morphofacies consists mostly of coalescent point bars (Figs. 8, 11), implying that the discharge energy was lower respect to lobe B. This suggests a rise of the base level following a rise of the water table.

In correspondence of an erosional cut in the frontal part of lobes B, C and E (Fig. 15) we distinguished a lower portion which we attributed to lobe B on top of which lobe C layers appear to

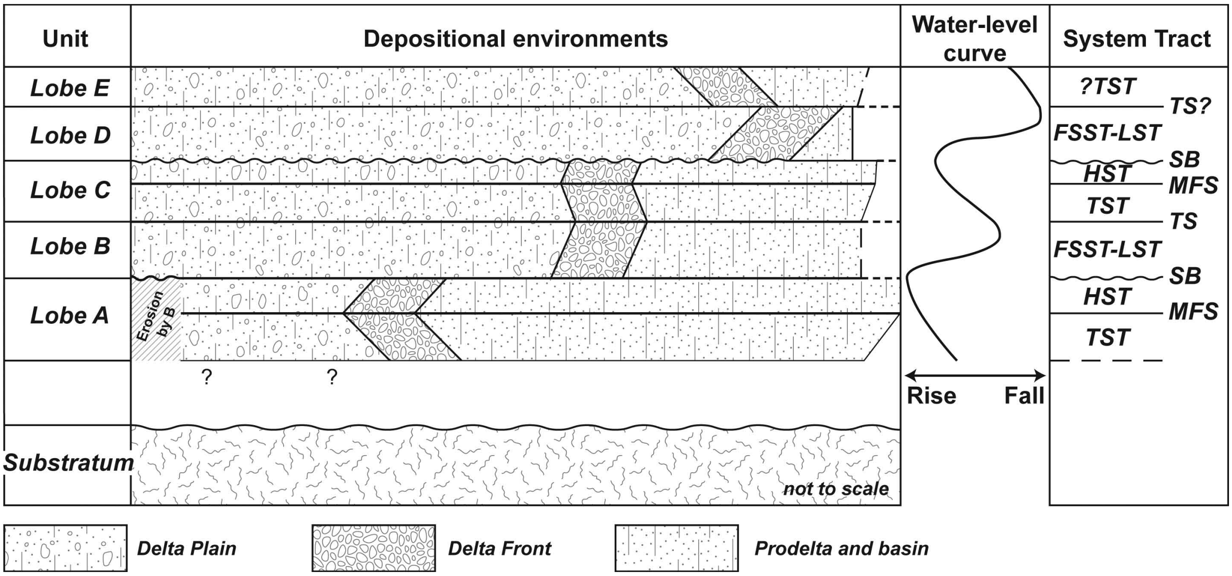

Fig. 13 - Space-time diagram with a tentative reconstruction of the depositional architecture and the related water-level fluctuations.

step back showing what it looks like a retrogradational stacking pattern. On top of these layers, still in correspondence of lobe C, progradation of clinoforms defining a possible downlap occurs.

This depositional architecture, together with the diminished discharge energy inferred by the distributary channels morphology, allow to hypothesize that lobe C might have been formed by a relative rise of the water table. We speculate that the lowermost part of the succession corresponds to a period of relative rise of the water table during which the sediment supply was unable to fill all the newly created accommodation space, that is a Transgressive Systems Tract. The uppermost part of the succession would correspond to a period with an excess of sedimentary input respect to the rate of creation of accommodation space, which is a Highstand Systems Tract. The surface dividing these systems, emphasized by the downlap surface, would correspond to a Maximum Flooding Surface (Fig. 13).

The next lobe D has been deposited following a southward shifting of the distributary pattern and cutting through lobes B and C delta plain deposits to reach the most distal positions recorded in the fan delta (Fig. 11). Moreover, the transition between delta plain and delta front deposits occur in the deepest position (Figs. 8, 11). The delta front is characterized by the presence of slightly inclined (from 4^{o} to 5^{o} according to HRSC DTM based measurements) prograding clinoforms. During the deposition of Lobe D, the previously deposited lobes would have been subjected to subaerial exposure.

The distal extension of lobe D, the transition between delta plain and delta front occurring in deeper position than in lobe C as well as the presence of prograding clinoforms are consistent with a formation of this lobe as a response to a

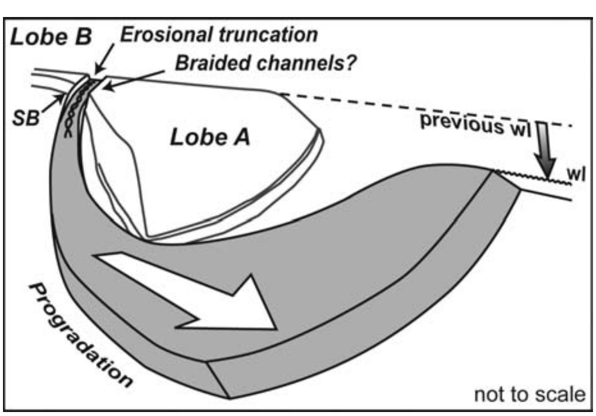

Fig. 14 - Interpretative sketch relative to the genetic evolution of lobe B. On the basis of the erosional truncation of A, the distal shifting and the lower elevation of the delta front and the presence of distributary channels, whose morphology suggests a higher discharge energy, we speculate that this lobe might have been formed following a forced regression. The previously deposited lobe A during this phase was not active and subjected to exposure. wl = water level; previous wl = maximum water level reached during the highstand.

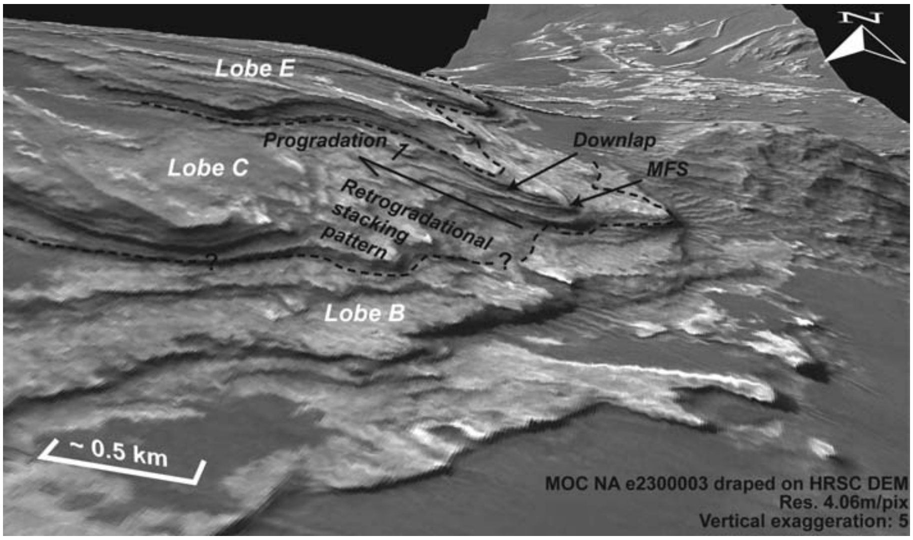

Fig. 15 - 3d view of the frontal part of lobes B, C and E (see Fig. 9 for location). Lowermost layers belonging to lobe C appear to progressively step back, suggesting to be organized in a retrogradational stacking pattern. Instead, in the uppermost part of lobe C progradation of clinoforms with the consequent formation of a downlap is observable. The downlap allows to emphasize a Maximum Flooding Surface.

drop of the water table with consequent drop of the base level of the erosion, which means a forced regression.

Accordingly, we interpret the transition between lobes C and D to occur in correspondence of a Sequence Boundary. Then Lobe D progradation would have persisted until the water level started to rise with a rate exceeding the capability of the sedimentary input to fill the newly created accommodation space.

We then speculate that lobe D corresponds to a Falling-Stage Systems Tract and to a Lowstand Systems Tract (Fig. 13). Also in this situation we have no elements to distinguish among the two systems tracts.

Lobe E formed following a northward shifting of the drainage pattern (Fig. 11). It represents the least complex lobe with a gently sinuous channel passing to meandering and then rectilinear close to the delta front (Fig. 8). The layer geometry of the delta front can be only tentatively interpreted as retrogradational (Fig. 15).

This possible retrogradational pattern, together with the fact that the transition between delta plain and delta front in this lobe is more proximal and located at higher elevation than lobe D, allow us to speculate that it has been formed following a relative rise of the water table (Fig. 13).

We interpret the Eberswalde fan delta as controlled by several water-level fluctuations which developed the complex sedimentary body that we tentatively interpret as formed by three depositional sequences, the first one corresponding to lobe A, the second to lobes B and C, and the third to lobes D and E (Fig. 13). The overall larger scale trend appears to be toward a progressive decreasing of the level of the water table (Fig. 13).

The reconstruction of water-level fluctuations and the inference of putative depositional sequences are obviously hampered by the resolution of available data, by the lack of subsurface observations and in general because the reconstruction of depositional environments is based on morphologies interpreted through remote sensing and not on a field-based facies analysis. Nevertheless, all the available data concur to demonstrate that switching among the different lobes has not been related to autogenic processes, intrinsic to the dynamic of the depositional system, but to allogenic processes which caused fluctuations of the level of water table. Moreover, these fluctuations appear to have a cyclic character. The controls on these fluctuations cannot be understood from our limited scenario, but climatic forcing and/or tectonic activity could be potential causes.

Interpretative scenario

A detailed geological and stratigraphic survey of the Eberswalde fan delta has been performed in order to define which sedimentary processes and depositional environments were present and their evolution through time.

We distinguished and mapped delta-plain, delta-front and prodelta depositional environments.

Distributary channels, mainly meandering but also rectilinear and braided, and interdistributary areas, with crevasse splays debouching in the flooding plain, have been recognized in the delta plain. The morphometric characteristics of the meanders are consistent with a bedload to mixed-load tractional sedimentary transport (Wood, 2006). Polygonal shrinkage cracks are extensively exposed in the delta plain and in general affect the whole deltaic deposits. This could be linked to thermal contraction on an evaporate-encrusted surface (Kocurek and Hunter, 1986; Schieber, 2007). These sandstones would have been subjected to subaerial exposure either in the exposed areas of the delta plain or in areas which underwent exposure following a drop of the water table. Later these polygons have been locally reworked by distributary channels which ought to an avulsion, occupied the areas in which they formed. Breccia deposits found in several places within the delta appear thus to consist at least partly of intrabasinal breccia.

The gently dipping layers of the delta plain become more inclined in correspondence of the delta front, and then again sub-horizontal in the prodelta.

In the delta front, the occurrence of mass flow has been hypothesized at places because of the textural characteristics recognized in some layers. The presence of these layers would pose constraints in terms of density contrast between the inflow and the basin waters, either hyperpycnal flows or inertia-dominated homopycnal flows.

In other locations of the delta front, bifurcation of distributary channels have been recognized. This geometry might suggest the importance of friction-related processes, which would imply that the water level during the formation of such systems was shallow.

In terms of granulometric range, the dominance either of inertia or friction-related processes, suggests a mixed load to bedload sedimentary transport, which is consistent with the morphometric characteristics of the distributary channels.

The presence of different depositional processes dominant in different period of the evolution of the fan delta suggests variations of the controls on the sedimentation through time. In order to understand this dynamic, the relative stratigraphy among the deltaic lobes has been assessed using cross cutting relationships and a tentative reconstruction of the depositional architecture has been carried on. Then the reconstructed depositional architecture has been interpreted in terms of base level change in order to infer the water table fluctuation.

We recognize three major cycles, which we tentatively interpret as depositional sequences.

The oldest depositional sequence started with water infilling the impact crater with a rate exceeding the one of sedimentary input, thus originating a retrogradational stacking pattern of the deltaic layers that we interpret as a formed in a Transgressive Systems Tract (Lobe A). Then, possibly following a relative decrease of the rate of water level rise, the succession started to prograde. We interpret this phase as a Highstand Systems Tract (Lobe A). The maximum landward extension of the water between the two system tracts is emphasized by the downlap and we interpret it as a Maximum Flooding Surface.

A following drop of the water table is suggested by the distal shifting of the delta front, by the erosion of part of the previous deposits and by the change of morphology of the distributary channels from meandering to possibly braided, suggesting an increasing of the energy discharge. These evidences suggest a drop of the base level, and we interpret the corresponding surface as a Sequence Boundary. We thus interpret lobe B progradation as developed during a Falling-Stage Systems Tract and the following Lowstand Systems Tract.

Lobe C is slightly more proximal and shallower, while the distributary channels become again meandering suggesting a decrease of the energy of water discharge. The stacking pattern appears to be retrogradational at the base and then progradational in the upper part of the lobe. On the basis of these elements, we speculate that lobe C has been deposited in correspondence of a Transgressive Systems Tract passing to a Highstand Systems Tract.

Another distal shifting of the distributary pattern and of the delta front suggests a drop of the water table with following consequent clinoforms progradation within lobe D. We interpret this distal shifting as related to a Sequence Boundary and the following clinoforms as deposited in correspondence of a Falling-Stage Systems Tract and a then of Lowstand Systems Tract.

Lobe E is more proximal and shallower, so we tentatively interpret it as formed in correspondence of a water level rise which might be related to a possible Transgressive Systems Tract.

According to this scenario the evolution of the

Eberswalde fan delta appears to be controlled by autogenic processes within the single lobes, where avulsion of the distributary channels originates the bright-dark cycles. Allogenic processes, such as tectonic activity and/or climatic forcing, would instead cause fluctuations of the level of the water table in the lake, consequently driving the switching among the different deltaic lobes.

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