# Stratigraphic analysis of the distributary fan in Eberswalde crater using stereo imagery

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[1] The eroded remains of a fluvial distributary network in Eberswalde crater are uniquely well preserved among similar structures on Mars. A quantitative analysis of the exposed stratigraphy has been performed to investigate the internal structure of the deposit. Using topographic information derived from stereo pairs of high-resolution Mars Orbiter Camera images, we have for the first time quantified the orientation of individual layers exposed along the distal end of the distributary network. In combination with topographic data from the Mars Orbiter Laser Altimeter, we have examined plausible scenarios for the formation of this structure. We find that the evidence is inconsistent with formation both as an alluvial fan and as a progradational delta. Instead, we find that an aggradational delta best fits the observed characteristics of the channel network and the Eberswalde basin as a whole. We conclude that the delta likely formed not in a stable long-lived lake but over the course of a small number of shorter lacustrine episodes, which were not sustained at equilibrium conditions.

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#### 1. Introduction

[2] The history of water on Mars remains a subject of vigorous debate. Evidence of hydrologic activity exists in diverse forms and on many scales around the planet [Carr, 1996]. However, it remains unclear exactly how much water was present on the surface and for how long, and whether sources of water were recharged by precipitation [Squyres and Kasting, 1994; Craddock and Howard, 2002]. Fanshaped deposits at valley termini have been recognized as valuable pieces of evidence for answering these questions, and their implications at the global scale have been discussed by Irwin et al. [2005] and others. The distributary network shown in Figure 1a is a unique sedimentary structure that provides new information regarding these questions. This fan-shaped deposit, fed by meandering channels, has been interpreted as strong evidence of persistent fluvial activity [Malin and Edgett, 2003; Moore et al., 2003]. The most prominent example of meandering is shown in Figure 1a, and several instances can be found along other channels in the image. The fan (located at 23.8°S, -33.6°E) is situated within Eberswalde crater (formerly known as Holden NE crater), a severely degraded, shallow basin which has been buried beneath ejecta from the Noachian age Holden crater, immediately to the southwest [Scott and Tanaka, 1986]. The distributary channels overlie this ejecta, and are estimated to be of Late Noachian age [Moore et al., 2003]. Previous estimates of formation

timescales for this structure have ranged from as little as decades [*Jerolmack et al.*, 2004], to as long as several million years [*Bhattacharya et al.*, 2005].

[3] We have previously described the extraction of topographic data from a Mars Orbiter Camera (MOC) narrow angle stereo pair at the edge of the fan [Lewis and Aharonson, 2004], via the method of Ivanov and Lorre [2002]. These high-resolution images and topographic models from Mars Global Surveyor [Albee et al., 2001] allow unprecedented studies of meter-scale features [Malin and Edgett, 2001]. MOC images have been used elsewhere to acquire high-resolution topographic information [Kirk et al., 2002]. Here, analysis of the topographic data is presented, with a focus on the structure of the layers exposed at the distal end of the fan. The morphology of these layers records the depositional and erosional processes which formed the Eberswalde fan. There are dozens of layers exposed along the edge of the landform, and they occur in a wide range of outcrop orientations and elevations. This presents a rare opportunity for studying the overall architecture of the deposit, which preserves both spatial and temporal variations in the depositional environment. Stereoderived topographic data is used to achieve a quantitative assessment of the structure of these layered materials, which can be used to evaluate likely depositional scenarios.

# 2. Geomorphic Observations

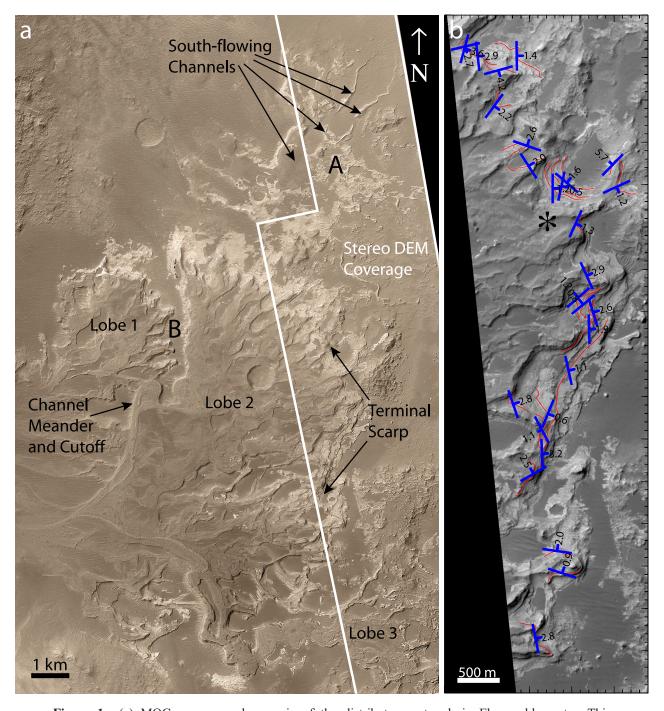
[4] An important aspect in deciphering the geologic history of the Eberswalde fan lies in determining the severity of aeolian erosion to which the deposit has been subjected. *Jerolmack et al.* [2004] estimated that the original volume was five times greater than the currently preserved

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**Figure 1.** (a) MOC narrow angle mosaic of the distributary network in Eberswalde crater. This landform comprises three main lobes, numbered here in inferred depositional sequence. Evidence of channel meanders and cutoffs can be seen in several places, suggesting sustained flow. Location A shows a group of south flowing channels adjacent to the much larger distributary network. A gap between lobes 1 and 2 where the layered deposits are discontinuous is labeled "B." These two depositional forms provide evidence that the Eberswalde channel network was never significantly more extensive. MOC stereo coverage in this area is shown, covering the finely layered outcrops along the terminal scarp. The mosaic was created by Malin Space Science Systems (M. C. Malin et al., Distributary Fan Near Holden Crater, NASA's Planetary Photojournal, http://photojournal.jpl.nasa.gov/, PIA04869, 13 November 2003). (b) Map of layer profiles used in this analysis. Red lines indicate the path of each profile, along a continuous layer outcrop. Blue symbols show the corresponding strike direction and values of the dip magnitude. An area where a vertical sequence of layers has a consistent eastward dip is denoted by an asterisk. Several other areas also exhibit consistent trends among adjacent layers. Four additional profiles, along outcrops farther to the south on lobe 3, are not shown in this plot. Minor tick marks denote 100 m intervals.

remains. A greater volume is required if the sediment was deposited in an alluvial fan which followed a smooth profile to the crater floor. This scenario also requires a 35 km erosional retreat of the distal end of the distributary system. Jerolmack et al. [2004] point to the scattered fluvial deposits around the floor of Eberswalde in support of a greater original extent of an alluvial fan, although they concede the evidence does not definitively discriminate between alluvial and deltaic scenarios. However, many of these channels have elevations and flow directions inconsistent with a direct relationship to the main distributary network. The alternative hypothesis is that the deposit represents the remains of a delta that built into a lake which partially filled Eberswalde crater at some point in its history. The deltaic scenario requires far less aeolian erosion because of the fact that the subaqueous margin of a delta can be much steeper than the profile required for a purely subaerial alluvial fan. In this case, the current scarp at the edge of the Eberswalde structure would be more representative of the original distal limit of the fluvial channels, as opposed to a purely erosional feature.

[5] While we find no solid evidence of a much more extensive alluvial fan, some observed features do suggest the modern scarp is close to the original distal limit of the deposit, favoring formation as a delta. In several places past the current margins of the distributary channels, other fluvial deposits are situated within the distance expected for a purely subaerial alluvial surface. In one instance, deposits associated with fluvial channels to the northeast of the fan lie as little as 1.5 km away (location A in Figure 1a). Using the MOC stereo topographic data described in detail below, it is clear that these channels flowed to the south, originating from a distinct source on the northern wall of the crater. There are several plausible scenarios which could produce the observed relationships between these channels and the larger, northeast flowing distributary network. To simplify this problem, we assume that all of the fluvial deposits were emplaced before significant aeolian erosion had occurred. Given this constraint, there are two possibilities for the order of deposition of the distributary system and the smaller south flowing channels nearby. If these channels were deposited after, or concurrent with the larger distributary network, they place a firm constraint on its original extent. If the south flowing channels were instead deposited first, the constraint is more ambiguous. However, a differential erosional mechanism would need to be invoked whereby several tens of meters of sediment from the large distributary network was stripped away, while these more delicate channels beneath (of order 10 m high and 30 m wide in some cases) remained well preserved. Such differential resistance to erosion would require a significant difference in cohesiveness or grain size, for example, though there is no independent evidence for such a difference here.

[6] As a second key relationship, the two largest lobes of the fan are separated by only hundreds of meters in places (location B in Figure 1a). Thus, using the labels in Figure 1a, the potential extent of channels in lobe 1 is limited by later channels in lobe 2. The distance between the lobes, however, is too great for this truncation to have been caused by fluvial erosion of lobe 1 by lobe 2 channels. This example is particularly difficult to explain by simple head-

ward retreat of an alluvial deposit, as erosion here would be near the center of the currently preserved structure. Instead, the current limit of the channels in lobe 1 is likely representative of their original termini.

[7] The two examples described here outline a scenario of fairly limited aeolian erosion within Eberswalde. From these observations, we suggest that the  $10^{\circ}-15^{\circ}$  distal slope of the fan, as measured from stereo data, is not primarily an erosional feature, but is instead a remnant of the original depositional form. Modest postfluvial erosional retreat of the scarp is possible, but is limited by this argument to be <1 km or so in lateral extent.

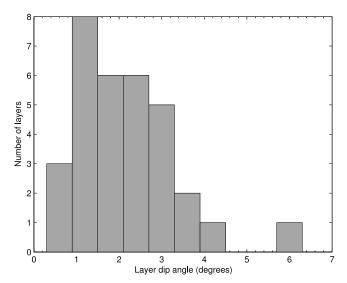
## 3. Stereo Topography

# 3.1. Methodology

- [8] For this study we have used high-resolution MOC narrow-angle images from the MGS spacecraft. These images have a maximum resolution of around 1.5 m/pixel and are typically 3 km wide. MOC has taken images of the Martian surface both in nadir and in various off-nadir orientations. Where coverage exists from multiple viewing angles, high-resolution stereogrammetry is possible.
- [9] Stereo images are processed according to the technique developed by *Ivanov and Lorre* [2002] and *Ivanov* [2003]. To begin, radiometric calibration of the images is performed using the Integrated Software for Imagers and Spectrometers (ISIS) software package. Calibrated images are then rectified using VICAR tools and the MGS telemetry data and then adjusted manually to bring them into a more precise alignment. When the stereo pair has been properly aligned, an automatic correlator is used to locate tie points between the two images. Tie points are typically collected in a 2-pixel grid, and hundreds of thousands are generally collected for a given pair of MOC images. VICAR routines are again used to extract elevation data from the tie points.
- [10] Once the elevation data has been collected, Digital Elevation Models are created by regridding, interpolating, and projecting the elevation data. The final DEMs are gridded at a resolution of 6 m/pixel in the horizontal direction. In the vertical direction, accuracy of the data is approximately 1-2 m. The DEMs in the Eberswalde region that have been used in this study include a component of the jitter reported by Ivanov and Lorre [2002] and Kirk et al. [2002]. This was removed by separating the parallax between the images into its along-track and cross-track components. The vibration onboard MGS is evidently limited to the along-track direction, so that any parallax in the crosstrack direction is free from jitter. A comparison shows longwavelength tilts in this area derived from the MOC stereo DEM differ from MOLA topographic measurements by less than 0.1°. This estimate represents an upper limit; the difference is difficult to constrain further because of the sparse distribution of MOLA points. As any discrepancies of this nature would be small compared to the topographic slopes being studied, the stereo DEM was not adjusted to conform to the MOLA data set.

## 3.2. Observations

[11] Two stereo pairs were used for our study, of images E14-01039/E23-00003 and E14-01039/E22-01159. The



**Figure 2.** Histogram of observed slopes, as determined from MOC stereo topography. The mean dip of the measured layers is 2.1°.

area for which stereo coverage is available is shown in Figure 1a. The DEMs produced in this area have good coverage over most of the original images. The automatic correlator fails to find matches in some particularly smooth or shadowed regions, but this is uncommon in areas with high-contrast features, including the layered outcrops.

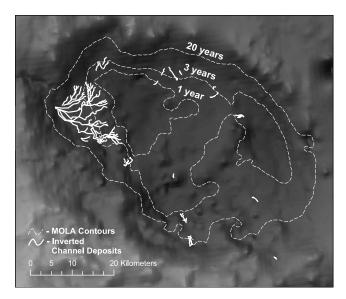
[12] The stereo-derived DEMs were used in conjunction with MOC imagery to extract elevation segments along the edges of exposed layers. Dozens of individual segments were selected manually, each ranging from a few hundred meters to over 1 km in length. Data was only taken where a layer outcrop was clearly continuous; no attempts were made to connect or extend layers where they become indistinct in the images. Efforts were made to choose layer exposures with some natural curvature in the horizontal direction, to provide more accurate constraints on the threedimensional geometry of the layer. This was done in recognition of the fact that a linear segment provides no information in the direction perpendicular to the line. Otherwise, segments were taken from a variety of areas within the DEM. For our analysis, we used 40 such segments along the margin of the layered deposits.

[13] Since each segment extracted here is much smaller than the overall extent of the fan, it is assumed that the layers should be very close to planar on this scale. To evaluate this hypothesis, and to gain a quantitative measure of the attitude of the layers, a plane was fit to each profile using linear regression. From the derived coefficients, the dip direction and slope are computed, along with their corresponding error estimates, on the basis of the confidence intervals. While a more mathematically precise error analysis can be derived than the one used here (R. Phillips, personal communication, 2005), our method is sufficient for discriminating poor fits. Segments for which the corresponding dip azimuth had an error of more than 30°, or for which the slope had an error of more than 1° were eliminated from further analyses. 80% of our sample was within these limits, while the remaining 20% fell outside of at least one of the constraints. The wide error bounds for some profiles can be traced mostly to noise in the DEM, or to a lack of significant curvature in the segment, which produces a poorly constrained fit. However, the large majority of continuous layer outcrops in the fan are well approximated by a plane. Those that are constrained by the fits according to the criteria above are shown in Figure 1b.

[14] The layered nature of this formation permits analysis of both vertical and lateral trends in addition to measurements of the structure as a whole. The mean gradient of all of the measured layers which could be well fit is 2.1°. Figure 2 shows a histogram of the observed slopes. The dip angles measured are consistently shallow, and have a standard deviation of 1.1°. The average dip direction is roughly eastward, parallel to the channel direction in this part of the fan, though there is wide variation within the data set as indicated by the strike-dip marks in Figure 1b. One trend among the sampled layers is that in many cases the layers have a component of dip in the direction perpendicular to the surrounding channels, in addition to the expected down-channel slope. Several of the layers exhibit this trend over hundreds of meters. No signs of postdepositional deformation are obvious from MOC imagery, indicating the cross-channel slopes are original depositional attributes. The reason for these strike directions is unclear. However such an attribute is consistent with the complex architecture associated with deltaic deposition, where erosional surfaces, levees and overbank deposits can all lead to nonparallel strata [Reading, 1996; Prothero and Schwab, 2004]. A second important trend is lateral and vertical consistency of the measured dips. One notable occurrence of this trend is marked with an asterisk in Figure 1b. Several layers here exhibit comparable eastward dips, at different outcrops and at varying levels in the stratigraphic sequence. This may indicate long-standing flow patterns here and in other outcrops where this trend is found. Regions where strikes and dips are more widely scattered may record a more dynamic depositional history.

### 4. Basin Analysis

[15] While stereo-derived topographic data is available over a restricted area, Mars Orbiter Laser Altimeter (MOLA) data provides a far more extensive, though coarser coverage of the entire basin into which the fluvial network once drained. Here, the 128 pixel per degree (ppd) MOLA gridded elevation data is utilized to examine the broader topography of Eberswalde crater [Smith et al., 2001]. It has been hypothesized that the fluvial deposits in Eberswalde have undergone significant burial and exhumation, accounting for the relative lack of cratering on presently exposed surfaces [Malin and Edgett, 2003; Moore et al., 2003]. This scenario could imply a modern basin surface which is significantly altered from that at the time of fluvial deposition, complicating potential lake volume estimates and other calculations. However, evidence for the exposure of the original depositional surface is present in the form of fluvial channels which are found in several places on the floor of the crater, as seen in MOC images R07-00821, R07-01352, E21-00076, and E23-00003. These deposits have been mapped on the basis of available MOC imagery, and are shown in Figure 3. The presence of these widespread



**Figure 3.** Estimated time to fill Eberswalde crater to various contours, based on the MOLA 128 pixel per degree gridded data set. Inverted channel deposits are shown in white. The large channel network on the west side of the crater is the layered deposit discussed here, which may have formed as a delta. Other channel deposits are preserved around the floor of Eberswalde, suggesting that the modern basin topography is similar to that at the time of fluvial activity. Contours denote fill times based on the 700 m<sup>3</sup>/s estimate of flow rate into the crater by *Moore et al.* [2003]. A theoretical paleolake at the 3 year level or higher covers many of these deposits, indicating that the water level was below this elevation at the time of deposition.

channels suggests that the present topography is similar to that at the time of fluvial deposition over most of the basin. This argues against significant net infilling as well as extensive aeolian erosion of the basin floor in the time since fluvial activity ended in Eberswalde. Furthermore, it is likely that the main delta and the channel deposits found elsewhere in the crater are genetically related. There is no evidence to indicate significant gaps in time between depositional episodes, such as intervening (and morphologically distinct) strata between fluvial deposits. When they occur in close proximity to each other, all channels and their associated deposits appear to share a common underlying surface. In addition, all fluvial deposits have been subject to roughly similar degrees of aeolian erosion and cratering, which argues for a similar age and geologic history. This assumption places an additional constraint on the size of any long-standing lake, as all channel deposits are expected to have formed subaerially. With the assumption that other fluvial deposits are genetically related to the main delta, and therefore show that the basin topography is similar to that at the time of deposition, lake volume estimates are derived from the MOLA 128 ppd DEM. The -1400 m contour is approximately the highest lake level which does not have higher elevation than clear fluvial deposits, and is also the level at which the uppermost channels of the main delta discharge. At this contour, the calculated basin volume is approximately 24 km<sup>3</sup>. Moore et al. [2003] estimated the mean discharge of the distributary system, using observed

channel width and meander wavelengths, as well as contributing basin size. Their estimated mean flow rate was 700 m<sup>3</sup>/s. Using these estimates, the basin would fill to -1400 m within 1.2 years of sustained flow, and begin flooding the delta. This simple calculation ignores losses due to evaporation and infiltration of water into the subsurface, as the conditions at the time of formation have large uncertainties. Fill times for various higher contours within the basin are shown in Figure 3, but all are on a timescale of years. A delta would have to be rapidly aggrading in order to maintain equilibrium with a rising base level, if such a flow rate was sustained for months to years. This depositional model is in contrast to one of a standard progradational delta, which occurs under static base level conditions.

## 5. Implications for Formation

[16] The distributary deposits in Eberswalde crater were formed either as an alluvial fan or as a delta. However, the alluvial fan hypothesis is found to be unsatisfactory. Strata in a simple alluvial fan should grade gently onto the underlying surface at the distal end, which would require that the deposit in Eberswalde was originally far more extensive at the time of deposition. With a roughly 100 m stack dipping at 2° or less, these deposits would have extended further by at least several kilometers. Jerolmack et al. [2004] estimate an original extent as large 35 km past the current terminus of the layers, with the assumption of an alluvial profile. Spatial relationships between the distributary network and nearby fluvial deposits, as well as between different sets of channels within the structure, argue against this depositional origin, as outlined above. It is noted that the term fan delta has been used to describe an alluvial fan which terminates at a body of water. However, much of the distinction lies in the nature of the feeder system, as opposed to the stratigraphy which is the focus of this work [Postma, 1990]. Because of the presence of a standing body of water, the stratigraphy is more similar to deltas than purely subaerial alluvial fans [Prior and Bornhold, 1990; Dabrio, 1990]. Therefore fan deltas are considered to be within the broader category of deltas for the purposes of this analysis.

[17] The primary difference between an alluvial fan and a delta is the presence of a prodelta lake in the latter case. A resulting morphologic distinction lies in the bedding orientations. In the case of a delta, the bed form is tripartite, including more steeply dipping foreset beds on the delta front. These beds can exhibit a range of steepness, depending on the nature of the sediment and depositional environment [Summerfield, 1991]. Foreset beds are often inclined at or near the angle of repose for coarse-grained Gilbert-style deltas, exhibiting a dip of up to 30° in some cases, but can be much lower in the case of very fine sediment, down to less than 1° [Reading, 1996]. However, the presence of very shallow foreset beds would require a greater degree of erosion, and is not favored by the same argument as that for an alluvial fan. Foresets are formed as flow velocity declines rapidly upon entering a standing body of water and coarser sediment can no longer be moved or kept in suspension [Nichols, 1999]. In a classic progradational delta, these beds make up the bulk of the volume of the delta, as shown in Figure 4a [Prothero and Schwab, 2004].

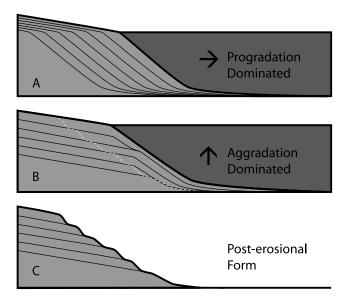


Figure 4. Schematic cross section of a progradational versus an aggradational delta. (a) Progradational delta, the bulk of which will be made of steeply dipping foresets. This occurs under static base level conditions, as coarser sediment is transported to the ends of distributaries and is deposited on the delta slope. (b) Aggradational delta, in which the bulk of the sediment load will be deposited in shallower topset beds, as accommodation space increases because of a rising base level. (c) Hypothetical cross section of the eroded structure seen in Eberswalde crater, which may have been deposited as an aggrading delta.

In the case of the Eberswalde formation, these steeply dipping layers would be exposed at the distal end, even after a modest amount of erosion has occurred on the delta front. However, the slopes of the beds measured here are uniformly shallow. As stated above, these layers cannot simply be low-angle foreset beds, which would be vulnerable to the same evidence against formation as an alluvial fan. Therefore the stratigraphic data argues for a different depositional origin.

[18] One resolution to the dual problems of small basin size and observed bedding orientation is an aggradational delta. As there is no outlet from Eberswalde crater at the level of the channels, any steady flow at the rates estimated by Moore et al. [2003] should produce standing water in the basin. Because of the size of this basin, it would fill rapidly under these flow conditions. To accommodate this base level change, much of the sediment supply would be deposited in the form of shallow topset beds. This process is expected when the vertical increase in the accommodation space of a delta, caused by rising water levels, is comparable to or greater than the sediment flux into the system. Aggradation-dominated deltaic growth has been described by Milton and Bertram [1995]; Muto and Steel [1992], and investigated experimentally by *Muto* [2001]. These studies highlight the fact that, in an ideal system with a steady base level rise and a constant sediment supply, a delta will eventually transition to an aggradation-dominated state, with deposition occurring mainly in topset beds.

Figure 4 illustrates the two end-members discussed here for deltaic growth. In the aggradational delta scenario, subsequent erosion at the distal end could strip away the thinner foreset layers, leaving a scarp of exposed topsets. If this is the case at Eberswalde, there appears to have been relatively little transgression or retreat of the shoreline accompanying the base level rise. The complete stack of layers is exposed over a relatively short lateral distance, implying a fairly static delta margin. The aggradational model is buttressed by the fact that the most recent channels in this structure are also the highest in elevation as measured from stereo data, and also noted by Jerolmack et al. [2004]. Evidence of fluvial down cutting, which would indicate a base level drop, has not been identified. This implies that deposition occurred mostly during periods dominated by rising lake levels. Also, the lack of widespread down cutting suggests a limited number of episodes for fluvial and lacustrine activity within this crater. As it is implausible that the entire deposit was emplaced on a timescale of months to years, as implied by the estimated basin filling time, this may be evidence for a much smaller mean flow rate over long timescales, and/or the importance of loss mechanisms from the system (mainly evaporation and infiltration) which are not included in this estimate. Alternatively, episodes of falling lake levels, though they may have occurred, simply failed to produce evidence of down cutting at the present surface. In this case, erosion could have occurred alternately with aggradation over the course of a larger number of filling and drying cycles.

[19] The small volume of Eberswalde crater relative to the size of the delta provides a rough constraint on the formation timescale for these fluvial deposits. Malin and Edgett [2003] estimated the current volume of the sediment within the delta to be approximately 6 km<sup>3</sup>. We assume that the original volume of sediment at the time of deposition was similar to the currently preserved volume, as our model calls for limited scarp retreat. At a typical sediment/water volume ratio of 3%, as used by Jerolmack et al. [2004] for sandy sediment, this translates to a formative water volume of 200 km $^3$ . As the basin below the -1400 m contour is only 24 km<sup>3</sup>, this requires the basin to be filled more than 8 times in order to deliver the required volume of sediment. This requires at least 7 basin volumes of water to be lost in the process of forming the delta (the lake can be filled at the end of deposition, accounting for one basin volume), either through evaporation or infiltration. For a mean lake area of 240 km<sup>2</sup> and a loss rate L (m/yr) over that area, we can estimate the time required to remove this water from the basin at 700/L years. The value of L is unconstrained given the limited knowledge of the depositional environment. However, for typical terrestrial lacustrine loss rates of 1-10 m/yr [Tyler et al., 1997; Irwin et al., 2005], we estimate a minimum formation time of several hundred years. This is slightly longer, but in general agreement with the previous estimate of Jerolmack et al. [2004], who used a sediment transport model to estimate a minimum formation time for the delta of 50 years.

## 6. Summary

[20] The geologic history of the Eberswalde fan is accessible through its well-preserved layered form. Stratigraphic

studies of depositional structures on Mars such as this one are finally possible with high-resolution stereo imagery. Stereo-derived topographic data was used to examine the structure of individual layers which outcrop at the distal end of the deposit. This analysis revealed that the exposed layers have uniformly shallow slopes, and are not consistent with the steep foreset beds found in many terrestrial coarsegrained deltas. Volume calculations of Eberswalde crater revealed that the basin should fill to the level of the preserved channels in roughly one year under estimated flow rates. These observations and others presented here have shown the inconsistencies associated with both an alluvial fan and a prograding delta for the origin of the Eberswalde deposit. A potential solution to the observed characteristics has been proposed, in the form of a rapidly aggrading delta. In this scenario, the exposed layers were deposited as deltaic topset beds, as the lake level in this crater rose over a timescale of years. Modest erosional retreat of the delta front by subsequent aeolian activity would have erased the volumetrically smaller foresets. This scenario implies the Eberswalde deposits formed not in a sustained long-lived lake, but more likely within a small number of shorter lacustrine episodes marked by a constantly rising base level, which were never able to reach equilibrium conditions.

[21] **Acknowledgments.** We thank John Grotzinger and Kerry Sieh for illuminating discussions and Anton Ivanov for sharing software he developed. This work was supported by NASA's Mars Data Analysis Program grants NAG5-13326 and NAG5-13232.

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