Influence of fault-controlled topography on fluvio-deltaic sedimentary systems in Eberswalde crater, Mars

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[1] Eberswalde crater was selected as a candidate landing site for the Mars Science Laboratory (MSL) mission based on the presence of a fan-shaped sedimentary deposit interpreted as a delta. We have identified and mapped five other candidate fluvio-deltaic systems in the crater, using images and digital terrain models (DTMs) derived from the Mars Reconnaissance Orbiter (MRO) High Resolution Imaging Science Experiment (HiRISE) and Context Camera (CTX). All of these systems consist of the same three stratigraphic units: (1) an upper layered unit, conformable with (2) a subpolygonally fractured unit, unconformably overlying (3) a pitted unit. We have also mapped a system of NNE-trending scarps interpreted as dip-slip faults that pre-date the fluvial-lacustrine deposits. The post-impact regional faulting may have generated the large-scale topography within the crater, which consists of a Western Basin, an Eastern Basin, and a central high. This topography subsequently provided depositional sinks for sediment entering the crater and controlled the geomorphic pattern of delta development. **Citation:** Rice, M. S., S. Gupta, J. F. Bell III, and N. H. Warner (2011), Influence of fault-controlled topography on fluvio-deltaic sedimentary systems in Eberswalde crater, Mars, *Geophys. Res. Lett.*, *38*, L16203, doi:10.1029/2011GL048149.

1. Introduction

[2] The identification of putative ancient fluvio-deltaic sedimentary systems on Mars has great significance for the astrobiological potential of Martian sedimentary rocks; however, the context of how such systems have developed and built stratigraphy is poorly constrained. On Earth, the accumulation of sedimentary successions is commonly associated with tectonic subsidence controls, such as in fault-controlled sedimentary basins [*Gupta et al.*, 1998]. In these settings, there is commonly an intimate relationship between topography created by structures such as faults and folds, and the geometry, distribution, and sediment dispersal pathways of fluvio-deltaic systems [*Gupta et al.*, 1999]. On Mars, accommodation space for fluvio-deltaic systems is typically considered to be provided by impact crater topography; the role of intra-crater, structurally generated topography has not previously been recognized.

[3] Here, we investigate the role of structurally controlled topography in creating intra-crater basins and topographic highs in Eberswalde crater, and we examine how this topography influences the distribution and sediment dispersal pathways of source-to-sink sedimentary systems within this proposed Mars Science Laboratory (MSL) landing site [*Grant et al.*, 2011]. We use images and Digital Terrain Models (DTMs) from the Mars Reconnaissance Orbiter (MRO) to: (1) map structural lineaments in Eberswalde crater; (2) characterize their topographic properties and identify structurally controlled topographic highs and basins; and (3) relate six proposed fluvio-deltaic systems to this structurally controlled topographic template. Our observations suggest that the spatial distribution and evolution of fluvio-deltaic systems in Eberswalde crater may be strongly influenced by intra-crater structural topography, thus providing a new model for controls on these sedimentary systems. Furthermore, we can infer the distribution of deep-water environments where low energy deposits may be sampled from this topographic control.

2. Setting

[4] Eberswalde crater is centered at 33° W 24° S within the Erythraeum region of Mars, immediately NNE of Holden crater along the Uzboi-Ladon-Morava (ULM) system [e.g., *Grant and Parker*, 2002]. The network of valleys that traverse the intercrater plains north of Holden crater appear to have transported sediment into western Eberswalde crater, building a layered, fan-shaped landform interpreted as a lacustrine delta [*Malin and Edgett*, 2003; *Moore et al.*, 2003; *Wood*, 2006; *Lewis and Aharonson*, 2006; *Pondrelli et al.*, 2008] or possibly an alluvial fan [*Jerolmack et al.*, 2004].

[5] Elsewhere in Eberswalde crater, inverted channels and plateaus of layered rocks suggest a complex history of fluvial activity and deposition in the basin [*Lewis and Aharonson*, 2006; *Pondrelli et al.*, 2008; *Rice and Bell*, 2010]. Two lobate plateaus in the north of the crater have been interpreted as other remnant deltas [*Pondrelli et al.*, 2008; *Rice and Bell*, 2010]. *Pondrelli et al.* [2008] noted the presence of linear scarps at the front of the Eberswalde delta, which they interpreted as syn-sedimentary faults, and they proposed a large fault system cutting the crater's center; the extent of such faulting and its influence on sedimentation patterns, however, has not been recognized.

3. Data and Methods

[6] We used images from the MRO Context Camera (CTX) [*Malin et al.*, 2007] to generate a 6 m/pix mosaic

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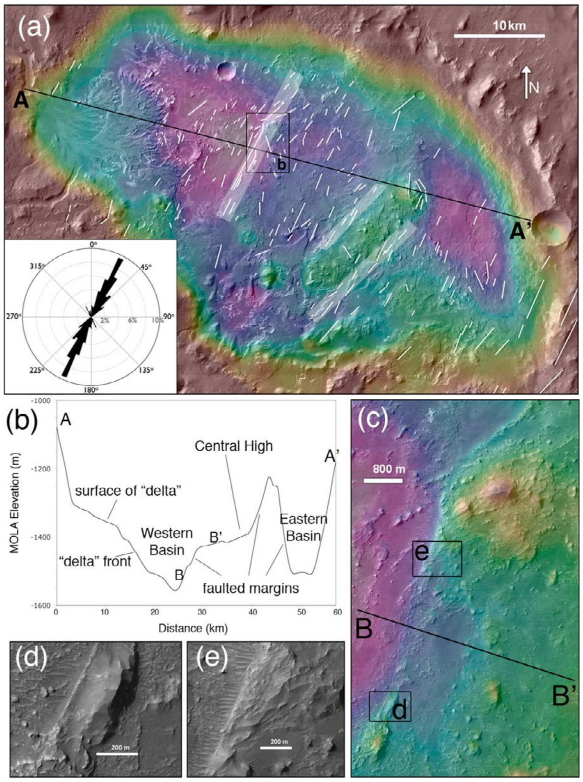

Figure 1. (a) MOLA elevation map (color scale: red = high = −1000 m; white = low = −1600 m), draped over a CTX mosaic, showing lineations interpreted as dip-slip faults (white lines), with rose plot indicating their orientations relative to compass directions (data binned at 5° intervals; the circles indicate percentages of total faults at 2% intervals). White shaded regions indicate the faulted margins marked in Figure 1b. The black line from A to A' indicates the location of the topographic profile shown in Figure 1b. The location of Figure 1c is indicated by the black rectangle. (b) MOLA profile across crater (from A to A' as shown in Figure 1a, with detail from B to B' indicated in Figure 1c); (c) HiRISE DTM (from PSP_008272_1560 and PSP_010474_1560, overlain on image PSP_010474_1560) showing detail of lineaments in central Eberswalde (color scale: red = high = −1200 m; white = low = −1600 m); (d, e) HiRISE images (from PSP_010474_1560) of linear scarps interpreted faults, locations shown in Figure 1c.

base map of the crater, and we analyzed ~0.27 m/pix High Resolution Imaging Science Experiment (HiRISE) images [*McEwen et al.*, 2007] covering the majority of the crater floor. To identify possible structural features, we mapped obvious linear features, noting stratigraphic and topographic evidence for lateral (strike-slip) or vertical (dip-slip) offset along these lineaments that could be suggestive of faulting. Mars Orbiter Laser Altimeter (MOLA) data [*Zuber et al.*, 1992; *Smith et al.*, 2001] provided regional-scale topographic context at ~1 m vertical resolution at a local grid spacing of ~ 0.86 × 0.43 km^2 (Figure 1a). We also used seven publicly available DTMs derived from HiRISE stereo pairs [*Kirk et al.*, 2008; *McEwen et al.*, 2010] to quantify the vertical offset along the identified structural features. Six fluvio-deltaic systems (inverted, sinuous landforms that, at lower elevations, terminate at fan-shaped plateaus of layered rock) were mapped and stratigraphic units were identified.

4. Results

4.1. Structural Geometry and Topography of Eberswalde Crater

[7] We have identified 233 linear features within Eberswalde crater that we interpret as faults (Figure 1a) based on vertical offsets (our map includes scarps taller than ~5 m). The rose plot in Figure 1a shows that two thirds of these features trend within 15° to 45° from north. All of these features are characterized by near-vertical scarps; we observed no lateral offsets associated with these lineaments.

[8] Analysis of MOLA, CTX and HiRISE topography data show that Eberswalde crater contains a ~100–300 m topographic high that separates two topographic lows: the "Western Basin" and the "Eastern Basin" (Figure 1). The boundary between the Western Basin and the topographic

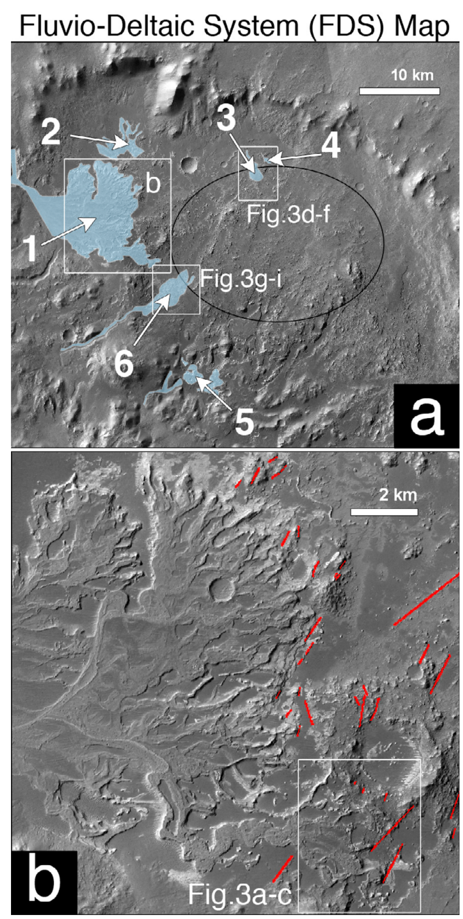

Figure 2. (a) Proposed fluvio-deltaic system (FDS) map for Eberswalde crater overlain on a CTX mosaic (made from images P01_001336_1560_X1_24S033W and P01_001600_1560_X1_23S033W), showing the location and extents of FDS1–6; (b) detail of FDS1, with red lines indicating locations of linear scarps (CTX image P01_001336_1560_X1_24S033W). Location is indicated in Figure 2a.

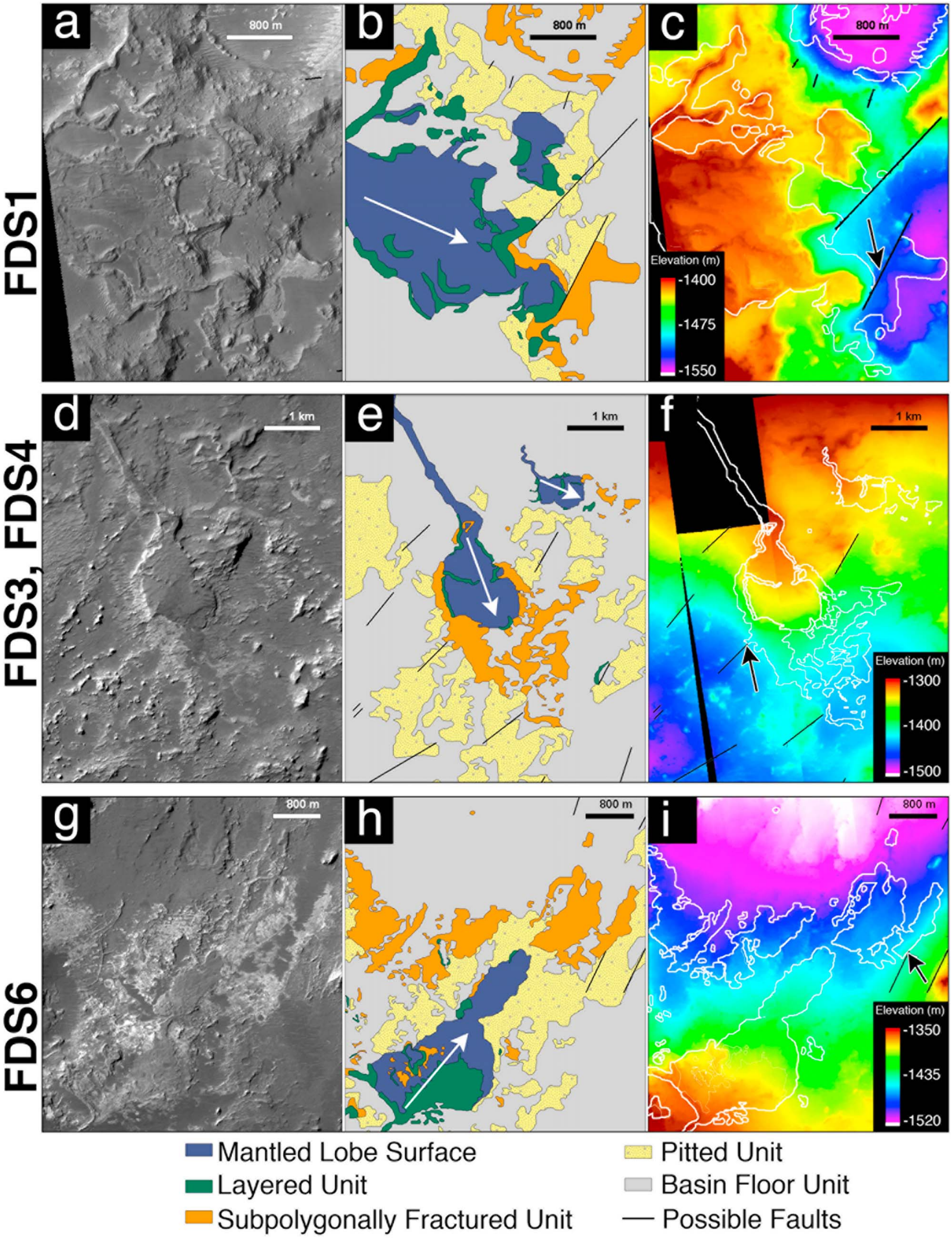
FDS1
a
800 m
b
800 m
c
800 m
Elevation (m)
-1400
-1475
-1550
FDS3, FDS4
d
1 km
e
1 km
f
1 km
Elevation (m)
-1300
-1400
-1500
FDS6
g
800 m
h
800 m
i
800 m
Elevation (m)
-1350
-1435
-1520
Mantled Lobe Surface
Layered Unit
Subpolygonally Fractured Unit
Pitted Unit
Basin Floor Unit
Possible Faults

Figure 3

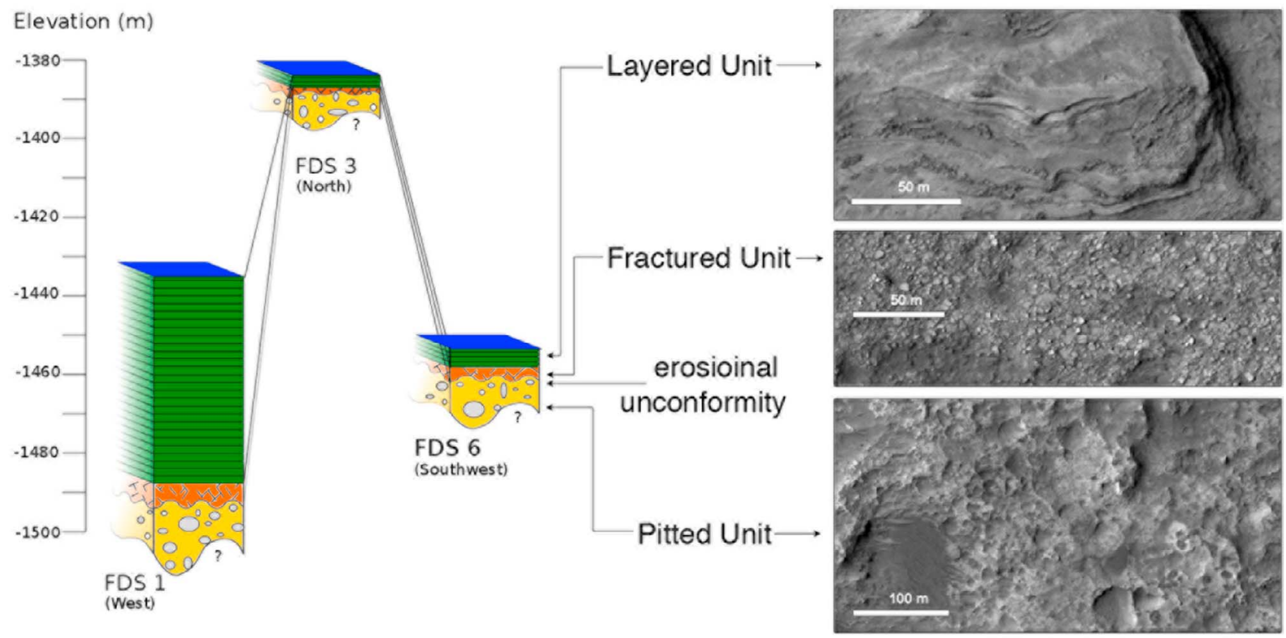

Figure 4. Simplified stratigraphic columns of proposed fluvio-deltaic systems FDS1 (Western Basin), FDS3 (on the central high) and FDS6 (Western Basin), indicating the elevations and inferred thicknesses of the lower pitted unit, the subpolygonally fractured unit, and the layered unit. These three units define the stratigraphy of all six fluvio-deltaic systems observed in Eberswalde crater, and the colors correspond to those mapped in Figure 3. Dips measured at FDS1 are 1–3° toward the center of the crater [*Lewis and Aharonson*, 2006]. HiRISE examples of each unit (ESP_019757_1560) are shown.

high is marked by a series of distinct lineaments (the most prominent shown in Figure 1c).

4.2. Fluvio-deltaic Systems

[9] Six putative fluvio-deltaic systems in Eberswalde crater (FDS1–6) are displayed in Figure 2a. These include the primary "delta," which extends 13 km by 11 km and covers 115 km^2 of the Western Basin (FDS1; Figure 2b), three systems in the north of the crater (FDS2-4), and two in the south (FDS5–6) that have not previously been reported. No evidence for fluvio-deltaic activity has been observed in the Eastern Basin. We focus our detailed analyses on FDS1 (Figures 3a–3c), FDS3–4 (Figures 3d–3f) and FDS6 (Figures 3g–3i) because HiRISE stereo imaging has not yet been acquired for FDS2 and FDS5.

[10] All six systems consist of the same three stratigraphic units: (1) an upper layered unit, conformable with (2) a subpolygonally fractured unit, unconformably overlying (3) a lower pitted unit [*Rice and Bell*, 2010]. Examples of each unit are shown in Figure 4, and unit maps for FDS1, FDS3–4 and FDS6 are provided in Figure 3.

4.2.1. Western System (FDS1)

[11] The front of FDS1, the main Eberswalde "delta" (Figure 2b), is characterized by a ~50 m stack of layered rock that forms cliff faces and "stair-step" geometries. These layers have measured dips of 1–3° [*Lewis and Aharonson*, 2006], and some appear to be shedding boulders that have fallen to the bottom of cliff faces. This layered unit conformably overlies a thin (<8 m) unit that consists of angular, subpolygonal blocks (with no observed hierarchical patterns) and extends ~2 km from the base of the layered unit toward the center of the crater. The subpolygonally fractured unit unconformably overlies a pitted unit, which covers a large portion of the crater floor and is characterized by quasi-circular depressions in light-toned rock, occurring as dense clusters of ~1–30 m pits.

[12] The FDS1 deposits appear to have been transported into the crater via a large channel that cuts the western crater rim and enters the Western Basin. The layered unit is fan-shaped in planform and extends ~11 km east toward the deepest portion of the basin, preserving sinuous and meandering ridges on its surface covered by a thin mantling material. The ridges appear to be grouped into multiple

Figure 3. Maps of individual proposed fluvio-deltaic systems: (a) HiRISE detail (image ESP_019757_1560) of the easternmost extent of FDS1 (location shown in Figure 2b); (b) unit map of the easternmost extent of FDS1; (c) HiRISE DTM (from ESP_019757_1560 and ESP_020034_1560) of the easternmost extent of FDS1; (d) CTX detail (P01_001600_1560_X1_23S033W) of FDS3 and FDS4 (location shown in Figure 2a); (e) unit map of FDS3 and FDS4; (f) HiRISE DTM (from ESP_019190_1560 and ESP_019335_1560) of FDS3 and FDS4; (g) CTX detail (P01_001336_1560_X1_24S033W) of FDS6 (location shown in Figure 2a); (h) unit map of FDS6. (i) HiRISE DTM (from ESP_019757_1560 and ESP_020034_1560) of FDS6. White outlines indicate extents of fluvio-deltaic sediments. Black arrows indicate relationships of sediments to potential faults. White arrows indicate inferred inflow directions.

deposits, which have been mapped in previous studies as three [*Bhattacharya et al.*, 2005] or five [*Wood*, 2006; *Pondrelli et al.*, 2008] distinct deltaic lobes.

[13] The front of FDS1 is characterized by NNE-trending scarps (Figure 3b). At the easternmost extent of FDS1 (Figure 3a), which has been interpreted as some of the youngest deposits of this system [e.g., *Wood*, 2006], the layered and subpolygonally fractured units are bounded by a structural lineament (arrow in Figure 3c), while the pitted unit appears modified by the possible fault (Figure 3c). In places, the pitted unit is topographically higher than the subpolygonally fractured unit (Figures 3b and 3c), suggesting that the subpolygonally fractured deposits conformed to preexisting topography.

4.2.2. Northern Systems (FDS3–4)

[14] Two smaller, fan-shaped features in the north of the crater (Figures 3d–3f) were noted by *Pondrelli et al.* [2008]. FDS3 and FDS4 originate at the basinward ends of sinuous ridges along the northern crater wall and are superposed on the crater's central topographic high; the surface of FDS3 is at elevation −1385 m, roughly 50 m above the front surface of FDS1. The subpolygonally fractured and layered units at FDS3 overly a NNE-trending lineament that has formed a scarp in the pitted unit (arrow in Figure 3f).

4.2.3. Southwestern System (FDS6)

[15] The FDS6 deposits appear to have been transported into the Western Basin via a channel that cuts the southwestern rim of Eberswalde crater. The surface of FDS6 (Figure 3g) preserves sinuous and digitate ridges that have eroded into a stair-step pattern of layered rock near the southwest crater rim; sinuous landforms and subpolygonally fractured material extend ~3.5 km toward the eastern edge of the Western Basin (Figure 3h). The layered and subpolygonally fractured units that comprise this system are oriented parallel to the NNE-trending lineaments that form the topographic divide immediately to the east (Figure 3i); these features modify the pitted unit and are overlain by the subpolygonally fractured unit.

5. Discussion

[16] We interpret the lineaments in Eberswalde crater to be dip-slip faults because we observe vertical offsets and no lateral offsets. The dominant NNE directionality of the faults is inconsistent with the stresses expected from the impact event that formed Eberswalde crater (which should be radial and parallel to the crater walls) [*Melosh*, 1989]. Rather, the faults follow this NNE trend across the width of the crater floor and across its northern rim, onto the highland plains north of the crater, as well as south onto the divide between Holden and Eberswalde craters. We therefore infer that larger, regional post-impact stresses must be responsible for the observed faulting. For example, the NNE orientation is consistent with thrust faulting and wrinkle-ridge formation predicted in this region due to the loading-induced stresses from the formation of Tharsis [*Anderson et al.*, 2001; *Andrews-Hanna et al.*, 2008]. Current age estimates for Tharsis place the bulk of its formation during the late Noachian [*Fassett and Head*, 2011], which predates age estimates of fluvio-lacustrine activity in Eberswalde crater (ranging from late Noachian/early Hesperian [*Moore et al.*, 2003] to Amazonian [*Grant and Wilson*, 2011]). Alternatively, a regionally extensive extensional regime has been invoked to explain a similar NNE trend of extensional fractures associated with formation of Morava Valles and Iani Chaos [*Warner et al.*, 2011]. These chaos features occur north of Eberswalde crater and are part of the same ULM fluvial system.

[17] The faults in Eberswalde bound a central high in the crater which may be a complex, up-faulted structure. The pitted unit, which covers most of the crater floor in both basins as well as the central high, is the lowest stratigraphic unit and the material in which most scarps occur. While *Pondrelli et al.* [2008] interpreted this unit as lacustrine sediments, we have observed no layering or other characteristics that support that hypothesis. Also, the pitted morphology is inconsistent with the observed erosional morphology of other putative lacustrine sediments on Mars [e.g., *Milliken and Bish*, 2010; *Wray et al.*, 2011]. We therefore propose three possible interpretations for the pitted unit: (1) the pits result from heterogeneous erosion of an ancient surface saturated with small impact craters; (2) the pits formed from de-volatilization and degradation of an ancient, basal impact melt surface; or (3) the light-toned material may be the erosionally resistant matrix of a megabreccia (possibly from the Holden impact event [*Grant et al.*, 2011]), and the pits are the "holes" left by removed/eroded megaclasts. In support of (3), 20–500 m of ejecta from the Holden impact is expected to have blanketed the floor of Eberswalde crater based on empirical expressions for the radial decay of ejecta thickness by *Garvin and Frawley* [1998]. Consistent with all interpretations, the pitted unit is likely the exposed remnants of ancient impact crater floor material and unrelated to the younger, fluvio-deltaic systems.

[18] We interpret the layered unit, which comprises the lobate units associated with each fluvio-deltaic system, to be deltaic sediments; and we interpret the extensive subpolygonally fractured unit, which lies conformably beneath each exposure of the layered unit, to be delta bottomset deposits and/or lacustrine sediments. Because the faults occur in the pitted unit but do not modify the overlying subpolygonally fractured or layered units, the fluvio-deltaic activity must have post-dated the faulting in Eberswalde crater and thus is unlikely the result of processes associated or contemporaneous with the Eberswalde impact itself. Indeed, the deposition of fluvio-deltaic sediments within Eberswalde appears to have been controlled by the fault-related topography. For example, the subpolygonally fractured unit associated with FDS3 overlies a faulted margin (Figure 3e), and the sinuous channels associated with FDS6 appear to follow the NNE-trending fault system (Figure 3h). These relationships imply that the topographic character of Eberswalde crater (the two basins and a central high) was in place prior to fluvio-deltaic activity. Following this line of reasoning, a significant amount of material that once filled the crater must have been removed, as implied by the inverted channels and deltas.

[19] The features we have mapped as fluvio-deltaic systems could be alluvial fans [e.g., *Jerolmack et al.*, 2004]; however, we note that the fan-shaped plateaus and layered deposits of FDS2–6 do not initiate at the break in slope associated with the wall of the crater, as might be expected for alluvial fan formation [e.g., *Williams et al.*, 2006]. Instead, channel bifurcation to create a fan-shaped sediment body occurs basinward of the crater rim implying that flu-

vially transported sediments were deposited along a shoreline and into a standing body of water. The multiple, bifurcating inverted channels preserved on FDS1, FDS3, and FDS6 are consistent with this interpretation.

[20] The topographic high within the center of the crater therefore predates sedimentation and likely lake development. The question, then, is whether the water level in the western basin was sufficient to inundate the pre-existing central high. The putative deltas FDS3–4 occur on top of the central topographic high, where there is also evidence for inverted channels and isolated mesas of material that are morphologically similar to the subpolygonally fractured and/or layered units of other fluvio-deltaic systems. Based on these observations, we suggest that the lake in Eberswalde crater must have covered the central high to a minimum depth of −1385 m. Also, the margins of the central high are not eroded into drainage networks (unlike the crater walls), suggesting that they may have been covered by water during the era of fluvial activity into Eberswalde crater. Although there are no crater rim fluvio-deltaic systems entering the Eastern Basin, a remnant of a sinuous channel network present along the topographic ridge separating the central high from the Eastern Basin provides evidence of possible overspill between the western lake system and the Eastern Basin. This overspill provides a possible means of stabilizing the water level, as the surface area rises considerably once the western sub-basin is flooded to this level.

[21] The presence of multiple fluvio-deltaic systems in Eberswalde crater, all exhibiting a consistent stratigraphic sequence, has implications for its potential as a Mars landing site. A rover might have opportunities to examine the chemistry, mineralogy, and organic material preservation potential of remnant deltas and associated lacustrine deposits that preserve fine-grained sediments transported from multiple distinct source regions, potentially containing geochemical signatures of past habitability. For example, the layered unit associated with FDS3 lies within the proposed MSL landing ellipse, as does the subpolygonally fractured unit associated with FDS6; these systems are thus more readily accessible than FDS1 (the primary "go-to" target for MSL in Eberswalde), the closest deposits of which are ~2 km from the edge of the proposed landing ellipse (Figure 2). The largest faults in the crater lie within the proposed MSL landing ellipse as well, and thus they would make easily accessible science targets for hypothesis testing about the relationship between sedimentation and faulting in Eberswalde crater. Also, our results suggest that an Eberswalde lake extended over the area of the proposed MSL landing ellipse on the central topographic high. Given the pre-existing topography, we predict that a rover could sample the deepest, lowest-energy sediments (that might best preserve organic materials) in the lowest, easternmost portion of the Western Basin.

6. Conclusions

[22] We have mapped 233 NNE-trending linear scarps in Eberswalde crater that we interpret as dip-slip faults formed under regional stresses. We have also mapped the stratigraphic units associated with six fluvio-deltaic systems in the crater, and based on the relationships of these units to the faults, we infer the following sequence of events: (1) Eberswalde crater forms; (2) the pitted unit is deposited (potentially as modified Eberswalde basement rock or ejecta from the Holden crater impact), covering most of the crater floor; (3) extensive faulting, possibly from regional stresses related to the formation of Tharsis, creates the Western Basin, Eastern Basin, and central high within the crater; (4) at least six fluvio-deltaic systems form, with the geomorphic pattern of delta development controlled by the fault-induced topography; (5) crater fill material is excavated, leaving the inverted channels and deltas observed in present-day Eberswalde.

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