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A possible synoptic source of water for alluvial fan formation in southern Margaritifer Terra, Mars

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ABSTRACT

The morphometry and occurrence of crater-bound fans in southern Margaritifer Terra that were active from around the Hesperian–Amazonian boundary into the Early Amazonian is consistent with emplacement related to synoptic precipitation. Precipitation, possibly occurring as snow, may have been locally influenced by topography and (or) orbital variations. It is not known how much of the total sediment inventory in the fans relates to this late activity versus possible earlier events where water may have been available from alternate sources such as impact-related melting of ground ice. Winds may have concentrated late occurring precipitation into existing relief and (or) preexisting alcoves that facilitated physical weathering to produce fine sediments later incorporated into fans. Two of the craters containing fan deposits, Holden and Eberswalde, were finalists for the MSL landing site. Results suggest that exposed and accessible fan sediments at both crater sites may record a late period of colder, drier conditions relative to early Mars that was punctuated by ephemeral water-driven activity.

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1. Introduction

Alluvial deposits within impact craters on Mars have been studied to characterize the amount and style of runoff responsible for their formation and to constrain the climate in which they formed (Cabrol and Grin, 2001; Crumpler and Tanaka, 2003; Malin and Edgett, 2003; Moore et al., 2003; Irwin et al., 2005a; Moore and Howard, 2005; Weitz et al., 2006; Kraal et al., 2008; Grant and Wilson, 2011; Williams et al., 2011). Alluvial deposits on Mars are scattered across much of the cratered highlands (Irwin et al., 2005a; Di Achille and Hynek, 2010; Wilson et al., 2012), with apparent concentrations in southern Margaritifer Terra, southwestern Terra Sabaea, and southwestern Tyrrhena Terra (Moore and Howard, 2005).

Previous studies of intracrater alluvial fan deposits (e.g., Moore and Howard, 2005; Kraal et al., 2008) relied mostly on analyses of visible (VIS) and infrared (IR) images from the Thermal Emission Imaging System (THEMIS Christensen et al., 2004). With the increasing coverage of high resolution data from the High Resolution Imaging Science Experiment (HiRISE, McEwen et al., 2007a) and Context Camera (CTX, Malin et al., 2007) instruments on the Mars Reconnaissance Orbiter, however, it is possible to reevaluate the distribution, morphometry and setting of the deposits. These higher resolution data (~0.25–0.50 m pixel scale for HiRISE and 6 m pixel scale for CTX) were used to establish that fan surfaces in southern Margaritifer Terra were deposited near the Hesperian–Amazonian boundary or during the early Amazonian (Grant and Wilson, 2011) and enables more confident definition of relatively smaller-scale characteristics related to sources of runoff responsible for their emplacement.

This study explores relationships between the fans and their host craters in the context of the previously described distribution and age of the alluvial fans in the southern Margaritifer Terra region of Mars (Grant and Wilson, 2011) to understand the sources of water and climate enabling their formation.

2. Fan morphometry and characteristics of host craters

The study area in southern Margaritifer Terra extends from 20°S to 35°S between 320°E and 340°E (Fig. 1). Table 1 summarizes morphometry for craters with and without fans in the study area and while there are no clear trends in occurrence that can be used to uniquely characterize craters with fans, there are some intriguing attributes that may provide insight into their distribution. Some caution must by employed in interpretation of these data, however, because the observed distribution of crater-bearing fans may not reflect the entire regional population if some fans are masked by later mantling deposits (Grant and Wilson, 2011).

With these caveats in mind, all of the alluvial deposits occur at the downstream terminus of source valleys, most of which head

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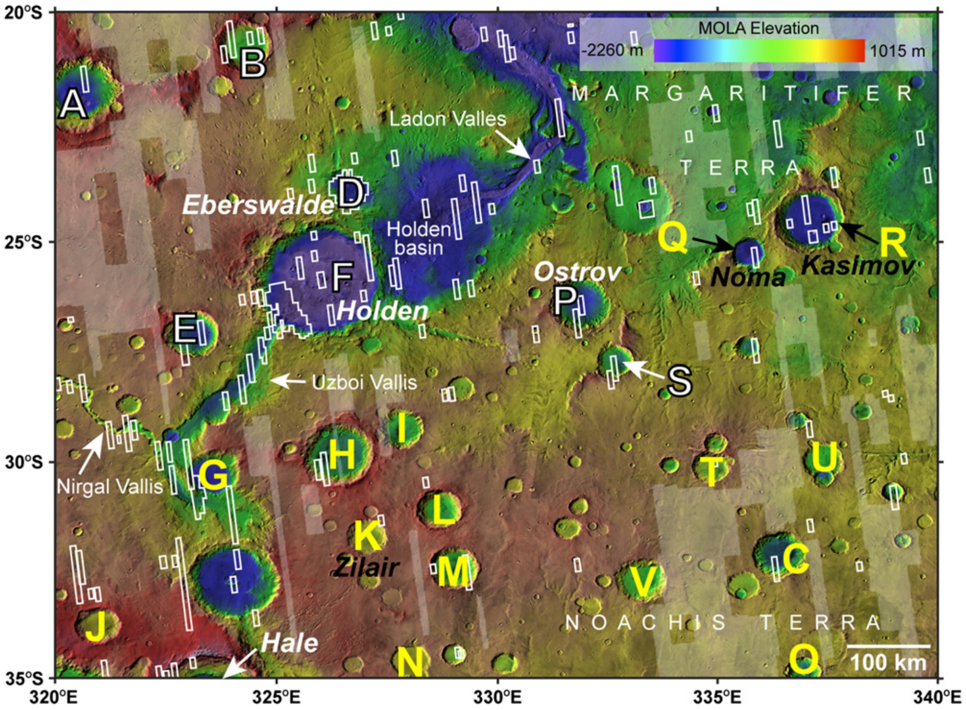

Fig. 1. Study area in southern Margaritifer Terra with place names discussed in text (modified from Grant and Wilson, 2011). Craters > 50 km in diameter with labels were included in the study; white and yellow labels indicate craters with and without fans, respectively (see Table 1). MOLA topography over subset of THEMIS global daytime IR mosaic. Shaded white indicates gaps in CTX coverage (as of 1/2012) and white boxes are HiRISE footprints (as of 1/2012).

Table 1

Characteristics of deposits identified within craters included in this study. Craters A through V correspond to labels in Fig. 1. Minimum elevation (Min. Elev.) is relative to MOLA datum. Crater depth for craters without fans is the difference between the average rim elevation around the crater and the lowest elevation of the crater floor. For craters with fans, the crater depth is the difference between the height of the rim(s) adjacent to the best-preserved fans and the lowest elevation of the crater floor. Interpreted playa surfaces are characterized by scabby, light toned deposits (LTD) that are typically higher in thermal inertia and occur on the crater floors. They are often somewhat circular in plan view and are located at the terminus of fluvial channels or fans.

Label (Fig. 1)	Crater Name	Lat. (°S)	Lon. (°E)	Diam. (km)	Min. Elev. (m)	Crater depth (m)	Location of fans	Nature of crater floor
A	None	21.8	320.6	99	–1800	3250	N (best), E, S, W	Playa (?), LTD, fans, central peak, landslide
B	None	20.65	324.28	69	–680	2810	N (best), S	Playa, LTD, fans
D	Eberswalde	23.76	326.7	65.3	–1500	1060	W (best), N, SW[a]	LTD, deltas
E	None	27.2	323.1	64	–1400	2405	N, E, W	Playa, LTD, fans, landslide
F	Holden	26.14	326	154	–2370	3233	N, S, W	Playa (?), LTD, fans
P	Ostrov	26.54	331.8	73	–1532	2059	N, S, E, W	Playa (?), fans, central peak
S	None	27.8	332.6	43	–1117	1678	N, E, S (best), W	LTD, fans
C	None	32.2	336.4	72	–1217	1651	None	Channels, playa (?) LTD, filled/mantled
G	None	30.4	323.55	58	–1500	2078	None	LTD, filled/mantled
H	None	29.9	326.4	80	–1072	2435	None	Playa (?), LTD, filled/mantled
I	None	29.4	327.9	55	–1052	1947	None	LTD, filled/mantled
J	None	33.8	321	50	–6	1497	None	Filled/mantled
K	Zilair	31.8	327	48	–228	1264	None	Filled/mantled
L	None	31.2	328.7	49	–919	2182	None	Filled/mantled
M	None	32.5	329	57	–880	1943	None	Filled/mantled
N	None	34.6	328	57	–23	834	None	Filled/mantled
O	None	34.8	336.9	38	–1164	1585	None	Channels, filled/mantled
Q	Noma	25.4	335.6	42	–1733	1695	None	Playa (?), LTD, channels, mantled
R	Kasimov	24.9	337.1	91	–1629	1975	None	Playa, LTD, channels, mantled
T	None	30.2	334.8	49	–448	1208	None	Channels, LTD, filled/mantled
U	None	30	337.4	47	–796	980	None	Filled/mantled
V	None	32.7	333.3	59	–759	1672	None	Channels, LTD, filled/mantled

[a] Largest fan delta on western side of the crater, smaller deposits elsewhere (see Rice et al., 2011).

in well-developed alcoves eroded into bounding crater walls. Valleys sourcing deposits in Eberswalde crater are the exception as they drain a basin extending well beyond the rim of the bounding crater, eroding into the continuous ejecta deposit associated with Holden crater (e.g., Pondrelli et al., 2008). Based on comparison to terrestrial fans (e.g., Ritter et al., 1995) the deposits (hereafter called "fans") vary in form, ranging from accumulations apparently emplaced subaerially or into only ephemeral or shallow standing water (Fig. 2) to those appearing steep fronted and more akin to fan deltas emplaced into deeper standing water (e.g., Eberswalde crater, Pondrelli et al., 2008). In most instances, the transition between fans to any inferred distal

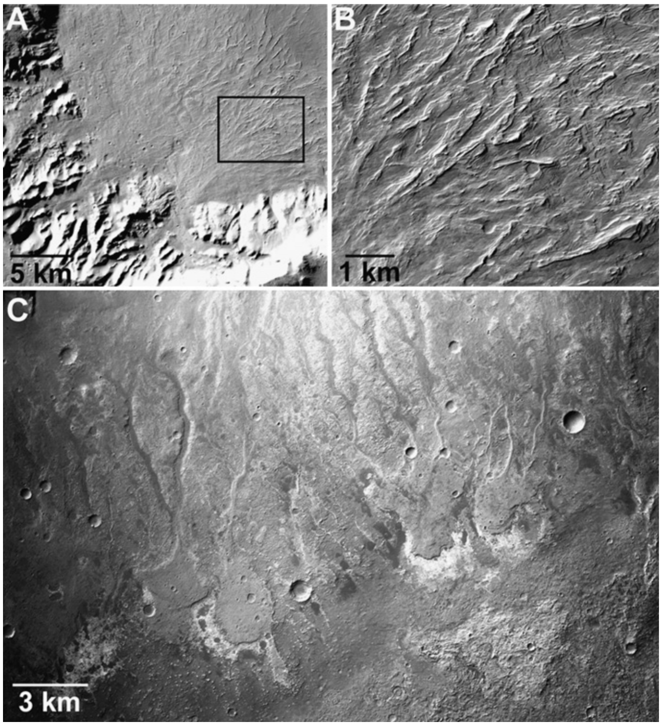

Fig. 2. Examples of fans in craters "S" and "B," see Fig. 1 for context. (A) Fans in crater "S" originating from well-developed alcoves in the southwestern crater wall. Black box indicates location of (B). CTX image B01_009999_1519_XI_28S027W (5.2 m pixel scale). (B) Detail of differentially eroded deposits on fan surface. More resistant, presumably coarser (gravel sized) deposits stand in positive relief after intervening finer (sand sized and perhaps smaller) material has been removed by eolian processes (Moore and Howard, 2005). (C) The upper portions of the fans originating from the northern rim in crater "B" are characterized by valleys and ridges inferred to be the inverted expression of channels, similar to those in Holden crater. However, lobes at the termini of the deposit are somewhat rounded, positive-relief features that are suggestive of deposition into shallow standing water. CTX image P17_007692_1590_XN_21S035W (5.2 m pixel scale).

alluvial, playa or lacustrine sediments is continuous and is assumed to be contemporary.

Seven out of 22 craters greater than 50 km in diameter in the study area contain well-developed alluvial fans (Moore and Howard, 2005; Kraal et al., 2008; Grant and Wilson, 2011). The fans tend to occur in larger craters that average 81 km across (±36 km), while craters without fans are smaller and average 57 km in diameter (±14 km) (Table 1). Some of the smaller craters in the study region, such as Murgoo crater (~25 km across, 23.9°S, 337.5°E), or those heavily mantled by more recent deposits (e.g., Kasimov 24.7°S, 337.6°E), were not included in the study, but may also possess alcoves and fans. Mantling deposits are identified in many craters (Table 1), mostly in the southern section of the study area (Grant and Wilson, 2011), suggesting that additional fans may be buried. As a result of this distribution, the average latitude of craters preserving fans is 24.8°S, whereas craters without fans average nearly 31°S.

Clues to the source and amount of water responsible for deposition of sediments comprising the fans can be gleaned from their morphometry. It is important to note, however, that the morphometry only relates to exposed materials and fans (i.e., those not mantled by younger deposits) and may not fully describe conditions and processes responsible for emplacement of the bulk of what is typically hundreds of meters of sediment. In general, fan morphometry and the conclusions drawn from it are consistent with those noted by Moore and Howard (2005) and Kraal et al. (2008), which is not unexpected given that many fans were included in both prior studies. With this in mind, the following summary is provided to present a more comprehensive assessment that encompasses the distribution of fans mapped herein.

Basins sourcing the fans head high on the bounding crater walls and the alcoves they form are complex, generally 1–2 km deep and sometimes extend more than 10 km beyond the average crater rim position (e.g., crater A). Fan surfaces are characterized by slopes of ~1–2° and are of intermediate brightness in THEMIS nighttime thermal images, appearing comparable to the values observed on most surfaces outside the bounding craters. By contrast, associated distal alluvial, playa, or shallow lacustrine sediments often appear brighter in THEMIS nighttime thermal images. This is likely a reflection of the distal deposits being relatively more indurated which is supported by the eroded expression of remnants that maintain steep slopes or scarps, thereby implying some internal strength. Fans are often marked by easily defined lobes and a series of ridges radiating from near their apex (Fig. 2). On some fans, these ridges form a complex, crisscrossing network of relief, whereas on others they occur as variably meandering landforms sometimes exposing U-shaped features along their margins (Fig. 3). In Holden crater, interpretation of a HiRISE Digital Terrain Model (DTM) shows the ridges are 10–15 m high (Fig. 4) and the similar map scale of ridges on fans in other craters suggests this is typical. Negative relief features,

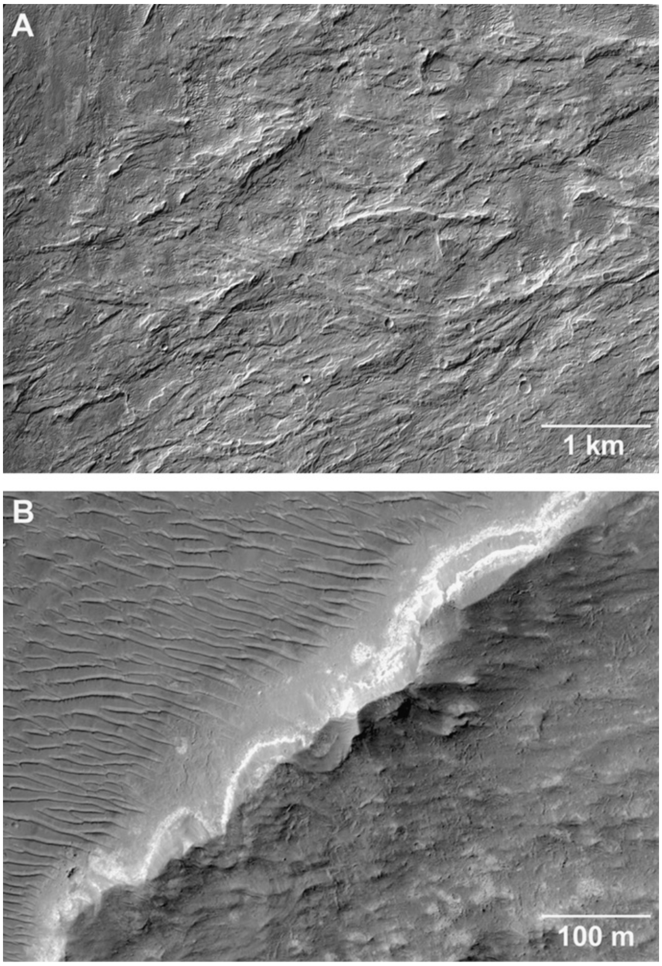

Fig. 3. (A) Inversion of relief on the fan surface in crater "A" preserves cross-cutting channels as ridges. HiRISE image ESP_016975_1585 (26 cm pixel scale) near 21.4°S, 320.7°E (see Fig. 1 for context). (B) Possible cross-section through inverted paleochannel in crater "E." HiRISE image ESP_017054_1525 (52 cm pixel scale) near 27.1°S, 323.3°E (see Fig. 1 for context).

such as fan-head trenches or other evidence of active incision, are not apparent on many of the fans.

Fans tend to be best developed in craters with the lowest floor elevation and greatest relief between their rim and floors (Table 1). Craters possessing fans average 2356 m of relief (±817 m) as compared to craters without fans that display an average of 1663 m of relief (±451 m). There is poor correlation between crater diameter and the occurrence of fans or the azimuth at which fans occur within craters, though they may be slightly more common on the northern semicircle. This distribution may be skewed by the relatively small number of fans or influenced by fan exposure or preservation. Where present, central peaks do not source fans, but are sometimes embayed by alluvium from fans heading along the crater walls. The central peaks in Holden, Ostrov, and crater A are surrounded by abrupt breaks in slope and local relief (Fig. 5). In Holden, this break in slope and relief occurs near −2060 m (Grant et al., 2010). In Ostrov and Crater A, the break in slope appears to be close to −1450 m and −1550 m, respectively, but the position of Mars Orbiter Laser Altimeter (MOLA) tracks and locations of individual shot points along the tracks introduce uncertainty. In the case of Ostrov crater, reentrants into the central peak are headed by terraced accumulations of sediment. Deposits interpreted as playa or shallow lacustrine depositional settings (Grant and Wilson, 2011) are not well correlated with the elevation of crater floors and evidence of longer-lived and (or) deeper standing bodies of water are rare with the exception of Eberswalde and Holden craters (Malin and Edgett, 2003; Moore et al., 2003; Grant et al., 2008a).

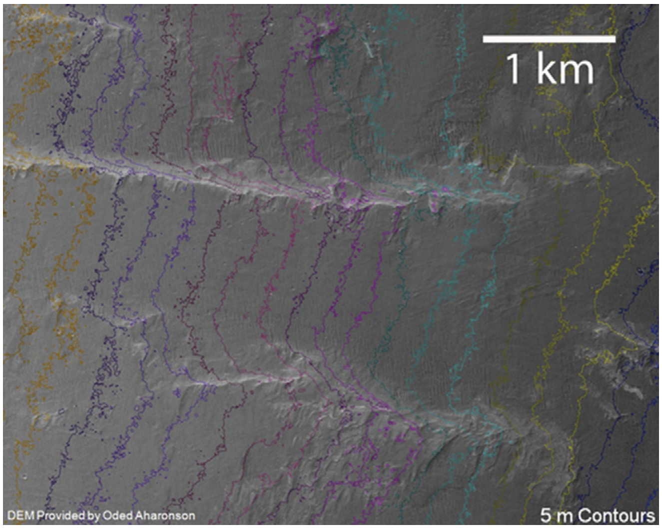

Fig. 4. Ridges interpreted as inverted, relict distributary channels crossing from west-to-east on the fans fringing the western wall of Holden crater near 26.6°S, 325.2°E. Contour lines are from a DTM created using stereo HiRISE images (courtesy of Oded Aharonson) and are presented in a 5 m interval that indicates the ridges are ~10–15 m high and were likely formed when differential deflation of intervening finer-grained sediments left the somewhat coarser channel bed sediments standing in relief. The spacing of the ridges/distributaries is measured in hundreds of meters. HiRISE images PSP_001468_1535 and PSP_002154_1530 (26 cm pixel scale and 52 cm pixel scale, respectively). North is toward the top of image.

The ridges on most fans are interpreted to be the expression of channels whose relief has been inverted by relatively more erosion of intervening fan surfaces. This interpretation is consistent with the radial distribution of the ridges relative to the fan apices, and the expectation that channel bed sediments are likely coarser, and (or) better cemented and therefore more resistant than intrachannel sediments (Matthews, 1974). A similar interpretation exists for the origin of ridges on the Eberswalde crater

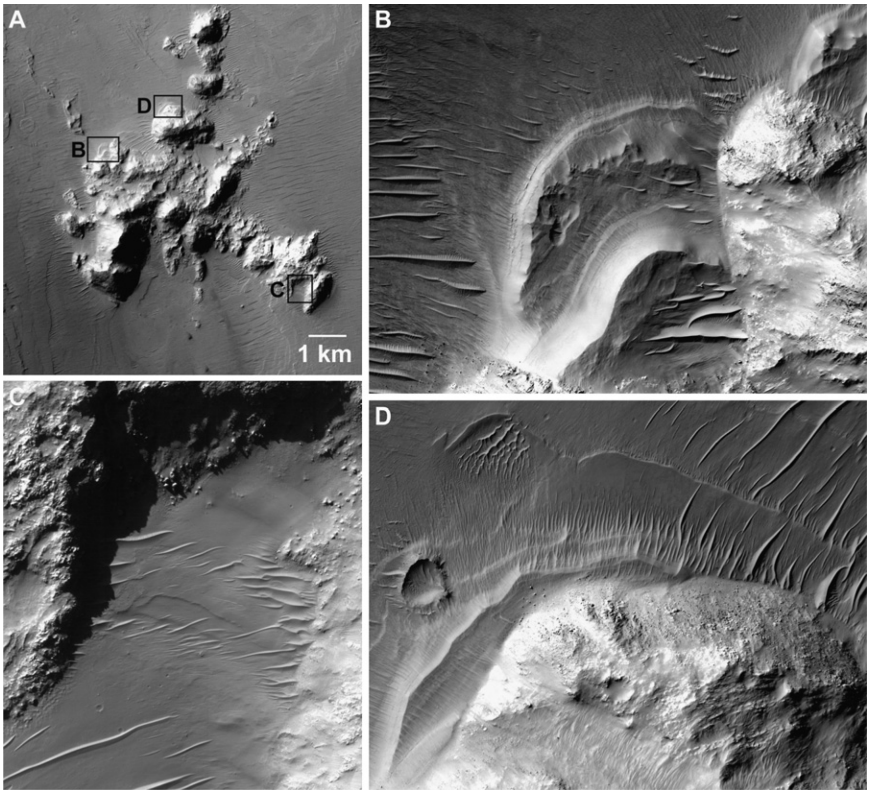

Fig. 5. Central peak of Ostrov, crater “P” (see Fig. 1 for context). Despite the lack of fans on the central peak in Ostrov crater (A), coarsely bedded, rounded terraces (B–D) on the floor of the crater around the edges and in alcoves of the central peak materials may be evidence for reworking by standing water on the crater floor. (A) Central peak in Ostrov crater. Subset of CTX image P17_007639_1514_XN_28S027W (5.14 m scaled pixel width). (B) Subset of HiRISE image ESP_017357_1530 (26 cm pixel scale), 153.5 m across. (C) Subset of HiRISE image ESP_017357_1530 (26 cm pixel scale), 182.5 m across. (D) Subset of HiRISE image ESP_017357_1530 (26 cm pixel scale), 101 m across.

fan delta (Moore et al. 2003) and elsewhere on Mars (Burr et al., 2010). In this model, the U-shaped feature along one ridge in crater A (Fig. 3B) is the expression of a sediment-filled channel coring the ridge, an interpretation broadly consistent with terrestrial examples (Boggs, 2001). Ridge relief coupled with limits on the original depth of the incised channels indicates the current expression of the fans records up to ~20 m of erosion.

As noted by Moore and Howard (2005), the size and gradient of the fans they studied are consistent with abundant gravel-sized sediment. Examination of HiRISE images of the fans reveals what appear to be fairly uniform and block-free surfaces and outcrops along the walls of small craters on fan surfaces, consistent with a finer-grained nature of the fans. Moreover, widespread removal of material from between channels, in the absence of evidence for incision, indicates efficient eolian erosion and requires a significant fine component of sand and perhaps even silt in exposed fan sediments. Because the in situ breakdown of coarser sediments on the fans to create a significant fine component is not consistent with the differential erosion creating the ridges, the fine-grained nature of the fan surfaces likely reflects the original depositional inventory. Finally, the relatively uniform fan slopes (where measured) and lack of fan head trenches indicate their current form reflects deposition under relatively low-to-moderate discharge and uniform climate.

The source of water responsible for creating the fans was probably precipitation (Moore and Howard, 2005). The poor correlation between the elevation of a crater floor and the occurrence of deposits interpreted as playa or lacustrine coupled with alcoves eroded into crater rims makes it unlikely that groundwater has played an important role in generating runoff. If late fan evolution was related to precipitation (rain or snow), however, it most likely occurred on crater rims and exteriors rather than on the fans and crater floors. There is a paucity of ridges heading on fan surfaces and few that are not approximately radial to fan apices as might be expected for features arising from precipitation falling directly on the fans; although erosion of fan surfaces may have removed evidence of shallow channels if they were ever present. The lack of fans and obvious source alcoves on central peaks within some craters (e.g., in Ostrov crater) further imply minimal precipitation and runoff on surfaces within craters. Breaks in slope and relief coupled with terraced sediments around the bases of crater central peaks does suggest some reworking there by water, likely related to ponded discharge from the fans. Limited correlation between wall relief and where fans are best developed may imply orographic influence on precipitation, however, the lack of a well-developed concentration of fans within a particular azimuth range on bounding crater walls suggests prevailing winds were not a dominant influence on their distribution.

In summary, fan morphometry indicates deposition of exposed materials was probably related to precipitation under relatively unchanging climate that was mostly limited to bounding crater rims and exteriors. There might have been a minor orographic enhancement of precipitation in some craters. Discharge responsible for deposition on fan surfaces was fairly uniform and emplaced mostly fine-grained material that has since undergone ~20 m of erosion.

3. Possible sources of water for the fans

The fans in southern Margaritifer Terra incorporate a sizeable inventory of sediments derived from erosion of large alcoves around the interior of bounding crater rims. Fan morphometry is most consistent with precipitation as the source of water leading to emplacement of exposed fan sediments (Moore and Howard, 2005), but it is important to note that fan deposition may have occurred over an extended time during multiple periods of activity relating to a variety of water sources (Grant et al., 2008a; Grant and Wilson, 2011; Kite et al., 2011; Mangold, 2011). Therefore, the current surface expression of the fans may only reflect the final stage of emplacement, possibly burying evidence of any older deposits related to alternate processes or sources of water.

Precipitation responsible for the current expression of the fans could include either local or regional-scale to perhaps global sources of rain or snow. Local precipitation could be related to the impact-induced release of volatiles (Maxwell et al., 1973; Kite et al., 2011; Mangold, 2011), with runoff resulting in valley incision and the formation of fluvial features on and near the newly formed crater and its ejecta deposits (e.g. Maxwell et al., 1973; Brakenridge et al., 1985; McEwen et al., 2007b; Tornabene et al., 2007; Williams and Malin, 2008; Morgan and Head, 2009; Harrison et al., 2010; Jones et al., 2011). Such water-driven activity is thought to be the result of excavation and melting of subsurface ice during and shortly after the impact (Jones et al., 2011) and may persist up to 10^4 or 10^5 years (Newsom et al., 1996; Abramov and Kring, 2005). Although the broad distribution of the mapped fans (Fig. 1) and their apparent common age (Grant and Wilson, 2011) argues against a local crater-related source of water for emplacement of sediments on fan surfaces, there are several young, large craters in the area (e.g., Hale crater) that warrant exploration of the possibility.

The ejecta from Hale, a 125 × 150 km crater located just to the south of the study area (36°S, 324°E), is incised by numerous valleys (Jones et al., 2011) and the crater likely formed between the Early to middle Amazonian (Jones et al., 2011) and Hesperian–Amazonian boundary (Cabrol et al., 2001). Although Hale may be approximately the same age as the exposed sediments on the fans, there are several reasons to conclude that crater formation and fan deposition are not linked. First, the mapped fans occur in craters that are up to 700–800 km from Hale (Fig. 1) and additional alluvial fan deposits occur at even greater distance (though their relative ages remain to be confirmed, see Wilson et al., (2012). Second, there appears to be little correlation between Hale and the azimuth of craters containing fan deposits as might be expected for a relatively local source of water vapor under the influence of prevailing winds. Third, many of the craters without fans preserve relatively older deposits on their floors and are located closer to Hale than craters with fans (Grant and Wilson, 2011). By contrast, a water source related to the Hale impact leads to the expectation of more fans closer to the crater, which is not the case. Hence, the formation of crater Hale does not appear to be responsible for the formation of the alluvial fan deposits.

Holden crater (26°S, 326°E) is 150 km in diameter and is middle-to-late Hesperian in age (Irwin and Grant, in press), thereby making its formation another potential local source of water and heat capable of triggering fan deposition. Some valleys do incise the ejecta deposit surrounding Holden and some of these source the Eberswalde delta complex (Mangold, 2011), although estimates of the range in expected discharge from these valleys may be difficult to reconcile with the emplacement of the delta (Irwin, 2011). Many of the mapped fans, however, are unrelated to these valleys and (or) lie well beyond the limit of Holden's ejecta. And like at Hale, craters bearing fans occur up to hundreds of km away from Holden and are located at a range of azimuths to the crater (though there is a general paucity of fan-bearing craters south of Holden). While some early alluvial deposition within Holden and nearby (e.g., in Eberswalde) could be related to the Holden impact (Kite et al., 2011; Mangold, 2011), there is additional evidence from the crater rim and fans around

Holden that there was a gap in time between the Holden impact and when exposed fan sediments were emplaced.

A measure of any gap in time between the formation of Holden crater and emplacement of exposed fan materials can be made by examining how many (if any) craters emplaced on the rim or ejecta of Holden appear modified by the proposed late activity responsible for the emplacement of fan materials. Newly formed surfaces created by the Holden impact event should be crater free. With increasing time after the impact, however, exposed surfaces around the crater become more likely to be peppered by later impacts. If we infer that any craters formed on Holden's rim prior to the onset of fan activity would have been simultaneously modified by the same fluvial processes, then the number of degraded craters on Holden's rim (Fig. 6) records a gap in time between when Holden formed and later occurring fan activity. Occurrence of few or no modified craters likely means fan activity immediately followed Holden's formation, whereas the presence of more numerous degraded craters requires a longer interval between Holden's formation and onset of fan activity.

Because erosion around impact craters is slope dependent, with greater erosion occurring in higher relief and steeper near-rim areas and lesser erosion on lower relief, more permeable surfaces mantled by ejecta (Grant and Schultz, 1993a; 1993b; Grant et al., 2008b), the distribution of any modified craters may be limited primarily to the steeper, near-rim areas around Holden. A search of Holden's higher-relief, near-rim region rim reveals six degraded craters ranging in diameter from just under 2 km to Bigbee crater at nearly 20 km in diameter (Fig. 6). The distribution of these craters around Holden's rim indicates they are not related to the impact of a fragmented bolide from a single impact event. Assuming the modification of these six craters was contemporaneous with the fluvial activity responsible for the latest period of fan activity, there must have been a gap in time between the impact that formed Holden crater and the formation of the alluvial fans in Holden to allow these six craters to accumulate on Holden's rim.

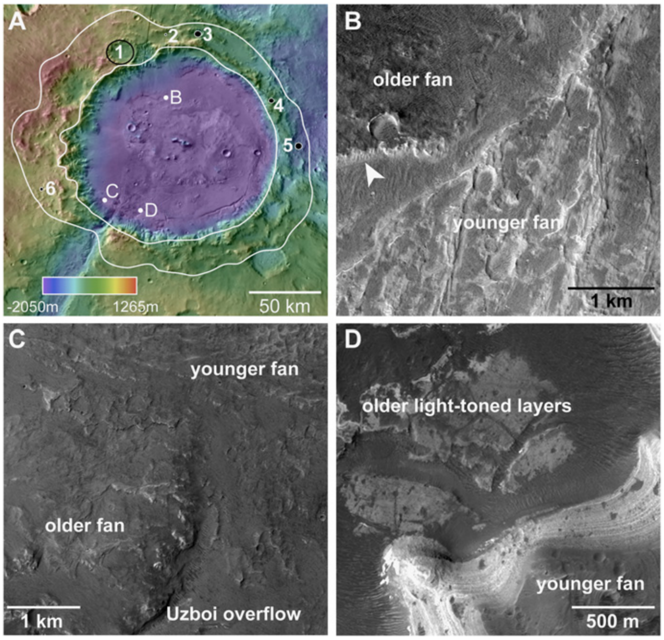

Fig. 6. (A) Holden crater with approximate extent of high-relief rim indicated by solid white lines (covering ~18,000 km^2). At least six craters on the rim of Holden are degraded, suggesting a significant amount of time was required after the Holden impact to allow these craters to accumulate before being modified by fluvial activity. Diameters of degraded craters: crater 1 (Bigbee crater, 19.3 km); crater 2 (1.6 km); crater 3 (5 km); crater 4 (3.9 km); crater 5 (5.4 km) and crater 6 (2.7 km). MOLA topography over subset of THEMIS daytime IR global mosaic. Locations B, C and D show additional morphological evidence for a gap in time between Holden crater formation and late fan activity. (B) Arrow head indicates crater wall excavated into older fan that was later filled by younger alluvium. Subset of HiRISE image ESP_012676_1545 (52 cm pixel scale). (C) Older fan materials are cut by Uzboi overflow channel and later filled by younger fan sediments (top). Subset of HiRISE image ESP_019889_1530 (26 cm pixel scale). (D) Light-toned layered deposits on the floor of Holden were cut by fractures before later burial by younger fan deposits. Subset of HiRISE image PSP_003077_1530 (26 cm pixel scale).

Depositional relationships between fans flanking the north, southwest, and south walls of Holden crater show evidence for multiple periods of formation and support the conclusion that any deposition associated with crater formation was followed by a later period of fan activity. Fans flanking the northern wall of the crater (Fig. 6B) were active before being locally excavated by a small impact. Later activity on the fans subsequently breached and partially filled the resultant crater. On fans along the southwest wall of the crater (Fig. 6C), discharge associated with the overflow of Uzboi Vallis to the south (Grant et al., 2008a; 2010) incised pre-existing fans, but these channels were partially filled during later fan activity. Finally, along the south wall of the crater (Fig. 6D), light-toned layered deposits were likely emplaced in a lacustrine setting that was accompanied by early fan activity (Grant et al., 2008a). These deposits were subsequently fractured and then overlain by younger fan materials, thereby implying a gap in time between the depositional events. While any one of these relationships between what appear to be older versus younger fan materials could reflect essentially continuous events, collectively they are most consistent with a gap in time between the formation of Holden crater and the deposition of the exposed fan materials. All other large craters in the region are older than Hale and Holden craters and are thus not considered to be likely sources of water for fan activity. This observation, together with the regional distribution of the fans, indicate a more synoptic, late source of water is required for their formation.

If synoptic precipitation (in the form of rain or snow) was responsible for the fans, there should be morphological evidence of simultaneous water-driven erosion elsewhere on Mars. Late water-related erosion has been suggested (e.g., Gulick and Baker, 1990; Carr, 1996, 2006; Mangold et al., 2004; Fassett and Head, 2008; Dickson et al., 2009; Fassett et al., 2010) and some events appear contemporary with the deposition of fan surfaces. These include valley incision on some Martian volcanoes (Gulick and Baker, 1990; Fassett and Head; 2008), a possible overlap between fan activity and late valley incision elsewhere in Margaritifer Terra (Baker and Partridge, 1986), a variety of putative supraglacial and proglacial valleys (Fassett et al., 2010), and late geomorphic activity in the Electris region (Grant and Schultz, 1990) that included valley incision (Howard and Moore, 2011). In addition, Moore and Howard (2005) suggested that other fans on Mars were possibly contemporaneous with those in the study area, thereby implying synoptic precipitation could account for late fan activity.

One possible source for late water-driven activity on the fans and elsewhere is water that was debouched into the northern lowlands during late outflow channel formation (e.g., Rotto and Tanaka, 1995; Carr, 2006; McEwen et al., 2012). Much of this water may have been stored as groundwater prior to outflow activity (e.g., Grant and Parker, 2002) and its release would have reinvigorated a global hydrologic cycle on Mars upon release onto the surface from where it could be redistributed as precipitation in the southern highlands (Luo and Stepinski, 2009). Under this scenario, synoptic precipitation and any associated runoff would have continued, perhaps accentuated by volcanic activity (Caudill et al., in review), topography, and (or) orbital variations (e.g., Laskar et al., 2004), until the inventory of water in the northern lowlands was depleted via trapping in the highlands and (or) was buried in situ (Mouginot et al., 2012). In the absence of later periods of outflow activity (McEwen et al., 2012) or other means for enabling widespread availability of water at the surface, runoff related to global scale precipitation on Mars likely came to an end.

The distribution and appearance of fans within some craters and the apparently fine-grained nature of the sediments comprising fan surfaces may provide additional clues about the form and intensity of late occurring precipitation. The limited correlation between where fans occur relative to physical crater characteristics such as floor elevation and wall relief (Table 1) coupled with the apparent absence of channels heading on fan surfaces or central peaks suggests that precipitation was not capable of generating widespread runoff and required concentration to enable erosion of sediments from within source alcoves. Moreover, the absence of exposed coarse sediments or fan-head trenches coupled with the low slope of fan surfaces implies predominantly uniform and limited intensity runoff emerged from alcoves and transported an existing inventory of fine sediments likely produced in situ by weathering. Flashy, more intense runoff and resultant flushing of alcove sediments via debris flows or other high energy processes is not possible because it would lead to more coarse fragments, steeper slopes, and likely some fan head trenching (though these processes could have characterized any earlier periods of fan construction).

Although speculative, one mechanism for concentrating precipitation to enable in situ weathering and subsequent transport of fine sediments onto the fans involves repeated, but limited, snowfall that was concentrated by the wind into pre-existing depressions that would include preexisting alcoves. The topography of some present-day alcoves could provide a local setting where a deep snow pack could accumulate and be protected from sunlight. Other rim depressions or topography, perhaps related to underlying structure, may also have been created during crater formation and are observed around the margin of some relatively pristine craters in areas lacking fluvial modification (e.g., volcanic plains, see Fig. 7). Such depressions could also trap snow and lead to erosion of alcoves capable of trapping even more snow. Hence the distribution of fans within craters could be controlled more by the location and orientation of impact generated topography and (or) later erosion of it to form alcoves rather than orientation around the crater relative to insolation.

The requirement of having pre-existing topography deep enough to trap and protect snow could also explain why fans are present in some craters and not others. Larger craters with greater rim circumference afford more possibilities for the expression of such relief (Fig. 7) and may create settings more favorable for fan formation. Snow could be orographically enhanced to some degree along crater rims, consistent with some alcoves/fans occurring where wall/rim relief is greatest (Table 1). By contrast, snow not concentrated and protected in this manner would either evaporate or melt and mostly infiltrate, consistent with the general absence of contemporary valleys on fan surfaces, central peaks, and most surfaces outside of the craters. The collection network sourcing the fan delta in Eberswalde crater is the exception, but water draining through that system could be groundwater with origins traced to melting snow trapped along the outer rim of Holden.

Accumulated snow within rim depressions and (or) pre-existing alcoves would be in contact with rocks such that occurrence of repeated intervals of freezing and thawing would facilitate physical weathering to produce an inventory of fines (e.g., Hallet et al., 1991). On Earth, freeze–thaw cycles often occur annually or over shorter time scales (Selby, 2000; French, 2007) and can result in "hydro fracturing," frost shattering, and (or) the granular disintegration of rocks (French, 2007). This process produces significant gravel and finer materials in some lithologies (e.g., sedimentary or coarse granular igneous, Selby, 2000; Hereford, 2002). On Mars, annual or even longer freeze–thaw cycles in highly fractured/disrupted rocks around the interior rims of impact craters could yield similar results in some lithologies when the effects accumulate over time scales related to orbital forcing. A possible dependence on, or influence by, lithology necessary to produce mostly fines when subjected to physical weathering by freeze–thaw could contribute to the preferential development of alcoves and fans in some craters.

The accumulation and later melting of snow could occur annually and (or) may be accentuated by orbital variations over longer periods. In either case, however, melting must occur gradually and result in fairly uniform, but limited runoff capable of carrying fine sediment onto the fan surfaces. If correct, this scenario would continue until the source of water for precipitation was lost and any snow remaining in alcoves either melted or slowly evaporated.

4. Summary

The morphometry and occurrence of crater-bound fans in southern Margaritifer Terra indicate deposition of exposed sediments likely relates to a late period of synoptic precipitation.

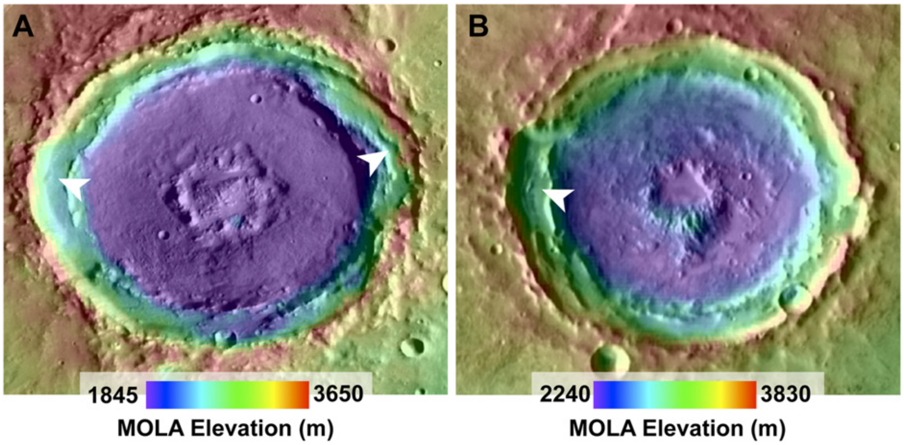

Fig. 7. Many relatively pristine complex impact craters on Mars lack fluvial modification, such as crater Martin (A; 290.67°E, 21.19°S, diameter is 61.4 km) and a nearby unnamed impact crater (B; 293.9°E, 20.3°S; diameter is 38 km). These craters are roughly comparable in size to some of the fan-bearing craters in Margaritifer Terra and exhibit impact related rim relief or possible "proto alcoves" (white arrows) that could serve as depressions capable of trapping and accumulating snow. MOLA topography over daytime THEMIS IR data.

Water may have been related to the redistribution of water from the northern lowlands to the cratered southern highlands following outflow channel formation (Luo and Stepinski, 2009) and fan occurrence within craters was perhaps influenced locally by topography and (or) orbital variations. Earlier periods of precipitation-induced runoff and (or) more local runoff related to impact release of water may have contributed to construction of the fans and it is not known how much of the overall sediment inventory in the fans relates to the late activity discussed here. Nevertheless, the distribution of the fans coupled with the fine-grained nature of the surface sediments implies late occurring precipitation was possibly snow whose accumulation and melting could have been modulated over time by season and (or) orbital cycles. Concentration of snow into existing depressions and (or) pre-existing alcoves along crater rims would have allowed it to accumulate and facilitate physical weathering. The resultant inventory of fine sediment was later transported onto the fans during periods of melting. If correct, this interpretation suggests the fans may be associated with a globally occurring late period of water activity on Mars (Howard et al., 2005; Irwin et al., 2005b; Moore and Howard, 2005; Fassett and Head, 2008; Wray et al., 2009; Grant et al., 2011a; Howard and Moore, 2011).

Two of the craters containing the fan deposits, Holden and Eberswalde craters, were finalists for the MSL landing site (Grant et al., 2011b). If our interpretations are correct, then the exposed sediments on the fans relate to a late period of widespread precipitation (Grant and Wilson, 2011) dominated by snowfall and occasional melting that directly influence the past habitability at the sites. Instead of being characterized by long-lived wet conditions during the early history of Mars, accessible materials at landing sites on fans in Holden and Eberswalde craters may provide insight into a late occurring, relatively colder, drier and less sustained period punctuated by wet conditions.

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