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Local late Amazonian boulder breakdown and denudation rate on Mars

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[1] Inactive fan surfaces become smoother and develop desert pavement over time by weathering and erosion. We use this mechanism to estimate late Amazonian boulder breakdown and surface denudation rates on a young (~1.25 Ma) (Schon et al., 2009) fan on Mars. This is done by comparing boulder size and surface relief between lobes of different ages. The boulder breakdown rate is 3.5 m/Myr, surface smoothing (denudation) rate is approximated as 0.89 m/Myr. These rates exceed previous estimates for the Amazonian by orders of magnitude. We attribute this to locality, high initial smoothing rates after morphological activity and obliquity and eccentricity-driven variation in the availability of (metastable) liquid water, which acts as a catalyst for weathering during these periods. The results have major implications for process interpretation of Martian landforms, as they imply that typical small-scale morphology may be subdued within <1 Myr. **Citation:** de Haas, T., E. Hauber, and M. G. Kleinhans (2013), Local late Amazonian boulder breakdown and denudation rate on Mars, *Geophys. Res. Lett.*, *40*, 3527–3531, doi:10.1002/grl.50726.

1. Introduction

[2] Small alluvial fan systems are among the youngest landforms created by liquid water on Mars, many of which formed in the very late Amazonian [*Malin and Edgett*, 2000; *Reiss et al.*, 2004; *Schon et al.*, 2009]. They provide compelling evidence for conditions adequate for localized, short duration, surficial flow of liquid water in the last few millions of years on Mars. These fans aggrade through highly episodic runoff or mass-flow events. Consequently, large parts of fans are generally inactive and subject to weathering and erosion for prolonged periods. As a result, the morphology and texture of fan surfaces are often more effectively influenced by secondary processes of weathering and erosion than by primary processes of aggradation [*Blair and McPherson*, 1994, 2009]. On Earth, weathering and erosion generally lead to a decrease in surface relief (denudation) and particle size, which often results in the formation of smooth desert pavement.

[3] Fan surface denudation and pavement development are observed on fans in both hot-arid environments [*Wells et al.*, 1987; *McFadden et al.*, 1989; *Al-Farraj and Harvey*, 2000; *Frankel and Dolan*, 2007] and Arctic [*André*, 1990] and Antarctic environments [*Webb and Fielding*, 1999], despite the different environmental conditions. This suggests that these processes are independent of climate, as long as one or more agents for weathering and erosion are present. In the cold-arid environment of Mars, such agents include salt weathering [*Malin*, 1974; *Jagoutz*, 2006], insolation weathering (thermal fatigue) [*McFadden et al.*, 2005; *Viles et al.*, 2010], aeolian weathering [e.g., *Thomas et al.*, 2005], and chemical weathering, mainly by acidic volatiles in the post-Noachian [*Hurowitz and McLennan*, 2007; *Chevrier and Mathé*, 2007]. Indeed, rocks altered by one or more of these processes were identified on the Martian surface by multiple Martian Rovers [e.g., *Thomas et al.*, 2005; *Jagoutz*, 2006].

[4] However, the late Amazonian Martian boulder breakdown rate, the rate of disintegration of boulders in all dimensions into rock fragments on a nearly planar surface induced by weathering, is currently unknown. Recent large-scale surface denudation rates have been estimated by crater degradation and concentration of blueberry surface lag averaged over a prolonged period (0.4 Ga) [*Golombek et al.*, 2006]. This ignores that initial weathering rates of small-scale morphology immediately following formation are much higher because weathering and the consequent relief attenuation is partly driven by local surface gradient. We compare boulder size and surface relief between lobes of different age on a fan in eastern Promethei Terra (35°S, 131°E), which has a crater retention age of ~1.25 Ma [*Schon et al.*, 2009], to determine very late Amazonian (~1.25–0 Ma) boulder breakdown and surface denudation rates.

2. Fan Surface Denudation and Boulder Breakdown Rate

[5] The fan in eastern Promethei Terra is located in a 5 km wide crater. A single, large, well-developed, gully system and two smaller gully systems are present on the steep north-eastern wall of this crater. The large system with four distinct generations of lobes (Figure 1a) provides clear evidence of episodic deposition. The oldest lobe (lobe 1) is superposed by secondary craters [*Schon et al.*, 2009] that provide a robust maximum age for the other lobes. The secondary crater population originates from the formation of the 7 km wide Gasa crater, located ~100 km southwest of the gully system. Crater counts yield an estimated retention age of 1.25 Ma for the Gasa impact crater, with an uncertainty range of 2.4–0.6 Ma [*Schon et al.*, 2009], although that range could be larger based on recent examination of young crater retention age estimates [*Daubar et al.*, 2013].

[6] The four generations of lobes on the fan identified by *Schon et al.* [2009] are all distinct in morphology

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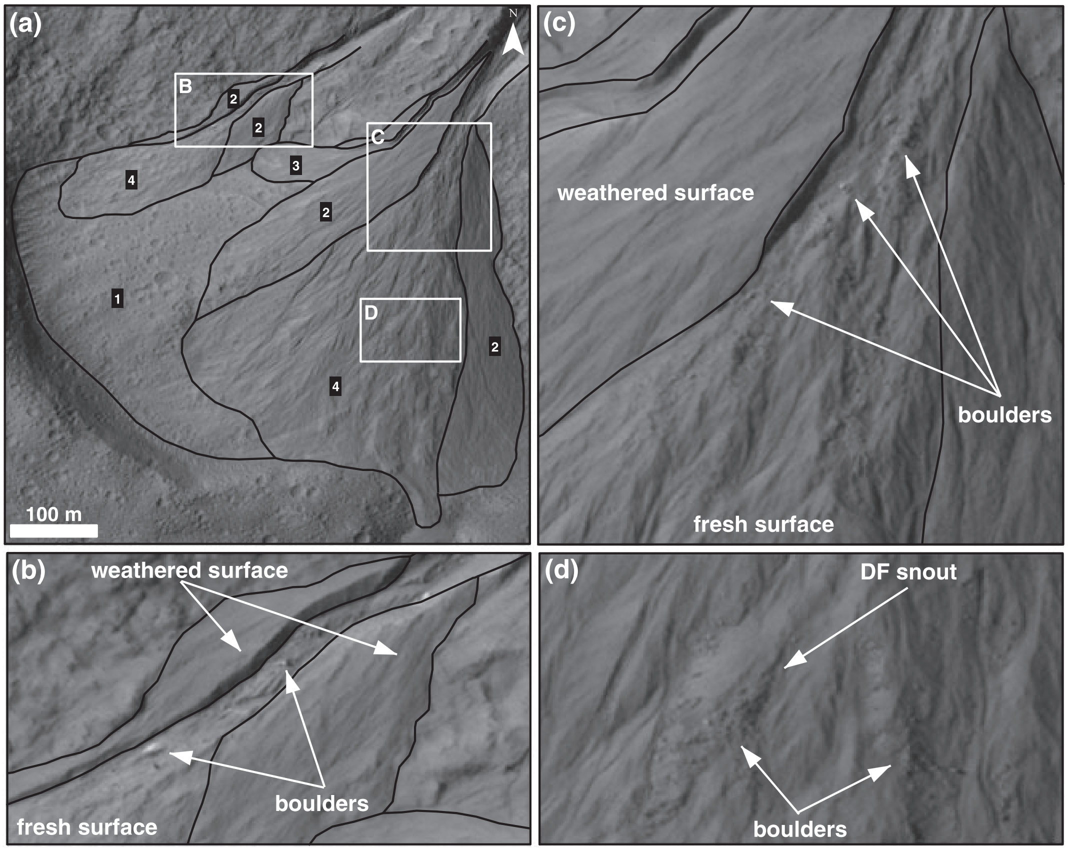

Figure 1. Gully-fan system on a crater wall in eastern Promethei Terra (35°S, 131°E), with four distinct lobes identified by *Schon et al.* [2009]. (a) Lobe 1 is the oldest lobe and retains a dense population of secondary craters. (d) The youngest lobe (4) shows many relief and clear morphological features, such as debris-flow lobes, and snouts. (b,c) Additionally numerous boulders, up to 4.9 m in size, are visible on its surface. Lobe 2 and 3 show less relief than lobe 4, and no boulders are visible. This indicates that weathering and erosion had a severe effect on fan surface between the formation time of lobe 2 and 4. HiRISE: PSP_002293_1450 is shown in this image due to a more favorable sun altitude, boulder measurements are performed on ESP_012459_1450 due to the higher spatial resolution (0.25 m versus 0.50 m).

and texture. The oldest lobe is strongly altered by the impact of the secondary acraters. As a result, no original morphological or textural features can be identified on its surface. In contrast, the youngest lobe (lobe 4) shows a large amount of relief, with proximal and medial parts that are dominated by channels and levees and a distal part that is dominated by debris-flow lobes. Lobe 4 shows many boulders >0.5 m on its surface (Figures 1b and 1c), concentrated close to the apex and along the margins of debris-flow snouts (Figure 1d). Lobes 2 and 3 show no boulders >0.5 m and have relatively smooth surfaces with little relief (Figures 1b and 1c). We attribute boulder breakdown and surface smoothing on these lobes to weathering and erosion. Surface smoothing by dust deposition can safely be neglected, as the fan is in a dust-free region [*Ruff and Christensen*, 2002] and there is no evidence for aeolian activity or significant dust deposition in the vicinity of the fan. Furthermore, *Schon et al.* [2012] indicate that Gasa crater, and thus the fan, postdates the local ice-dust mantle.

[7] The minimum age of the youngest lobe can be constrained by the relation between gully activity and climate. Gullies are generally believed to have formed by top-down melting of frost, snow, and/or ice, which has accumulated in favorable locations like alcoves [e.g., *Costard et al.*, 2002; *Dickson et al.*, 2007; *Dickson and Head*, 2009; *Williams et al.*, 2009]. This means that gullies on Mars can only have been active when there was accumulation of frost, snow, and/or ice in alcoves and when this was able to melt. The last glacial period on Mars, inferred from enhanced obliquity [*Laskar et al.*, 2004], was between ~2.1 and 0.4 Ma [*Head et al.*, 2003]. During this period, ice-rich layers were deposited as a meters thick mantle from the poles to approximately 30°N and 30°S [*Head et al.*, 2003]. Additionally, General Circulation Model results imply that during periods of enhanced obliquity centimeters of seasonal midlatitude, snow was present [*Costard et al.*, 2002; *Mischna et al.*, 2003; *Madeleine et al.*, 2009]. This snow could have concentrated into thicker snowpacks in topographic hollows like alcoves by aeolian transport [*Christiansen*, 1998]. Modeling by *Williams et al.* [2009] indicates that melting of these snowpacks was only possible during periods of high obliquity. This melting provided sufficient liquid water for the formation of fans on pole-facing midlatitude crater rims [*Dickson et al.*, 2007; *Marchant and Head*, 2007; *Morgan et al.*, 2010]. Therefore, melting, and thus fan aggradation, did probably not occur after 0.4 Ma [*Morgan et al.*, 2010; *Schon and Head*, 2011], which implies that lobe 4 predates 0.4 Ma. The maximum age of lobe 2 follows from the age of the

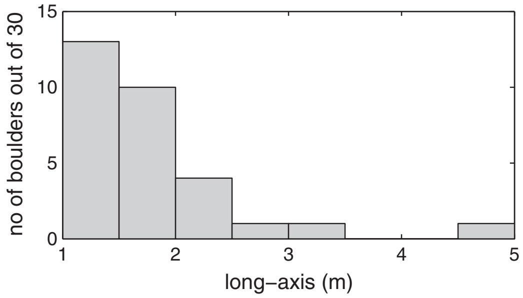

Figure 2. Distribution of the size of 30 boulders measured on the surface of lobe 4.

secondary crater population on lobe 1, lobe 2 thus postdates 1.25 Ma (2.4–0.6 Ma range). *Schon and Head* [2011] suggest meltwater from the degradation of an ice-rich mantling unit to be responsible for the initiation of gully formation in eastern Promethei Terra. They based this on the two smaller gullies that lack significant alcoves, preventing the accumulation of snow or ice, but have shallow incised feeder channels that originated from the degradation and melting of the ice-rich mantling unit. An ice-rich mantling unit could only have been present within the last glacial epoch, therefore, the maximum age of the fan is 2.1 Ma. This means that lobes 2–4 most likely formed between 1.25 and 0.4 Ma, but possibly between 0.6 and 0.4 Ma or 2.1 and 0.4 Ma given the uncertainty in the dating of the Gasa crater impact.

[8] We measured the long-axis of 30 clearly visible boulders on lobe 4 (see supporting information for details). Most boulders (23 out of 30) have a long-axis <2 m (Figure 2). The three largest boulders have a long-axis of 4.9, 3.5, and 2.8 m. Boulders of this size are commonly found on terrestrial debris-flow fans [e.g., *Beaty*, 1963, 1990]. The map-projected pixel size of the HiRISE image hosting the fan is 0.25 m (ESP_012459_1450), which implies that the uncertainty of the long-axes is about 0.25 m. A survey of boulders in the catchment area indicates that boulders with long-axis >2 m are common, but that the boulder with a long-axis of 4.9 m is exceptionally large. No boulders could be identified on lobes 1–3, which means that the maximum particle size on these lobes is less than two times the pixel size (<0.5 m). Given the smaller combined surface area of lobes 2 and 3 (two-thirds the area of lobe 4) and the size distribution of boulders in the catchment, we assume the maximum boulder size that was present on lobe 2 after deposition to be 3.5 m, ± 1 m.

[9] Dividing the difference in boulder size by the age difference between lobe 2 and 4 yields a boulder breakdown rate of 3.5 m/Myr for the most realistic scenario of shattering of boulders with long-axis of 3.5 m to rock fragments <0.5 m over a period of between 1.25 and 0.4 Ma. The most aggressive scenario of breaking down of boulders with a long-axis of 4.5 m over 0.6–0.4 Ma leads to a boulder breakdown rate of 20.0 m/Myr, while a boulder breakdown rate of 1.2 m/Myr is inferred for the most conservative scenario of shattering of 2.5 m boulders over 2.1–0.4 Ma.

[10] The initial relief on terrestrial debris-flow dominated fans is generally in the order of 0.5–3 m [*Beaty*, 1963; *Hooke*, 1987; *Beaty*, 1990; *Whipple and Dunne*, 1992; *Lowey*, 2002; *Kim and Lowe*, 2004]; in the Mars-like climate of Antarctica, the initial relief is in the order of 2 m [*Webb and Fielding*, 1999]. Based on visual interpretation of the available images, including an anaglyph stereo pair, the relief on lobe 2 has decreased by at least a factor of two relative to lobe 4. As a most plausible scenario, we assume 1.5 m of initial relief on lobe 4 and assume a 50% decrease of relief on lobe 2 with respect to lobe 4 from 1.25 to 0.4 Ma, for this scenario we obtain a surface denudation rate of 0.89 m/Myr. A denudation rate of 7.50 m/Myr is inferred for the most aggressive scenario of 50% decrease of 3 m initial relief between 0.6 and 0.4 Ma, whereas the most conservative scenario of 50% decrease of 0.5 m relief between 2.1 and 0.4 yields a denudation rate of 0.15 m/Myr.

3. Discussion

[11] Martian denudation rates have been estimated by crater degradation [*Golombek et al.*, 2006, and references therein], denudation of Meridiani plateau [*Hynek and Phillips*, 2001], deflation of Husband Hill [*Grant et al.*, 2006], and concentration of blueberry surface lag [*Golombek et al.*, 2006]. Together, these estimates nearly span the entire Martian history, 3.95–0 Ga. Although large differences are present between sites, in general, the highest denudation rates occur in the Noachian (0.8–7.7 m/Ma) and rates decline toward the Amazonian ($2 \cdot 10^{-5}$–0.1 m/Ma). The most recent estimates span the period 0.4–0 Ga and are $1.2 \cdot 10^{-2}$ m/Ma based on crater degradation and $1.3 \cdot 10^{-3}$ m/Ma based on the concentration of blueberry surface lag [*Golombek et al.*, 2006].

[12] Our very late Amazonian denudation rate estimate (0.89 m/Ma), which ignores spatial and temporal variation, is orders of magnitudes higher than the estimates of *Golombek et al.* [2006] and approximates Noachian values. This implies that local rates can be much higher over short-time periods, even on very recent timescales (<1 Ma). These local weathering rates are of great importance in the climatic interpretation of landforms. We hypothesize the following causes for the much faster weathering: First, weathering and denudation rates are site specific. Moreover, denudation rate is generally gradient-driven, whereas the timescale is determined by the volume eroded [*Kleinhans*, 2005]. Therefore, denudation rates inferred from crater rims are naturally lower than rates inferred from fan surfaces. Second, as smoothing rates are surface gradient-driven, they are highest shortly after abandonment [*Frankel and Dolan*, 2007]. Hence, denudation rate estimates are highest when they are inferred from recently abandoned surfaces. Third, the long timespan of the estimates of *Golombek et al.* [2006] means that the estimates of net denudation comprise cycles of relatively high and low weathering, and thus indirectly erosion and denudation. This means that denudation rates that are estimated over prolonged periods include more periods of relatively low denudation rates, which decreases the estimated net denudation rate.

[13] The spasmodic behavior of weathering rates over time can be explained by the availability of (metastable) liquid water on Martian slopes. In arid environments, frost, salt, and chemical weathering rates are all limited by moisture availability. Given adequate moisture, these weathering mechanisms substantially exceed insolation weathering rates [*Warke*, 2013]. Gully activity and fan formation, during periods of high obliquity [e.g., *Dickson and Head*, 2009], imply the presence of sufficient liquid water for enhanced salt and

chemical weathering and possibly frost weathering during certain periods and at certain locations in the late Amazonian. Moreover, *Head et al.* [2011] showed that in order to have metastable liquid water on Martian boulders, obliquity must be high, eccentricity must be high, and water ice must be deposited on the rocks, criteria that are fulfilled during several short periods in the last glacial period (2.1–0.4 Ma). These observations indicate that enhanced weathering rates induced by the presence of (metastable) liquid water in the late Amazonian occurred within several relatively short periods in the last glacial epoch. Consequently, denudation rates were significantly slower from 0.4 to 0 Ma than from 1.25 to 0.4 Ma. This is confirmed by the morphological and textural characteristics of the fan in eastern Promethei Terra. The youngest lobe, which has been inactive for at least 0.4 Ma, still shows distinct morphological features like debris-flow lobes and large boulders (Figure 1), and has thus only experienced minor alterations by weathering and erosion. In contrast, the surface of lobe 2 and 3 is relatively smooth and shows no boulders. Hence, we interpret these lobes to have experienced relatively high weathering and denudation rates from 1.25 to 0.4 Ma.

[14] The high, late Amazonian, surface denudation rate in eastern Promethei Terra has significant implications for process interpretation of Martian landforms, as small-scale morphology indicative of the formative processes is likely to be removed within ~1 Myr. This poses particular problems to alluvial fan interpretation, as the visual presence or absence of levees and lobes could otherwise be used to determine whether a fan was dominantly formed by fluvial or debris-flow processes [e.g., *Dickson and Head*, 2009; *Levy et al.*, 2010; *Reiss et al.*, 2011].

4. Conclusions

[15] We estimated late Amazonian Martian boulder breakdown and surface denudation rates on a very young (~1.25 Ma) fan in eastern Promethei Terra (35°S, 131°E) from differences in boulder size and surface relief between two distinct lobes of different ages. We estimate that the local boulder breakdown rate during the last glacial period was 3.5 m/Myr and local surface denudation rate was 0.89 m/Myr. These values exceed larger scale late Amazonian denudation rate estimates by orders of magnitude. This implies that small-scale morphology indicative of formative processes is mostly removed within ~1 Myr even in the very recent history of Mars. We ascribe the high local late Amazonian weathering and denudation rates to a combination of location dependency, high initial smoothing rates following morphological activity, and variations in obliquity and eccentricity causing periods favorable for the presence of (metastable) liquid water with consequent enhanced weathering rates.

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