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1 **Evidence for thermal-stress-induced rockfalls on Mars Impact Crater Slopes**

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10 **Abstract**

11 Here we study rocks falling from exposed outcrops of bedrock, which have left tracks on the slope over
12 which they have bounced and/or rolled, in fresh impact craters (1-10 km in diameter) on Mars. The
13 presence of these tracks shows that these rocks have fallen relatively recently because aeolian processes
14 are known to infill topographic lows over time. Mapping of rockfall tracks indicate trends in frequency
15 with orientation, which in turn depend on the latitudinal position of the crater. Craters in the equatorial
16 belt (between 15°N and 15°S) exhibit higher frequencies of rockfall on their N-S oriented slopes
17 compared to their E-W ones. Craters >15° N/S have notably higher frequencies on their equator-facing
18 slopes as opposed to the other orientations. We computed solar radiation on the surface of crater slopes
19 to compare insolation patterns and rockfall spatial distribution, and find statistically significant
20 correlations between maximum diurnal insolation and rockfall frequency. Our results indicate that solar-
21 induced thermal stress plays a more important role under relatively recent climate conditions in rock
22 breakdown and preconditioning slopes for rockfalls than phase transitions of H₂O or CO₂ at mid and
23 equatorial latitudes. Thermal stress should thus be considered as an important factor in promoting mass-
24 wasting process on impact crater walls and other steep slopes on Mars.

25 **Keywords**

26 Mars, surface; Thermal stress; Ices; Solar radiation; Weathering;

27 **Highlights**

- 28 • We studied rockfalls in impact craters on Mars focusing on orientation patterns with latitude.
- 29 • Equator-facing rockfalls are more numerous than pole-facing ones between -50° and +40°.
- 30 • Comparison with insolation patterns indicates an important role of thermal stress in Mars
31 rockfalls.

32 **1-Introduction**

33 Geomorphological processes are active at the surface of Mars at present day. Repeat-coverage and high
34 resolution images (better than 50 cm/pix - McEwen *et al.*, 2007) have revealed terrestrial-like
35 gravitational mass movements (Tsige *et al.*, 2016) ranging in size from landslides (Lucchitta, 1978) to
36 single rockfalls (Roberts *et al.*, 2012; Senthil Kumar *et al.*, 2019). The spatial distribution of tracks left
37 on slope-materials by falling rocks has been used as a passive seismometer on Mars and the Moon
38 (Roberts *et al.*, 2012; Senthil Kumar *et al.*, 2016; Senthil Kumar *et al.*, 2019). On Mars, few studies
39 have been carried out investigating the factors that control rockfall activity. From single images alone,
40 rockfalls appear to occur in a similar way as they do on Earth: a clast detaches from a cliff and rolls or
41 bounces downslope, while leaving a track in the surface (Fig. 1 & 2A). However, weathering
42 mechanisms leading to rockfall could differ substantially given the environment and climatic differences
43 between Mars and Earth. For instance, liquid water plays a major-role in terrestrial slope stability (e.g.,
44 Terzaghi, 1962). The involvement of water in active surface processes on Mars is widely debated (e.g.,
45 Schmidt *et al.*, 2017; Ojha *et al.*, 2017). Since liquid water is generally not stable today on the martian
46 surface (Farmer, 1976; Haberle *et al.*, 2001; Hecht, 2002), it is unlikely, however, that water plays such
47 an important role in slope instability on Mars as it does on Earth. (Tsige *et al.*, 2016).

48 On the other hand, Eppes *et al.* (2015) have linked boulder fracture patterns from *Mars Exploration*
49 *Rover* (MER) *Spirit* images to directional solar-induced thermal stress on Mars. Further, on Earth,
50 Collins and Stock (2016) showed that, on Earth, rockfalls can be linked to thermal stress. Therefore, we
51 consider thermal stress as a potential weathering mechanism linked to rockfall activity on Mars at
52 present day. In order to evaluate its relative importance, we have catalogued recent rockfalls on the
53 slopes of fresh impact crater walls across a range of latitudes to highlight different patterns of frequency,
54 block size and orientation. Craters walls are receiving different amount of insolation depending on their
55 orientation and latitude. Therefore, they are exposed to relative differences of potential thermal stress
56 intensity. If a link exists between thermal stress and rockfall activity, then there should be an aspect
57 relationship between them.

58 **2- Theoretical Background**

59 **2.1- Slope Stability**

60 Slope stability is a well-documented topic on Earth, especially in terms of geohazards related to
61 landslides and rockfalls. Mechanically, a rockfall can be modelled as small-scale mass movement. It is
62 a result of the breakup of an individual rocky object from the top of a slope (Selby *et al.*, 1982). Figure
63 1 outlines the factors that can contribute to a rockfall event.

64 Exposed rock (i.e. an outcrop) at the top of a topographic slope will be subject to gravity, and cohesion
65 counteracts gravity's pull resisting material failure and rockfall. A steep slope is the primary factor in
66 controlling rockfall as the tangential component of the gravitational acceleration is a function of the
67 slope angle. For failure to occur, the material needs to undergo a loss of cohesion as well. In a natural
68 setting, environmental stresses lead to the growth of fractures via subcritical fracture that occurs due to
69 stress magnitudes much lower than the critical strength of the rock (e.g. Eppes and Keanini, 2017). Over
70 time, subcritical fracture growth results in loss of cohesion and reduction in material strength overall.

71 **2.2- Longevity of rockfall tracks**

72 Aeolian processes are active at the surface of Mars today (Bourke *et al.*, 2008; Hansen *et al.*, 2011) and
73 study of the wheel tracks left by MER *Opportunity* and *Spirit* show that they persist for more than one
74 martian year (Geissler *et al.*, 2010; Sullivan *et al.*, 2008). Rover tracks are susceptible to infill because
75 they are located in areas where aeolian grains are easy to transport (Sullivan *et al.*, 2008, 2005). On the
76 other hand, rockfall tracks are located on sloping terrains, and may have slower infill rates because they
77 are not exposed to the same aeolian transport mechanisms. To be conservative therefore we estimate
78 that a meter-scale rockfall track could persist for more than a thousand years, and we acknowledge that
79 this rate will vary from one context to another (aeolian activity, track depth and width, and substrate).
80 Although this time period is short over geological timescales, orbital forcing related climate cycles are
81 relevant (Laskar *et al.*, 2004) and should be considered. We assume that if a track can still be observed,
82 the rockfall should be recent and the weathering mechanism involved should still be ongoing at the
83 surface today.

84 **2.3 Thermal stress**

85 High temperature contrasts experienced by rock surfaces in diurnal cycles lead to thermal expansion of
86 the material at the surface, but less so at depth, and hence rock breakdown. This mechanism is widely
87 studied on Earth. Rock breakdown linked to solar-induced thermal stresses is known to occur in very
88 arid environments in both cold (e.g. Antarctica, Lamp *et al.*, 2017) and hot deserts (Hall, 1999; McKay
89 *et al.*, 2009; Eppes *et al.*, 2010). Recent studies demonstrated that high stress can be correlated to high
90 absolute maximum temperature and diurnal temperature range. These temperature parameters could thus
91 be used as proxies of thermal stress (Boelhouwers and Jonsson, 2013; Collins *et al.*, 2018; Eppes *et al.*,
92 2016; Molaro and Byrne, 2012).

93 Thermal stress could cause rock breakdown on airless bodies (e.g. The Moon) (Molaro *et al.*, 2015,
94 2017) as well as on Earth (Eppes *et al.*, 2010; Warren *et al.*, 2013). Therefore on Mars, arid conditions
95 and high surface temperature gradients (e.g. Spanovich *et al.*, 2006) suggest that thermoelastic stress
96 might also occur on the surface at present day. Viles *et al.* (2010) have been able to lower the strength
97 of pre-stressed basaltic rocks under martian atmospheric conditions by exposing them to Mars-like
98 diurnal cycles temperature variations. Based on boulder fracture patterns from *Mars Exploration Rover*
99 (MER) *Spirit* images, Eppes *et al.* (2015) advocate active thermal stress-related rock breakdown. This
100 directional relationship between thermal stress on Mars and the fracture patterns could exist also on rock
101 walls. Growth of fractures caused by repetitive thermal stress cycles could lead to a fall, as known from
102 Earth (Collins and Stock, 2016; Do Amaral Vargas *et al.*, 2013; Gischig, 2016). If such a relation exists
103 on Mars, there should be a correlation between number of rockfalls and maximum temperatures or/and
104 maximum temperature ranges on slopes.

105 **3- Material and methods**

106 **3.1- Site Selection**

107 Impact craters are widely distributed over the martian surface, and for that reason, can be used as sample
108 locations to test the potential factors controlling rockfall distribution. Conveniently, they are circular
109 allowing a relatively unbiased assessment of slope-orientation influence. Here, we focus on relatively
110 fresh impact craters (Fig. 2B), from 1 to 10 km in diameter (Fig. 3) to reduce the influence of slope-

111 inheritance from other long-term processes. Impact craters with a diameter <10 km tend to have a
112 “simple” bowl-shaped morphology, whereas craters with diameters >10 km tend to have a more complex
113 morphology (Melosh, 1989), including multiple wall terraces, which could complicate our analysis. Site
114 selection was made by cross-referencing the global database of Mars impact craters from Robbins and
115 Hynek (2012), and image data availability. Selected craters are located between 50°S and 40°N with
116 most of them being located between 30°S and 30°N (Fig. 3) to avoid the latitude-dependent mantle
117 (LDM). LDM is a meter-thick layer of ice and dust covering at least 23% of the surface that extends
118 from the mid-latitudes to the poles (Conway and Balme, 2014; Kreslavsky and Head, 2002). It is a
119 draping unit which likely formed during the many orbital variation-driven climate excursions that have
120 occurred during the Amazonian period (Kreslavsky and Head, 2002). Fresh craters covered by LDM
121 would introduce a bias in the results since they would tend to cover the slopes making rockfall tracks
122 harder to observe, we decided to discard craters where it can be observed.

123 **3.2- Dataset and mapping**

124 Throughout this paper, we use the clast nomenclature suggested by Bruno and Ruban (2017). Because
125 most of the clasts mapped in this study range from 1 to 10 m, we will refer to them as “blocks” as
126 opposed to “boulders”, the term usually used, which refers to clasts smaller than 1 m in diameter
127 according to this nomenclature.

128 In order to map rockfalls in impact craters, we have used images from *High Resolution Imaging Science*
129 *Experiment* (MRO) instrument aboard the *Mars Reconnaissance Orbiter* (MRO), which provides a
130 spatial resolution up to 0.25 m/pixel (McEwen *et al.*, 2007) as listed in supplementary material, Table
131 1. Map-projected images were integrated in *ArcGIS*© 10.4 to identify and map recent rockfall tracks.
132 We digitized the tracks left by the clasts as they fell (Fig. 2A) and where possible the long axis of block
133 at the end of the track. From these polylines, we calculated their angle with respect to geographic north.
134 For length measurements, we used a sinusoidal projection centered on the crater to avoid the distortion
135 linked to map projection.

136 We used two different ways of evaluating frequency, using a normalized and a non-normalized
137 representation for the distribution of rockfall track orientations. For both methods, we first calculated

138 the number of rockfall tracks in 20° azimuth bins for each crater in a given latitude range. For the
139 normalized distribution, we calculated for each crater the percentage of the total number of tracks in that
140 crater for each azimuth bin. For each crater, the percentage of rockfalls in each bin is then relative to the
141 number of rockfalls in the crater. We then calculated the mean percentage of tracks for each bin in all
142 craters in this specific latitude range (Fig. 4, right). For the non-normalized distribution, the number of
143 tracks in each bin was summed for every azimuth bin in each crater in each latitude set (Fig. 4 left), then
144 the percentage is calculated relative to the total number of rockfall in the latitude range.

145 **3.3- Topographic measurements**

146 In order to assess variations in slope angle from crater-to-crater, or for different slope-orientations, for
147 a sub-sample of our craters we examined the slope angle at the bedrock outcrops. Where it was possible,
148 we generated Digital Terrain Models (DTM) at 24 m/pix from stereo-pairs of MRO Context camera
149 (CTX) images at ~6 m/pix (Malin *et al.*, 2007) using the *Ames Stereo Pipeline* (Broxton and Edwards,
150 2008). Before gridding, the generated point clouds were vertically controlled to Mars Orbiter Laser
151 Altimeter (MOLA) elevation point data (PEDR) from Mars Global Surveyor.

152 DTM accuracy was estimated by calculating the root mean square (RMS) between the elevation of the
153 MOLA points and the mean elevation of the CTX DTM in a circle of 168 m in diameter surrounding
154 those points. This diameter corresponds to the pulse diameter estimated from the point spread function
155 (PSF) of MOLA instrument (Neumann, 2003). RMS results are reported in supplementary material,
156 Table 2.

157 In order to estimate the slope of the crater wall outcrops, we split each crater into orientation bins,
158 totaling 18 arc-segments each covering 20° of azimuth. In each bin, we extracted the elevation of every
159 point between 50 and 200 m from the crater rim from where the clasts should typically fall. This
160 elevation range is corresponds to where rock outcrops are generally observed (Conway *et al.*, 2018), and
161 may vary from a crater to another. We extract the slope value for each bin by taking the slope of a linear
162 fit between the elevation and the distance from the rim for every DTM pixel.

163 **4-Results**

164 We recorded 2040 recent rockfall tracks in 39 impact craters among which, 1584 tracks had an
165 associated clast. Figure 4 displays the frequency of rockfalls in craters with respect to the orientation of
166 the crater wall, for different latitude ranges. Both the normalized and non-normalized plots show similar
167 overall trends in each latitude range. The mid-latitude craters have the most rockfall tracks on the
168 equator-facing slopes, in the northern and southern hemisphere. Northern mid-latitude craters have the
169 highest number of rockfall tracks on the N-NE slopes ($> 40\%$ combined between $N0^\circ$ and $N80^\circ$) in both
170 normalized and non-normalized plots. S slopes have very few recorded rockfall tracks ($< 20\%$ in total
171 from $N100^\circ$ to $N260^\circ$) in both normalized and non-normalized plots. The mean vector inferred from
172 these distributions is respectively $N13.3^\circ \pm 19.1$ and $N15.1^\circ \pm 19.6$ (95% confidence interval) for
173 normalized and non-normalized distribution. Rayleigh and Rao's test for the null hypothesis of
174 uniformity yield P-value < 0.01 for normalized distribution and 0.05 for non-normalized distribution.

175 In the southern mid-latitudes, equator-facing slopes of craters have the most rockfall tracks. The
176 normalized results show that up to 70% of the total number of rockfall tracks occur on the S slopes (i.e.
177 north-facing, from $N100^\circ$ to $N260^\circ$), whereas the non-normalized results only $\sim 60\%$ of total rockfall
178 tracks occur in the same range. The non-normalized plot has larger percentage of rockfall tracks on the
179 pole-facing slope (20% in total between $N340^\circ$ and $N40^\circ$) than the normalized results (2-3% on average
180 in the same bins). The mean vector inferred from these distributions is respectively $N178.3^\circ \pm 27.6$ and
181 $N141.6^\circ \pm 15.0$ (95% confidence interval) for normalized and non-normalized distribution. Rayleigh and
182 Rao's test for the null hypothesis of uniformity yield P-value < 0.01 in both cases.

183 At equatorial latitudes, there are more rockfall tracks on N-S-oriented slopes compared to E-W-oriented
184 slopes. Specifically, the non-normalized distribution shows two peaks of 8% between $N300^\circ$ - $N320^\circ$ and
185 $N0^\circ$ - $N20^\circ$, and another one from $N120^\circ$ to $N160^\circ$ (15% combined). In the normalized distribution, the
186 fraction of rockfall tracks is greater between $N340^\circ$ and $N20^\circ$ (18% combined) and from $N180^\circ$ to
187 $N200^\circ$ (9%) compared to the non-normalized distribution. A peak in the $N140^\circ$ - $N160^\circ$ bin (7%) is also
188 apparent in the normalized distribution. Mean vector from $N270^\circ$ to $N90^\circ$ (northern slopes) is

189 respectively $N0.0^{\circ}\pm12.9$ and $N322.5^{\circ}\pm4.0$ for normalized and non-normalized distribution, while it is
190 $N176.6^{\circ}\pm13.6$ and $N165.2^{\circ}\pm4.0$ for southern slopes, with P-value < 0.01 in each case.

191 **5- Rockfall clast size**

192 **5.1- Magnitude-Frequency of rock volume**

193 Figure 5 shows the cumulative frequency-volume distribution of martian rockfalls mapped in this study.

194 Magnitude-cumulative frequency (MCF) distribution is commonly modelled by a power law in the
195 middle section, with a deviation at the low and high sections (Corominas *et al*, 2017). The power-law
196 exponent (referred to as “scaling parameter”) is thought to represent the fracture susceptibility of the
197 rock mass under consideration. The scaling parameter of rockfalls in impact craters from our catalog is
198 -1.23.

199 On Earth, the scaling parameter of the power law usually varies from -0.90 to -0.40, depending on
200 geological, morphological and climatic conditions (Corominas, *et al*. 2017), but also varies based on the
201 technique used to measure the rock-dimensions. Using Terrestrial Laser Scanner (TLS)-generated 1
202 m/pix DTM to measure in-situ detachable rock volumes on a rock cliff (chute of Forat Negre, Andorra),
203 Mavrouli *et al.*, (2015) found an exponent of -1.3 while previous study yielded a value of -0.9 (Santana
204 *et al.*, 2012) for the same investigated area when using rockfall scar measure with TLS. The higher value
205 of scaling factor for Mars compared to Earth could be explained by a difference in mapping method but
206 could also represent a difference in the rock mechanics between the two planets.

207 **5.2- Median length of clasts**

208 Figure 6 shows the median long-axis length of rockfall clasts in each impact crater with respect to
209 latitude. The median size of recent rockfalls in the southern hemisphere is higher at the mid-latitudes
210 than near the equator in Hesperia Planum and other locations on Mars (Fig. 6). The median size of blocks
211 is greater than 2.5 m at latitudes $>35^{\circ}\text{S}$ and decreases down to 2 m close to the equator. A weaker similar
212 trend is observed in the northern hemisphere in Syrtis Major Planum and in the martian northern
213 lowlands. To confirm whether this trend exists in the northern hemisphere more data would be needed
214 $>25^{\circ}\text{N}$.

215 **6- Influence of slope on rockfalls**

216 The sub-sample of ten craters with DTMs allows us to investigate the relationship between rockfall
217 frequency and slope angle at the source. The aim of this analysis is to determine whether a systematic
218 variation in slope angle with orientation and latitude could explain the frequency distribution of rockfall
219 tracks reported in Figure 4. These craters are equally distributed within the latitude range of our total
220 sample set of 39 craters, and we find that >88% of rockfalls originate from slopes steeper than 32° (Fig.
221 7A).

222 Mars gravity is only 38% of Earth, therefore the question arises whether internal friction angle differs
223 on Mars and Earth, where it is ~30°. Early experiments carried out by Viking landers have shown that
224 angle of internal friction on Mars appears to be similar to typical Earth values, ranging from 27 to 39°
225 (Moore *et al.*, 1987). Therefore, the 32° value we found (Fig. 7A) is in line with expectations. The DTM
226 resolution (24 m/pix) means we are measuring the overall slope value within the assumed rockfall source
227 area, rather than the meter-scale slope from where the rocks detach.

228 The distribution of slope angle values follows a normal distribution for slopes with and without rockfalls
229 (Fig 7B). However, the distribution of slopes with rockfalls is shifted towards higher values of
230 topographic gradient, in accordance with the expectation that increasing slope angle should increase
231 rockfall activity (Fig. 1).

232 Mid-latitude equator-facing slopes on Mars are known to be steeper than pole-facing slopes (Kreslavsky
233 and Head, 2003; 2018) and this could potentially explain the higher frequency of rockfalls on equator-
234 facing slopes at our mid-latitude sites. The proposed explanation for this asymmetry is deposition and
235 removal of the LDM (Kreslavsky and Head, 2018), although recent work has shown it could be related
236 to enhanced glacial erosion on pole-facing slopes (Conway *et al.*, 2018). Low-angle impact craters can
237 display specific ejecta and interior morphologies (Herrick and Hessen, 2006), with a latitude-dependent
238 frequency (Barlow and Bradley, 1990). Non-circular rim morphologies could create azimuthal
239 variations in slope value in walls and influence rockfall activity.

240 Although rockfalls preferentially occur on steeper slopes, slope steepness alone does not condition
241 rockfalls. Figure 7C shows that a significant proportion of steep slopes do not have any rockfall tracks.
242 For instance, 30% of 36-38° slopes have no rockfall tracks (Fig. 7C). Slopes angles of 42-44° slopes
243 have no recorded rockfall tracks, but they only represent less than 2% of the population, meaning that
244 this low proportion of rockfalls at steep slopes could be a statistical bias. Slopes steeper than 32°
245 (excluding 42-44°) represent 27% of the measured population and have a proportion with rockfall tracks
246 ranging from 52% to 10% (Fig. 7C). Therefore, if rockfall activity was dictated by topographic gradient
247 only, the proportion of steep slopes with rockfalls should become closer to 100% the steeper the slope
248 becomes. Such a correlation is not found in our results. Moreover, our impact craters are relatively fresh
249 with a circular bowl-shaped morphology (Fig. 2B) and have been selected so to avoid influence of slope-
250 inheritance from other long-term processes and LDM (see Section 3.1). Therefore, an anisotropic
251 process must be involved in rock breakdown and rockfall activity on Mars at present-day to explain the
252 observed frequency in occurrence of rockfall tracks in orientation with latitude (Fig. 4).

253 **7- Other sources of rockfalls in impact craters**

254 Ejecta blankets contain abundant clasts (ranging in size from silt to several ten-of-meter-large blocks)
255 and can extent to the upper interior walls of impact craters (Krishna and Senthil Kumar, 2016; Senthil
256 Kumar *et al.*, 2014). In addition, ejecta layer is underlain by bedrock highly fractured during the impact
257 (Senthil Kumar, 2005; Senthil Kumar and Kring, 2008). Both of those impact-related clasts are potential
258 source of rockfalls in craters as they can simply fall due to gravity. However, the distribution of these
259 rockfalls would be random, independent on slope orientation, which is in contrast with our highly
260 oriented distribution. (Fig. 4).

261 As impact craters in this study are relatively young, they also could be exposed to ongoing modification
262 process such as impact crater collapse (Melosh and Ivanov, 1999) which could be the source of rockfalls.
263 This factor, however, should also act randomly and is not expected to cause any latitude-dependent
264 orientation pattern of rockfall on crater walls.

265 At mid-latitudes ($>30^\circ$), crater walls may display gullies that could be a source of rockfalls (Harrison *et*
266 *al.*, 2015). However, gullies between 30° and 40° prevail on the pole-facing slopes (Conway *et al.*, 2019)

267 while rockfalls seem to occur preferentially on equator-facing slopes at those latitudes (Fig. 4). One
268 could also argue that gullies have the opposite effect and tend to mitigate rockfall activity, or simply
269 introduce a bias in the mapping itself by reducing their visibility. However, this would need to cause
270 lower detection of rockfalls on craters at $>30^\circ$ latitudes, which is not the case. Our data indicate relatively
271 constant rockfall frequency from 15° to $40/50^\circ$ in both hemispheres (Fig. 4).

272 **8- Marsquakes**

273 Although most of the rockfall energy is provided by gravity, loss of material cohesion may not be
274 sufficient to trigger rockfall. Other local sources of energy could play this role.

275 Rockfall activity has been used to infer present-day seismic activity on Mars and on the Moon (Roberts
276 *et al.*, 2012; Senthil Kumar *et al.*, 2016; Brown and Roberts, 2019). During earthquakes, energy
277 decreases with distance from epicenter. Keefer (1984) noted that spatial frequency and intensity of slope
278 instabilities increase closer to earthquake epicenter. For instance, Roberts *et al.* (2012) reported an
279 increase in clast size and spatial distribution of recent block falls on along *Cerberus Fossae* floor around
280 a specific location and exclude other triggering factors than recent marsquakes. Marsquakes could thus
281 also affect the rockfall distribution. In addition, rockfalls be caused by neighbor impacts or wind but
282 only in rare cases. All in all, however, this phenomenon may occur only locally and could not explain
283 the specific pattern observed here (Fig. 4).

284 **9-Weathering mechanism**

285 **9.1- Phase changes of ice**

286 On Earth, phase change of water from liquid to solid is usually responsible for rock-breakdown and can
287 result in a rockfall. Freezing and thawing are rare on Mars as liquid water is unstable under current
288 atmospheric conditions (average pressure of 6 mbar - Farmer, 1976; Haberle *et al.*, 2001; Hecht, 2002)
289 although special regions have been identified where this could happen (e.g. Chevrier *et al.*, 2009) and
290 availability of metastable liquid water can affect weathering rate, even during the late Amazonian period
291 (De Haas *et al.*, 2013).

292 Compared to liquid water, water ice is abundant on Mars and the ice itself can change volume and can
293 produce stresses of >5 MPa (Mellon, 1997). Hence, rock may be broken down by the seasonal and/or
294 diurnal thermal contraction. Ground ice is thought to exist from the mid to high latitudes ($>45^\circ$) on
295 modern Mars, and has been documented in multiple locations using both orbital (Boynton *et al.*, 2002;
296 Byrne *et al.*, 2009; Dundas *et al.*, 2018; Mouginot *et al.*, 2010) and in-situ data (Mellon *et al.*, 2009).
297 Also, ground H₂O ice is inferred to exist from the observed distribution of CO₂ seasonal ices on pole-
298 facing crater slopes at latitudes as low as 25° in the southern hemisphere (Vincendon *et al.*, 2010a).

299 In addition to water, CO₂ seasonal frost resulting from condensation of atmospheric CO₂ in winter is
300 known to form a continuous >10 g/cm² layer which extends from polar caps to 60° in latitude in both
301 hemispheres (James *et al.*, 2005; Kelly *et al.*, 2006). Small patches of seasonal frost can also be found
302 in shadowed pole-facing slopes at latitudes as low as 33° S with modeled concentration reaching 8 g/cm²
303 (Schorghofer and Edgett, 2006). Thin layers (<1 mm) of diurnal CO₂ frost also exists at low latitude,
304 down to the equator, on low thermal inertia, dusty units (Piqueux *et al.*, 2016).

305 Small concentrations of water ice are associated with CO₂ frost, even at mid-latitudes (Schorghofer and
306 Edgett, 2006; Carrozzo *et al.*, 2009; Vincendon *et al.*, 2010b) and surface H₂O ice frost deposits were
307 observed by the Viking lander 2 at 47.64° N (Farmer, 1976). Vincendon *et al.*, (2010b) observed water
308 ice deposits ranging from 2 to 200 μ m at latitudes as low as 13° S and 32° N combining data from imaging
309 spectrometers and a modeling approach. These thin deposits are derived from atmospheric humidity
310 (recorded in TES data - Smith, 2002) generated by sublimation of ground water ice and polar caps.
311 Higher relative humidity itself can also increase crack growth velocity (Nara *et al.*, 2017). Relative
312 humidity is greater for a higher water vapor contain and a lower temperature (Harri *et al.*, 2014), meaning
313 crack growth velocity increase could be the highest at the mid-latitude and above, where water content
314 is greater (Smith, 2002) and temperatures lower.

315 Martian rockfalls linked to phase changes of H₂O and CO₂ should occur where they are expected to
316 condense and/or be preserved from previous ice ages, namely on pole-facing slopes in the mid to high-
317 latitudes and little to nowhere at the equator. Our results show that rockfalls occur on equator-facing

318 slopes both in the mid and equatorial latitudes (Fig. 4), suggesting that such a trend does not exist at
319 these latitudes, and that another mechanism is involved.

320 **9.2- Solar radiation model**

321 Latitude-dependence of rockfall orientation trends indicates that insolation plays a role on source-rock
322 breakdown and preconditioning rockfall occurrence on impact craters slopes. For this reason,
323 thermoelastic stress may be likely to play this role.

324 To assess the variation of insolation on latitude, we computed solar insolation over a typical DTM of a
325 crater placed at different latitude positions. We used the publicly available HiRISE DTM
326 (DTEEC_002118_1510_003608_1510_A01) of Zumba crater (Fig. 2B) to represent a typical fresh
327 crater. The DTM was reduced to 10 m per pixel and we only considered the crater walls to achieve a
328 reasonable tradeoff between resolution and computation time. For each pixel, a “viewshed”, which
329 provides information on the sky visibility in every direction, is first derived from the DTM (Rich *et al.*,
330 1994). The model then computes solar incidence angle of each pixel with respect to slope angle and
331 orientation, and sun position in the sky at a given moment. We ran the model for a martian day (sol)
332 every 10° of solar longitude (Ls) for the whole martian year. For each sol, direct insolation in W/m² is
333 computed every half an hour of local time. The daily mean is then calculated by averaging the solar flux
334 at each step for the entire sol. Equations making up the mathematical framework of our model are all
335 extracted from Appelbaum and Flood (1990). Details on the model are available in the supplementary
336 materials (Appendix A1). We obtained a raster that represents the maximum diurnal average insolation
337 received by the crater walls at a given latitude over a martian year.

338 **9.3- Orbital parameters**

339 The lifetime of the tracks left by rockfalls could be up to several tens of thousands of years (see section
340 2.5). This timescale requires that changes in orbital parameters be considered when studying latitude-
341 dependent processes depending on insolation. During the last 100,000 years, the eccentricity of Mars’
342 orbit has ranged from 0.075 to 0.118, being 0.093 today (Laskar *et al.*, 2004). Eccentricity influences
343 seasonal contrasts (see section 7.2), and therefore it is unlikely to play a role in the relative rates of
344 weathering for different slope orientations at different latitudes. In the same period the obliquity has

345 ranged from 22.5° to 26.8° (25.2° today - Laskar *et al.*, 2004), which is likely too small to have any
346 noticeable effect on the insolation patterns per orientation with latitude. However, during the same
347 period, Mars has experienced two full precession cycles, implying that the solar longitude at which
348 perihelion occurs has changed significantly. For instance, 22,700 years ago, Mars' perihelion occurred
349 at $L_s = 90^\circ$ (Laskar *et al.*, 2004), meaning that maximum insolation was received during the northern
350 summer (Fig. 8) and meaning solar insolation was at its yearly maximum on north-facing slopes at the
351 equator. This is the opposite of the situation today. With perihelion at $L_s = 90^\circ$, north-facing slopes at
352 the equator would experience maximum diurnal and seasonal temperature contrasts, as it is currently the
353 case for S-facing slopes. Precession cycles should therefore be considered when computing insolation
354 received by crater slopes during the last 100,000 years. For each crater, we have then computed
355 maximum diurnal average insolation for specific values of solar longitude of perihelion to estimate the
356 average over a full precession cycle.

357 **9.4 Comparison with rockfall distribution**

358 The insolation model was run at the latitude of each crater, every 45° of solar longitude of perihelion,
359 to cover a full precession cycle. To allow comparison with rockfall distribution, we have binned
360 insolation data with same method used for rockfall tracks (Section 3 – Fig.4). The bins are then averaged
361 for a specific latitude range and compared to a corresponding rockfall distribution for the same range.
362 Results are plotted in Fig. 9. Altogether, we can observe a significant linear correlation (Pearson $r=0.69$;
363 $R^2=0.48$; P-value <0.01) between maximum diurnal insolation averaged for a full precession cycle and
364 rockfall frequency (Fig. 9).

365 **9.5 Insolation and thermal stress**

366 Thermal stress is intrinsically higher where contrasts of temperature are greater, thus, one can expect it
367 to be stronger where solar flux is higher. Molaro *et al.* (2015) claim that temporal gradient of temperature
368 alone is a poor proxy for thermal stress at grain-scale and suggest using absolute temperatures and offset
369 from diurnal means. The same conclusions are shared by Boelhouwers and Jonsson (2013), as well as
370 Molaro and Byrne (2012). Solar flux and temperature are different physical quantities, but accurate
371 temperature models are far more complex than insolation models and would make computation time for

372 such a long timescale far greater. Also, temperature, including peak temperature, is controlled by solar
373 flux and thermal properties of the material. Different rock compositions will have different thermal
374 properties which also affect thermal stress intensity. However, one can expect thermal properties of
375 rocks to be roughly the same within one crater, therefore only solar flux variations would control
376 temperature disparities between walls. Higher the solar flux received by a surface within a sol, higher
377 will be its maximum temperature, and potentially the thermal stresses experienced by the material
378 underneath it. Our results indicate a spatial correlation between maximum diurnal insolation (and
379 potentially average daily temperature range) and rockfall activity at the mid and equatorial latitudes
380 (Fig. 9).

381 Overall, insolation is higher close to the equator than at the mid-latitudes, suggesting that thermal-related
382 weathering should be more efficient here. This could provide an explanation for why we observe a lower
383 median size of clasts (yet more numerous) at lower latitudes (Fig. 6).

384 These rockfalls could have occurred either during previous precession conditions and the track preserved
385 or be recent rockfalls derived from bedrock weakened during previous precession conditions. The latter
386 is more likely, as thermal stress is only responsible for preconditioning outcrops for rockfalls, not
387 triggering them (Fig. 1). Equatorial north-facing slopes could have been weathered over longer-period
388 but rockfalls would occur more recently. Hence, our results also indicate that the delay between
389 weathering and rockfall is probably constrained to recent orbital conditions (last 100,000 years) as it
390 does not seem to be affected by obliquity variations which have a longer timespan (e.g. $>10^\circ$ at >100 ka
391 - Laskar *et al.*, 2004). If rock breakdown occurred over similar timescales to obliquity cycles then, mid-
392 latitude craters should have a similar frequency of rockfalls to equatorial craters because obliquity has
393 changed from 15 to 45° in the last 10 Myrs (Laskar *et al.*, 2004), meaning the location of maximum
394 insolation transfers between the equator and the mid-latitudes. Assuming a relatively constant obliquity
395 in the last 100 kyrs, reversed perihelion would not change insolation conditions to the point where a
396 switch of maximum solar flux between north and south facing slopes would occur in the mid-latitudes,
397 as it does at the equator, so no change in the rockfall distribution would be expected.

398 **10- Conclusion**

399 We report on the first detailed study of individual recent rockfalls in impact craters on Mars inferred
400 from the presence of tracks on the crater walls. We observe that the frequency of rockfalls and their
401 orientation is dependent on latitude. The frequency of rockfall tracks is higher on the equator-facing
402 slopes at the latitudes between 15°N/S and 40°N/50°S. In equatorial impact craters, the frequency of
403 rockfall tracks is higher on both the north- and south-facing slopes compared to the east- and west-facing
404 slopes (Fig. 4). Median clast size tends to decrease towards higher latitudes (Fig. 6). Topographic
405 analysis shows that the signals observed are not a direct consequence of systematic variations in rock
406 wall slopes (Fig. 7). Thus, these trends are more likely to be linked to the weathering mechanism
407 responsible for rock breakdown prior to the rockfall rather than the slope inclination (Figs. 1). In
408 addition, the observed patterns argue against a role of H₂O or CO₂ phase changes in preconditioning
409 slopes for rockfalls, considering that most rockfalls occur in the equatorial area where these volatiles
410 are scarce or lacking. Instead, thermal stress-driven subcritical cracking (Collins et al., 2018; Eppes and
411 Keanini, 2017) related to high contrasts in surface temperature is more likely to be responsible for rock
412 breakdown on modern Mars. Comparison between our results and a solar flux model (Fig. 9) emphasizes
413 the potential role of diurnal temperature cycles at preconditioning slopes for rockfalls. We suggest that
414 thermal stress must be developed over timescales long enough for full cycles of precession to occur (Fig.
415 8) in order to explain the bimodal peaks in rockfall frequency at the equator.

416 Our study shows the key role of thermal stress in rock-breakdown on Mars. Thermal stress should thus
417 be considered as an important factor in promoting mass-wasting process on impact crater walls..

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657 **Appendix A1 - Solar Radiation Model**

658 Our model computes daily mean solar insolation for every pixel of the input Digital Terrain Model
 659 (DTM), at a specific sol/Solar longitude (Ls). Each pixel has a slope and an aspect value as well as
 660 information about visibility in every direction (“viewshed”). Viewshed is computed for every pixel using
 661 *Skyline_3d* and *SkylineGraph_3d* function of *ArcPy* Python package for *ArcGIS* (Rich *et al.*, 1994).
 662 Equations 1-8 making up the mathematical framework of our model are all extracted from Appelbaum
 663 & Flood (1989).

664 **Sun map calculation**

665 Each sol is split in 48 equal timesteps, for which we calculate solar elevation angle (α_s) (Eq. 1) and Sun
 666 azimuth angle ϕ_s (Eq. 2).

$$667 \quad \sin \alpha_s = \cos \omega \cos \delta \cos \varphi + \sin \delta \sin \varphi \quad (1)$$

$$668 \quad \cos \phi_s = \frac{\sin \delta \cos \varphi - \cos \omega \cos \delta \sin \varphi}{\sin(\theta)} \quad (2)$$

669 where ω is the hour angle (Eq. 3), δ the solar declination (Eq. 4), φ is the latitude, and θ is the solar
 670 zenith angle ($\theta = 90^\circ - \alpha_s$). When $\omega < 0$, Sun azimuth angle should be subtracted of 180° . Hour angle
 671 can be obtained with the following equation:

$$672 \quad \omega = 15 \text{ LST} - 180 \quad (3)$$

673 where *LST* is the local solar time in Martian hour. 15° is the rotation speed of Mars per Martian hour.

674 Solar declination angle can be calculated using the following equation:

$$675 \quad \sin \delta = \sin \delta_0 \sin Ls \quad (4)$$

676 where δ_0 is Mars obliquity and L_s is the solar longitude. Comparison of Sun position in the sky at each
677 step and visibility provided by the viewshed assess whether solar flux should be calculated or not.

678 **Direct irradiance calculation**

679 Solar constant S (W/m²) is the solar flux received at the top of the atmosphere (Eq. 5).

$$680 \quad S = S_{Mean} \left(\frac{1 + ecc \cos(L_s - L_{sp})}{1 - ecc^2} \right)^2 \quad (5)$$

681 where ecc is the eccentricity, L_s the solar longitude, L_{sp} solar longitude of perihelion and S_{Mean} the
682 mean solar constant (for Mars: 586 W/m²).

683 Direct solar radiation D (W/m²) is the fraction of solar flux reaching the surface, and it is given by Eq.
684 6:

$$685 \quad D = S e^{-\tau m(\theta)} \cos i \quad (6)$$

686 where τ is the optical depth of martian atmosphere, i the incidence angle (Eq. 8) and $m(\theta)$ the airmass
687 which can be approximated by Eq. 7:

$$688 \quad m(\theta) \cong \frac{1}{\cos \theta} \quad (7)$$

689 **Slope correction**

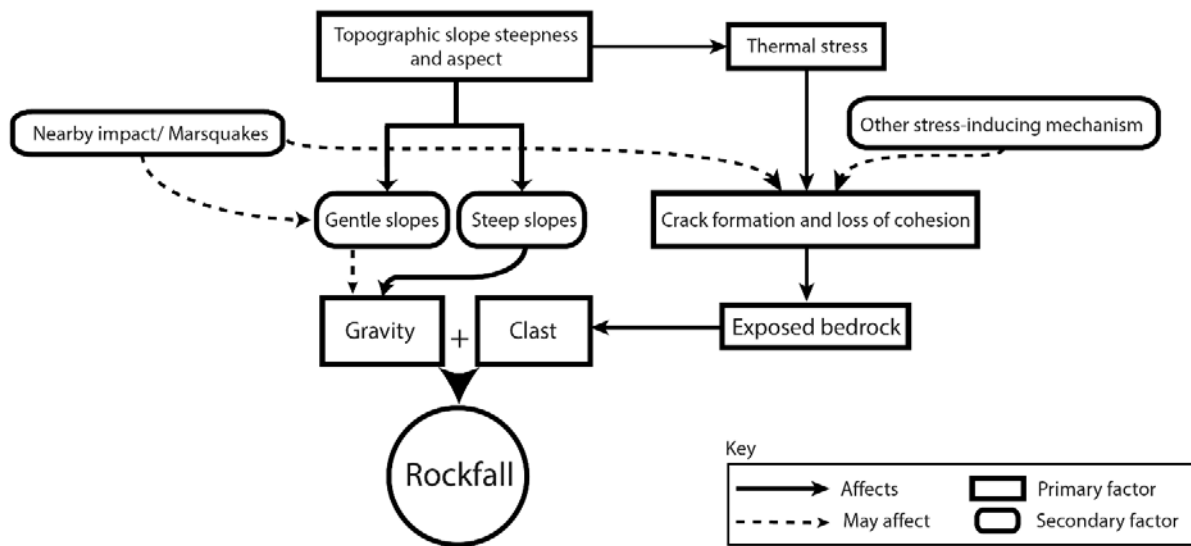
690 Incidence angle of the solar flux with respect to a tilted surface is calculated (Eq. 8) and included in Eq.
691 6.

$$692 \quad \cos i = \cos \theta \cos G_z + \sin \theta \sin G_z \cos(\alpha_s - G_a) \quad (8)$$

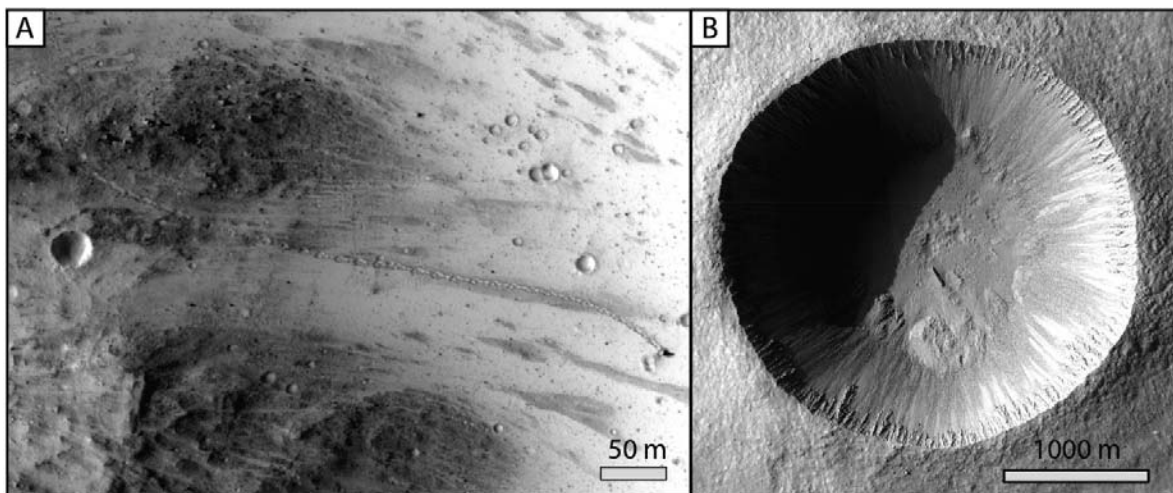
693 where G_z is the slope inclination and G_a is the slope orientation.

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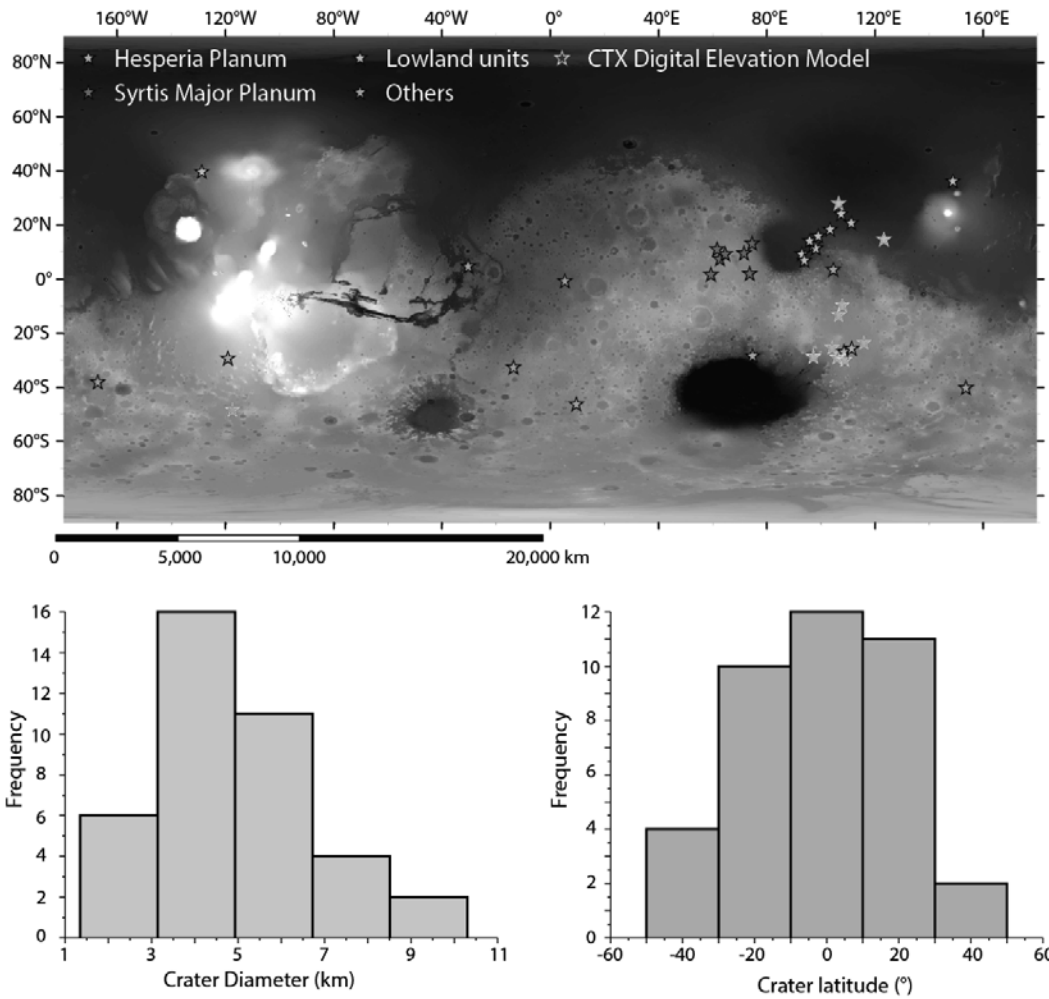
695



1 Fig.1. Schematic diagram illustrating how thermal stress could influence rockfall activity. Firstly, a
 2 topographic gradient is needed. The slope value and orientation control the amount of insolation received
 3 by the surface, and hence the potential solar-induced thermal stress intensity. Energy is mostly provided by
 4 gravity, although marsquakes may also contribute (e.g. Roberts et al., 2012). Crack formation mechanism
 5 is required to weaken the exposed material and reduce its cohesion.



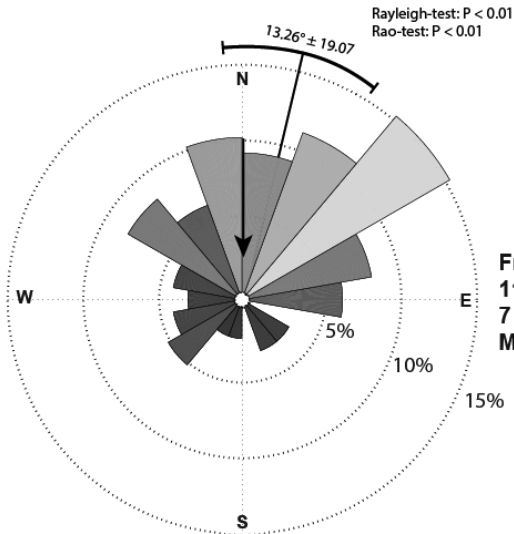
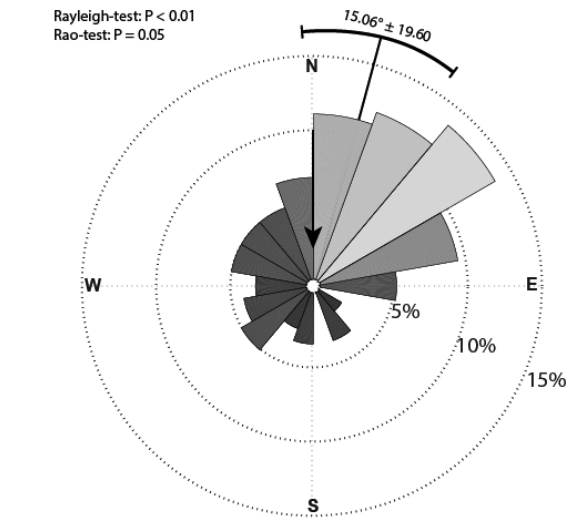
6 Fig. 2. **A:** Example of a recent rockfall displaying a clear track caused by rolling/bouncing with a clast at
 7 the end. *HiRISE* image: ESP_037190_1765. **B:** *Zumba* crater, a morphologically fresh impact crater
 8 representative of those used in this study. *HiRISE* image: PSP_002118_1510.



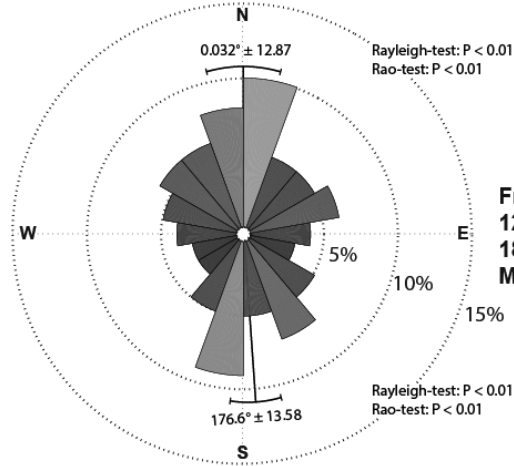
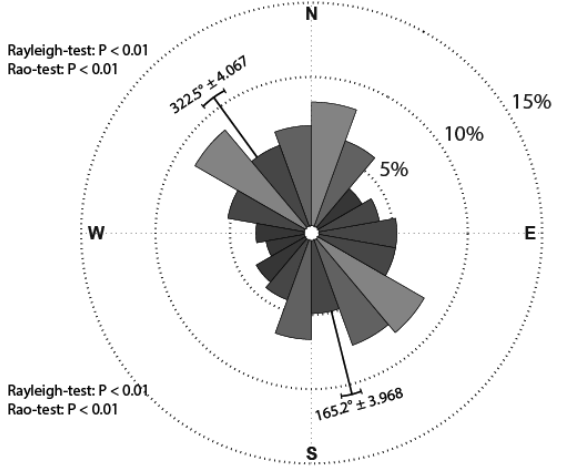
9 Fig. 3. Global distribution of 39 impact craters where fresh rockfall tracks and their associated clasts were
 10 mapped. **Bottom left:** The distribution of crater diameter for our sampled craters. **Bottom right:** The
 11 distribution of craters studied by latitude.

Non-normalized distribution

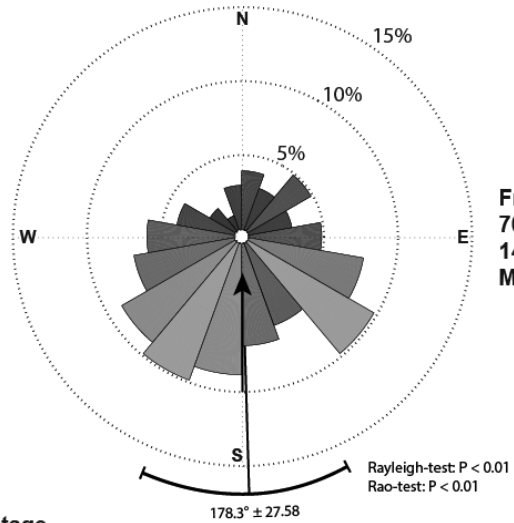
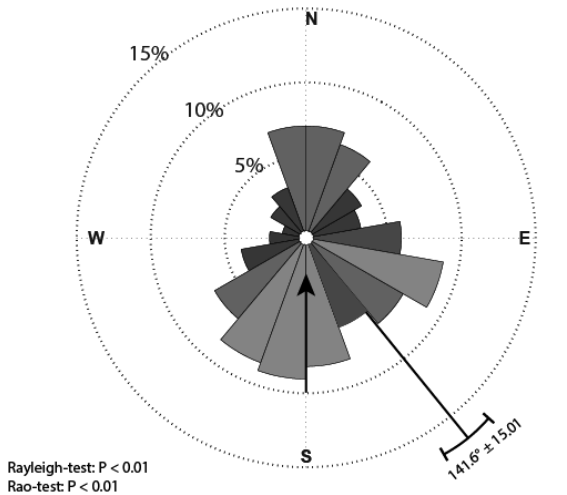
Normalized distribution



From 15°N to 40°N
114 rockfall tracks
7 impact craters
Mean crater diameter: 3.73 km

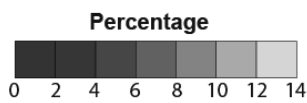


From 15°S to 15°N
1218 rockfall tracks
18 impact craters
Mean crater diameter: 4.49 km

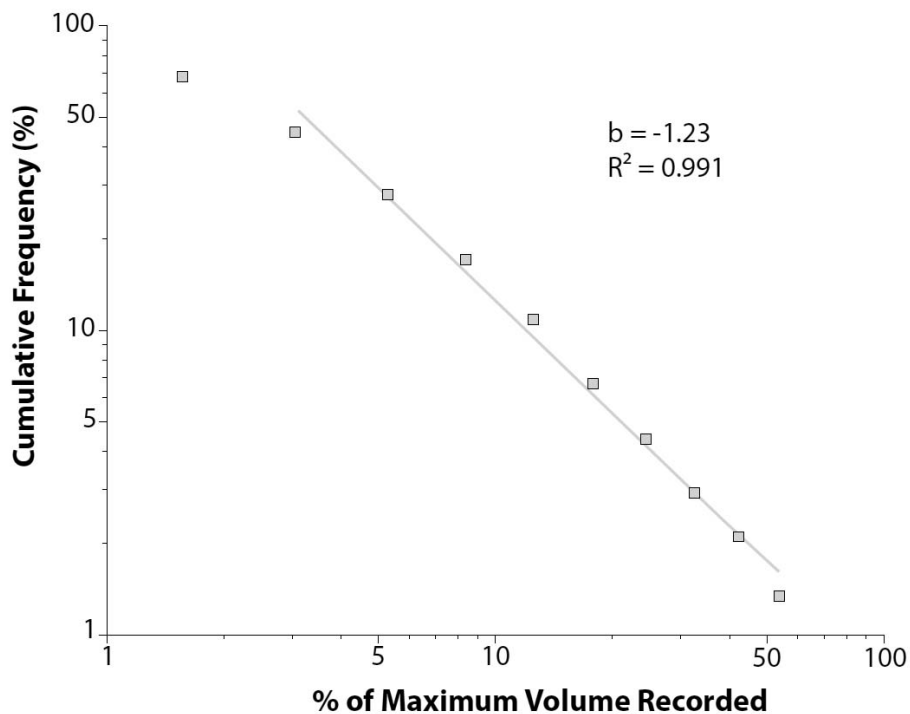


From 50°S to 15°S
708 rockfall tracks
14 impact craters
Mean crater diameter: 4.37 km

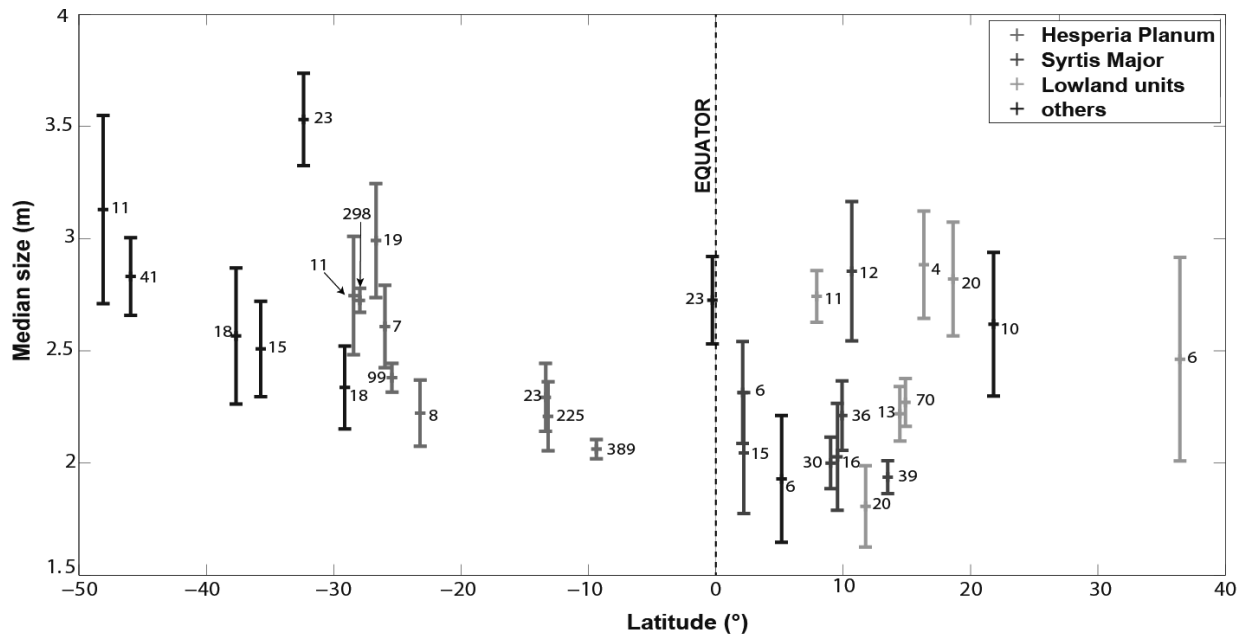
Rayleigh-test: $P < 0.01$
Rao-test: $P < 0.01$



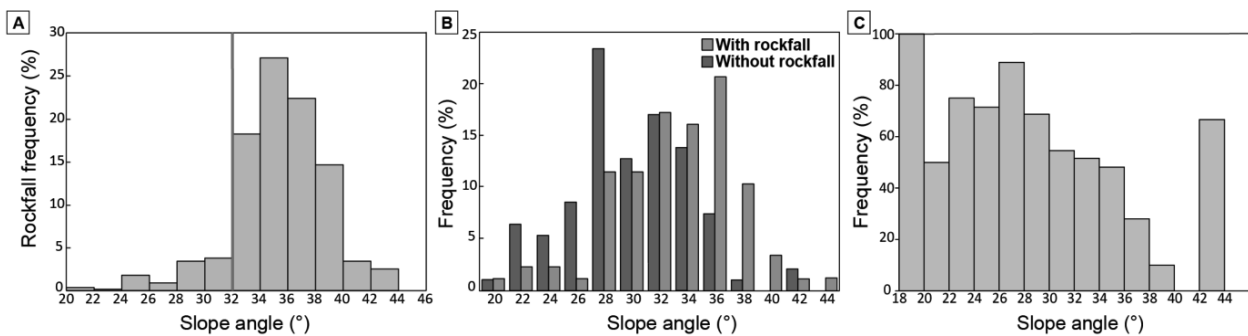
13 Fig. 4. Distribution of rockfall tracks by orientation in impact craters within different latitude ranges,
 14 derived using two different methods. All directions are with respect to the crater centers (e.g. North in the
 15 roses refers to northern slopes, i.e. South facing, arrows indicate equator direction). **Left:** non-normalized
 16 distributions, where the number of rockfall tracks in each orientation bin is summed for every crater in the
 17 specific latitude range and expressed as a percentage of the total number of rockfall tracks in this latitude
 18 range. This method emphasizes the signal from craters which have a large rockfall population (>100).
 19 **Right:** normalized distribution where the percentage of rockfalls is calculated for each orientation bin in
 20 each crater from which the mean is then derived for all craters in each latitude range. This method
 21 emphasizes the signal from craters having a relatively low rockfall population (< 20). Lines correspond to
 22 vector means with 95% confidence interval depicted by brackets. Rao's spacing test and Rayleigh statistical
 23 test were performed for the null hypothesis of uniformity. Since equatorial plots display two distinct trends,
 24 we calculated two vector means for each half of the plots, assuming the other half is uniform.



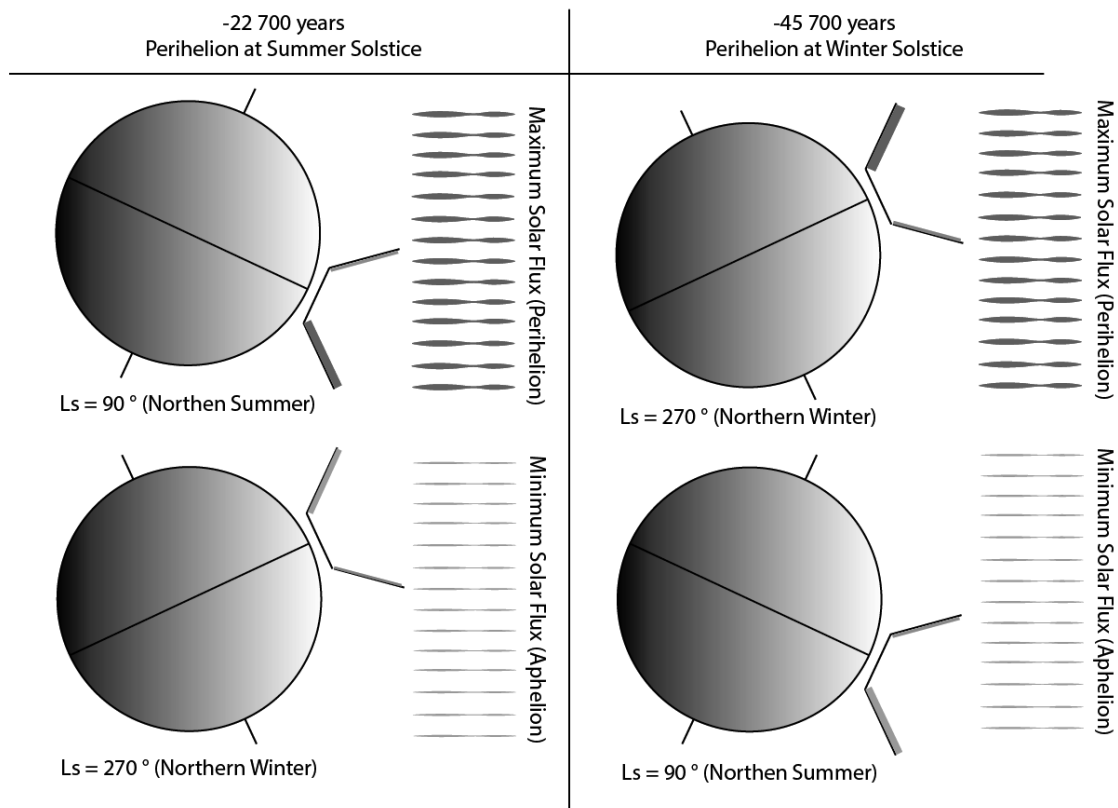
26 Fig. 5. Magnitude-cumulative frequency (MCF) relationship of clasts derived from martian rockfalls.
 27 Volume is calculated from diameter assuming an elliptical-shaped object with an aspect ratio of 0.8 (Kumar
 28 et al., 2019) and is normalized to the maximum volume recorded Power-law fit is shown.



29 Fig. 6. Median long axis size of the rockfall clasts with respect of the latitude in each crater where recent
 30 rockfalls were mapped. The numbers next to each bar correspond to the number of clasts recorded in each
 31 crater. The error bars represent the standard errors. The craters with larger populations have lower standard
 32 errors. Craters are sorted by region to account for lithology variations, as different rock compositions would
 33 induce different thermal properties and thermal stress response.

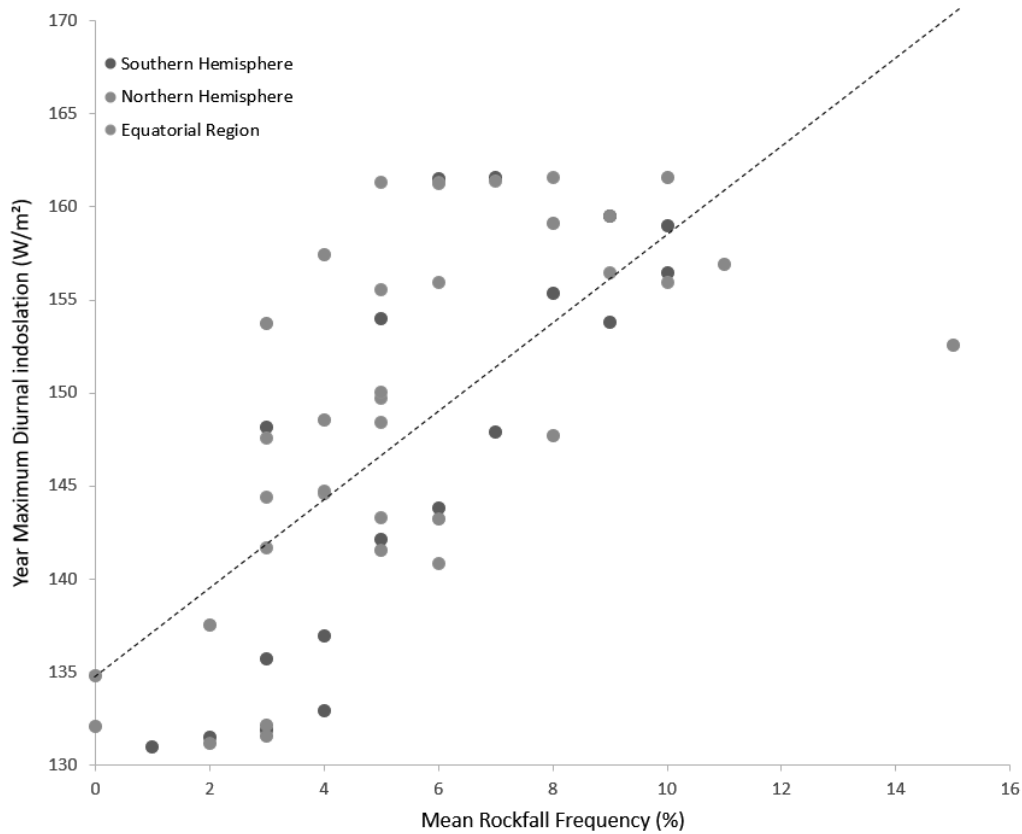


34 Fig. 7. Rockfall track frequency compared with slope derived from eleven digital terrain models. Slope is
 35 calculated for a 150 m wide area starting 50 m below crater rim, which is the most probable boulder source.
 36 Craters are divided into 20° bins in which rockfalls are counted. A slope value is attributed to each rockfall
 37 track, corresponding to the slope in the bin where it is located. **A:** Frequency of rockfall tracks against slope
 38 value. Rockfall tracks occur more frequently on slopes steeper than 32°. **B:** Frequency of all slopes with
 39 and without rockfall tracks. In both, the distribution is normal, but with different medians. **C:** Frequency
 40 distribution of slope angles for slopes without any observed rockfall tracks. 100% of slopes between 18 and
 41 20° are devoid of rockfalls because they are not steep enough (Fig. 1). 28% of slopes between 36 and 38°
 42 do not display any rockfall either. B and C highlight that a steep slope alone is not enough for a rockfall to
 43 occur, and that a stress-inducing mechanism is also necessary to allow cohesion loss of the material (Fig.
 44 1).



45 Fig. 8. Insolation received by a north- or south-facing slope located at the equator in two opposite cases. At
 46 45.7 ka, the longitude of perihelion was very similar to the present day ($L_s = 251^\circ$), south-facing slopes

47 received maximum insolation. At 22.7 ka at the opposite sense of perihelion, north-facing slopes received
48 maximum insolation at the equator.



49 Fig .9. Year maximum diurnal insolation plotted with normalized rockfall frequency in northern, southern
50 hemisphere, as well as equatorial region. Average diurnal insolation is computed for the latitude of each
51 crater in a given range (from 50°S to 15°S and 15°N to 50°N). The model runs for a whole martian year
52 every 45° of solar longitude of perihelion, to have an average over a full precession cycle. The solar data is
53 then binned the with same method used for rockfall tracks (Section 3 – Fig.4) and an average insolation
54 value is obtained for the given latitude range. Solar data bins are compared to their corresponding
55 normalized rockfall frequency bins (Fig. 4). P-value for the null-hypothesis is <<0.01 in both plots.

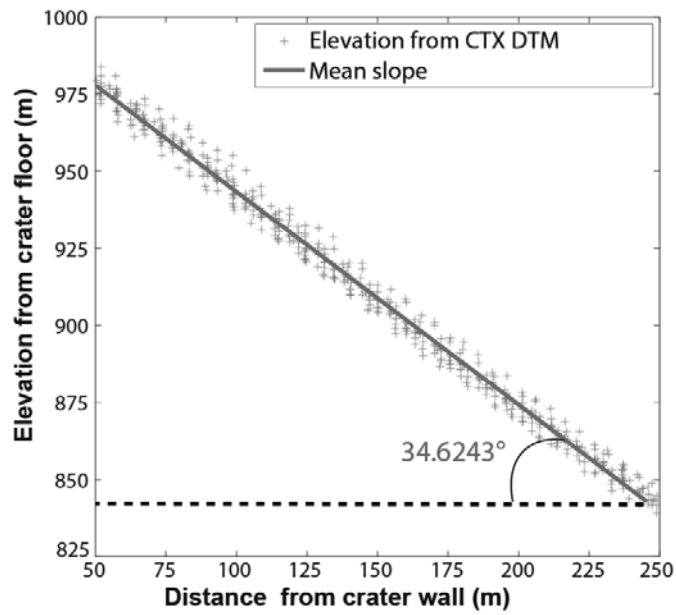


Fig. S1. Example of slope extraction from the CTX DTMs. Each point corresponds to a pixel value from the DTM in a 20° bin of azimuth with their distance from crater slope. The linear fit used to calculate the slope is shown in red together with the derived slope angle.

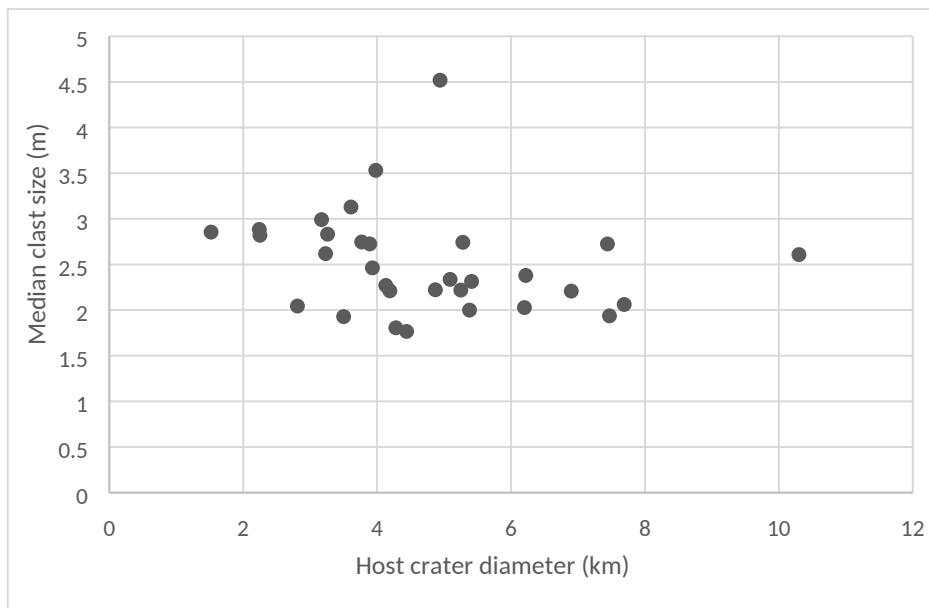


Fig. S2 Median clast size of rockfalls with respect to the host crater diameter