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1 **Morphological characterisation of landforms produced by springtime seasonal activity on**
2 **Russell Crater megadune, Mars**

3
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21 **Abbreviated title:** Seasonal activity on Russell Crater megadune

22

23 **Abstract**

24

25 We describe in detail an annual seasonal process that occurs on the surface of the Russell Crater
26 megadune on Mars. We give these features the name ‘perennial rills’, because their surface
27 topographic expression persists from year-to-year and they form a distinctive, downstream
28 branching network of small channels, or rills. We used time series images, elevation data from
29 stereo photogrammetry and spectral data to characterise the evolution of these features over six
30 Mars Years. Growth and modification of these networks occurs abruptly in spring (at approx.
31 solar longitude 200°) after most of the seasonal CO_2 ice has sublimated. We find that the peculiar
32 morphology of perennial rills seems to be the only aspect that sets them apart from active linear
33 dune gullies. By comparison to terrestrial analogues we identified two conditions favouring the
34 production such a network: a) the presence of an impermeable layer and b) the repeated
35 formation of obstacles in front of propagating channels. We find that the most plausible
36 formation mechanisms that can explain the formation of both the perennial rills and active linear
37 dune gullies are levitating CO_2 blocks, or liquid debris flows of water/brine, but neither can
38 completely satisfy all the observational evidence.

39

40 **Keywords:** Mars; water; ice; sediment transport; martian gullies; CO_2 ; seasonal processes

41 Active martian surface processes that are linked to the seasonal cycle are responsible for the most
42 prevalent surface changes observed over recent decades and their origin is heavily debated.
43 Repeat imaging by high resolution (better than 10 m/pix) sensors has enabled us to investigate
44 how martian surface features evolve with time and assess their intra-annual variability. Seasonal
45 processes result in surface changes that are small in scale (tens to hundreds of metres) and
46 although the majority only leave ephemeral visual traces some cause measurable topographic
47 change (e.g. spider-like-forms, Piqueux et al., 2003). Seasonal processes acting on dark martian
48 sand dunes are particularly active and they have a wide range of timings and morphologies.
49 These include: formation and extension/modification of gully-channels, alcoves and fans,
50 formation of pits, appearance/evolution of ephemeral dark spots/flows with or without bright
51 halos, and formation of dust devil tracks (e.g., Pasquon et al., 2016, 2018). This study focuses on
52 a phenomenon that was first noticed by Reiss et al. (2010a) on the Russell Crater megadune (Fig.
53 1; 54.5°S; 12.7°E), and here we report on its annual recurrence and detail its morphology. This
54 phenomenon occurs during spring and is characterised by the abrupt appearance of a network of
55 distributary narrow depressions, or channels, which extend downslope. We use the term
56 ‘perennial rills’ to distinguish this landform from other seasonal landforms (Fig. 2) that also
57 appear on the Russell Crater megadune. These perennial rills form on and between the large
58 linear dune gullies, which densely cover the megadune’s lee slope (Fig. 3). We use the term
59 perennial, because they persist for one or more Mars Year.

60 With the exceptions of dust devil tracks, seasonal processes on dunes have been directly
61 linked to the annual extension and recession of the seasonal ice-deposits, which extend
62 downwards from the poles (continuously to ~50° latitude; e.g., Piqueux et al., 2015). These
63 deposits develop over winter, with a relatively small amount of water-ice being laid down first,
64 followed by CO₂ ice (Ivanov and Muhleman, 2001). The CO₂ ice is estimated to be ~0.5 m thick

65 at the latitude of Russell Crater (Cull et al., 2010; Smith et al., 2001) and is thought to
66 metamorphose into translucent slab-ice during autumn/winter. In the winter/spring this ice cover
67 regresses towards the pole, with first the sublimation of CO₂ ice, followed by the sublimation of
68 H₂O ice (e.g., Bapst et al., 2015). The sublimation of CO₂ ice is one of the explanations proposed
69 for the formation of dark spots and dark flows that appear on the surface of dunes covered with
70 seasonal CO₂ ice (Piqueux et al. 2003; Kieffer et al., 2006; Kieffer, 2007; Hansen et al. 2011,
71 2013; Gardin et al., 2010). However, other mechanisms have also been proposed for the
72 formation of these features, including the development of a centimetre-to-decimetre thick layer of
73 temporary liquid sub-surface water or brines (Möhlmann, 2010; Kereszturi et al., 2011b).

74 The aims of this study are 1) to characterize the morphology of the perennial rills and how
75 they evolve with time, 2) to document their evolution in context with the other seasonal processes
76 on the dune, 3) to identify potential terrestrial analogues in order to place constraints on their
77 formation, in order to determine whether and how their formation is linked with the seasonal ices
78 and with the (presumably) longer term evolution of the linear dune gullies on the Russell Crater
79 megadune.

80

81 *Study area*

82 This study area is located on the megadune which is found within a dunefield on the floor of
83 Russell Crater (54.5°S, 12.7°E; see Fig. 1). The megadune is about 36 km long, 10 km wide and
84 500 m high and has been formed by aeolian transport and deposition (Gardin et al., 2010). The
85 major constituent of the dark sand-sized sediments forming dunes on Mars is thought to be
86 pyroxene with some olivine (e.g., Achilles et al., 2017; Tirsch et al., 2011), probably detrital
87 minerals of volcanic origin. The pole-facing western lee slope has an average slope of 10° (Reiss

88 et al. 2010a) and more than 300 “linear” dune gullies are visible on this face (Reiss and Jaumann,
89 2003). No gullies are observed on the gentler stoss slope to the east which has a mean slope of 5°.
90 Linear dune gullies are a particular sub-class of martian gullies that have a distinct morphology
91 (Diniega, 2014) and are found not only on sand dunes, but also on other sand-covered slopes
92 (Auld and Dixon, 2016). These gullies comprise a relatively small (compared to their overall
93 length) tributary source area, an extremely long, almost constant-width channel (extending almost
94 the whole slope-length) following the direction of the slope and an abrupt terminus, often
95 associated with terminal pits (Jouannic et al., 2012; Pasquon et al., 2016). The preferential
96 orientation of linear gullies on S-SW flanks is thought to be related to insolation processes (e.g.
97 Balme et al., 2006 ; Pasquon et al., 2016), but could also be related to the restriction of gullies to
98 steep slopes (e.g., Conway et al., 2017).

99 The linear dune gullies on the Russell Crater megadune are known to undergo seasonal
100 changes including: 1) linear gully growth/extension, including formation of pits, 2) development
101 of dark-spots and dark-flows, 3) appearance of bright halos, 4) formation and erasure of dust
102 devil tracks and 5) development of perennial rills, which are the focus of this study. Previous
103 work on these phenomena will be outlined in the following sections.

104

105 ***Summary of previous work on seasonal processes on dunes***

106 *Gully modifications*

107 Linear dune gullies are a sub-class of martian gullies (Conway et al. 2018) composed of a
108 relatively long and narrow channel, with a relatively restricted alcove and terminal deposits (on
109 the Russell Crater meagdune they can be ~2 km long for ~10 m wide). They are found in 33
110 dune-filled craters - Russell Crater included – exclusively in the southern hemisphere (Pasquon et

111 al., 2016) and represent ~4.8% of the total number of gully sites (Auld and Dixon, 2016). The
112 channel is often perched in the downstream part and lateral levees of ~1 m can be observed
113 (Jouannic et al., 2015). The linear dune gullies on the Russell Crater megadune are the largest
114 known, probably because the Russell megadune is the largest dune on which such gullies are
115 found. Recent changes observed in the linear gullies on the Russell Crater megadune include
116 channel extension and reworking, as well as CO₂ frost evolution in the gully channel (Reiss et al.,
117 2010a). Dundas et al. (2012) reported on the appearance of bright “blocks” in linear dune gully
118 channels contemporaneously with the gully modifications. Recent activity of linear dune gullies
119 has been observed in 53% of the sites where they occur (Pasquon et al., 2016). Active linear dune
120 gullies can lengthen by ~100 m per Mars Year between the end of winter and the beginning of
121 spring (L_s 167.4°-216.6°, where L_s stands for Solar Longitude, which describes the position of
122 Mars in its orbit around the Sun, i.e., the seasons). This growth coincides spatially, as well as
123 temporally, with the appearance of digitate-shaped, dark patches (whose albedo is low compared
124 to the surrounding terrain) that encompass the active gully site – termed “Recurring Diffusing
125 Flows” (RDF; Pasquon et al., 2016). These modifications occur on south-southwest facing slopes
126 with a mean slope of 13.9°, and where the slope just below the crest is >20° (Pasquon et al.,
127 2016). CO₂ frost sublimation (Dundas et al., 2012; Dundas et al., 2015) and CO₂ driven dry
128 processes (Diniaga et al., 2010; Diniaga et al., 2013) have been suggested to be the cause of these
129 recent modifications in martian dune gullies, because the modifications always coincide with the
130 end of the CO₂ defrosting period. However, because the exact mechanism producing these
131 changes remains elusive, other processes particularly those involving the production of small
132 amounts of liquid water are still under consideration (Pasquon et al., 2016, 2018).

133

134 *Dark spots and dark flows*

135 Various seasonal low albedo features have been previously identified on the relatively high
136 albedo frosted dune surfaces of the polar regions of Mars. These features can be divided in two
137 morphologic groups: dark spots, including those associated with spider-like structures (e.g.,
138 Christensen et al., 2005; Kieffer et al, 2006; Kossacki and Kopystynski, 2004; Malin et al., 1998;
139 Piqueux et al., 2003; Hansen et al. 2010, Thomas et al. 2010) and dark flow-like features
140 (Kereszturi et al., 2009; Kereszturi et al., 2010; Gardin et al., 2010; Möhlmann, 2010; Raack et
141 al., 2015). Dark spots are low albedo circular to oblate patches, which tend to grow and coalesce
142 with time (Fig. 2c). Dark flows often initially look like dark spots, but later develop into elongate
143 digitate structures, which stretch downhill, sometimes following ripple-furrows (Fig. 2b). Both
144 are tens to hundreds of metres in size. Two processes have been proposed to explain the
145 formation of these features on dunes: 1) a centimetre-to-decimetre thick layer of temporary liquid
146 sub-surface water or brines (Möhlmann, 2010, 2011; Kereszturi et al., 2011b); 2) a geyser-
147 process triggered by the basal sublimation of seasonal CO₂ ice-slab whereby CO₂ gas, dust and
148 sand erupt from underneath the slab-ice and avalanche down the slope of dunes (Piqueux et al.
149 2003; Kieffer et al., 2006; Kieffer, 2007; Gardin et al., 2010). The dark spots and dark flows on
150 the Russell Crater megadune were previously described by Gardin et al. (2010) and occur during
151 winter, nucleating on positive topography and bright cracks in the CO₂ slab-ice. These dark
152 features (spots and flows) are generally aligned along cracks, in particular on the steeper slopes
153 of the megadune. Gardin et al. (2010) estimated that these kinds of flows transport in the order of
154 0.25 to 0.5 m³ per metre width per year. Hence, the volume of material mobilised over the course
155 of a single year by this transport process would be undetectable, even at the best imaging
156 resolution of 25-50 cm/pixel.

157

158 *Bright halos*

159 The dark flows are sometimes surrounded by a bright halo, which has higher albedo than the dark
160 flow and the surrounding terrain (Fig. 2d), in previous work these were also termed “white
161 collars” (Kereszturi et al., 2010 ; Kereszturi et al., 2011b ; Möhlmann, 2010). Previous studies
162 have reported the presence of bright halos around dark spots on dunes in general in the southern
163 hemisphere (Kereszturi et al., 2009). Kereszturi et al. (2011a) report that these halos have a CO₂
164 frost signature. They noted that bright halos emerge immediately after the disappearance of the
165 dark flows and dark spots, when the temperature is above 170 K in Russell Crater (Kereszturi et
166 al., 2011b). These bright haloes have also been associated with the RDF that surround active
167 gully sites (Pasquon et al. 2016).

168

169 *Dust devil tracks*

170 Dust devils are low pressure vortices, found on both Earth and Mars (e.g., Greeley et al. 2005;
171 Reiss et al., 2010b, 2011b). The first active dust devils were identified on Mars in Viking orbiter
172 images (Thomas and Gierasch, 1985). These spiralling vortices are caused by heating of near-
173 surface air by insolation. They transport small particles such as dust and fine sand, and are
174 suggested to be responsible for a significant part of the dust transport on Mars (Balme and
175 Greeley, 2006). They are a common active process on Mars (e.g., Balme and Greeley, 2006;
176 Cantor et al., 2006; Fisher et al., 2005; Malin and Edgett, 2001; Reiss et al., 2011a; Stanzel et al.,
177 2006) and change the surface albedo by removing dust (Neakrase et al. 2016) and forming
178 curving tracks on the surface (Fig. 2e). Dust devil tracks are not reported on surfaces where, and

179 at times of year when, the seasonal ice is present. Their tracks can be used as an indicator of
180 when the seasonal ices have completely sublimated from a surface.

181

182 **Materials and methods**

183 Using 87 High Resolution Imaging Science Experiment (HiRISE, 25 - 50 cm/pix) images (Table
184 1) over a 125 month period (November 2006 - April 2017; Mars Years 28 - 33), we followed the
185 evolution of the surface of the Russell Crater megadune over time. We applied the same
186 Transverse Mercator projection centred on 13°E to all HiRISE images, and manually refined the
187 metre-scale co-alignment between the images. For non-nadir images we used an ortho-rectified or
188 nadir image as a reference and then by using a network of 10-20 control points we manually
189 corrected for the topographic distortion. Areas and lengths of features were measured directly
190 from shapes digitised onto the HiRISE images in ArcGIS. To estimate the growth rate of
191 different seasonal process with time we mapped all of the features on subsequent HiRISE images
192 (as in Ceamanos et al., 2011) for the first three Mars Years. The change in area was divided by
193 the time interval between images, to determine a growth rate. In order to allow comparison
194 between seasonal processes the results were normalised by the overall area affected by the
195 process.

196 We made a plan view map of the rills making up the perennial rill network for the 5 Mars
197 Years of observations, digitising each rill as a polyline feature in the first springtime image where
198 these features appear. To quantify how the density of the rill network changed with time we
199 calculated the fractal dimension of the polyline network digitised from the images as follows. The
200 statistical number-size distribution for a geomorphic feature can be scale invariant and in other
201 words fractal. For the distribution to be fractal, the number of line segments N with a

202 characteristic linear dimension greater than r should satisfy the relation $N = C/r^D$ where D is the
203 fractal dimension (Turcotte, 1997) and C a constant. This method allowed us to characterize the
204 spatial density and the scale invariance of the perennial rills. The fractal dimension of the
205 perennial rills was calculated using the box counting method of Turcotte (1997), whereby a
206 square mesh with a spacing of r is superposed onto the rill systems. N was determined by
207 counting the number of boxes which contain rills. This manipulation was performed in ArcGIS
208 by using the feature to raster tool with output cell sizes of 0.5, 0.75, 1.0, 1.5, 2.0, 2.5, 5.0, and
209 10 m and then counting the number of cells with data. N was then plotted on a log-log diagram
210 against the grid-scale r and a linear regression performed to ascertain the fractal dimension.
211 Sinuosity of line-features was calculated by taking the ratio of the length of the trace to the
212 straight-line end-to-end length.

213 We analysed one HiRISE and one HRSC (High Resolution Stereo Camera) DTM (Digital
214 Terrain Model) using the 3D analyst tools of ArcGIS software in order to estimate the value of
215 the slope in the different areas of interest. The HRSC data (H2247_0000) were level 4 HRSC
216 elevation data acquired from ESA's Planetary Science Archive (Scholten et al., 2005) with a
217 resolution of 75 m/pix. The HiRISE elevation data were derived from the stereo-pair
218 PSP_007018_1255 and PSP_007229_1255 using the methods described by Kirk et al. (2008) and
219 we estimate the vertical precision of this DTM to be ~0.62m. This DTM was produced by the
220 authors of Jouannic et al. (2012), where details on its production and precision can be found.
221 Absolute deviation of the HRSC elevation data from the MOLA (Mars Orbiter Laser Altimeter)
222 spot heights is reported to be on the order of 29 m with a standard deviation of 41 m (Gwinner et
223 al., 2009).

224 We performed a spectral analysis to determine the mineralogical surface composition.
225 CRISM suffers from high noise levels and multiple non-stochastic instrument artefacts in the

226 spectral and spatial domains. The sources of biases were overcome by using a standard set of
227 corrections that remove the instrument artefacts, the contaminating minerals and photometric
228 effects as described in Carter et al. (2013). Spectra from the corrected CRISM data were
229 compared to the entries in the RELAB spectral repository and Hanley et al. (2011) to ascertain
230 potential surface composition. Mapping of the identified minerals was undertaken in ENVI. We
231 analysed CRISM data FRT00005339 acquired at $L_s = 215^\circ$ during Mars Year 28.

232

233 **Observations of perennial rills**

234 In the following sections we divide our observations into three parts. Firstly, we present the
235 morphology of the perennial rills, secondly we present the changes observed in these features
236 over time, and thirdly we present our observations on the timing and distribution of the other
237 seasonal processes on Russell Crater megadune and place the perennial rills into this context.

238

239 *Perennial rill morphology*

240 The perennial rills are located on portions of the southwest-facing lee slope of the Russell Crater
241 megadune (Fig. 3). The perennial rills are usually found between ~200 m and 1000 m from the
242 crest of Russell Crater megadune (Fig. 3) with three small networks located at the termini of
243 existing linear dune gullies 3500 m from the dune crest. We assign each discrete perennial rill
244 system with a “Zone” which encompasses the total area affected by the system over the five MY
245 covered by this study. We identified 28 zones with active perennial rill systems. Each system
246 comprises a distributary system formed by numerous small branching, sinuous rills (sinuosity
247 index is ~1.1; Figs. 4 and 5). Their branching angles are typically ~ 45° and their direction
248 deviates from directly downslope (Fig. 5). The system of perennial rills which is located closest

249 to the dune crest (Zone 1) has a mean slope of $\sim 12^\circ$ (Fig. 3) and the other systems have lower
250 slopes, because they are located further down the lee slope. The maximum width of these small
251 channels is ~ 1 m without observable symmetric lateral deposits (levees). A zone with a lower
252 albedo than the surrounding dune (from here on termed the “dark zone”) extends over and
253 slightly beyond the area affected by the perennial rills (Figs.3, 4 and 5). This dark zone appears at
254 the same time as the new generation of perennial rills. Both the perennial rills and these dark
255 zones originate from linear dune gully channels, connecting to the southern edge of a channel
256 (with multiple rills breaching any given gully channel wall), or fanning out from linear dune
257 gully channel termini (three such systems are located at the base of the slope and three mid-
258 slope).

259 The 1 m/pix resolution of the HiRISE elevation data are insufficient to directly confirm
260 that the rills cause topographic change. Shadow measurements cannot be used, because no
261 distinct shadow-edge can be identified in the images. The rills are not wide enough to have a
262 distinct shadow cast on their floor by their walls, because their width is near the image resolution.
263 Nevertheless, the topographic expression of the rills can be inferred from the HiRISE images at
264 25 cm/pixel, using the following arguments: a) independent of the time of year the rills are picked
265 out by light-dark-light patterns in the images implying topographic shadowing, unrelated to the
266 distribution of seasonal ices, and b) relict rills, which are not reactivated the following year are
267 partially filled with aeolian ripples suggesting a topographic trap (Fig. 5). Using the plan-
268 dimensions of the rills alone we can make a reasonable estimate their depth. The width of the
269 perennial rills is ~ 1 m and it is reasonable to assume that the depth of the rills is not greater than
270 their width. In addition, given that the angle of repose for loose sand is $\sim 30^\circ$ on Mars (Atwood-
271 Stone and McEwen, 2013), hence the maximum depth of the rills should be ~ 0.3 m, but is likely
272 to be less.

273

274 *Changes observed in perennial rills*

275 The appearance of a new perennial rill system, or evolution of an existing system occurs abruptly
276 between L_s 183° and 221° in each Mars Year for which we have observations (MY 28-33) and
277 this is detailed further below. During the six Mars Years we observed the formation of 5 new
278 perennial rill systems >500 m long and 23 smaller systems (Table 2). Mars Years 32 and 33 were
279 most active both in terms of approximate surface area which underwent changes and in terms of
280 number of perennial rill systems that were active (Table 2). We only observed one system
281 >500 m long that was active in all Mars Years (Zone 1).

282 In the following sections we describe in detail each of the different changes (listed as a-e
283 below) observed in these rills systems, and we use Zone 1 as the case study to illustrate these
284 changes:

- 285 a) Growth of the area affected by the rill system and its associated dark zone;
- 286 b) Re-use and extension of individual rills;
- 287 c) Creation of new rills, either overprinting an older network or onto an unaffected dune
288 surface;
- 289 d) Disappearance of rills; and
- 290 e) Stability of the network density from year-to-year.

291

292 *Growth of the area affected by the rill system*

293 The size of the dark zone surrounding the perennial rills in Zone 1 grew over Mars Years 28-30
294 by $\sim 22\,000$ m² and in MY31 only changed slightly and decreased by $10\,000$ m² in MY32 having
295 the same area but different shape in MY33 (see Figs. 4 and 5). This sudden growth behaviour is

296 also shown by Zone 2 (to the left of Zone 1 in Fig. 3) which between MY30 and 31 extends from
297 ~40 m to ~400 m in length (350 m extension), further extending by 130 m in MY32 and 30 m in
298 MY33. We did not note any fading of the dark zones in the summer that followed their
299 appearance, but if a dark zone is not renewed then it appears faded after the frost has sublimated
300 the following Mars Year.

301

302 *Re-use and extension of rills*

303 In the upper part of the perennial rill systems we observe that the same rills tend to persist from
304 year to year (Figs.6b1, 6b2 and 6b3). These rills widen each year, increasing in width by 1 to ~4
305 m between MY 28 and 30. An example of rill-extension is shown in Fig.5. The rill marked with
306 an arrow is confined within a partly infilled larger gully channel. In Mars Year 28, this rill
307 lengthened downslope by about 86 m (Fig.5a), an extension previously observed by Reiss et al.
308 (2010a). In Mars Year 29, it further lengthened by ~ 145 m (Fig.5b) and in Mars Year 30 it
309 lengthened by ~190 m (Fig.5c). Another, less dramatic example is shown in Figs. 5g-i, where a
310 rill lengthens several tens of metres each Mars Year. In this example the rill extends through the
311 formation of new smaller rills at its terminus which diverge and extend downslope.

312

313 *Creation of new rills*

314 The majority of the new rills occur in the lower and distal part of an existing perennial rill system
315 (Figs.5d,-i), where we observe new rills and a resultant increase in sinuosity from year-to-year.
316 Here, new rills are easily identified, because they extend over previously unaffected surfaces of
317 the dune. Higher in the network only a few new rills appear (Figs.6b1, 6b2 and 6b3). These new
318 rills are in general shorter and narrower than the rills that have persisted over one or more Mars

319 Years. The new rills are ~1 m wide with a sinuosity index > 1.1 and the established rills are 1-5
320 m width with a sinuosity index < 1.05 . Sometimes whole networks spontaneously appear on the
321 dune surface without any apparent pre-existing network (e.g., Zone 15, Table 2).

322

323 *Disappearance of rills*

324 In the lower part of the system, the smaller rills are gradually overprinted and can be erased by
325 the extension of upslope rills during a new phase of activity (Figs.4, 5d-i). Rills can also
326 disappear without being overprinted (Figs.5g and 5h): the sinuous channels are gradually
327 transformed into ripples which are continuous with those found on the rest of the lee slope. This
328 transition is gradual (taking more than one Mars Year generally) and may also be aided by mass
329 wasting into the channel, or frost-driven processes, however no specific evidence is found either
330 for or against these additional processes.

331

332 *Density of rills*

333 The majority of the rills that make up the main branches of the rill systems are preserved from
334 one year to the next, but as highlighted above the topology of the network changes over time. The
335 fractal dimension of the perennial rill system ranges from $D = 1.132$ to $D = 1.209$ (Fig. 7). Unlike
336 the growth, the density of the network has no particular trend over time and its fractal nature is
337 preserved.

338

339 *Timing, growth rate, and distribution of seasonal processes and perennial rills*

340 *Dark spots*

341 The dark spots (Fig. 2c) are located on the low- and mid-slope parts of the Russell Crater
342 megadune lee slope, where slopes range from 2° to 24° with a mean of 10° . We observed that
343 when the slope is steeper, the dark spots are more extensive and more elongated (Figs. 8c1-8c6,
344 the slope is steeper on the top-left compared to the bottom-right of this image). The diameter of
345 the dark spots increases during winter (Fig. 8). They can reach a maximum diameter of ~ 30 m.
346 We observed the preferential formation of dark spots on the north-westward oriented flank of the
347 gully-channels. At the end of winter, most of the north-west-facing channel flanks have a dark
348 appearance, which could be due to the coalescence of dark spots (Figs. 8c1-8c6), or could be a
349 result of the removal of the CO_2 frost. Their first appearance is at L_s 115 - 136° (Fig. 9; Table 1).
350 The first image without dark spots is taken in early spring between L_s 206° and 221° (Figs. 8c6
351 and 9). During the first period of winter (L_s 158° to 179°), the growth rate of dark spots was $1.7 \times$
352 $10^{-8} \text{ m}^2 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ (i.e. a growth rate of $7.2 \times 10^{-2} \text{ m}^2 \cdot \text{s}^{-1}$ over a total area of $4.3 \times 10^6 \text{ m}^2$), then it
353 increases at the end of winter (L_s 179° to 182°) to reach $3.2 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ (i.e. a growth rate of
354 $1.4 \times 10^{-1} \text{ m}^2 \cdot \text{s}^{-1}$ over a total area of $4.3 \times 10^6 \text{ m}^2$).

355

356 *Dark flows*

357 The dark flows (Fig. 2b) are located on steeper terrain than the dark spots. They are found on the
358 first 200 m under the crest of the Russell megadune where the slope ranges from 12° to 28° (Fig.
359 3) with a mean slope of 19° (Figs. 8b1-8b6). Initially dark flows and dark spots have a similar
360 morphology (Fig. 8b2), but some dark spots evolve into dark flows (Figs. 8b3-8b5), which
361 become channelised between the aeolian ripples of the megadune, as described by Gardin et al.
362 (2010). The length and width of the dark flows increases during winter (Fig. 8). We found that
363 the dark flows appear later than the dark spots at around L_s 159 - 176° (Table 1). The first image

364 without dark spots and dark flows is taken in early spring between L_s 206° and 221° (Figs. 8b6
365 and 8c6, Fig. 9). During the first period of winter (L_s 158° to 179°), the growth rate of dark flows
366 is $4.2 \times 10^{-8} \text{ m}^2 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ (i.e. a growth rate of $1.2 \times 10^{-2} \text{ m}^2 \cdot \text{s}^{-1}$ over a total area of $2.8 \times 10^5 \text{ m}^2$),
367 then it increases at the end of winter (L_s 179° to 182°) to reach $7.8 \text{ m}^2 \cdot \text{s}^{-1} \cdot \text{m}^{-2}$ (i.e. a growth rate of
368 $2.2 \times 10^{-2} \text{ m}^2 \cdot \text{s}^{-1}$ over a total area of $2.8 \times 10^5 \text{ m}^2$).

369

370 *Bright halos*

371 Bright halos (Fig. 2d) appear during early spring from L_s 177° to 221° (Fig. 9, Table 1) and they
372 appear both around the perennial rills and other dark flows. They occur only on the steepest (from
373 12° to 28°) south-facing slopes. Bright halos typically appear on the image immediately
374 following the last image with dark flows and dark spots, with one exception in MY33 where they
375 appear on the same image. These halos are only visible in a single image each year, so we were
376 not able to ascertain if they grow.

377

378 *Dust devil tracks*

379 On the Russell Crater megadune, dust devil tracks (Fig. 2e) have an average width of 38 m
380 (ranging from 5 m to ~100 m), an average length of ~2.6 km and a mean sinuosity of ~1.3 (Verba
381 et al., 2010). During spring and summer, many dust devil tracks are visible at the surface of the
382 Russell Crater megadune (Figs. 8a1-8a6) between L_s ~200° and ~360° (Fig. 9, Table 1) with the
383 maximum number visible at L_s ~316° (Verba et al., 2010). The number of dust devil tracks seems
384 to increase sharply just after the complete sublimation of frost from the Russell Crater megadune,
385 and then slowly decreases until the region is covered again in CO_2 frost (Figs. 8a1-8a6). We
386 sometimes observed dust devil tracks during the spring defrosting period and they were located

387 exclusively on defrosted patches of the dune (e.g. north-facing slopes in early spring). Verba et
388 al. (2010) showed that Global Climate Models predict prevailing north-westerly winds consistent
389 with the dominant track direction in Russell Crater.

390

391 *Relative timing of perennial rill activity and distribution*

392 Table 1 provides a detailed breakdown of the HiRISE images used to constrain the timing of the
393 activity in perennial rills and Table 2 details the activity of each rill system. In Mars Year 28, we
394 noted the first series of changes in the perennial rill systems on the megadune's surface which
395 occurred sometime between L_s 198° and L_s 218° (mid-spring) (Fig.5a). These changes in the
396 Zone 1 rill system were previously briefly described by Reiss et al. (2010a). Considering the
397 whole period between Mars Year 28 and 33 the changes observed in the perennial rill system
398 occur in a tight L_s range, between 183° and 221° (Table 1; Fig. 9). Because the seasonal cap
399 retreat is known to be very constant (Brown et al. 2010; Bapst et al., 2015; Piqueux et al., 2015)
400 we can assume a negligible inter-annual variability, then rill-activity is most likely to occur
401 between L_s 200° and 202°. This is at the end of the CO₂ defrosting period and coincides with the
402 last observed dark spots and flows and the appearance of bright halos and the appearance of the
403 majority of dust devil tracks (Table 1, Fig. 9). The fact that dust devil tracks are so numerous
404 when the changes in the perennial rills occur attests to the fact that the majority of the surface of
405 the megadune has already been defrosted at this point in time. Both the rill system and associated
406 dark zone persist in the landscape after they first appear. The majority of the rill system persists
407 through the whole year (sometimes even visible through the CO₂ frost in winter) until it is
408 overprinted by the next generation of rill growth. The dark zone persists for the summer after its
409 appearance and can sometimes be seen again the following spring if it is not overprinted. The

410 changes in the rills are not gradual or incremental, they occur suddenly between two images, the
411 closest of which are only 6 sols apart (MY28, Table 1).

412 Using CRISM data Gardin et al. (2010) found that the last occurrence of seasonal CO₂ on
413 Russell Crater's dunefield was between L_s 182 and 217° and HiRISE data reveal the last frost at
414 L_s 197° was limited to the crest of the dune. From spectral data Reiss et al. (2010a) reported the
415 last CO₂ signature at L_s 198°, with the first CO₂-free measurement at L_s 215°. From our study we
416 noticed that the north-facing dune slopes defrosted first (at around L_s 140°), then the flat dune
417 areas, then the south-facing slopes (progressing upwards from the base), with the steep crest of
418 the south-facing slopes being the very last area to finally defrost, at around L_s 200°
419 contemporaneously with the earliest observed appearance of the perennial rills (Fig. 4). From
420 HiRISE data we cannot distinguish between CO₂ and H₂O ices.

421 Within the Russell Crater dunefield the perennial rills are restricted to discrete patches on
422 the main megadune lee slope (Fig. 3). Compared to the other seasonal processes described here
423 the extent of the perennial rills is localised, dark flows and spots occur continuously across large
424 areas. The areal extent of the perennial rills totals between $\sim 1.2 \times 10^6$ to 4.0×10^6 m² (Table 2)
425 compared to 4.3×10^6 and 2.8×10^5 m² for dark spots and dark flows respectively and dust devil
426 tracks can be found across the whole image.

427

428 ***Global Distribution of perennial rills and surface mineralogical content***

429 The seasonal processes on the Russell Crater megadune also occur on other dunes on Mars.
430 Hence, to assess whether there is a link between these seasonal processes (especially linear dune
431 gullies) and the perennial rills, we inspected HiRISE images taken in spring for 32 dunefields
432 located inside craters where linear dune gullies were observed by Pasquon et al. (2016). No

433 morphologies similar to perennial rills were observed on the surface of these dunefields,
434 suggesting that the conditions required for perennial rill formation are rare and restricted to the
435 Russell Crater megadune.

436 We identified hydrous minerals around the Russell Crater megadune in the interdune
437 areas adjacent to the SW and NE flanks, as shown in Figure 10 (black spectra). The best
438 laboratory matches to the CRISM spectra are a chloride hydrate, hydrated (opaline) silica,
439 sulfates, zeolites and Al-smectites. Figure 10c shows a HiRISE close-up of the SW exposure. The
440 hydrous minerals are found in a topographic low at the base of the dune, occurring mainly in
441 association with the light-toned outcrops located at the base of numerous gullies, but signatures
442 are also found on the neighbouring dark sand.

443

444 **Discussion**

445 *Comparison between perennial rills and linear dune gullies*

446 The perennial rill systems on the Russell Crater megadune are superimposed onto both the
447 gullied and non-gullied part of the megadune lee slope. Hence, the rills are younger than the
448 linear dune gullies. The perennial rills occur on the same lee slope as the linear dune gullies, but
449 they are smaller in spatial extent and in scale. Although both form channel-like features on the
450 dune surface, there are some notable morphologic differences between linear dune gullies and
451 perennial rills.

452 The perennial rills are characterised by a highly connected distributary network of narrow
453 (fractal dimension ranges from 1.147 to 1.209), sinuous channels (sinuosity is ~ 1.1). By contrast,
454 the linear dune gullies on the Russell Crater megadune are relatively straight (sinuosity ranges
455 from 1.01 to 1.06), parallel and generally occur as individual landforms rather than part of a

456 hierarchical network (Jouannic et al., 2012). The individual linear dune gullies have lengths of
457 about 2 km, slopes ranging from 5° to 25° and widths between 3-20 m. Where linear dune gully-
458 connections exist they form a tributary, rather than distributary configuration (Fig.5a). The distal
459 reaches of perennial rill systems are dominated by a large number of distributary digitate rills
460 resulting in an increase in the number of rills downslope (Figs.5d-i). By contrast, the number of
461 linear dune gullies and their density decrease downslope due to the capture of tributaries by trunk
462 channels.

463 Pasquon et al. (2016) found that changes in linear dune gullies and a phenomenon they
464 termed Recurring Diffusing Flows (RDF) occur during late winter/early spring between L_s 167.4°
465 and L_s 216.6° on Kaiser and Matara dunefields at 47°S and 50.5°S respectively. The timing of
466 this activity coincides with the timing of changes in perennial rills. The changes they noticed
467 included: the formation of new linear dune gullies, the extension of pre-existing channels and
468 formation of new pits (Reiss et al., 2010). Similarly to the changes we observe in perennial rills,
469 these gully-changes occur between two image acquisitions and were encompassed by a low
470 albedo area that persisted after the changes had occurred (RDF). Pasquon et al. (2016) noted that
471 RDF fade and can disappear from one year to the next, and they also noted that new linear dune
472 gullies can be overprinted by ripples in few Mars Years after their creation if they are not
473 reactivated, especially for those with lengths <150 m. These observations echo those for the dark
474 zone around perennial rills and our observations on the disappearance of the perennial rill
475 morphology if not reactivated. Pasquon et al. (2016) found linear dune gullies in Matara crater
476 extended by 120 m (on average, 291 measurements) and up to 800 m, consistent with the
477 extension in the largest perennial rill systems of ~ 350 m.

478 In contrast, the linear dune gully-changes noted by Pasquon et al. (2016) have a somewhat
479 different position and morphology from the perennial rills described here. Changes in linear dune

480 gullies generally occur at the base of the lee slope (although some occur mid-slope), whereas the
481 perennial rills occur predominantly towards the dune crest (Fig. 3). An important difference is the
482 association between linear dune gully growth and the appearance of new pits, which can form a
483 direct extension to a linear dune gully channel, or form as a “detached” pit. Pits are only
484 ambiguously observed associated with perennial rills, because they are at the limit of the image
485 resolution (Fig. 11).

486 Because of the very similar timing and association with a surrounding low albedo zone
487 (occasionally observed with a high albedo halo), it seems likely that the processes that form and
488 modify perennial rills are similar to those that trigger the changes observed in active linear dune
489 gullies, yet conditions specific to the Russell Crater megadune cause the perennial rills to express
490 a different morphology. The most notable difference between the Russell Crater megadune and
491 the other sites is its size – it is the largest dune with linear dune gullies on Mars and therefore the
492 linear dune gullies themselves are longer and wider. Hence, any given formation process needs to
493 be able to explain both the peculiar morphology of the perennial rills and that of the linear dune
494 gullies.

495

496 *Comparison with terrestrial morphologies*

497 The distributary network of channels observed in the perennial rill system is unusual for a mean
498 slope of 12° (Figs. 3, 5d), especially because the topography itself is not convex. In general, a
499 fluvial network on such topography would form a tributary network of contributory channels, or
500 almost-parallel channels, which is also seen for gullies on Mars (Fig.5a). We therefore sought a
501 terrestrial analogue which might inform us about the conditions/processes, which result in a
502 distributary network on such a steep slope angle.

503 We identified a network of channels on the surface of the glacier Eyjabjakkajökull in
504 Iceland, which share some of their morphological characteristics with the perennial rills on Mars.
505 We made field observations of these channels in July 2009 at the surface of Eyjabjakkajökull, an
506 outlet glacier that drains the north-eastern portion of the Vatnajökull glacier, Iceland
507 ($64^{\circ}39'57''\text{N}$, $15^{\circ}41'54''\text{W}$) on glacier slopes $\sim 10^{\circ}$, as measured on the ArcticDEM created by
508 the Polar Geospatial Center from DigitalGlobe, Inc. imagery. Such channels develop in summer
509 in response to surface meltwater flow on temperate glaciers (Fig. 12).

510 In their proximal sections, the channels are linear, slightly sinuous and run in the direction
511 of steepest slope of the glacier surface. Channel widths reach ~ 1 m at most and remain almost
512 constant along their ~ 500 m length (Fig. 12). These channels are thus similar in overall shape and
513 dimensions to the perennial rills observed on the Russell Crater megadune. In their distal
514 sections, these channels split into networks of distributary branches (Fig. 12a), with similar
515 topology to the perennial rills on Mars (Figs. 5d-f). The branching angles are from 45 - 90° and the
516 individual branches do not necessarily follow the line of greatest slope.

517 The channels observed at the surface of the Eyjabjakkajökull glacier form during the
518 summer melting period. At this time of the year, the glacier is covered by slush, a mixture of ice
519 crystals and meltwater at the melting point. Meltwater with floating ice particles pours out from
520 springs scattered on the glacier surface, then flows down over the surface of the glacier along
521 channels incised into the slush. In their proximal sections, the channels display little sinuosity and
522 their overall direction follows the steepest slope of the glacier surface. In the channel distal
523 sections, the meltwater infiltrates back into the glacier through a layer of permeable firn. This firn
524 layer is composed of snow accumulated at the glacier surface earlier in the year which has not yet
525 metamorphosed into ice.

526 The meltwater transports ice particles derived from the surface slush and possibly from
527 the underlying glacier ice. Where the meltwater infiltrates back into the firn, these ice particles
528 accumulate and form a small fan-shaped dam. As this dam builds, meltwater backs up behind the
529 dam, forming a pond. Once this pond reaches a critical size (~1 m in width and ~10 cm in
530 thickness), the meltwater breaks out sideways through the channel wall. The meltwater now
531 flows around the obstacle, forming a new branch that is laterally offset from the previous channel
532 tip. The previous channel tip then becomes inactive.

533 This damming-ponding-shifting process (Fig. 13) of channel tip propagation repeats again
534 and again through time and eventually leads to the formation of a distributary network (Fig. 12b).
535 The branching pattern in the channel distal sections is thus the result of repeated damming-
536 ponding-shifting events but, at any given time, meltwater flows in only one branch of the
537 network. Some of these channel features described here for Iceland, are also observed in
538 meltwater propagating along gullies in the Antarctic dry valleys (Dickson et al., 2017; Head et
539 al., 2012). The meltwater in the Antarctic dry valleys is produced from snowmelt and thaw of
540 ground ice during peak daytime temperatures and colder temperatures later in the day freeze the
541 meltwater forming a dam. The flow is then reactivated the following day, and deviation around
542 the previous day's frozen deposits causes channel migration. Similarly to Eyjabakkajökull, the
543 meltwater flows over an impermeable surface (ice table), capped by unsaturated sediment. The
544 Antarctic meltwater flows are surrounded by a halo of saturated ground, forming a dark zone
545 which encircles the flow. A third, yet smaller-scale example of this kind of flow-process is found
546 at the Kobuk sand dunes in Alaska where melting of niveo-aeolian deposits causes small debris
547 flows, with terminal distributary networks on their slip-faces at angles around 16° (Hooper and
548 Dinwiddle 2014). Similarly Hugenholtz et al. (2007) report on morphologies resulting from the
549 melting of niveo-aeolian deposits within dunes at Bigstick Sand Hills of southwestern

550 Saskatchewan, Canada. Most of the morphologies they report form lobate or digitate deposits
551 with poorly-defined channels, but they did find gully-fan complexes developed in blowout
552 hollows, often cross-cutting the other morphologies, but did not record the slope-angles of this
553 activity.

554 Cold-room experiments have also shown that channel-formation is favoured when liquid water
555 flows over a thawed surface layer ('active layer') which overlies impermeable permafrost
556 (Jouannic et al., 2015; Conway et al., 2011; Védie et al., 2008). The active layer is composed of
557 non-cohesive material similar to the firn layer in Iceland. During experiments where this layer
558 was dry (Jouannic et al., 2015; Conway et al., 2011), a darker halo of saturated substrate
559 surrounded the channels, similarly to larger meltwater flows in the Antarctic Dry Valleys
560 (Dickson et al., 2017; Head et al., 2012).

561 Gravity, atmospheric pressure and temperature conditions in these field and laboratory
562 examples are different to those prevailing at the Russell Crater megadune on Mars. Surface
563 materials also probably differ in their composition and physical properties. Therefore, arguing
564 that perennial rills on Mars form by processes identical to those responsible for the development
565 of channels at the surface of Eyjabjakkajökull glacier, for example, would be an over
566 interpretation of their morphological similarities. However, some of the same physical processes
567 may be at work, as discussed further below.

568

569 *Potential formation mechanisms*

570 Observations from the Icelandic analogue show that a process by which successive blockages and
571 breakouts are created can explain the distributary, branching system exhibited by the perennial
572 rills on Mars. In the Icelandic analogue the conditions which favour development of such a

573 system are: (i) the presence of an impermeable substrate or a very low infiltration rate, (ii) the
574 presence of a non-cohesive or erodible material at the surface, (iii) a mechanism leading to
575 repeated formation of dams at the front of the flow (high sediment load). The material migrates
576 by this erosional process from the upstream part to the downstream part.

577 The fact that the perennial rills on Mars diverge from one another argues for the creation
578 of a small amount of relief around the rills, such as lateral levees, even there is no direct
579 observation of this morphology on the images or DTM. This relief, similar to the damming of
580 rills in Iceland, could explain why perennial rills diverge and do not run straight downslope.
581 Some of these deviations could be also influenced by pre-existing aeolian ripples.

582 On Mars ice cemented permafrost is believed to be present in the first few tens of
583 centimetres to metre of the surface and is overlain with a desiccated layer of regolith (Mellon et
584 al., 2004). This condition is in diffusive equilibrium with the current state of the martian
585 atmosphere and the current daily and seasonal skin depth penetration. Following this logic
586 previous work has shown that at the latitude of the Russell Crater megadune (45°S) the ground
587 ice table should be located at 1 m for sand material (Mellon et al., 2004) and have been estimated
588 to be located at around 1.5 m locally by geomorphologic considerations (Jouannic et al., 2012). It
589 should be noted that on active dunes in the northern hemisphere the ice-cement is inferred to be
590 deep, or absent based on the presence of slip face failures penetrating tens to hundreds of metres
591 into the dune (Diniaga et al., 2017; Hansen et al., 2011,2013). On the other hand, Pasquon et al.
592 (2018) argued based on morphology that linear dune gullies should only form in the presence of
593 ground-ice in the near subsurface. This configuration fulfils criteria i) and ii) above. In order to
594 fulfil the final criterion a downslope transport mechanism is required that allows for flow-
595 damming-ponding and release cycles. Below, we discuss the various forms of downslope
596 transport that could be responsible for such rill-systems.

597

598 *Dry granular flow*

599 The simplest candidate transport mechanism is dry granular flow, which is responsible for slip-
600 face avalanches on terrestrial sand dunes (e.g., Nield et al., 2017; Sutton et al. 2013). However,
601 the rills are found on an average slope of 12° or less and are located at least 200 m away from the
602 crest of the dune which has a slope higher than 25° (Fig. 3). Dry grain flows can only initiate on
603 slopes greater than the static friction angle of sand grains (Allen, 1997). On Earth, the static
604 friction angle of dry granular soils is $>\sim 30^\circ$ (Philipponnat and Hubert, 2000) and on Mars, the
605 Mars Exploration Rovers determined static friction angle for very fine sand as ranging from 30°
606 to 37° (Sullivan et al, 2011). As a consequence, from a physical point of view dry granular flow
607 seems unable to explain the observed initiation angle and the runout distance (350-850 m) of the
608 perennial rills. Second, the rills erode the substrate at these relatively modest slope angles and
609 deviate from straight downhill. The erosive pattern suggests a basal shear stress in excess of that
610 which can be obtained by a dry granular flow on a relatively small slope. For a non-cohesive dry
611 sand of $\sim 200\text{-}250\ \mu\text{m}$ on a slope less than 10° , the velocity threshold for erosion is around $0.1\text{-}1$
612 ms^{-1} (Gargani, 2004) and would be difficult to reach without any fluid involvement. A granular
613 flow would need to be triggered with an initial velocity to reach this velocity threshold. Third, the
614 relatively high sinuosity and branching angles (Figs. 4 and 5) of perennial rills is not reproduced
615 by experiments or models of dry granular flow (Mangold et al., 2003), however such models do
616 not usually include multiple flows required to reproduce the ponding-damming-cycle.
617 Wind is the most common trigger for slip face avalanches on Earth, yet wind strength does not
618 significantly influence the angle required to trigger slip face avalanches (Sutton et al. 2013;
619 Pelletier, 2015). Given that the slip-faces of dunes on Mars have been measured to have similar

620 angles to on Earth (Ewing et al., 2017; Atwood-Stone and McEwen 2013), similarly steep ($>30^\circ$)
621 slopes should be required to trigger such avalanches on Mars. Slip face avalanches also have a
622 morphology unlike that of perennial rills, they usually possess a broad channel with narrow
623 flanking levees and tongue-shaped deposits (e.g., Sutton et al. 2013; Breton et al. 2008) and
624 whose superposition has not been overserved to develop a distributary network.

625 Therefore, given these observations, we believe that a fluidised flow is required to explain
626 our observations, as is the case in our Icelandic analogue. Candidate fluidised flows include CO₂-
627 gas supported flows and liquid water/brine supported debris flows, and are discussed further
628 below.

629

630 *Gas supported flow*

631 Perennial rills grow during the final stages of CO₂ defrosting on the dune, hence CO₂ gas supported
632 flows are an obvious fluid candidate. The presence of dark flows and spots on the image just prior
633 to rill-activity suggests that slab ice is present on the megadune's surface just before their
634 formation. The presence of a high albedo cover at the crest of the dune in the images when the
635 perennial rills first appear, suggests that CO₂ frost may remain, although HiRISE cannot distinguish
636 between H₂O and CO₂ frost (Fig. 4). Furthermore, the hypothesised presence of a water ice-rich
637 permafrost at depth in the Russell Crater megadune should favour the earlier sublimation of CO₂
638 frost compared to surfaces lacking an ice-rich permafrost (Vincendon et al. 2010; Jouannic. 2012).
639 In the earliest image we have in which the perennial rills first appear, dark flows, dark spots, bright
640 haloes, dust devil tracks and perennial rills all coexist (Fig. 4, MY33). Because of the gradual
641 acceleration in the growth of dark spots and dark flows that we observe, we think that the slab
642 decreases in thickness gradually over time.

643 Pilorget and Forget (2016) hypothesised that viscous debris flow-like morphologies can be
644 produced by gas-supported granular flows beneath the CO₂ ice slab, constrained by an ice-
645 cemented permafrost layer at tens of centimetre depth. The slab is repeatedly lifted and cracked by
646 pressure built up from basal sublimation, similar to the Kieffer model of spider formation (Kieffer
647 et al., 2006). Their modelling used the Russell Crater megadune as their primary case study. The
648 fact that such a flow is confined beneath a lid of CO₂ slab, makes damming-ponding-shifting
649 process less likely, as pressurised flows have less capacity to dam. Pilorget and Forget (2016)'s
650 modelling revealed that activity should be visible from L_s 149° until the sublimation of the slab is
651 complete. This timing is broadly consistent with the first appearance of dark flows (which could
652 be as early as L_s 150° in MY30, and for all MYs L_s 165 Table 1; Fig. 9) and the cyclical breaking
653 could explain the repeated activity of the dark flows as the season progresses. However, it seems
654 to be inconsistent with the timing of the perennial rill activity, which occurs when then CO₂ slab is
655 at its thinnest and restricted to the upper part of the dune (upslope of the perennial rills). Rill-
656 activity could be a result of the final cycle of slab-lifting which ultimately breaks and entrains the
657 slab to create a fluidised flow – a process put forward by Pilorget and Forget (2016). However, if
658 this was the case a spatial relationship might be expected between the dark flows and the rills,
659 which is not observed. Also perennial rills might be expected on every dunefield where the dark
660 flows are observed, which is also not the case.

661 Another hypothesis involving CO₂ is the rapid sublimation of CO₂ ice in the near subsurface
662 producing a density flow analogous to a terrestrial “nuée ardente” (Hoffman, 2002; Cedillo-Flores
663 et al., 2011; Raack et al., 2015). Recent laboratory work has shown that this kind of process could
664 trigger downslope sediment movement of sand-sized particles (Sylvest et. al., 2016, 2018).
665 However, the creation of a fluidised granular flow requires a sustained pore pressure, thus a
666 continuous supply of gas. Pilorget and Forget (2016) suggested such a flow could result from

667 inclusion of sublimating solid CO₂ particles within a granular flow, but this process has not been
668 demonstrated numerically or in the laboratory so there is no morphological information available
669 to compare to the perennial rills. Stewart and Nimmo (2002) suggest CO₂ sublimation in-flow
670 would not evolve sufficient gas to support fluidisation, meaning a sufficient reservoir of CO₂ must
671 initially sublimate to support the flow, but Dundas et al. (2017) argue that the frictional dissipation
672 during flow should be sufficient to sublimate some CO₂ and cause some degree of fluidisation.
673 Whether sufficient CO₂ ice is present at the end of defrosting to fluidise the flows that create the
674 perennial rills remains an open question for future research. .

675 CO₂-gas supported flows are proposed to be analogous in terms of behaviour and final
676 morphology to terrestrial pyroclastic flows (Pilorget and Forget, 2016), which can carve channels
677 and deposit lateral levees and terminal lobate deposits and therefore with multiple flow events
678 could conceivably dam and breach to create distributary networks (e.g. de Haas et al., 2016) . At
679 Ngauruhoe Volcano in New Zealand, distributary “levee and channel” deposits are found on slopes
680 between 10 and 20° (Lube et al. 2007) as a result of pyroclastic density currents, consistent with
681 the morphology expressed by the perennial rills. Further work is required to show that pyroclastic
682 flows are a suitable analogy, considering they are sustained by energies in excess of those generated
683 through sublimation (Conway and Balme, 2016).

684

685 *CO₂ blocks*

686 The “slab detachment” model was proposed by Diniega et al (2013), whereby slabs of CO₂ ice
687 detach from the cornice and travel downhill on a cushion of gas expelled by sublimation. The gas
688 expelled from the base of these blocks is able to displace sediment and form depressions in the
689 wake of the block (channels) and when the blocks stop they can form circular pits. CO₂ blocks

690 could conceivably form a distributary network of sinuous channels if many small-sized blocks were
691 released, which were deviated by ripples and the levees left by the passage of previous blocks. This
692 type of propagation could be similar to snowballs or “snow rollers” involved in loose wet
693 avalanches (Fig. 14) where gas is the lubricating fluid rather than liquid water. The reason such
694 small blocks would leave the linear gully channels mid-slope remains unexplained. Work by
695 Mc Keown et al. (2017) has shown that CO₂ blocks can explain the appearance of pits associated
696 with linear dune gully-activity – thus this mechanism can apply to both types of activity. However,
697 pit formation has not unambiguously been identified during the development of perennial rills. The
698 dark zones encompassing both linear dune gully activity (RDF) and also perennial rills could be
699 caused by disturbance of the sediment around the block by the gas being produced as they
700 sublimate. Dundas et al. (2012) reported the presence of a dark halos associated with bright blocks
701 found on the floor of linear dune gully channels on the Russell Crater megadune. It is unclear how
702 the (presumably) smaller blocks creating the perennial rills would create the extensive dark zone
703 surrounding the perennial rills. Further, if the dark zones are caused by disruption of sediments by
704 the CO₂ gas, it is difficult to explain how they persist through the following summer, given that
705 dust devil tracks are erased over a similar period. Further experimental work is needed to better
706 elucidate whether CO₂ blocks can create dark halos and morphologies similar to perennial rill
707 networks.

708 Rill-activity occurs when the last remnants of frost are visible at the crest of the dune and
709 our observations suggest that it may be in the form of slab ice. This is because in the earliest image
710 showing rill-development (MY33, L_s 202°) there dark spots and dark flows are still present, which
711 indicate the presence of slab ice. The new rills appear downslope of the brightest frost deposits
712 hosting the dark flows and spots – the expected configuration if they are formed by blocks
713 separating from the slab. In almost every image immediately following rill-activity (with the

714 exception of MY33) high albedo “spots” are visible (Fig. 4) and these were interpreted by Dundas
715 et al. (2012) as CO₂ ice blocks (because some of them cast shadows) – which would seem to support
716 the CO₂ block hypothesis. However, these blocks do not appear within the perennial rill network,
717 but in the surrounding linear dune gully channels (at bends, termini or tributary junctions) and do
718 not appear to spatially correlate with perennial rills or linear dune gully-activity. On the other hand,
719 presumably the blocks responsible for the perennial rills may be smaller than those associated with
720 the larger linear dune gullies, so may be below the resolution available with HiRISE. Without
721 catching a block “in the act” it is difficult to refute or prove this process is occurring in perennial
722 rills, but this would be a challenging observation to make.

723

724 *Liquid involvement*

725 As demonstrated by the terrestrial analogies a liquid supported debris flow is able to reproduce the
726 morphology of the perennial rills. The dark zone surrounding the perennial rills could be explained
727 by the percolation of water into the pore space, freezing and darkening the albedo as seen in the
728 terrestrial analogues (or removing the fines). The bright halos represent a re-condensed transient
729 surface frost (e.g., Kereszturi et al., 2011a,b). It is, however, difficult to explain the formation of
730 pits associated with active linear dune gullies with liquid water, but recent laboratory simulations
731 have highlighted some unusual morphologies produced by boiling liquid water (Raack et al., 2017;
732 Herny et al. 2018) that could address this issue.

733 The most significant problem comes in explaining the source of this liquid, when water is
734 only transiently metastable on Mars (e.g., Hecht 2002) and latent heat loss is a significant barrier
735 to melting. Recent experimental work has highlighted that even boiling of unstable water can have
736 significant effects on the surface topography (Massé et al., 2016; Raack et al., 2017; Herny et al.

737 2018). Sand can be ejected and accumulated at the front of the flow, which in our scenario could
738 produce an obstacle which deviates the flow, but this was not observed in these experiments (as
739 only individual flows were simulated). As stated at the beginning of this section our current
740 understanding of the martian water cycle indicates that ground ice should be present below the
741 surface of the Russell Crater megadune. Hence, the formation of the perennial rills on the Russell
742 Crater megadune could be periglacial in origin, involving the surface thaw of permafrost and
743 mobilisation of thaw fluids (Costard et al., 2002; Jouannic et al., 2012; Mangold et al., 2003; Védie
744 et al., 2008; Jouannic et al., 2015). Daily average temperatures above 0°C during an extended
745 period are required to thaw the ice in the subsurface because it takes time to propagate the thermal
746 wave to depth in the ground (Costard et al., 2002; Kreslavsky et al., 2008). Using a thermal model
747 of surface and the Thermal Emission Spectrometer (TES) measurements of Russell Crater
748 megadune, Reiss et al. (2010a) calculated the surface temperature between $L_s = 200^\circ$ and $L_s = 215^\circ$
749 coinciding with the timing of the perennial rill activity. Their results showed that the surface
750 temperatures of the Russell Crater megadune should range from ~195 K to ~275 K (Reiss et al.,
751 2010) and the melting point of water-ice could be reached for a few hours per day in the first few
752 centimetres of the ground. As TES measurements are taken over a ~3x6 km area and insolation
753 models consider only simple surface topography, local temperatures could in fact be higher and
754 last for longer than predicted by Reiss et al. (2010a). Conversely, as the perennial rills are located
755 on a pole-facing slope, local temperatures could also be colder and this is where the last frost is
756 observed (and where it is likely to be thicker).

757 As outlined above, the activity of perennial rills occurs as the last CO₂ ice is finally removed
758 from the surface at $\sim L_s 200^\circ$. At this time the “crocus line” or main boundary of the retreating CO₂
759 seasonal cap has already reached 75°S (Piqueux et al., 2015), meaning the remaining CO₂ ice at
760 the crest of the dune forms a cold trap. This could be a cold trap for water vapour, which is driven

761 out of the regolith in the surrounding terrain as the ambient temperature rises (e.g., Bapst et al.,
762 2015). Removal of CO₂ ice at the surface should locally induce a sudden temperature rise, hence
763 the source of water could be this cold-trapped water vapour in the near-surface regolith. The pulses
764 necessary to create the damming-ponding-breaching morphology (Fig. 13) on the Russell Crater
765 megadune could be generated by the diurnal freeze/thaw cycles of H₂O due to the
766 temperature/humidity variation near the melting point of water in early spring (Reiss et al., 2010a).
767 However, we do not have detailed knowledge of the local humidity conditions during the seasonal
768 cap retreat, and surface frosts observed elsewhere are only microns in thickness (e.g. Svitek and
769 Murray, 1990), so whether the supply from this frost would be sufficient to create hundred-metre
770 landforms is an outstanding problem.

771 In addition, dissolved salts can lower the freezing point and evaporation rates of water (e.g.,
772 Chevrier and Altheide, 2008), hence, further extending the period and duration of melting. The
773 presence of liquid brines on the present martian surface has been already suggested by in-situ
774 observations at the Phoenix landing site (e.g. Chevrier et al., 2009; Renno et al., 2009) and by
775 spectral observations of RSL (Ojha et al., 2015). Renno et al. (2009) also demonstrated, with the
776 investigation of in-situ Phoenix results, that the thermodynamics of freeze-thaw cycles ranging
777 from diurnal to geological time-scales can lead to the formation of saline solutions where ice exists
778 near the surface. From a morphological point of view, the slow melting of brine is able to trigger
779 small channel morphologies (Massé et al., 2016) as observed in perennial rills. However, even
780 though no direct signature of brines has been detected on the rills of the Russell Crater megadune,
781 CRISM data indicate salts could be present at the base of the dune (Fig. 10). This result suggests
782 brines could be formed in the Russell Crater region, but no direct link can be made to the formation
783 of the rills. Brines would only play an important role if water is sourced from the melting of ground
784 ice, because surface frosts would only come into limited contact with the salts.

785 Although melting of the first few centimetres-decimetres of ground ice could explain the
786 rills, the recharge of this system is an outstanding issue. This problem is somewhat ameliorated by
787 the results of recent experiments (Raack et al., 2017; Herny et al. 2018) which have revealed
788 efficient sediment transport by transient boiling water under martian conditions. These results
789 indicate that less water is required to produce morphologic changes at the surface compared to non-
790 boiling flowing water (which forms the channels in our Icelandic analogue). An average increase
791 in annual insolation over the last 20 kyr in the southern hemisphere of Mars (Laskar et al., 2004)
792 could explain the gradual increase of average surface temperature and, as a consequence, the
793 gradual melting of ground ice at depth. The increasing depth of the melting front with time could
794 be the source of the liquid that is involved in the perennial rill activity. The relatively recent
795 insolation increases could explain why the ground ice has not yet been completely depleted.
796 However, this reservoir is finite and this process will end when the ground ice becomes too deep
797 (1) for ice to melt, or (2) for liquid water to reach the surface. Another option is that because the
798 CO₂ ice forms a cold trap, more water vapour could be emplaced here than usually expected in the
799 martian regolith and this could be the source of fluid for the perennial rills. Further numerical and
800 experimental modelling work are required in order to address the outstanding issues regarding the
801 liquid water/brine hypothesis.

802

803 **Conclusions**

804

805 We have described in detail the formation and evolution of perennial rills on the surface of the
806 Russell Crater megadune and discriminate them from the other seasonal processes observed on
807 the dune. These perennial rills recur annually and can grow by up to $\sim 10^4$ m² per Mars Year in

808 the downslope direction and originate from the channels of linear dune gullies. They comprise a
809 distributary network with high branching angles ($\sim 45^\circ$) and high sinuosity on slopes of 12° or
810 less. They are surrounded by a larger low albedo zone, which persists through the following
811 summer and can sometimes be seen after the following spring. They appear and grow abruptly in
812 spring between L_s 183° and 221° (likely around L_s 200°) which is when the seasonal CO_2 ice
813 sublimation is coming to end and as the slab-ice is removed, as indicated by the disappearance of
814 dark spots and dark flows and the appearance of dust devil tracks. To our knowledge perennial
815 rills are unique to Russell Crater megadune, but our work suggests that they are produced by a
816 similar process to that which is responsible for annual changes observed in linear dune gullies –
817 hence any proposed formation process needs to explain both sets of observations.

818 Our observations on the formation of similar morphologies on a glacial surface in Iceland,
819 suggests that a distributary network of rills on slopes of 12° or less can be formed by: a) the
820 presence of an impermeable layer at the sub-surface b) an erodible layer on top, and c) the
821 repeated formation of small obstacles at the front of propagating channels. Conditions a) and b)
822 are widely acknowledged to be present on Mars, with an ice-cemented permafrost layer being
823 present under a decimetre to centimetre thick dry lag (Mellon et al., 2004; Jouannic et al., 2012
824 and 2015).

825 We rule-out fully dry flows for perennial rill formation due to the low slope on which they
826 form ($> \sim 12^\circ$) and their complex topology. We find that sub-slab sublimation generated flows
827 (Pilorget and Forget 2016) are unlikely, because the CO_2 slab is both thin and discontinuous at
828 the time when the perennial rills form. Fluidised granular flows supported by CO_2 gas, analogous
829 to pyroclastic flows on Earth, seem unlikely, because of the energies required to sustain ongoing
830 gas-production in such flows, but further work is needed to verify this for Mars. We find that
831 both levitating CO_2 blocks and liquid water/brine are potential formation mechanisms for

832 perennial rills (and active linear dune gullies), but both have outstanding difficulties. A lack of
833 analogues or laboratory data means the plausibility of levitating CO₂ blocks producing perennial
834 rill morphologies and the surrounding dark zone is hard to properly assess. However, the timing
835 of the perennial rill activity being coincident with the last phase of defrosting, and the appearance
836 of blocks in the surrounding landscape provides compelling support for this hypothesis. For
837 liquid water/brine hypothesis, the morphologies of the perennial rills are easily accounted for, yet
838 producing liquid water is particularly challenging under current martian conditions. We highlight
839 two factors that could favour the production of liquid water: i) the late-CO₂ forms a cold trap,
840 which could accumulate atmospheric ice, and would then melt upon the sudden temperature rise
841 when the CO₂ is finally removed and ii) increasing mean annual temperatures on Mars could be
842 increasing the depth of the active layer into the shallow ground ice on Russell Crater megadune.
843 However, the formation of pits via water/brine flow is harder to explain, but could be a result of
844 boiling liquid water. Further laboratory work and modelling is required to understand the
845 complex interplay of these volatiles under the rapidly changing springtime conditions on pole-
846 facing slopes of dunefields on Mars in order to better distinguish between these two leading
847 hypotheses.

848

849

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858 **References**

859

860 Achilles, C. N. et al (2017), Mineralogy of an Active Eolian Sediment from the Namib Dune,
861 Gale Crater, Mars, *J. Geophys. Res. Planets*, 122, doi:10.1002/2017JE005262.

862

863 Allen, P.A., 1997. *Earth Surface Processes*. Blackwell Science, Oxford.

864

865 Atwood-Stone, C., McEwen, A.S., 2013. Avalanche slope angles in low-gravity environments
866 from active Martian sand dunes. *Geophysical Research Letters* 40, 2929–2934.

867 doi:10.1002/grl.50586

868

869 Auld, K.S., Dixon J.C., 2016. A classification of martian gullies from HiRISE imagery. *Planetary*
870 *and Space Science* 131, 88-101.

871

872 Balme, M., Greeley, R., 2006. Dust devils on Earth and Mars. *Rev. Geophys.* 44, RG3003,

873 doi:10.1029/2005RG000188.

874

875 Balme, M., Mangold, N., Baratoux, D., Costard, F., Gosselin, M., Masson, P., Pinet, P., Neukum,
876 G., 2006. Orientation and distribution of recent gullies in the southern hemisphere of Mars:

877 Observations from High Resolution Stereo Camera/Mars Express (HRSC/MEX) and Mars

878 Orbiter Camera/Mars Global Surveyor (MOC/MGS) data. *J. Geophys. Res.* 111, E05001,

879 doi:10.1029/2005JE002607.

880

881 Bapst, J., Bandfield, J.L., Wood, S.E., 2015. Hemispheric asymmetry in martian seasonal surface
882 water ice from MGS TES. *Icarus* 260, 396–408. doi:10.1016/j.icarus.2015.07.025
883

884 Breton, C., Lancaster, N., Nickling, W.G., 2008. Magnitude and frequency of grain flows on a
885 desert sand dune. *Geomorphology* 95, 518–523. doi:10.1016/j.geomorph.2007.07.004
886

887 Brown, A.J., Calvin, W.M., McGuire, P.C., Murchie, S.L., 2010. Compact Reconnaissance
888 Imaging Spectrometer for Mars (CRISM) south polar mapping: First Mars Year of observations.
889 *J. Geophys. Res.* 115, E00D13. Doi: 10.1029/2009JE003333.
890

891 Cantor, B.A., Kanak, K.M., Edgett, K.S., 2006. Mars Orbiter Camera observations of Martian
892 dust devils and their tracks (September 1997 to January 2006) and evaluation of theoretical
893 vortex models. *J. Geophys. Res.* 111, E12002. doi:10.1029/2006JE002700.
894

895 Carter, J., Poulet, F., Murchie, S., Bibring, J.-P., 2013. Automated processing of planetary
896 hyperspectral datasets for the extraction of weak mineral signatures and applications to CRISM
897 observations of hydrated silicates on Mars. *Planetary and Space Science* 76, 53-67,
898 doi:10.1016/j.pss.2012.11.007.
899

900 Ceamanos, X., Douté, S., Luo, B., Schmidt, F., Jouannic, G.; Chanussot, J., 2011.
901 Intercomparison and validation of techniques for spectral unmixing of hyperspectral images: a
902 planetary case study. *IEEE Transactions on Geoscience and Remote Sensing*,
903 doi:10.1109/TGRS.2011.2140377.

904

905 Cedillo-Flores, Y., Treiman, A.H., Lasue, J., Clifford, S.M., 2011. CO₂ fluidization in the
906 initiation and formation of Martian polar gullies. *Geophys. Res. Lett.* 38, L21202,
907 doi:10.1029/2011GL049403.

908

909 Chevrier, V.F., Ulrich, R., Altheide, T.S., 2009. Viscosity of liquid ferric sulfate solutions and
910 application to the formation of gullies on Mars. *J. Geophys. Res.* 114, E06001,
911 doi:10.1029/2009JE003376.

912

913 Chevrier, V.F., Altheide, T.S., 2008. Low temperature aqueous ferric sulfate solutions on the
914 surface of Mars. *Geophys. Res. Lett.* 35, L22101, doi: 10.1029/2008GL035489.

915

916 Christensen, P.R., Kieffer, H.H., Titus, T.N., 2005. Infrared and visible observations of south
917 polar spots and fans. American Geophysical Union, Fall Meeting Abstract P23C-04.

918

919 Conway, S.J., Lamb, M.P., Balme, M.R., Towner, M.C., Murray, J.B., 2011. Enhanced runout
920 and erosion by overland flow at low pressure and sub-freezing conditions: Experiments and
921 application to Mars. *Icarus* 211, 443-457, doi:10.1016/j.icarus.2010.08.026.

922

923 Conway, S.J., Balme, M.R., 2016. A novel topographic parameterization scheme indicates that
924 martian gullies display the signature of liquid water. *Earth and Planetary Science Letters* 454, 36–
925 45. <https://doi.org/10.1016/j.epsl.2016.08.031>

926

927 Conway, S.J., Harrison, T.N., Soare, R.J., Britton, A.W. & Steele, L.J. 2017. New slope-
928 normalized global gully density and orientation maps for Mars. In: Conway, S.J., Carrivick, J.L.,
929 Carling, P.A., de Haas, T. & Harrison, T.N. (eds) *Martian Gullies and their Earth Analogues*.
930 Geological Society, London, Special Publications, 467. First published online November 27,
931 2017, <https://doi.org/10.1144/SP467.3>

932
933 Conway, S., de Haas, T. & Harrison, T.N. 2018. Martian gullies: a comprehensive review of
934 observations, mechanisms and the insights from Earth analogues. In: Conway, S.J., Carrivick,
935 J.L., Carling, P.A., de Haas, T. & Harrison, T.N. (eds) *Martian Gullies and their Earth*
936 *Analogues*. Geological Society, London, Special Publications, 467. First published online [to
937 follow] (17-313), <https://doi.org/10.1144/SP467.14>

938
939 Costard, F., Forget, F., Mangold, N., Peulvast, J.P., 2002. Formation of recent Martian debris
940 flows by melting of near-surface ground ice at high obliquity. *Science* 295, 110-113, doi:
941 [10.1126/science.295.5552.110](https://doi.org/10.1126/science.295.5552.110).

942
943 Cull, S., Arvidson, R. E., Mellon, M., Wiseman, S., Clark, R., Titus, T., Morris, R. V., McGuire,
944 P., 2010. Seasonal H₂O and CO₂ ice cycles at the Mars Phoenix landing site: 1. Prelanding
945 CRISM and HiRISE observations. *J. Geophys. Res.* 115, doi:10.1029/2009JE003340.

946
947 de Haas, T., van den Berg, W., Braat, L., Kleinhans, M.G., 2016. Autogenic avulsion,
948 channelization and backfilling dynamics of debris-flow fans. *Sedimentology* 63, 1596–1619.
949 doi:10.1111/sed.12275

950

951 Dickson, J.L., Head, J.W., Levy, J.S., Morgan, G.A. & Marchant, D.R. 2017. Gully formation in
952 the McMurdo Dry Valleys, Antarctica: multiple sources of water, temporal sequence and relative
953 importance in gully erosion and deposition processes. In: Conway, S.J., Carrivick, J.L., Carling,
954 P.A., de Haas, T. & Harrison, T.N. (eds) *Martian Gullies and their Earth Analogues*. Geological
955 Society, London, Special Publications, 467. First published online December 4, 2017,
956 <https://doi.org/10.1144/SP467.4>

957
958 Diniega, S., 2014. Linear Gullies (Mars), in: Hargitai, H., Kereszturi, Á. (Eds.), *Encyclopedia of*
959 *Planetary Landforms*. Springer New York, New York, NY, pp. 1–5. doi:10.1007/978-1-4614-
960 9213-9_582-1

961
962 Diniega, S., Byrne, S., Bridges, N.T., Dundas, C.M., McEwen, A.S., 2010. Seasonality of
963 present-day Martian dune-gully activity. *Geology* 38, 1047-1050, doi: 10.1130/G31287.1.

964
965 Diniega, S., Hansen, C.J., McElwaine, J.N., Hugenholtz, C.H., Dundas, C.M., McEwen, A.S.,
966 Bourke, M.C., 2013. A new dry hypothesis for the formation of martian linear gullies. *Icarus* 225,
967 526–537. doi:10.1016/j.icarus.2013.04.006

968
969 Diniega, S., Hansen, C.J., Allen, A., Grigsby, N., Li, Z., Perez, T. & Chojnacki, M. 2017. Dune-
970 slope activity due to frost and wind throughout the north polar erg, Mars. In: Conway, S.J.,
971 Carrivick, J.L., Carling, P.A., de Haas, T. & Harrison, T.N. (eds) *Martian Gullies and their Earth*
972 *Analogues*. Geological Society, London, Special Publications, 467. First published online
973 November 27, 2017, <https://doi.org/10.1144/SP467.6>

974

975

976 Dundas, C.M., McEwen, A.S., Diniega, S., Byrne, S., Martinez-Alonso, S., 2010. New and recent
977 gully activity on Mars as seen by HiRISE. *Geophys. Res. Lett.* 37, L07202, doi:
978 10.1029/2009GL041351

979

980 Dundas, C.M., Diniega, S., Hansen, C.J., Byrne, S., McEwen, A.S., 2012. Seasonal activity and
981 morphological changes in Martian gullies. *Icarus* 220, 124-143, doi:10.1016/j.icarus.2012.04.005

982

983 Dundas, C.M., Diniega, S., McEwen, A.S., 2015. Long-term monitoring of martian gully
984 formation and evolution with MRO/HiRISE. *Icarus* 251, 244–263 [http:](http://dx.doi.org/10.1016/j.icarus.2014.05.013)
985 [//dx.doi.org/10.1016/j.icarus.2014.05.013](http://dx.doi.org/10.1016/j.icarus.2014.05.013)

986

987 Dundas, C.M., McEwen, A.S., Diniega, S., Hansen, C.J., Byrne, S. & McElwaine, J.N. 2017. The
988 formation of gullies on Mars today. In: Conway, S.J., Carrivick, J.L., Carling, P.A., de Haas, T.
989 & Harrison, T.N. (eds) *Martian Gullies and their Earth Analogues*. Geological Society, London,
990 Special Publications, 467. First published online November 27, 2017,
991 <https://doi.org/10.1144/SP467.5>

992

993 Ewing, R. C. et al 2017. Sedimentary processes of the Bagnold Dunes: Implications for the eolian
994 rock record of Mars, *J. Geophys. Res. Planets*, 122, doi:10.1002/2017JE005324.

995

996 Fisher, J.A., Richardson, M.I., Newman, C.E., Szwast, M.A., Graf, C., Basu, S., Ewald, S.P.,
997 Toigo, A.D., Wilson, R.J., 2005. A survey of Martian dust devil activity using Mars Global

998 Surveyor Mars Orbiter Camera images. *J. Geophys. Res.* 110, E03004.
999 doi:10.1029/2003JE002165.
1000
1001 Gardin, E., Allemand, P., Quantin, C., Thollot, P., 2010. Defrosting, dark flow features and
1002 dune activity on Mars: example in Russell Crater. *J. Geophys. Res.* 115, E06016,
1003 doi:10.1029/2009JE003515.
1004
1005 Gargani, J., 2004. Contribution à l'étude de la vitesse critique d'érosion des sols cohésifs, *C.R.*
1006 *Geoscience*, 336, p.561-566, 2004.
1007
1008 Gough, R.V., Chevrier, V.F., Baustian, K.J., Wise, M.E., Tolbert, M.A., 2011. Laboratory studies
1009 of perchlorate phase transitions: Support for metastable aqueous perchlorate solutions on Mars.
1010 *Earth Planet. Sci. Lett.* 312, 371-377, doi:10.1016/j.epsl.2011.10.026.
1011 Gwinner, K., Scholten, F. et al. 2009. Derivation and validation of high-resolution digital
1012 elevation models from Mars Express HRSC-data. *Photogrammetric Engineering & Remote*
1013 *Sensing*, 75, 1127– 1142.
1014
1015 Greeley, R., 2005. Martian variable features: New insight from the Mars Express Orbiter and the
1016 Mars Exploration Rover Spirit. *Journal of Geophysical Research* 110.
1017 <https://doi.org/10.1029/2005JE002403>
1018
1019 Hanley, J., V. F. Chevrier, J. B. Dalton, and C. S. Jamieson, 2011, Reflectance spectra of low-
1020 temperature chloride and perchlorate hydrates relevant to planetary remote sensing. 42nd Lunar
1021 and Planetary Science Conference, abstract# 2327.

1022

1023 Hansen, C.J., Thomas, N., Portyankina, G., McEwen, A., Becker, T., Byrne, S., Herkenhoff, K.,
1024 Kieffer, H., Mellon, M., 2010. HiRISE observations of gas sublimation-driven activity in Mars'
1025 southern polar regions: I. Erosion of the surface. *Icarus* 205, 283–295.
1026 <https://doi.org/10.1016/j.icarus.2009.07.021>

1027

1028 Hansen, C.J., Bourke, M., Bridges, N.T., Byrne, S., Colon, C., Diniega, S., Dundas, C.,
1029 Herkenhoff, K., McEwen, A., Mellon, M., Portyankina, G., Thomas, N., 2011. Seasonal Erosion
1030 and Restoration of Mars's Northern Polar Dunes. *Science* 331, 575-578, doi:
1031 [10.1126/science.1197636](https://doi.org/10.1126/science.1197636).

1032

1033 Hansen, C.J., Byrne, S., Portyankina, G., Bourke, M., Dundas, C., McEwen, A., Mellon, M.,
1034 Pommerol, A., Thomas, N., 2013. Observations of the northern seasonal polar cap on Mars: I.
1035 Spring sublimation activity and processes. *Icarus* 225, 881–897.
1036 <https://doi.org/10.1016/j.icarus.2012.09.024>

1037

1038 Head, J., Dickson, J. L., Levy, J. S., Baker, D. M. H., Marchant, D. R., 2012. Antarctic Dry
1039 Valleys: Geological Processes in Hyperarid, Hypothermal Environments and Implications for
1040 Water on Mars. *Geophysical Research Abstracts* 14, EGU2012-12381-1.

1041

1042 Hecht, M.H., 2002. Metastability of liquid water on Mars. *Icarus* 156, 373–386.
1043 [doi:10.1006/icar.2001.6794](https://doi.org/10.1006/icar.2001.6794)

1044

1045 Herny, C., Conway, S.J., Raack, J., Carpy, S., Colleu-Banse, T. & Patel, M.R. 2018. Downslope
1046 sediment transport by boiling liquid water under Mars-like conditions: experiments and potential
1047 implications for Martian gullies. In: Conway, S.J., Carrivick, J.L., Carling, P.A., de Haas, T. &
1048 Harrison, T.N. (eds) *Martian Gullies and their Earth Analogues*. Geological Society, London,
1049 Special Publications, 467. First published online February 6, 2018,
1050 <https://doi.org/10.1144/SP467.10>
1051
1052 Hoffman, N., 2002. Active polar gullies on Mars and the role of carbon dioxide. *Astrobiology* 2,
1053 313-323, doi:10.1089/153110702762027899.
1054 Hooper, D.M., Dinwiddie, C.L., 2014. Debris flows on the Great Kobuk Sand Dunes, Alaska:
1055 Implications for analogous processes on Mars. *Icarus* 230, 15–28.
1056 doi:10.1016/j.icarus.2013.07.006
1057
1058 Hugenholtz, C.H., Wolfe, S.A., Moorman, B.J., 2007. Sand–water flows on cold-climate eolian
1059 dunes: environmental analogs for the eolian rock record and Martian sand dunes. *Journal of*
1060 *Sedimentary Research* 77, 607–614. Doi: 10.2110/jsr.2007.063
1061
1062 Ivanov, A. B., Muhleman, D. O., 2001. Cloud Reflection Observations: Results from the Mars
1063 Orbiter Laser Altimeter. *Icarus* 154 (1), 190-206.
1064
1065 Jouannic, G., Gargani, J., Costard, F., Ori, G.G., Marmo, C., Schmidt, F., Lucas, A., 2012.
1066 Morphological and mechanical characterization of gullies in a periglacial environment: the case
1067 of the Russell dune (Mars). *Planetary and Space Science* 71, 38-54,
1068 doi:10.1016/j.pss.2012.07.005.

1069

1070 Jouannic, G. 2012. PhD Thesis. Geomorphologic study of the dynamic of debris flow formation
1071 on Mars : comparative approach Earth / Mars. University Paris-Sud, 264 p.

1072

1073 Jouannic G., J.Gargani, S. Conway, F. Costard, M. Balme, M. Patel, M. Massé, C. Marmo, V.

1074 Jomelli, G. Ori. 2015. Laboratory simulation of debris flows over a sand dune: Insights into
1075 gully-formation (Mars). *Geomorphology*, 231, 101-115.

1076

1077 Kereszturi, A., Möhlmann, D., Berczi, Sz., Ganti, T., Kuti, A., Sik, A., Horvath, A., 2009. Recent
1078 rheologic processes on dark polar dunes of Mars: Driven by interfacial water? *Icarus* 201, 492-
1079 503, doi: 10.1016/j.icarus.2009.01.014.

1080

1081 Kereszturi, A., Möhlmann, D., Berczi, S., Ganti, T., Horvath, A., Kuti, A., Sik, A., Szathmary, E.,
1082 2010. Indications of brines related local seepage phenomena on the northern hemisphere of Mars.
1083 *Icarus* 207, 149-164, doi: 10.1016/j.icarus.2009.10.012.

1084

1085 Kereszturi, A., Vincendon, M., Schmidt, F., 2011a. Water ice in the dark dune spots of
1086 Richardson crater on Mars. *Planetary and Space Science* 59, 26-42, doi:
1087 10.1016/j.pss.2010.10.015.

1088

1089 Kereszturi, A., Möhlmann, D., Berczi, S., Ganti, T., Horvath, A., Sik, A., Szathmary, E., 2011b.
1090 Possible role of brines in the darkening and flow-like features on the Martian polar based on
1091 HiRISE images. *Planetary and Space Science* 59, 1413-1427, doi: 10.1016/j.pss.2011.05.012.

1092

1093 Kieffer, H.H., Christensen, P.R., Titus, T.N., 2006. CO₂ jets formed by sublimation beneath
1094 translucent slab ice in Mars' seasonal south polar ice cap. *Nature* 442, 793–796, doi:
1095 10.1038/nature04945.
1096

1097 Kieffer, H. H., 2007. Cold jets in the Martian polar caps. *J. Geophys. Res.*, 112, E08005,
1098 doi:10.1029/2006JE002816.
1099

1100 Kirk, R.L., Howington-Kraus, E., Rosiek, M.R., Anderson, J.A., Archinal, B.A., Becker, K.J.,
1101 Cook, D.A. et al., 2008. Ultrahigh resolution topographic mapping of Mars with MRO HiRISE
1102 stereo images: Meter-scale slopes of candidate Phoenix landing sites. *J. Geophys. Res.*, 113,
1103 doi:10.1029/2007JE003000.
1104

1105 Kossacki, J.K., Kopystynski, L., 2004. Non-uniform seasonal defrosting of subpolar dune field
1106 on Mars. *Icarus* 168, 201–204, doi: 10.1016/j.icarus.2003.11.010.
1107

1108 Kreslavsky, M.A., Head, J.W., Marchant, D.R., 2008. Periods of active permafrost layer
1109 formation during the geological history of Mars: Implications for circum-polar and mid-latitude
1110 surface processes. *Planet. Space Sci.* 56, 289-302, doi: 10.1016/j.pss.2006.02.010.
1111

1112 Laskar, J., Correia, A.C.M., Gastineau, M., Joutel, F., Levrard, B., Robutel, P., 2004. Long term
1113 evolution and chaotic diffusion of the insolation quantities of Mars. *Icarus* 170, 343-364,
1114 doi:10.1016/j.icarus.2004.04.005.
1115

1116 Lube, G., Cronin, S.J., Platz, T., Freundt, A., Procter, J.N., Henderson, C., Sheridan, M.F., 2007.
1117 Flow and deposition of pyroclastic granular flows: A type example from the 1975 Ngauruhoe

1118 eruption, New Zealand. *Journal of Volcanology and Geothermal Research* 161, 165–186.
1119 doi:10.1016/j.jvolgeores.2006.12.003
1120

1121 Malin, M.C. and 15 colleagues, 1998. Early views of the Martian surface from the Mars orbiter
1122 camera of Mars Global Surveyor. *Science* 279, 1681–1685, doi: 10.1126/science.279.5357.1681.
1123

1124 Malin, M.C., Edgett, K.S., 2001. Mars Global Surveyor Mars Orbiter Camera: Interplanetary
1125 cruise through primary mission. *J. Geophys. Res.* 106, 23429-3570, doi:
1126 10.1029/2000JE001455.
1127

1128 Mangold, N., Costard, F., Forget, F., 2003. Debris flows over sand dunes on Mars: Evidence for
1129 liquid water. *J. Geophys. Res.* 108, 5027, doi:10.1029/2002JE001958.
1130

1131 Massé M., Conway S., Gargani J., M. R. Patel, K. Pasquon, A. McEwen, S. Carpy, V. Chevrier,
1132 M. R. Balme, L. Ojha, M. Vincendon, F. Poulet, F. Costard, G. Jouannic, 2016. Transport
1133 processes induced by metastable boiling water under Martian surface conditions. *Nature*
1134 *Geoscience*, 9, 425-428.
1135

1136 Mellon, M.T., Feldman, W.C., Prettyman, T.H., 2004. The presence and stability of ground ice in
1137 the southern hemisphere of Mars. *Icarus* 169, 324–340.
1138

1139 Möhlmann, D., 2010. Temporary liquid water in upper snow/ice sub-surfaces on Mars? *Icarus*
1140 207, 140-148, doi: 10.1016/j.icarus.2009.11.013.
1141

1142 Möhlmann, D., 2011. Latitudinal distribution of temporary liquid cryobrine on Mars. *Icarus* 214,
1143 236-239, doi: 10.1016/j.icarus.2011.05.006.
1144

1145 Möhlmann, D., Thomsen, K., 2011. Properties of cryobrines on Mars. *Icarus* 212, 123-130, doi:
1146 10.1016/j.icarus.2010.11.025.
1147
1148 Neakrase, L.D.V., Balme, M.R., Esposito, F. et al. , 2016 *Space Sci Rev.* 203: 347.
1149 doi:10.1007/s11214-016-0296-6
1150
1151 Nield, J. M., Wiggs, G. F., Baddock, M. C., & Hipondoka, M. H., 2017. Coupling leeside
1152 grainfall to avalanche characteristics in aeolian dune dynamics. *Geology*, 45(3), 271-274, doi:
1153 10.1130/G38800.1
1154
1155 Ojha, L., Wilhelm, M.B., Murchie, S.L., McEwen A.S., Wray J.J., Hanley J., Massé
1156 M., Chojnacki M., 2015. Spectral evidence for hydrated salts in seasonal flows on Mars. *Nature*
1157 *Geoscience*, 8, 829-832. doi:10. 1038/ngeo2546
1158
1159 Pasquon, K., Gargani, J., Massé, M., Conway, S.J., 2016. Present day formation and seasonal
1160 evolution of linear dune gullies on Mars. *Icarus* 274, 195-210.
1161
1162 Pasquon K., J. Gargani, M. Nachon, M. Massé, S. J. Conway, G. Jouannic, M.Balme, F. Costard,
1163 M. Vincendon, 2018. Are the different gully morphologies due to different processes on the
1164 Kaiser dune field? in: Conway S.J., Carrivick J. L., Carling P. A., de Haas T. and Harrison T. N.
1165 (Eds.), *Martian Gullies and their Earth Analogues*. The Geological Society of London, Special
1166 Publications, 467, <https://doi-org.insu.bib.cnrs.fr/10.1144/SP467.13>
1167

1168 Pelletier, J.D., 2015. Controls on the large-scale spatial variations of dune field properties in the
1169 barchanoid portion of White Sands dune field, New Mexico: Controls on dunes at White Sands.
1170 *Journal of Geophysical Research: Earth Surface* 120, 453–473.
1171 <https://doi.org/10.1002/2014JF003314>
1172
1173 Philipponnat, G., Hubert, B., 2000. *Fondations et ouvrages en Terre*, second edition Eyrolles
1174 Edition, France.
1175
1176 Pilorget, C., Forget, F., 2016. Formation of gullies on Mars by debris flows triggered by CO₂
1177 sublimation. *Nature Geosci* 9, 65–69. <https://doi.org/10.1038/ngeo2619>
1178
1179 Piqueux, S., Byrne, S., Richardson, M.I., 2003. Sublimation of Mars' southern seasonal CO₂ ice
1180 cap and the formation of spiders, *J. Geophys. Res.* 108, E85084, doi:10.1029/2002JE002007.
1181
1182 Piqueux, S., Kleinböhl, A., Hayne, P.O., Kass, D.M., Schofield, J.T., McCleese, D.J., 2015.
1183 Variability of the martian seasonal CO₂ cap extent over eight Mars Years. *Icarus* 251, 164–180.
1184 doi:10.1016/j.icarus.2014.10.045
1185
1186 Raack, J., Conway, S.J., Herny, C., Balme, M.R., Carpy, S., Patel, M.R., 2017. Water induced
1187 sediment levitation enhances down-slope transport on Mars. *Nature Communications* 8, 1151.
1188 <https://doi.org/10.1038/s41467-017-01213-z>
1189

1190 Raack, J., Reiss, D., Appéré, T., Vincendon, M., Ruesch, O., Hiesinger, H., 2015. Present-Day
1191 Seasonal Gully Activity in a South Polar Pit (Sisyphi Cavi) on Mars. *Icarus* 251, 226–243.
1192 <https://doi.org/j.icarus.2014.03.040>
1193

1194 Reiss, D., Erkeling, G., Bauch, K.E., Hiesinger, H., 2010a. Evidence for present day gully
1195 activity on the Russell crater dune field, Mars. *Geophys. Res. Lett.* 37, L06203,
1196 [doi:10.1029/2009GL042192](https://doi.org/10.1029/2009GL042192).
1197

1198 Reiss, D., Raack, J., Rossi, A.P., Di Achille, G., Hiesinger, H., 2010b. First in-situ analysis of
1199 dust devil tracks on Earth and their comparison with tracks on Mars. *Geophysical Research*
1200 *Letters* 37, n/a-n/a. <https://doi.org/10.1029/2010GL044016>
1201

1202 Reiss, D., Zanetti, M., Neukum, G., 2011a. Multitemporal observations of identical active dust
1203 devils on Mars with the High Resolution Stereo Camera (HRSC) and Mars Orbiter Camera
1204 (MOC). *Icarus* 215, 358-369, [doi:10.1016/j.icarus.2011.06.011](https://doi.org/10.1016/j.icarus.2011.06.011).
1205

1206 Reiss, D., Raack, J., Hiesinger, H., 2011b. Bright dust devil tracks on Earth: Implications for their
1207 formation on Mars. *Icarus* 211, 917–920. <https://doi.org/10.1016/j.icarus.2010.09.009>
1208

1209 Reiss, D., and R. Jaumann, 2003. Recent debris flows on Mars: Seasonal observations of the
1210 Russell Crater dune field, *Geophys. Res. Lett.*, 30, 1321, [doi:10.1029/2002GL016704](https://doi.org/10.1029/2002GL016704), 6.
1211

1212 Renno, N.O., Bos, B. J., Catling, D., Clark, B.C., Drube, L., Fisher, D., Goetz, W., Hviid, S. F.,
1213 Keller, H. U., Kok, J. F., Kounaves, S. P., Leer, K., Lemmon, M., Madsen, M. B., Markiewicz,

1214 W. J., Marshall, J., McKay, C., Mehta, M., Smith, M., Zorzano, M. P., Smith, P. H., Stoker, M.,
1215 Young, S. M., 2009. Possible physical and thermodynamical evidence for liquid water on Mars.
1216 J. Geophys. Res. 114, E00E03, doi:10.1029/2009JE003362.

1217
1218 Scholten, F., Gwinner, K., Roatsch, T., Matz, K.-D., Wählisch, B., Giese, B., Oberst, J., Jaumann,
1219 R., Neukum, G., 2005. Mars Express HRSC Data Processing – Methods and Operational
1220 Aspects. Photogramm. Eng. Remote Sens. 71, 1143–1152.

1221
1222 Smith, D. E., Zuber, M. T., Neumann, G. A., 2001. Seasonal Variations of Snow Depth on Mars.
1223 Science 294 (5549), 2141-2146.

1224
1225 Stanzel, C., Pätzold, M., Greeley, R., Hauber, E., Neukum, G., 2006. Dust devils on Mars
1226 observed by the High Resolution Stereo Camera. Geophys. Res. Lett. 33, L11202.
1227 doi:10.1029/2006GL025816.

1228
1229 Stewart, S.T., Nimmo, F., 2002. Surface runoff features on Mars: Testing the carbon dioxide
1230 formation hypothesis. J. Geophys. Res.-Planets 107, doi:10.1029/2000JE001465.

1231
1232 Sullivan, R., Anderson, R., Biesiadecki, J., Bond, T., Steward, H., 2011. Cohesions, friction
1233 angles, and other physical properties of Martian regolith from Mars Exploration Rover wheel
1234 trenches and wheel scuffs. J. Geophys. Res. 116, E02006, doi:10.1029/2010JE003625.

1235

1236 Sutton, S.L.F., McKenna Neuman, C., Nickling, W., 2013. Lee slope sediment processes leading
1237 to avalanche initiation on an aeolian dune. *Journal of Geophysical Research: Earth Surface* 118,
1238 1754–1766. doi:10.1002/jgrf.20131
1239

1240 Svitek, T., Murray, B., 1990. Winter frost at Viking Lander 2 site. *Journal of Geophysical*
1241 *Research* 95, 1495. <https://doi.org/10.1029/JB095iB02p01495>
1242

1243 Sylvest, M.E., Conway, S.J., Patel, M.R., Dixon, J.C., Barnes, A., 2016. Mass wasting triggered
1244 by seasonal CO₂ sublimation under Martian atmospheric conditions: Laboratory experiments.
1245 *Geophysical Research Letters* 43, 12,363–12,370. doi:10.1002/2016GL071022
1246

1247 Sylvest, M.E., Dixon, J.C., Conway, S.J., Patel, M.R., McElwaine, J.N., Hagermann, A. &
1248 Barnes, A. 2018. CO₂ sublimation in Martian gullies: laboratory experiments at varied slope
1249 angle and regolith grain sizes. In: Conway, S.J., Carrivick, J.L., Carling, P.A., de Haas, T. &
1250 Harrison, T.N. (eds) *Martian Gullies and their Earth Analogues*. Geological Society, London,
1251 *Special Publications*, 467. First published online February 26, 2018,
1252 <https://doi.org/10.1144/SP467.11>
1253

1254 Thomas, P., Gierasch, P.J., 1985. Dust devils on Mars. *Science* 230, 175-177, doi:
1255 10.1126/science.230.4722.175.
1256

1257 Thomas, N., Hansen, C.J., Portyankina, G., Russell, P.S., 2010. HiRISE observations of gas
1258 sublimation-driven activity in Mars' southern polar regions: II. Surficial deposits and their
1259 origins. *Icarus* 205, 296–310. <https://doi.org/10.1016/j.icarus.2009.05.030>

1260

1261 Tirsch, D., Jaumann, R., Pacifici, A., Poulet, F., 2011. Dark Aeolian sediments in Martian craters:
1262 Composition and sources. *J. Geophys. Res.* 116, E03002, doi:10.1029/2009JE003562.

1263

1264 Turcotte, D.L., 1997. *Fractals and Chaos in Geology and Geophysics*, Cambridge University
1265 Press, Cambridge.

1266

1267 Védie, E., Costard, F., Font, M., Lagarde, J.L., 2008. Laboratory simulations of Martians gullies
1268 on sand dunes. *Geophys. Res. Lett.* 35, L21501, doi:10.1029/2008GL035638.

1269

1270 Verba, C.A., Geissler, P.E., Titus, T.N., Waller, D., 2010. Observations from the High Resolution
1271 Imaging Science Experiment (HiRISE): Martian dust devils in Gusev and Russell craters. *J.*
1272 *Geophys. Res.* 115, E09002, doi:10.1029/2009JE003498.

1273

1274 Vincendon, M., Mustard, J., Forget, F., Kreslavsky, M., Spiga, A., Murchie, S., Bibring, J.-P.,
1275 2010. Near-tropical subsurface ice on Mars. *Geophysical Research Letters* 37,
1276 doi:10.1029/2009GL041426. doi:10.1029/2009gl041426

1277 **Figure Captions**

1278 **Figure 1.** Location of the Russell Crater megadune. **(a)** Colour-coded Mars Orbiter Laser
1279 Altimeter (MOLA) elevation data with overlain THEMIS Day IR Controlled Mosaic from USGS
1280 Astrogeology centred on Russell Crater, with inset bottom-left showing its location on the global
1281 MOLA hillshade map. The location of panel **(b)** is marked with a black box. **(b)** The THEMIS
1282 Day IR Controlled Mosaic overlain with CTX (ConTeXt camera) image F06_038335_1253
1283 showing the location of the studied megadune within the Russell crater dunefield and of Figure 3
1284 in the black box. North is up in all images. MOLA credit: NASA/JPL/MOLA Science team. CTX
1285 image credit: NASA/JPL-Caltech/MSSS.

1286
1287 **Figure 2.** Summary of the presently active (perennial and ephemeral) processes observed at the
1288 surface of the Russell Crater megadune. **(a)** Perennial rills (HiRISE image ESP_021918_1255, L_s
1289 = 265°). **(b)** Dark flows (HiRISE image PSP_002548_1255; L_s = 182°); **(c)** Dark spots (HiRISE
1290 image PSP_002548_1255; L_s = 182°). **(d)** Bright halos (HiRISE image ESP_020784_1255, L_s =
1291 210°). **(e)** Dust devil tracks (HiRISE image PSP_005383_1255, L_s = 323°). HiRISE Image
1292 credits: NASA/JPL/University of Arizona. North is up in all images.

1293
1294 **Figure 3.** Overview of perennial rills within the study site. **(a)** Location map of the perennial rills
1295 on the Russell Crater megadune, CTX image F06_038335_1253 overlain with HiRISE image
1296 PSP_003326_1255 labelled with numbered Zones referred to in the text. **(b)** CTX image overlain
1297 with slope map derived from a 10 m/pix median filter smoothed HiRISE digital elevation model
1298 DTEEC_007018_1255_007229_1255_A01. The colours are explained in the key. The
1299 topographic profile line A-A' was located along the line of steepest decent (perpendicular to

1300 contour lines). (c) Topographic long profile A-A' whose position is shown in panel (b). Slopes
1301 indicated for each segment are calculated using a linear least squares fit over all the elevation
1302 points in each segment. HiRISE Image credit: NASA/JPL/University of Arizona. CTX image
1303 credit: NASA/JPL-Caltech/MSSS.

1304
1305 **Figure 4.** Evolution of the perennial rill system in Zone 1 of the Russell Crater megadune over 6
1306 Mars Years with each image taken in early spring. The surface area of the perennial rills
1307 increases each Mars Year, the extent from the previous year is indicated with a dotted yellow
1308 outline. Image numbers are: (a) PSP_003326_1255, (b) ESP_012213_1255, (c)
1309 ESP_020784_1255, (d) ESP_029764_1255, (e) ESP_038335_1255, and (f) ESP_047078_1255.
1310 HiRISE Image credits: NASA/JPL/University of Arizona.

1311
1312 **Figure 5.** Evolution of the distal reaches of the perennial rills. (a-f) Changes in rill morphology
1313 inside a linear dune gully are visible between HiRISE images PSP_003326_1255,
1314 ESP_012213_1255, and ESP_020784_1255. (a) In MY 28 ($L_s = 217.8^\circ$), a small rill has
1315 lengthened by ~86 m (arrowed and marked by an appearance of low albedo zone) within a wider
1316 pre-existing gully-channel and the dark zone has grown by ~16600 m². (b) In the next Mars Year
1317 (MY 29, $L_s = 221.2^\circ$), the dark zone has further expanded by ~10000 m² and the rill lengthened
1318 by ~145 m (marked by arrows). (c) By MY 30 ($L_s = 209.9^\circ$) the dark zone has expanded by a
1319 further ~9300 m² and the rill lengthened by ~190 m. Panels (d), (e) and (f) are detailed cutouts
1320 from parts (a), (b) and (c) focussing on the distal part of perennial rills and highlighting the
1321 digitate pattern of secondary rills downslope of the major rills. Panels (g) and (h) show the partial
1322 disappearance of small secondary rills (white arrows) located around the central major rill in
1323 HiRISE images PSP_003326_1255 and PSP_012213_1255, which may be due to deposition of

1324 aeolian material between the two images (the surface develops ripples). (i) Appearance of small
1325 new rills in ESP_020784_1255 (grey arrows), where 3 new small branches appear at the terminus
1326 of the major rill. HiRISE Image credits: NASA/JPL/University of Arizona. North is up in all
1327 images.

1328
1329 **Figure 6.** Evolution of the upstream part of the perennial rill over 3 Mars Years (MY 28-30). The
1330 black continuous lines in panels b1-b3 correspond to the major rills that remain unchanged from
1331 one Mars Year to the next. The black dashed lines in panels b1-b3 correspond to rills that are
1332 disappearing (probably becoming infilled). The white continuous lines in panels b1-b3
1333 correspond to new major rills formed in the preceding Mars Year. There are few changes in this
1334 part of the network, compared to downstream (compare with Fig. 5). HiRISE Image credits:
1335 NASA/JPL/University of Arizona. North is up in all images.

1336
1337 **Figure 7.** The evolution in fractal dimension of the perennial rills in Zone 1 over MY 28-32 (the
1338 dark zone in MY33 was only partly visible, so the new parts of the network could not be easily
1339 ascertained). (a) The evolution of the rill network in Zone 1 represented by linework in MY 28-
1340 32 (shown as images in Fig. 4). (b) Log-log plot of number of grid-squares containing rills (N)
1341 against the grid-spacing (r). The gradient of the linear regression line gives an estimate of the
1342 fractal dimension (D) of the perennial rills for each Mars Year, and is indicated in the legend.

1343
1344 **Figure 8.** Series of HiRISE images showing the seasonal evolution of (a) dust devil tracks, (b)
1345 dark flows, (c) dark spots and (d) bright halos on Russell Crater megadune. a1)
1346 PSP_002548_1255; a2) PSP_003326_1255; a3) PSP_004038_1255; a4) PSP_005383_1255; a5)
1347 PSP_005528_1255; a6) PSP_007018_1255; b1) ESP_001440_1255; b2) PSP_001981_1255; b3)

1348 PSP_002337_1255; b4) PSP_002548_1255; b5) PSP_002904_1255; b6) PSP_004038_1255; c1)
1349 PSP_001440_1255; c2) PSP_001981_1255; c3) PSP_002337_1255; c4) PSP_002482_1255; c5)
1350 PSP_002548_1255; c6) PSP_003326_1255; d1) ESP_011580_1255; d2) ESP_012213_1255; d3)
1351 ESP_013136_1255; d4) ESP_020217_1255; d5) ESP_020784_1255; d6) ESP_021562_1255.

1352 HiRISE Image credits: NASA/JPL/University of Arizona. North is up in all images.

1353

1354 **Figure 9.** Active processes observed at the surface of the Russell Crater megadune as a function
1355 of solar longitude (L_s , see Table 1 for source images), each HiRISE image is marked with a
1356 hollow circle. **(a)** Timing of changes in perennial rills, where the first image with a change is
1357 marked with a cross. For each Mars Year the period between the first image with a change and
1358 the one preceding it is marked by a grey box – the darker the grey the greater the number of Mars
1359 Years. **(b)** Timing of dark spots and flows. The period where dark spots are observed in all Mars
1360 Years is shown with a light grey box and the period for which dark flows are seen in all Mars
1361 Years in a darker shade of grey. **(c)** The timing of presence of images with dust devil tracks are
1362 marked by filled circles, and the grey box marks continuous presence in all Mars Years (with the
1363 exception of one image in MY32). **(d)** A summary of all the observations, where a thick line
1364 marks the most probable timing given data from all Mars Years, the thin line possible timings
1365 based on data from individual Mars Years and a dotted line indicating presence of the features,
1366 yet conflicting data from different Mars Years. Note that although CO_2 ice is not detected in our
1367 data before L_s 120° , other datasets and models suggest that it should be present (e.g., Piqueux et
1368 al. 2015).

1369

1370 **Figure 10.** Hydrous mineralogy of the Russell Crater megadune. **(a)** CRISM mineral map of
1371 hydrous minerals on the Russell Crater megadune (in blue) over a CTX image. The footprint of

1372 the CRISM observation is in dashed black lines. **(b)** CRISM spectra from the possible hydrous
1373 mineral outcrops and laboratory spectra for comparison. Two CRISM spectra are shown in black.
1374 Tentative laboratory matches are shown in colour: chloride hydrate (brown), opaline silica
1375 (green), the sulfate jarosite (blue), the sulfate bassanite (orange), the zeolite mordenite (purple)
1376 and an Al-rich smectite (red). Laboratory spectra originate from the RELAB spectral repository
1377 and Hanley et al. (2011). **(c)** HiRISE close-up of the area outlined by a dotted white line in panel
1378 **(a)** in the south-western part of the hydrous mineral exposure. The HiRISE, CTX and CRISM
1379 acquisitions were made on the same day.

1380

1381 **Figure 11.** Possible pits associated with perennial rills in MY28-32 in a-d compared to typical
1382 pits associated with activity in linear dune gullies (Pasquon et al. 2016) in MY30-32 e-g. Possible
1383 pits are identified by circles on the images a-d, but are too numerous to label for the linear dune
1384 gullies. In the a-d sequence MY31 is not shown because of poor image quality and MY33
1385 because of frost deposits. All images are shown at the same scale as indicated in panel **(a)**.
1386 HiRISE images: **(a)** PSP_003326_1255 **(b)** ESP_012213_1255 **(c)** ESP_020784_1255 **(d)**
1387 ESP_038335_1255 **(e)** ESP_020770_1300 **(f)** ESP_029038_1305 **(g)** ESP_038255_1300. HiRISE
1388 Image credits: NASA/JPL/University of Arizona.

1389

1390 **Figure 12.** Channels with distributary patterns in their downstream sections, developing at the
1391 surface of a melting glacier in Iceland. **(a)** These channels are on Eyjabakkajökull, an outlet
1392 glacier that drains the northwestern margin of the Vatnajökull glacier, Iceland (64°39'57''N,
1393 15°41'54''W). The dark region in the upper part of the picture comprises a surface slush layer
1394 that has developed by melting of the underlying massive and impermeable glacier ice, whereas
1395 the white region below comprises a layer of permeable (melting) firn covering massive and

1396 impermeable glacier ice. **(b)** Zoom on the distal part of the channels, showing the frontal ice
1397 dams successively built at tips of each branch of the distributary pattern.

1398
1399 **Figure 13.** Scenario for the formation of a distributary channel network. (a) Meltwater produced
1400 during the warmer hours of the day triggers a first pulse (T_1). (b) The liquid fraction of the flow
1401 refreezes and/or ice particles build-up due to infiltration of the liquid at the end of the flow-front
1402 T_1 . The older immobile deposits from flow (T_1) present a small topographic obstacle for the new
1403 flow (T_2), hence deflecting its path.

1404
1405 **Figure 14.** Loose wet snow avalanche on the eastern slopes of Mount Morrison in the Sierra
1406 National Forest, California. Image taken as part of the monitoring programme of the Eastern
1407 Sierra Avalanche Center on 11th March 2018. The avalanche was released on a $\sim 40^\circ$ slope from
1408 the snow in the rocky chutes, the snow balls (or roller balls) have rolled chaotically across the
1409 slope leaving trails behind them and do not necessarily follow the line of steepest decent. Source:
1410 <http://www.esavalanche.org/content/loose-wet-avalanches-morrison-and-little-morrison>

1411

Table 1. Summary of *HiRISE* images and *CRISM* hyperspectral data used in this study

| MY | HiRISE | CRISM | L_s | Acquisition date | Dark spots | Dark flows | Dust devil tracks | Bright halo | Perennial rills | CO ₂ ice |
|----|-----------------|-------------|---------|------------------|------------|------------|-------------------|-------------|-----------------|---------------------|
| 28 | PSP_001440_1255 | MSW00003047 | 136.335 | 2006-Nov-16 | X | | | | | X |
| 28 | PSP_001981_1255 | FRT000039DF | 157.704 | 2006-Dec-28 | X | | | | | X |
| 28 | PSP_002337_1255 | HRS00004006 | 172.628 | 2007-Jan-25 | X | X | | | | X |
| 28 | PSP_002482_1255 | FRT000042AA | 178.915 | 2007-Feb-05 | X | X | | | | X |
| 28 | PSP_002548_1255 | HRS000043BC | 181.817 | 2007-Feb-10 | X | X | X | | | X |
| 28 | PSP_002904_1255 | | 197.894 | 2007-Mar-10 | X | X | | | | |
| | | FRT00005339 | 214.6 | 07/04/2007 | - | - | - | - | - | X |
| 28 | PSP_003326_1255 | MSW0000550B | 217.794 | 2007-Apr-12 | | | X | X | X | |
| 28 | PSP_003682_1250 | | 235.118 | 2007-May-10 | | | X | | | - |
| 28 | PSP_003748_1250 | | 238.364 | 2007-May-15 | | | X | | | - |
| 28 | PSP_004038_1255 | FRT000061B2 | 252.689 | 2007-Jun-07 | | | X | | | |
| 28 | PSP_004249_1255 | FRT0000659F | 263.109 | 2007-Jun-23 | | | X | | | |
| 28 | PSP_005238_1255 | FRT000078DF | 310.265 | 2007-Sep-08 | | | X | | | |
| 28 | PSP_005383_1255 | FRT00007C73 | 316.793 | 2007-Sep-19 | | | X | | | |
| 28 | PSP_005528_1255 | FRT00007F9E | 323.202 | 2007-Oct-01 | | | X | | | |
| 28 | PSP_006161_1250 | | 349.77 | 2007-Nov-19 | | | X | | | - |
| 29 | PSP_006873_1255 | FRT0000966B | 17.18 | 2008-Jan-13 | | | | | | |
| 29 | PSP_007018_1255 | MSW00009A0E | 22.5 | 2008-Jan-25 | | | | | | |
| 29 | PSP_007229_1255 | | 30.113 | 2008-Feb-10 | | | | | | - |
| 29 | PSP_007519_1255 | FRT0000A3D5 | 40.368 | 2008-Mar-04 | | | | | | |
| 29 | PSP_009879_1255 | FRT0000C55B | 122.233 | 2008-Sep-04 | X | | | | | X |
| 29 | PSP_010090_1255 | MSP0000C9D3 | 130.055 | 2008-Sep-20 | X | | | | | |
| 29 | PSP_010301_1255 | FRT0000CD8E | 138.06 | 2008-Oct-07 | X | | | | | X |
| 29 | PSP_010446_1255 | MSP0000CFE5 | 143.678 | 2008-Oct-18 | X | | | | | |
| 29 | PSP_010868_1255 | MSP0000D767 | 160.636 | 2008-Nov-20 | X | X | | | | |
| | | FRT00010589 | 185.0 | 03/01/2009 | - | - | - | - | - | |
| 29 | ESP_011580_1255 | MSP00010873 | 191.503 | 2009-Jan-14 | X | X | | | | |
| 29 | ESP_012213_1255 | MSP0001171F | 221.24 | 2009-Mar-05 | | | X | X | X | |
| 29 | ESP_012569_1255 | | 238.638 | 2009-Apr-01 | | | X | | | - |
| 29 | ESP_013136_1255 | HRS00012B0D | 266.636 | 2009-May-16 | | | X | | | |
| 30 | ESP_017237_1255 | FRT000179B1 | 71.342 | 2010-Mar-31 | | | | | | |
| 30 | ESP_018516_1255 | | 115.721 | 2010-Jul-09 | X | | | | | - |
| 30 | ESP_018872_1255 | FRT0001A2D9 | 128.778 | 2010-Aug-06 | X | | | | | |
| 30 | ESP_019083_1255 | | 136.752 | 2010-Aug-22 | X | | | | | - |
| 30 | ESP_019439_1255 | | 150.671 | 2010-Sep-19 | X | | | | | - |
| 30 | ESP_019650_1255 | | 159.227 | 2010-Oct-05 | X | X | | | | - |
| 30 | ESP_019861_1255 | | 168.028 | 2010-Oct-22 | X | X | | | | - |
| 30 | ESP_020217_1255 | | 183.455 | 2010-Nov-18 | X | X | | | | - |

| | | | | | | | | | | |
|----|-----------------|-------------|---------|-------------|---|---|--------|---|---|---|
| 30 | ESP_020428_1255 | | 192.942 | 2010-Dec-05 | X | X | CLOUDS | | | - |
| 30 | ESP_020784_1255 | FRT0001CAEC | 209.487 | 2011-Jan-01 | | | X | X | X | - |
| 30 | ESP_021496_1255 | | 244.086 | 2011-Feb-26 | | | X | | | - |
| 30 | ESP_021562_1255 | | 247.348 | 2011-Mar-03 | | | X | | | - |
| 30 | ESP_021918_1255 | | 264.934 | 2011-Mar-31 | | | X | | | - |
| 30 | ESP_022340_1255 | | 285.481 | 2011-May-03 | | | X | | | - |
| 31 | ESP_025597_1255 | | 55.79 | 2012-Jan-12 | | | X | | | - |
| 31 | ESP_027364_1255 | | 116.864 | 2012-May-28 | X | | | | | - |
| 31 | ESP_028063_1255 | | 143.076 | 2012-Jul-22 | X | | X | | | - |
| 31 | ESP_028208_1255 | | 148.786 | 2012-Aug-02 | X | | X | | | - |
| 31 | ESP_028419_1255 | | 157.29 | 2012-Aug-18 | X | | X | | | - |
| 31 | ESP_028630_1255 | | 166.037 | 2012-Sep-04 | X | | X | | | - |
| 31 | ESP_028841_1255 | | 175.037 | 2012-Sep-20 | X | X | X | | | - |
| 31 | ESP_029263_1255 | | 193.805 | 2012-Oct-23 | X | X | X | | | - |
| 31 | ESP_029408_1255 | | 200.483 | 2012-Nov-03 | X | X | X | | | - |
| 31 | ESP_029619_1255 | | 210.389 | 2012-Nov-20 | - | - | CLOUDS | - | - | - |
| 31 | ESP_029764_1255 | | 217.313 | 2012-Dec-01 | | | X | | X | - |
| 31 | ESP_029830_1255 | | 220.492 | 2012-Dec-06 | | | X | | | - |
| 31 | ESP_030120_1255 | | 234.626 | 2012-Dec-29 | | | X | | | - |
| 31 | ESP_030186_1255 | | 237.872 | 2013-Jan-03 | | | X | | | - |
| 31 | ESP_030542_1255 | | 255.459 | 2013-Jan-31 | | | X | | | - |
| 31 | ESP_030898_1255 | | 272.975 | 2013-Feb-28 | | | X | | | - |
| 31 | ESP_031755_1255 | | 313.387 | 2013-May-05 | | | X | | | - |
| 31 | ESP_032533_1255 | | 346.696 | 2013-Jul-05 | | | X | | | - |
| 32 | ESP_033456_1255 | | 22.131 | 2013-Sep-15 | | | | | | - |
| 32 | ESP_034089_1255 | | 44.613 | 2013-Nov-03 | | | X | | | - |
| 32 | ESP_034234_1255 | | 49.632 | 2013-Nov-15 | | | X | | | - |
| 32 | ESP_034445_1255 | | 56.879 | 2013-Dec-01 | | | X | | | - |
| 32 | ESP_036357_1255 | | 123.302 | 2014-Apr-29 | X | | | | | - |
| 32 | ESP_037280_1255 | | 159.117 | 2014-Jul-10 | X | | | | | - |
| 32 | ESP_037702_1255 | | 176.971 | 2014-Aug-12 | X | X | X | | | - |
| 32 | ESP_038335_1255 | | 205.645 | 2014-Sep-30 | | | X | X | X | - |
| 32 | ESP_038467_1255 | | 211.885 | 2014-Oct-10 | | | X | | | - |
| 32 | ESP_038797_1255 | | 227.793 | 2014-Nov-05 | | | | | | - |
| 32 | ESP_039153_1255 | | 245.294 | 2014-Dec-03 | | | X | | | - |
| 32 | ESP_039298_1255 | | 252.466 | 2014-Dec-14 | | | X | | | - |
| 33 | ESP_043267_1255 | | 57.07 | 2015-Oct-19 | | | X | | | - |
| 33 | ESP_044678_1255 | | 105.484 | 2016-Feb-06 | | | | | | - |
| 33 | ESP_045377_1255 | | 130.855 | 2016-Apr-01 | X | | X | | | - |
| 33 | ESP_045588_1255 | | 138.878 | 2016-Apr-17 | X | | X | | | - |
| 33 | ESP_046089_1255 | | 158.789 | 2016-May-26 | X | | X | | | - |
| 33 | ESP_046155_1255 | | 161.511 | 2016-May-31 | X | | | | | - |
| 33 | ESP_046511_1255 | | 176.619 | 2016-Jun-28 | X | X | X | | | - |

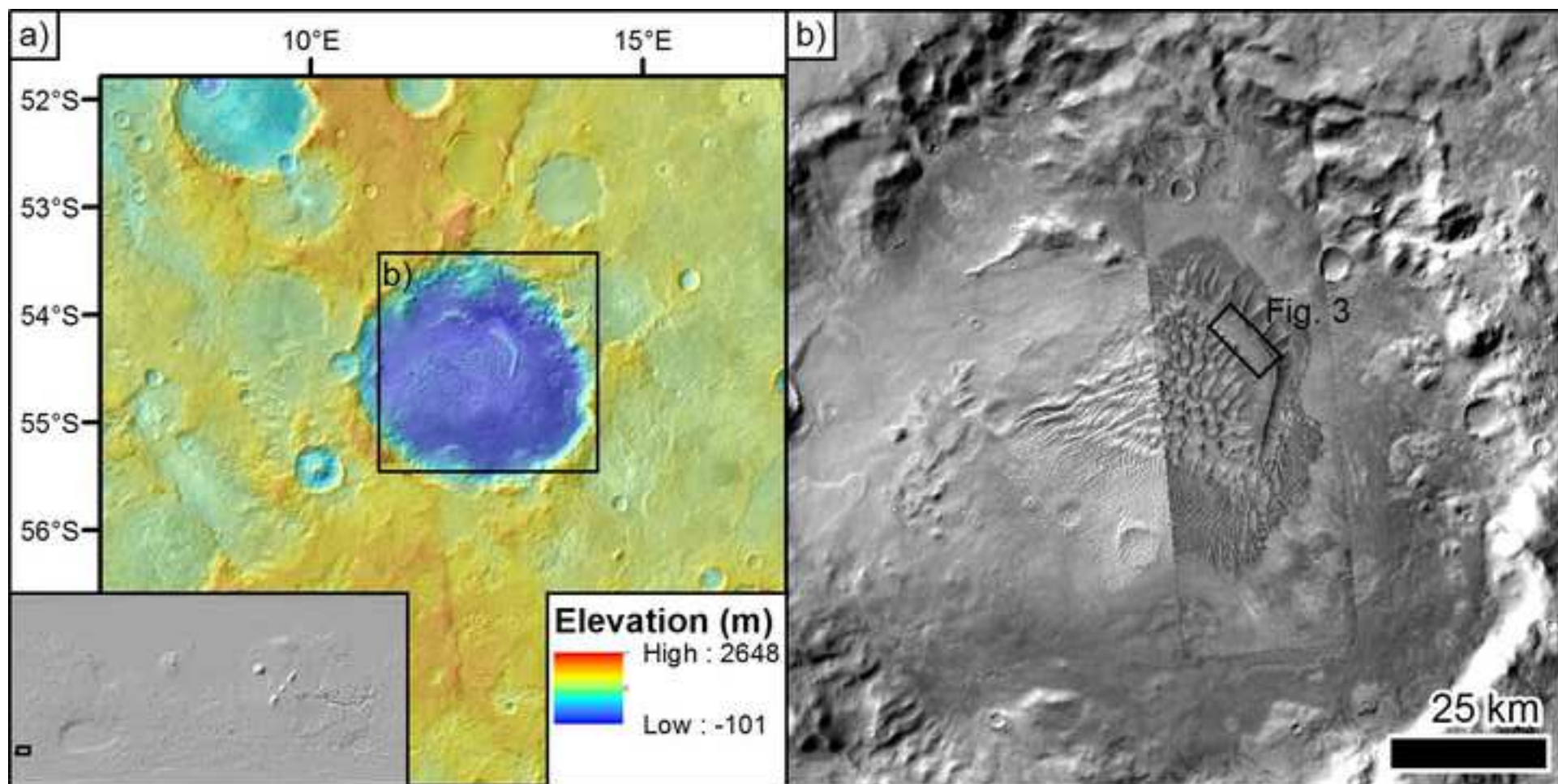
| | | | | | | | | | |
|----|-----------------|---------|-------------|---|---|---|---|---|---|
| 33 | ESP_046722_1255 | 185.918 | 2016-Jul-15 | X | X | X | | | - |
| 33 | ESP_046867_1255 | 192.455 | 2016-Jul-26 | X | X | X | | | - |
| 33 | ESP_047078_1255 | 202.175 | 2016-Aug-11 | X | X | X | X | X | - |
| 33 | ESP_047434_1255 | 219.063 | 2016-Sep-08 | | | X | | | - |
| 33 | ESP_047790_1255 | 236.42 | 2016-Oct-06 | | | X | | | - |
| 33 | ESP_049148_1255 | 302.427 | 2017-Jan-20 | | | X | | | - |
| 33 | ESP_049992_1255 | 339.563 | 2017-Mar-26 | | | X | | | - |
| 33 | ESP_050203_1255 | 348.216 | 2017-Apr-12 | | | X | | | - |

The presence of each seasonal activity (dark spot, dark flow, dust devil tracks, bright halo, new perennial rills and CO₂) is marked as an “X” in the table for each line and “-“ indicates no data (or no suitable data) available. Note that although CO₂ ice is not detected in our data before Ls 120°, other datasets and models suggest that it should be present (e.g., Piqueux et al. 2015).

Table 2. Activity of perennial rill zones per year

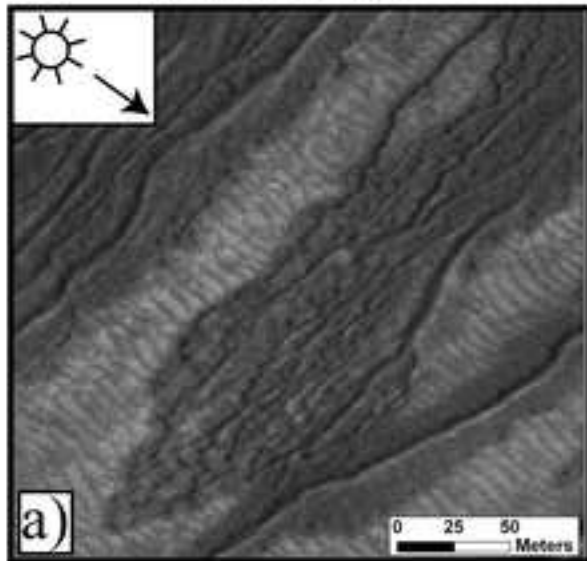
| Zone ID | MY28 | MY29 | MY30 | MY31 | MY32 | MY33 | Area (m ²) |
|--|--------|--------|--------|--------|--------|--------|------------------------|
| 1 | X | X | X | X | X | X | 56993 |
| 2 | | | X | X | X | X | 54839 |
| 3 | | | X | | X | X | 36957 |
| 4 | X | X | X | | X | X | 26610 |
| 5 | ND | | | | X | X | 38487 |
| 6 | ND | X | | | X | X | 83907 |
| 7 | ND | | | | X | X | 15884 |
| 8 | ND | | | | X | X | 9729 |
| 9 | ND | | | | X | X | 8006 |
| 10 | ND | | X | | X | X | 3422 |
| 11 | | | | | | X | 2172 |
| 12 | | | | | | X | 2490 |
| 13 | | | | | | X | 2797 |
| 14 | | | X | | X | X | 3946 |
| 15 | | | | | | X | 1974 |
| 16 | X | X | X | X | | | 6521 |
| 17 | X | X | | | X | X | 4747 |
| 18 | X | | | | X | X | 21334 |
| 19 | X | | X | | X | X | 6104 |
| 20 | | X | X | | X | X | 5117 |
| 21 | | | | ND | X | ND | 2527 |
| 22 | | | X | | X | | 2016 |
| 23 | | | X | ND | X | | 1353 |
| 24 | X | | X | | X | X | 3393 |
| 25 | | | | | X | | 4548 |
| 26 | X | X | X | | X | | 7084 |
| 27 | X | | X | | X | | 2853 |
| 28 | | | X | | X | | 2279 |
| Surface area active per year (m ²) | 135640 | 190980 | 219488 | 118354 | 402135 | 388909 | |
| Number of sites active per year | 9 | 7 | 15 | 3 | 23 | 20 | |

The ID refers to those marked on Fig. 4. “X” in any given MY=Mars Year column meaning that zone grew or changed during the previous year. “ND” indicates No Data (zone located outside HiRISE image extent) and blank means no activity noted. “Area” refers to the total active area over the whole observation period.



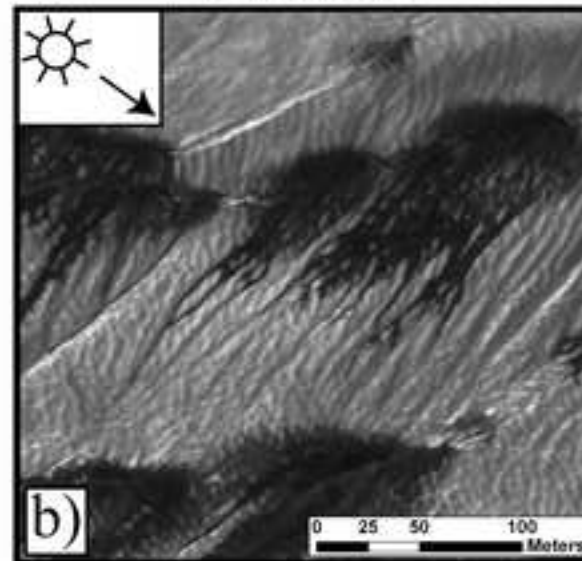
Perennial morphologies

Perennial rills

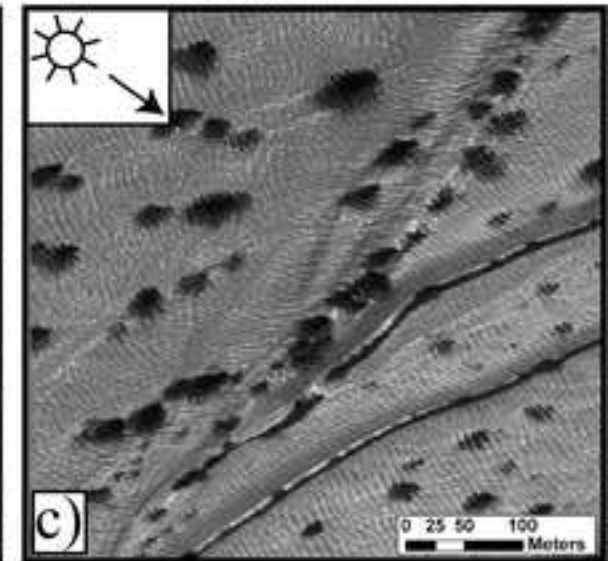


Ephemeral morphologies

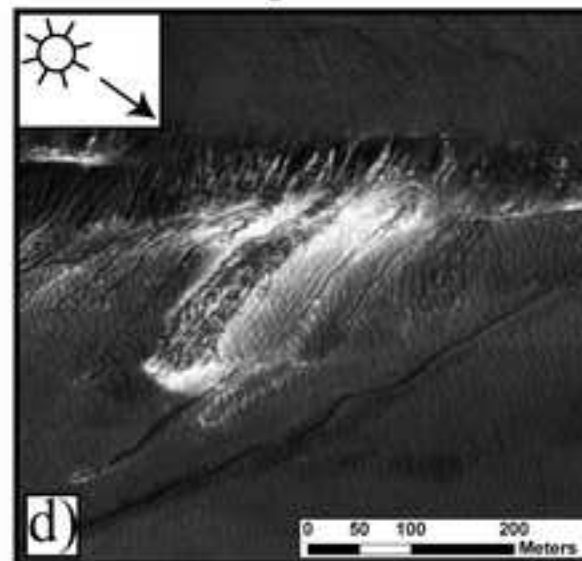
Dark flows



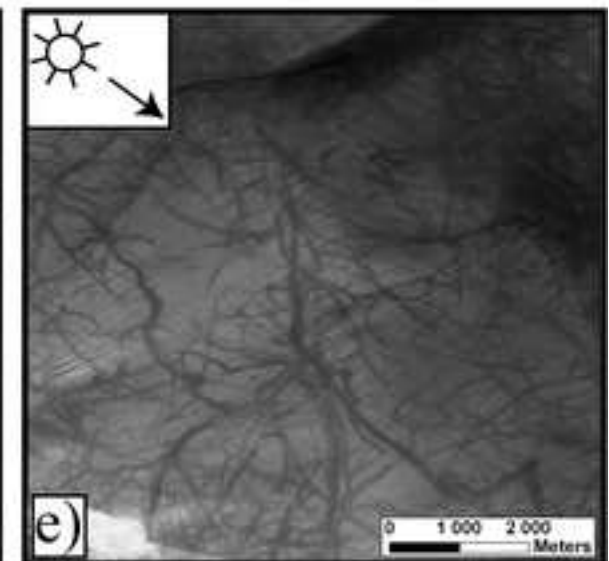
Dark spots

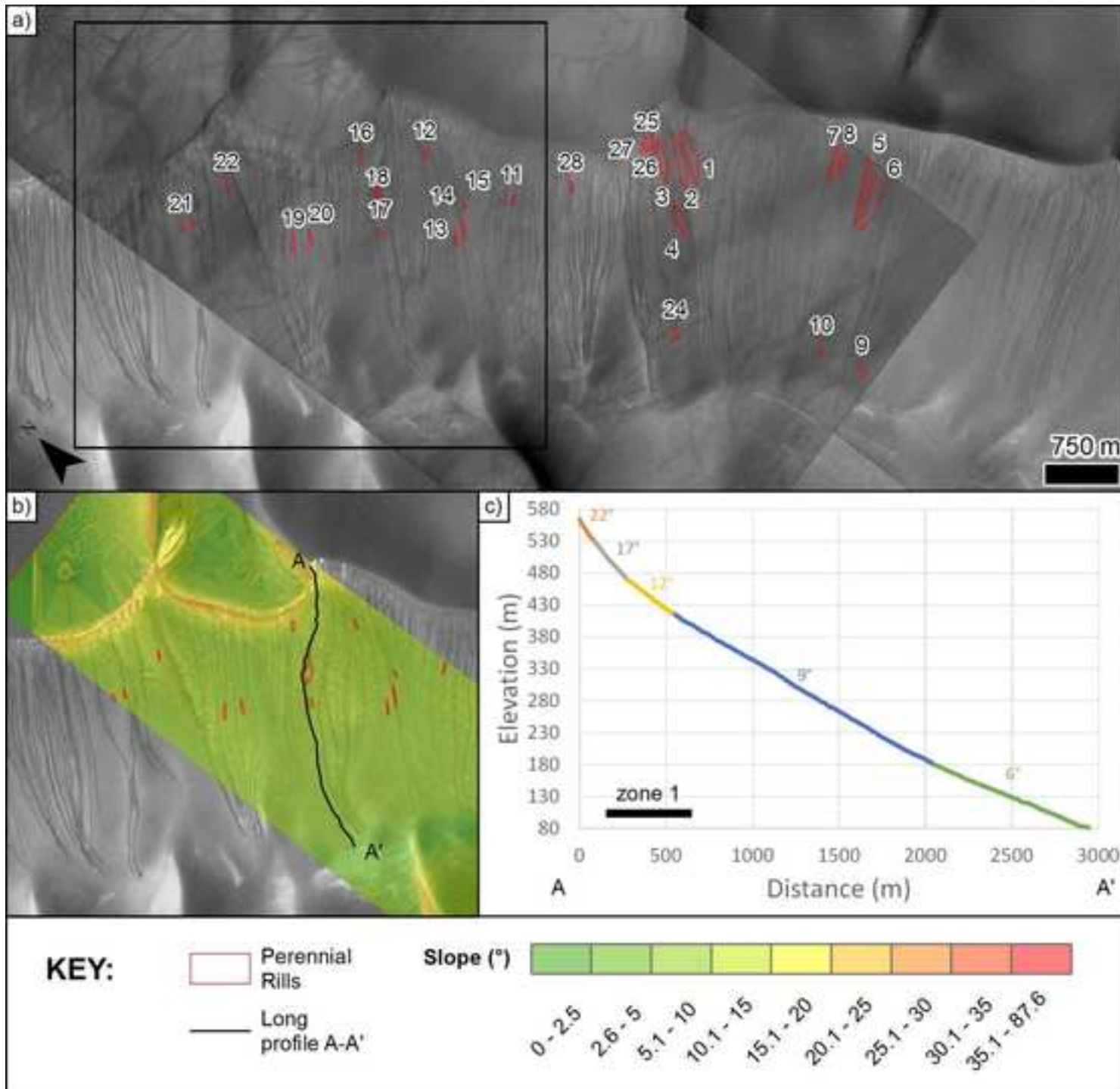


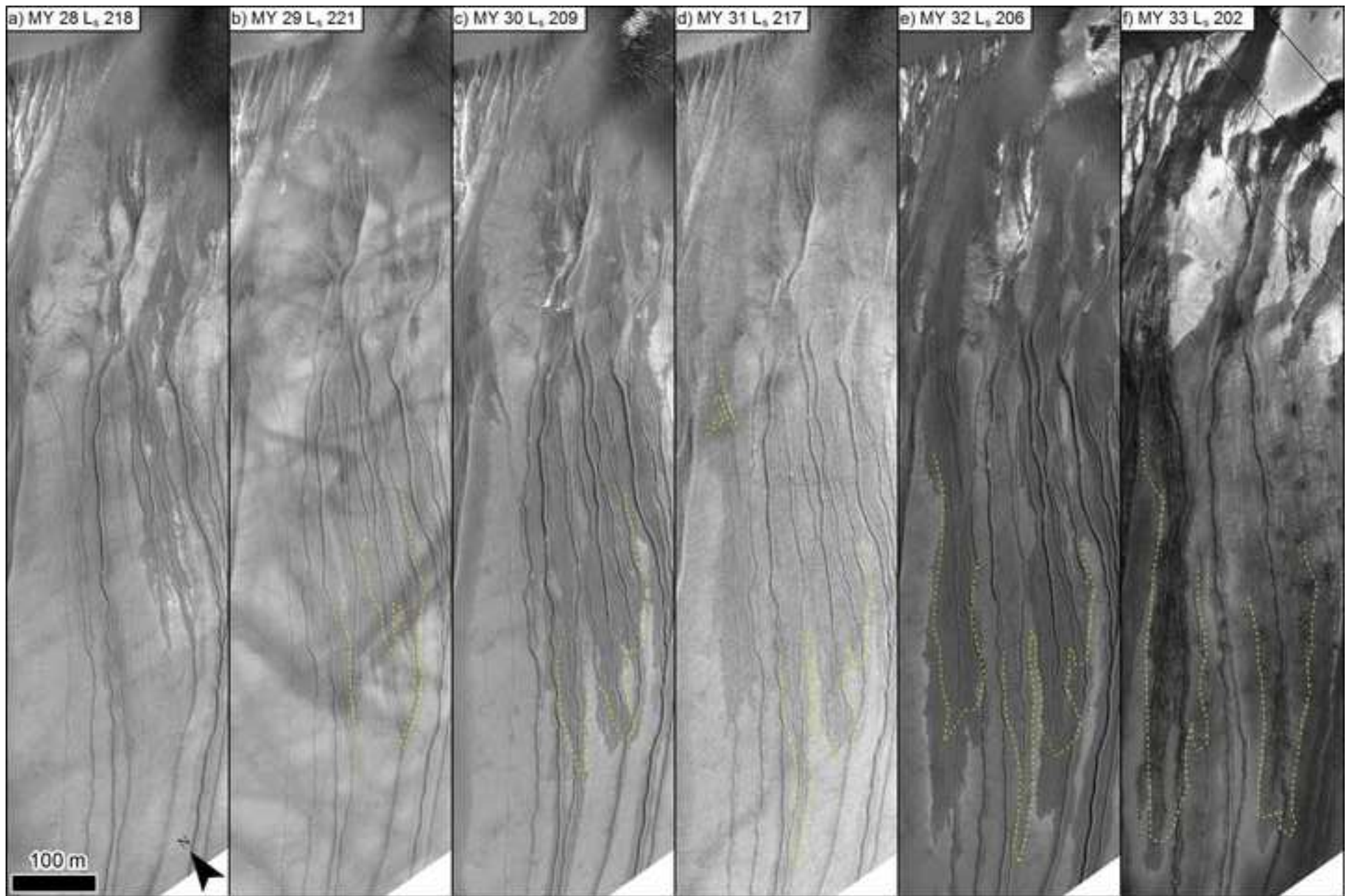
Bright halo

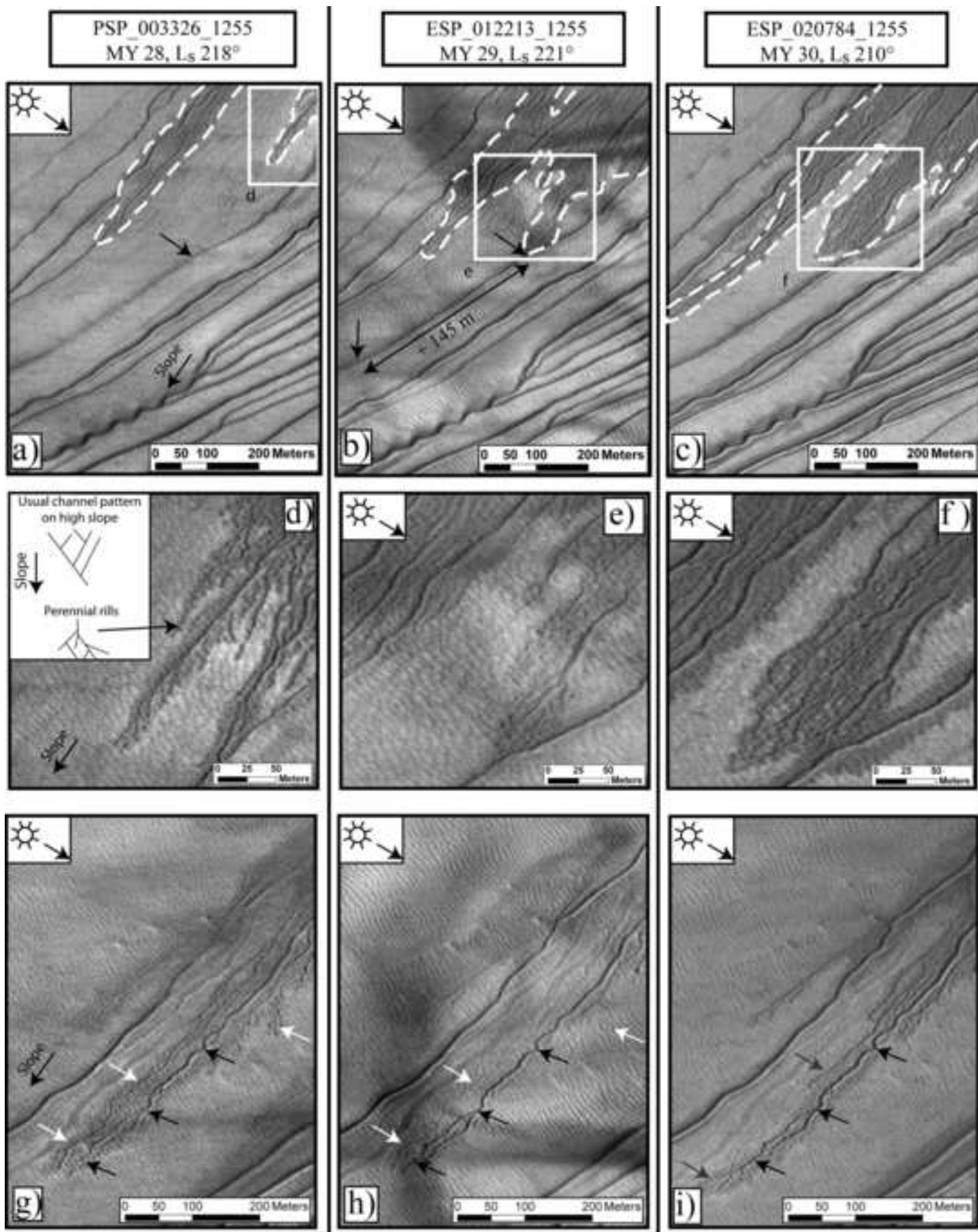


Dust devil tracks









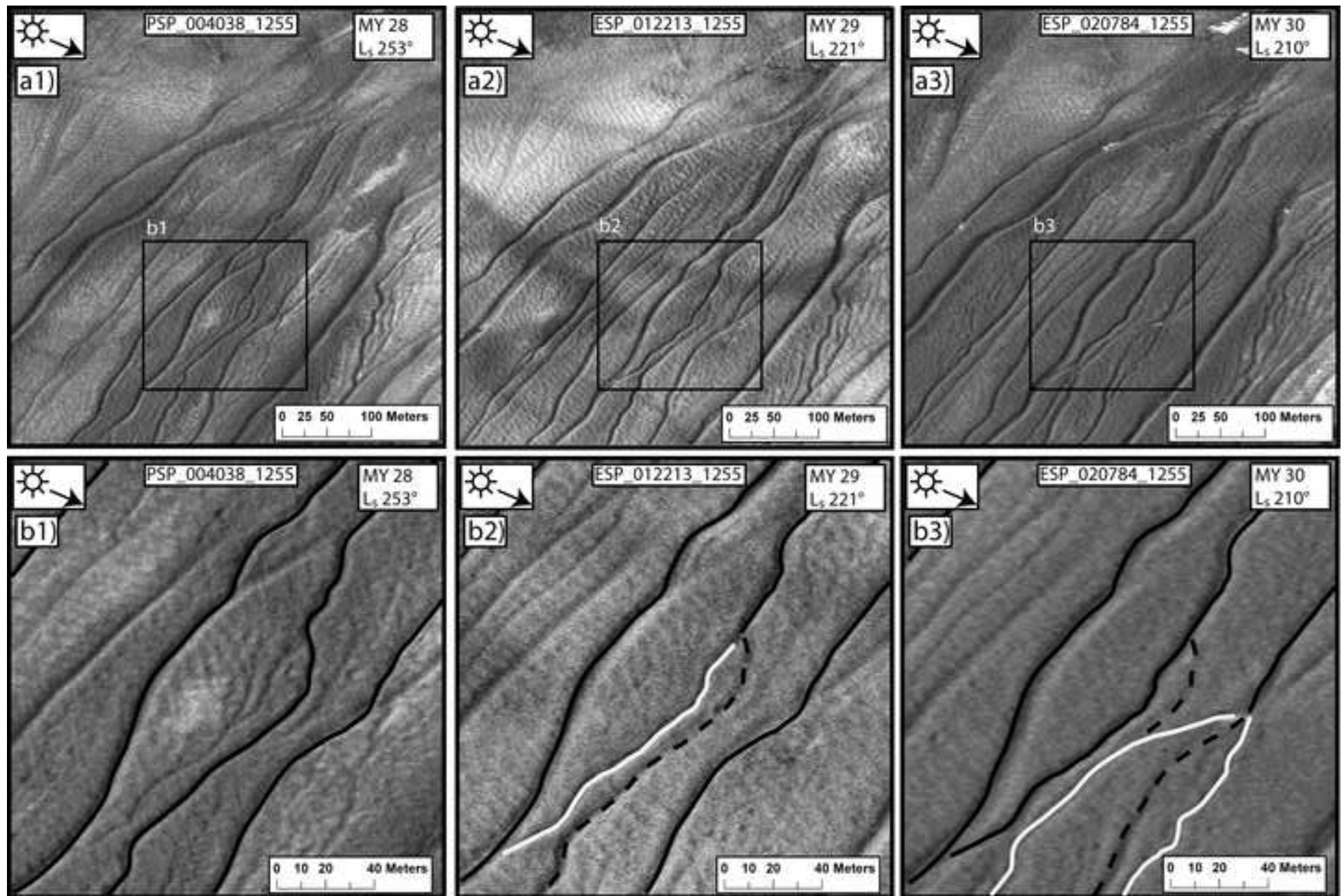


figure 7

