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1 Present-day development of gully-channel sinuosity by carbon
2 dioxide gas supported flows on Mars

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27 Martian gullies have been widely studied, but their formation mechanism is still under
28 debate. Their channels generally trend straight downslope, but some display

29 sinuosity. Seasonally active gullies are common on sand dunes and their channels
30 have been reported to develop sinuosity. Here, we perform a detailed analysis of a
31 gully on a dune within Matara Crater (49.5°S; 34.9°E) where development of channel
32 sinuosity has taken place over 5 martian years (MY29-33) of observation. This study
33 was performed using HiRISE images, HiRISE elevation data, spectroscopic CRISM
34 data and a 1D GCM for surface temperature modelling. The morphological evolution
35 of the gully suggests a significant seasonal contribution of fluid. Each year we
36 observed material collapse and accumulation in the alcove, followed by transport
37 events during which lateral migration and extension of the channel occur together
38 with growth of the debris apron. Over one martian year, the debris apron propagated
39 by almost 140 meters from an initial length of 800 meters. These transport events
40 occur in the middle of winter when CO₂ frost is still present and are contemporaneous
41 with the beginning of the defrosting. We propose that the activity and the sinuosity
42 development in the gully could be explained by: 1) a flow composed of sand and CO₂
43 gas, producing morphologies similar to those in hyper-concentrated flows on Earth
44 and 2) contribution of material from alternating of the alcove source location.

45 Keywords: Mars; Mars surface; Mars climate; Geological processes; Ices.

46 **1 Introduction**

47 **1.1 Context and objective**

48 Since their first observation by Malin and Edgett (2000), martian gullies have
49 been abundantly studied (e.g., Harrison et al., 2015). Despite this profusion of
50 research, no clear consensus on their formation mechanism has been reached. The
51 two main hypotheses for the formation of martian gullies involve either melting of
52 water ice or sublimation of CO₂ ice (e.g., Conway et al., 2018). The difficulty in
53 converging toward a unique interpretation may be related to the significant variability
54 in morphologies (Auld and Dixon, 2016) associated with the term “gully”, as this
55 variability may indicate that various processes form or modify gullies.

56 Gullies are generally composed of an alcove, a channel and an apron (Malin and
57 Edgett, 2000; Harrison et al., 2015), and in some cases the channel can be highly
58 sinuous (e.g., Mangold et al., 2010; Pasquon et al., 2016; Dundas et al., 2017).
59 Active modification of gullies has been recently observed on Mars (Reiss and
60 Jaumann, 2003; Reiss et al., 2010; Diniega et al., 2010; 2013; Hansen et al., 2011;

61 Dundas et al., 2010; 2012; 2015; 2017; Raack et al., 2015; Jouannic et al., 2012;
62 Pasquon et al., 2016, 2018), including reports of the development of channel
63 sinuosity (Dundas et al., 2017). The timing of this present-day activity is generally
64 constrained to the autumn to early spring when CO₂ ice is present on the surface.
65 Although Vincendon (2015) found that only H₂O ice was present during some of the
66 reported activity and Pasquon et al. (2016) found that linear gullies on sand dunes
67 are only active as the last CO₂ frost is removed, conditions cited as particularly
68 favorable for water ice melt (Kossacki and Markiewicz, 2004).

69 Here we perform detailed analysis of the development and migration of a sinuous
70 channel observed over 5 martian years (MY29-33) of a gully located on the dunefield
71 of Matarra Crater (49.5°S; 34.9°E). The aim of this study is to better understand the
72 processes leading to the development of channel sinuosity and the role of volatiles
73 H₂O and CO₂ in developing this morphology.

74 **1.2 Martian gullies**

75 Gullies on Mars are common and are mainly located between 30° and 50°N/S.
76 They are particularly abundant in the southern hemisphere (e.g., Balme et al., 2006;
77 Dickson et al., 2007; Harrison et al., 2015; Dundas et al., 2015). Most gullies are
78 observed on crater walls, central peaks, valley walls and mesas (e.g., Malin and
79 Edgett, 2000; Dundas et al., 2010; 2012; 2015; Harrison et al., 2015; Raack et al.,
80 2015), but gullies are also found entirely within superficial sediments, such as on
81 sand dunes (e.g., Diniega et al., 2010; Hansen et al., 2011; Dundas et al., 2012;
82 Jouannic et al., 2012; 2018; Pasquon et al., 2016; 2018). Gullies originating at
83 bedrock surfaces, such as crater walls, are far more common than gullies on sand
84 dunes, which form ~0.6% of all gullies (Conway et al., 2018), yet 35% of active
85 gullies are on sand dunes (Dundas et al., 2015). Multiple processes have been
86 proposed to explain the formation of gullies including: liquid water from ground water
87 aquifers (Malin and Edgett, 2000; Mellon and Phillips, 2001; Heldmann and Mellon,
88 2004; Heldmann et al., 2005; Malin et al., 2006), geothermal activity (Gaidos, 2001;
89 Hartmann, 2001), melting of shallow ground ice (Costard et al., 2002; Reiss and
90 Jaumann, 2003; Mangold et al., 2003; 2010; Miyamoto et al., 2004; Balme et al.,
91 2006; Reiss et al., 2010; Conway et al., 2011; Jouannic et al., 2012; 2015; Conway
92 and Balme, 2016), snowmelt (Lee et al., 2001; Christensen, 2003; Dickson et al.,
93 2007; Védie et al., 2008; Hauber et al., 2011; Williams et al., 2009), frosted granular

94 flow (Hugenholtz, 2008), CO₂-supported debris flows or blocks (Hoffman, 2002; Ishii
95 and Sasaki, 2004; Di Achille et al., 2008; Diniega et al., 2010; Cedillo-Flores et al.,
96 2011; Dundas et al., 2012; 2017; Pilorget and Forget, 2015), release of liquid CO₂
97 (Musselwhite et al., 2001), dry mass wasting (Treiman, 2003; Shinbrot et al., 2004),
98 and the presence of brines (Knauth and Burt, 2002; Ojha et al., 2015; Massé et al.,
99 2016).

100 Some gullies are still active today and the timing of their activity suggests that
101 they are triggered by seasonal processes (e.g., Dundas et al., 2010; Pasquon et al.,
102 2016). Seasonal processes have been generally attributed to the defrosting of CO₂
103 (e.g., Dundas et al., 2012; 2015; 2017). CO₂ is omnipresent on Mars: when the
104 temperature decreases in winter, deposits of solid CO₂ and a small quantity of water
105 ice can accumulate at the surface from direct condensation of the atmosphere in
106 contact with the cold surface or through precipitation of ice crystals from the cold
107 atmosphere. During winter, such deposits i) cover all surfaces above ~60° latitude, ii)
108 are discontinuous from 40° to 60° latitude (Schorghofer and Edgett, 2006; Vincendon
109 et al., 2010b; Diniega et al., 2013), and iii) are limited to pole-facing slopes nearer the
110 equator (Vincendon et al., 2010b; Dundas et al., 2015; 2017). These deposits can be
111 up to meters in thickness near the poles (Smith et al., 2001), but are generally sub-
112 centimeter thickness at lower latitudes (Vincendon, 2015). Most of this frost is
113 composed of CO₂ that can reach a few centimeters in thickness (Diniega et al., 2013;
114 Dundas et al., 2015), and H₂O is a minor component estimated to be of the order of
115 micrometers in thickness (Kereszturi et al., 2009; Gardin et al., 2010; Vincendon et
116 al., 2010b).

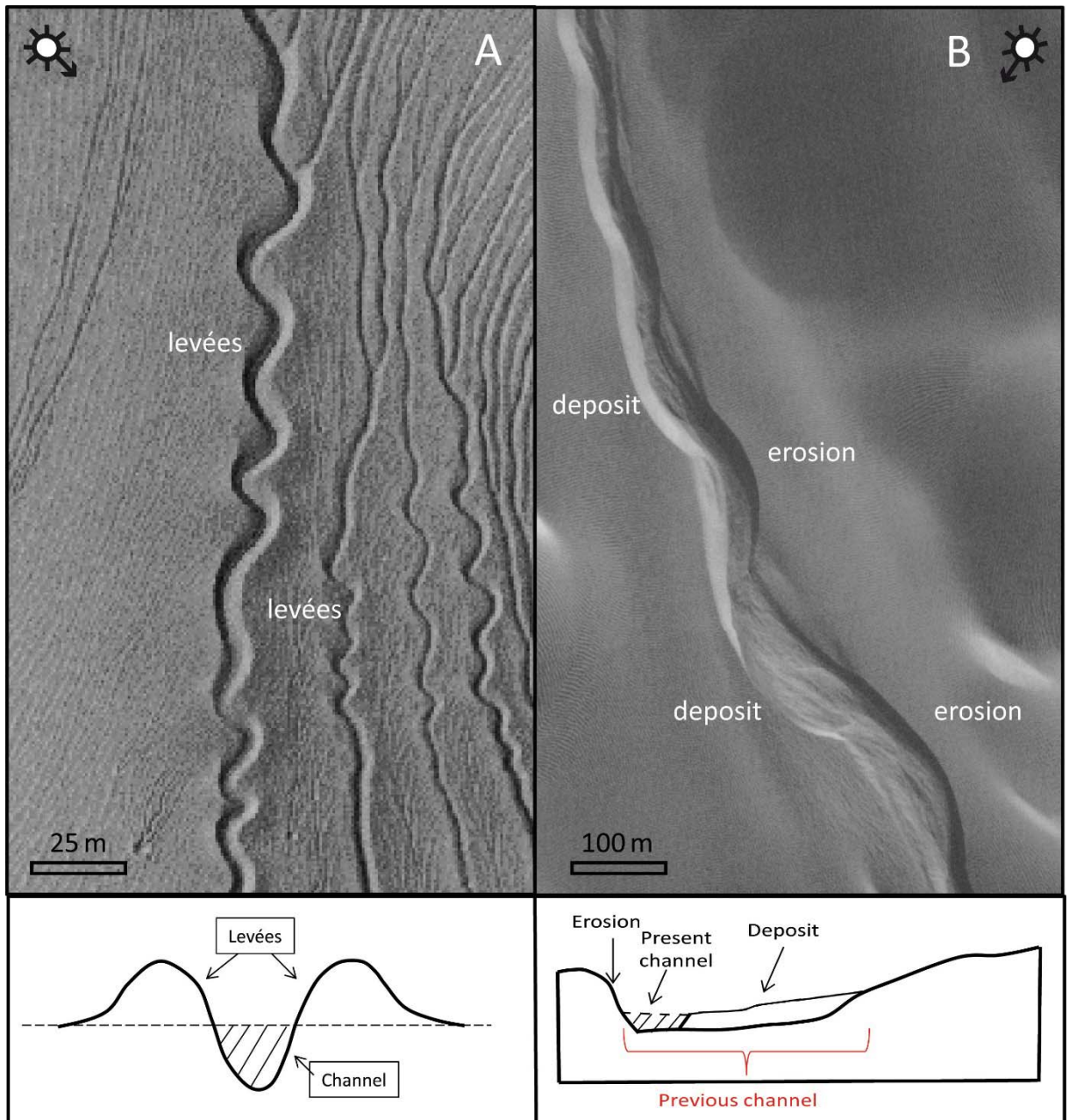
117 An impermeable layer of ground ice under a thin layer of dry regolith is thought to
118 exist on Mars (e.g., Mellon et al. 2004; Vincendon et al., 2010a; Jouannic et al.,
119 2015; Dundas et al., 2018). It is also hypothesized to be present within dunes (e.g.,
120 Fenton and Hayward 2010). Two indications point to this: i) material is transported
121 over kilometers during gully activity indicates limited infiltration and a thin active layer,
122 ii) the CO₂ ice sublimates earlier than predicted because the ice within the dunes
123 increases their thermal inertia (Vincendon et al., 2010b; Jouannic et al., 2012).

124 **1.3 Sinuous gullies**

125 Gullies are generally composed of an alcove, a channel and a debris apron,
126 but many different types of gullies exist: those without an apron; those with numerous

127 alcoves contributing to a single channel, those with a relatively small debris apron,
128 those with no tributaries, those with many tributaries, or those with or without lateral
129 levees, etc... Auld and Dixon (2016) defined seven morphological classes of gullies
130 and all of these classes can have channel sinuosity. The sinuosity of a channel is
131 determined by the sinuosity index "S", which is the ratio between the total channel
132 length (L1) and the straight line from the top to the bottom of the channel (L0). For a
133 channel to be classed as sinuous it must have a sinuosity index, $S > 1.05$ (Mangold
134 et al., 2010). On Mars, gullies with sinuous channels are located adjacent to gullies
135 without sinuous channels, hence are found in both hemispheres of Mars and more
136 frequently between 30° and 50° in latitude (Malin and Edgett, 2000; Balme et al.,
137 2006). These sinuous gullies occur over a large range of elevations (Mangold et al.,
138 2010). However, they do not often occur at low elevation (Mangold et al., 2010).
139 Channels generally have widths of up to a few meters (Mellon and Phillips, 2001) and
140 lengths up to a few kilometers (Heldmann and Mellon, 2004). They often become
141 narrower and shallower downslope (Mangold et al., 2010). Sinuous channel occur on
142 slopes between 10° and 20° , but most precisely between 12° and 14° (Mangold et
143 al., 2010). Their preferential orientation is pole-facing slopes (Mangold et al., 2010)
144 similar to the general population (e.g., Conway et al. 2017).

145 Two different types of channel sinuosity are visible in gullies on Mars: 1)
146 sinuosity of channels expressed between symmetric lateral levees (Fig. 1A) usually
147 found in "linear" dune gullies, 2) sinuosity developed with both in-channel erosion and
148 deposition (see Edwards and Liverpool, 1995) (Fig. 1B).



149

150 Fig. 1. A) Example of sinuous gully channels with levees on Mars. B) Example of a sinuous gully
 151 channel without lateral levees and with areas of erosion as well as sedimentation in the channel.

152 The first type of sinuosity is thought to be caused by debris flow processes and the
 153 second could be due to hyper-concentrated flow (Mangold et al., 2010). Debris flows
 154 are composed of a mix of liquid water and solid material ranging between 20 and
 155 60% with a grain size ranging from micrometers to meters scale (e.g., Allen, 1985;
 156 Coussot and Meunier, 1996). Debris flows can be generalized as viscous flows, with
 157 a viscosity ranging from 1 to 10000 Pa.s, which can transport boulders several
 158 meters in size. They can propagate over slopes $<10^\circ$ and even down to 1 to 2° on
 159 Earth. Hyper-concentrated flows are liquid water flows, which typically contain more

160 than 30% of solid material. Hyper-concentrated flows can have an intermediate state
161 between turbulent stream flows and laminar viscous debris flows (e.g., Allen, 1997).
162 Mangold et al. (2010) concluded that sinuous gully channels are formed by the same
163 processes as straight ones. The present-day initiation and migration of sinuous
164 channels have been reported by Dundas et al., (2015; 2017): on crater walls at
165 37.5°S; 222.9°E and at 38.9°S; 196°E and on dunes at 47.6°S; 30.4°E and at 49.5°S;
166 34.9°E. These morphologies are interpreted to be driven by processes related to the
167 seasonal CO₂ frost (Dundas et al., 2015; 2017). Dundas et al. (2017) report that
168 sinuous channels were observed to migrate and become more sinuous. Cutoff of a
169 channel bend was also reported, analogous to the formation of an oxbow lake in a
170 meandering stream (Dundas et al., 2017). Dundas et al. (2017) suggest that
171 energetic flows are required to create such sinuous channels. Linear dune gullies
172 have been described as being formed by debris flow processes (Mangold et al.,
173 2003; Jouannic et al., 2012). Recently linear dune gullies have been shown to be an
174 active seasonal phenomena (Diniiega et al., 2013; Pasquon et al., 2016; Jouannic et
175 al. 2018). Linear dune gullies, despite their name, can have a straight or a sinuous
176 channel (e.g., Pasquon et al., 2016). New linear dune gullies have been observed to
177 form as well as the lengthening of existing gullies, yet no sinuosity initiation, or
178 sinuosity migration, has yet been reported in linear dune gullies.

179 **1.4 Gully on Matara Crater dunefield**

180 The gully investigated in our study is located on the low albedo intra-crater
181 dunefield of Matara Crater (49.5°S; 34.9°E). These dunes are mainly composed of
182 volcanic sands with basaltic (Paige and Keegan, 1994; Herkenhoff and Vasavada,
183 1999), or andesitic (Bandfield, 2002) origin. They are likely constituted of sand with a
184 proximal source (Thomas, 1982; Ward and Doyle, 1983). On Mars, dunefields are
185 most common at latitudes above 40°S and around the north polar cap (>75°N)
186 (Hayward et al., 2014). The present-day activity of this gully has been related to the
187 seasonal defrosting of CO₂ (Diniiega et al., 2010; Dundas et al., 2012; 2017), but the
188 associated mechanism, the physical state of the CO₂, and the nature and amount of
189 the solid material involved have not been studied in detail.

190 2 Methods

191 2.1 Morphology

192 We performed a detailed survey of one gully using all available HiRISE images
193 of that location. The HiRISE camera, onboard the MRO (Mars Reconnaissance
194 Orbiter) spacecraft, possesses 14 CCD (Charge-Coupled Device) detectors, which
195 operate in the visible (from 536 to 692 nm) and in the infrared (approximately 874
196 nm) (McEwen et al., 2010). We separated the gully into two areas: 1) the alcove and
197 the beginning of the channel and 2) the channel and the debris apron (Fig. 2D).
198 Changes between images were identified on the RDR (Reduced Data Record) geo-
199 referenced images. The RDR data are calibrated, geo-referenced with change in
200 scale, rotation and translation, and map projected to highlight morphological
201 differences between images. Length, width and area were directly measured on the
202 RDR HiRISE images. Uncertainty on measurements is estimated by determining the
203 reproducibility and the variability of the measurement. Variations in emission angle,
204 roll direction and lighting conditions exist between images and can lead to error in
205 plan-view measurements.

206 The estimation of the timing of any observed activity is limited by the time
207 sampling of the available observations. Here, we will provide the solar longitude (L_S)
208 of the first image showing a morphological change and the L_S of the preceding image
209 without the change. The duration of surface frost was determined by visual inspection
210 of the HiRISE images. 44 HiRISE images cover the gully studied over 5 Martian
211 Years (MY29-33) with a better temporal coverage in MY30-32.

212 One HiRISE Digital Terrain Model (DTM) is available for the studied sinuous
213 gully. This DTM was produced from images ESP_022115_1300 and
214 ESP_022392_1300 by the HiRISE team and enable topographic measurements
215 better than 25 cm of relative vertical precision (McEwen et al., 2007). Slope angles
216 were estimated by taking a topographic profile along the line of steepest decent and
217 making a linear fit over the area of interest.

218 To estimate the erosion and the deposition volume of the Matara dune-gully we
219 used the topographic reconstruction method of Conway and Balme (2014) which
220 consists of estimating the initial topography prior to the gully formation. In brief, we
221 used the topographic contours either side of the gully to estimate the position of the
222 contours across the dune before the gully formed. These contours are then used as

223 the input to a Natural Neighbor interpolation to produce a gridded elevation dataset.
224 This estimated topography is then subtracted from the real topography to estimate
225 the overall volumes of deposition and erosion. Given the irregular topography of the
226 dune, the errors are likely larger than in Conway and Balme (2014). Therefore in
227 order to estimate the potential errors on this calculation, we linearly connected the
228 contours either side of the gully and re-performed our analysis – we used the
229 difference between these two volumes as an estimate of the magnitude of error.

230 **2.2 Simulation of surface temperature and frost occurrence**

231 We used the one-dimensional energy balance code developed at the
232 Laboratoire de Météorologie Dynamique in Paris (Forget et al., 1999) and modified to
233 simulate ice condensation on sloping terrain with inputs from a general circulation
234 model (Spiga and Forget, 2008; Forget et al., 2008; Vincendon et al., 2010a, 2010b)
235 to assess the climatic conditions on the Matara Crater dunefields.

236 CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) images
237 were used to inform these simulations. CRISM is an imaging spectrometer with a
238 spatial resolution of 18 m/pixel that covers the visible to infrared wavelengths from
239 383 to 3960 nm (Murchie et al., 2004). The CRISM images were used to estimate the
240 timing of formation and disappearance of ices using a similar approach to that
241 presented in Vincendon (2015). These timings were refined using small-scale bright
242 frost detections in HiRISE images (Table 1). We then compare these observational
243 constraints to the outputs of a climate model.

244 Simulations were performed for the pole-facing slope (azimuth = 180°) of an
245 alcove with a slope angle of 24° (cf. active alcove of the sinuous gully, Fig. Suppl.
246 Material 1).

247 The model outputs are:

- 248 - The masses of CO₂ and H₂O ice accumulated on the ground as a function
249 of L_S: these masses are converted to thicknesses using densities of 1.62.
250 10³ and 0.92.10³ kg.m⁻³ respectively.
- 251 - The temperature of the surface every half an hour.

252 Model parameters used for the numerical simulation are given in Table1. Model
253 parameters such as CO₂ ice albedo and ground ice depth are tuned, similarly to
254 Vincendon et al. (2010), to fit the model to the observations of ice previously reported

255 from near-IR spectroscopy (Vincendon 2015) as well as to the frost occurrence as
 256 observed in our study.

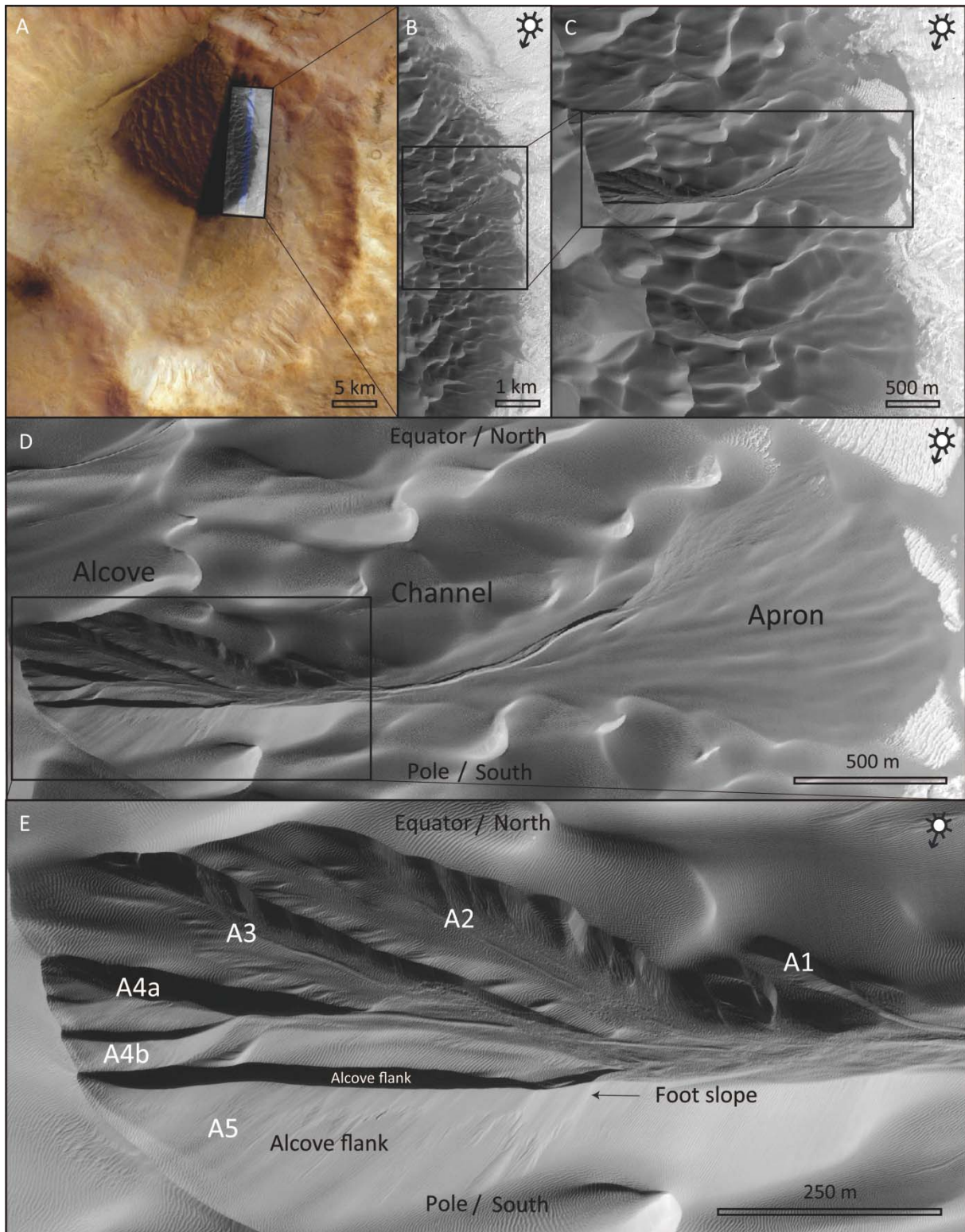
Surface albedo			Emissivity		Wind	Thermal Inertia ($J.m^{-2}.s^{-1/2}.K^{-1}$)		Optical depth	Ground ice depth	Frost on HiRISE images	Alcove
<i>sand</i>	<i>CO₂ ice</i>	<i>H₂O ice</i>	<i>ground</i>	<i>ice</i>	(<i>m.s⁻¹</i>)	<i>ground</i>	<i>ground ice</i>	(<i>change with L_s</i>)	cm	L _s (°) beginning/end	Θ (°)
0.10	0.4 – 0.65	0.3	0.95	1	10	300	2120	0.46 – 1.17	19	[41.9-56.5 / 183.7-192.3]	24

257 Table.1. Model parameters used in this study for the numerical simulation of surface temperature and
 258 ice occurrence. Dust aerosol optical depth is given at a pressure of 700 Pa and for visible optical
 259 depths; it varies as a function of L_s according to an averaged, smoothed scenario derived from Spirit
 260 and Opportunity PanCam measurements (Lemmon et al., 2015; Vincendon et al., 2015). Θ is the slope
 261 angle and φ is the azimuth angle.

262 3 Results

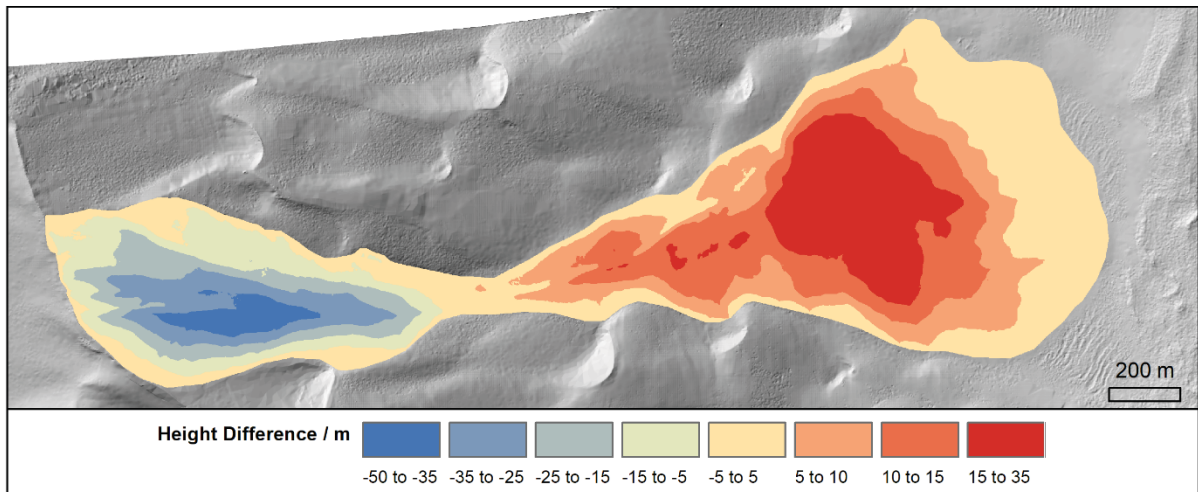
263 3.1 Overall morphology of the gully with channel sinuosity

264 The gully studied is located on the eastern part of the Matara Crater dunefield
 265 (49.5°S; 34.9°E) (Fig. 2). The dunefield is comprised of transverse dunes and is 16
 266 km across with a low albedo typical of dunes of Mars (Thomas, 1982). The
 267 investigated gully is composed of an alcove, a channel, and an apron (Fig. 2D) and
 268 measures almost 2700 meters in length (Fig. 2D). The alcove covers a surface area
 269 of $3.7 \times 10^5 \text{ m}^2$ and is constituted by 6 sub-alcoves that converge toward the channel.
 270 These different sub-alcoves are numbered A₁, A₂, A₃, A_{4a}, A_{4b} and A₅ in Fig. 2E. The
 271 channel covers a surface area of $3 \times 10^4 \text{ m}^2$, is ~1000 meters long with a maximum
 272 width of 60 m, and has several channel bends. The area of the apron is larger than
 273 that of the alcove with a total area of $7.9 \times 10^5 \text{ m}^2$. We estimated a volume of alcove
 274 erosion of $6 \times 10^6 \text{ m}^3$ (+/- $4 \times 10^6 \text{ m}^3$) and an apron deposit of $8 \times 10^6 \text{ m}^3$ (+/- 4×10^6
 275 m^3) (Fig. 3). Within the bounds of the error these two volumes are balanced. In
 276 MY29-33 1/5 of the area of the apron experienced changes (Fig. 4D).



277

278 Fig. 2. A) Matara Crater dunefields (49.5°S; 34.9°E) (Google Mars, HRSC image). B) and C)
 279 increasingly detailed view of the eastern part of the dunefield. D) Overview of the sinuous gully on the
 280 eastern edge of the Matara Crater dunefield (HiRISE image: PSP_006648_1300 L_s 8.8°). E) Detailed
 281 view of the alcove: the different sub-alcove are labelled A₁ to A₅ (B-E: HiRISE image:
 282 PSP_006648_1300, L_s 8.8°).

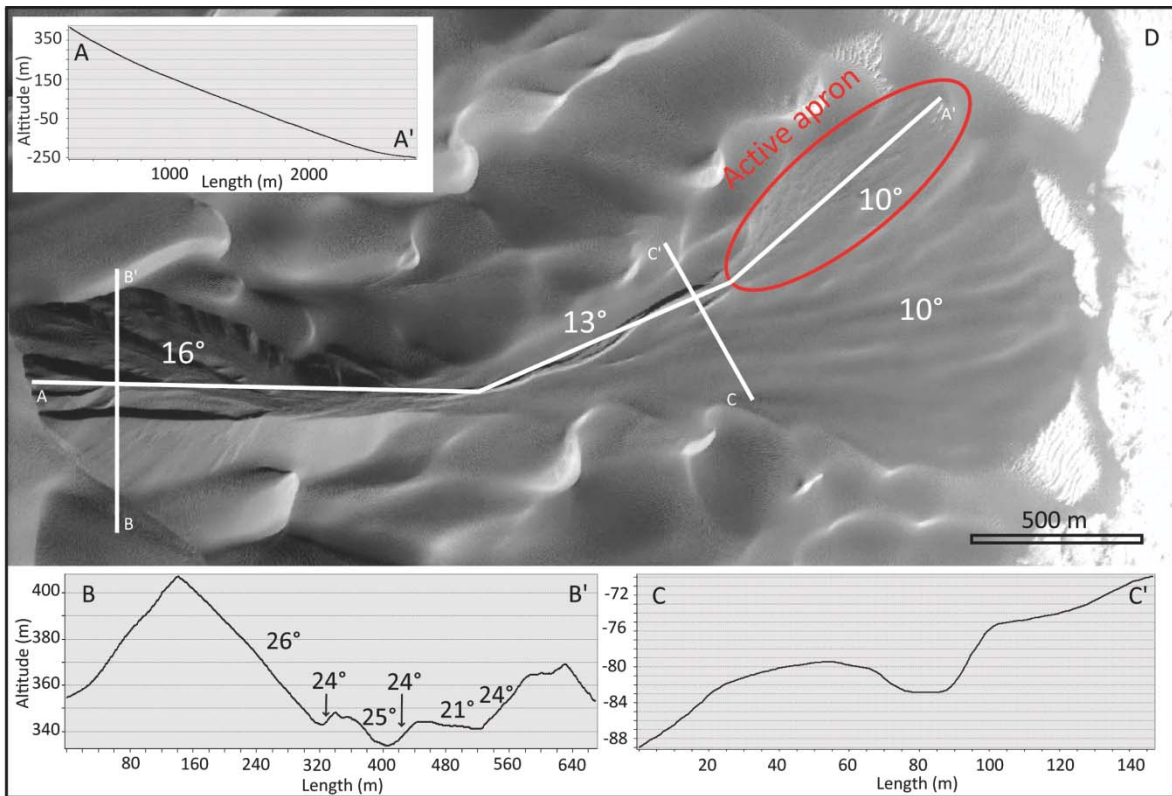


283

284 Fig. 3. Estimation of alcove erosion (shades of blue) and apron deposit thickness (shades of red) of
 285 the gully on Matara dunefield. The underlying hill shaded relief model is from the publicly available
 286 HiRISE DTM DTEEC_022115_1300_022392_1300_U01.

287 3.2 Slopes and cross-sections

288 Slopes measurements on cross sections and longitudinal profiles were made
 289 using the HiRISE DTM. The mean slope of the sinuous gully is $\sim 13^\circ$. The alcove has
 290 a slope of $\sim 16^\circ$, the channel $\sim 13^\circ$ and the active part of the apron $\sim 10^\circ$. The
 291 longitudinal cross-section of the gully is slightly concave (Fig. 4A). Two transversal
 292 cross-sections are presented: i) at the top of the alcove (Fig. 4B), ii) at the end of the
 293 channel (Fig. 4C). The alcove can be separated into different sub-alcoves that we
 294 have called: A_1 , A_2 , A_3 , A_{4a} , A_{4b} and A_5 (Fig. 2E) which have different slope angles
 295 (Fig. Suppl. Material 1). The morphology of the alcove and its constituent sub-alcoves
 296 is asymmetric. For example, in the case of the sub-alcove A_5 , the length of the
 297 equator-facing flank is greater than that of the pole-facing flank (Fig. 4B).
 298 Nevertheless, the average slopes of the opposing sub-alcove flanks are similar: the 6
 299 pole-facing flanks of the sub-alcoves have an average slope angle of 22.8° and the
 300 equator-facing flanks have an average slope of 23.2° (Fig. Suppl. Material 1).



301

302 Fig. 4. Topographic profiles of: A-A') along the gully length, B-B') across the upper part of the alcove
 303 (the slope along the line of steepest decent of A₅, A_{4a}, A₃ sub-alcoves are marked), C-C') across the
 304 lower end of the channel. D) Location of the topographic profiles on the image of the gully (HiRISE
 305 image: PSP_006648_1300, L_s 8.8°). Note that vertical exaggeration accentuates some of the slope
 306 differences and the slope angles quoted on the cross-profiles are not necessarily measured in the
 307 same plane as the displayed profile.

308

3.3 Evolution in the gully morphology

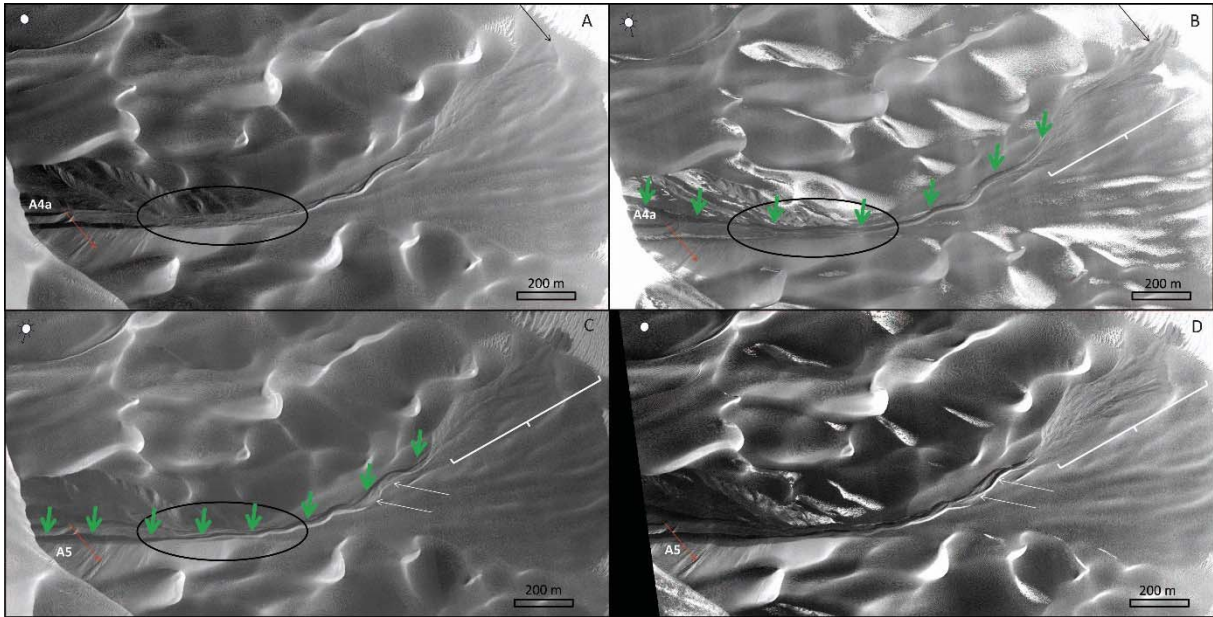
309 The studied gully was extremely active during MY29-33. Each year, we
 310 observed material transport: inside the alcove, and from the alcove on to the debris
 311 apron accompanied by development of sinuosity of the channel. These changes will
 312 be summarized in the following sections.

3.3.1 Alcove changes

314 The alcove of this gully is composed of 6 different sub-alcoves that converge
 315 towards the channel: A₁, A₂, A₃, A_{4a}, A_{4b} and A₅ (Fig. 2E). The cross-section in Fig. 4B
 316 illustrates the typical topographic configuration of these sub-alcoves. During MY29-
 317 33, we observed activity in different sectors of the alcove (Figs. 5ABC; Suppl.
 318 Material 2AB). Part of the alcove is considered “active” when a change in the
 319 morphology is observed. These changes due to erosion or deposition are easily

320 observable at the transition between the alcove and the channel of the gully (Figs.
321 Suppl. Material 3; 5ABC; 6AB).

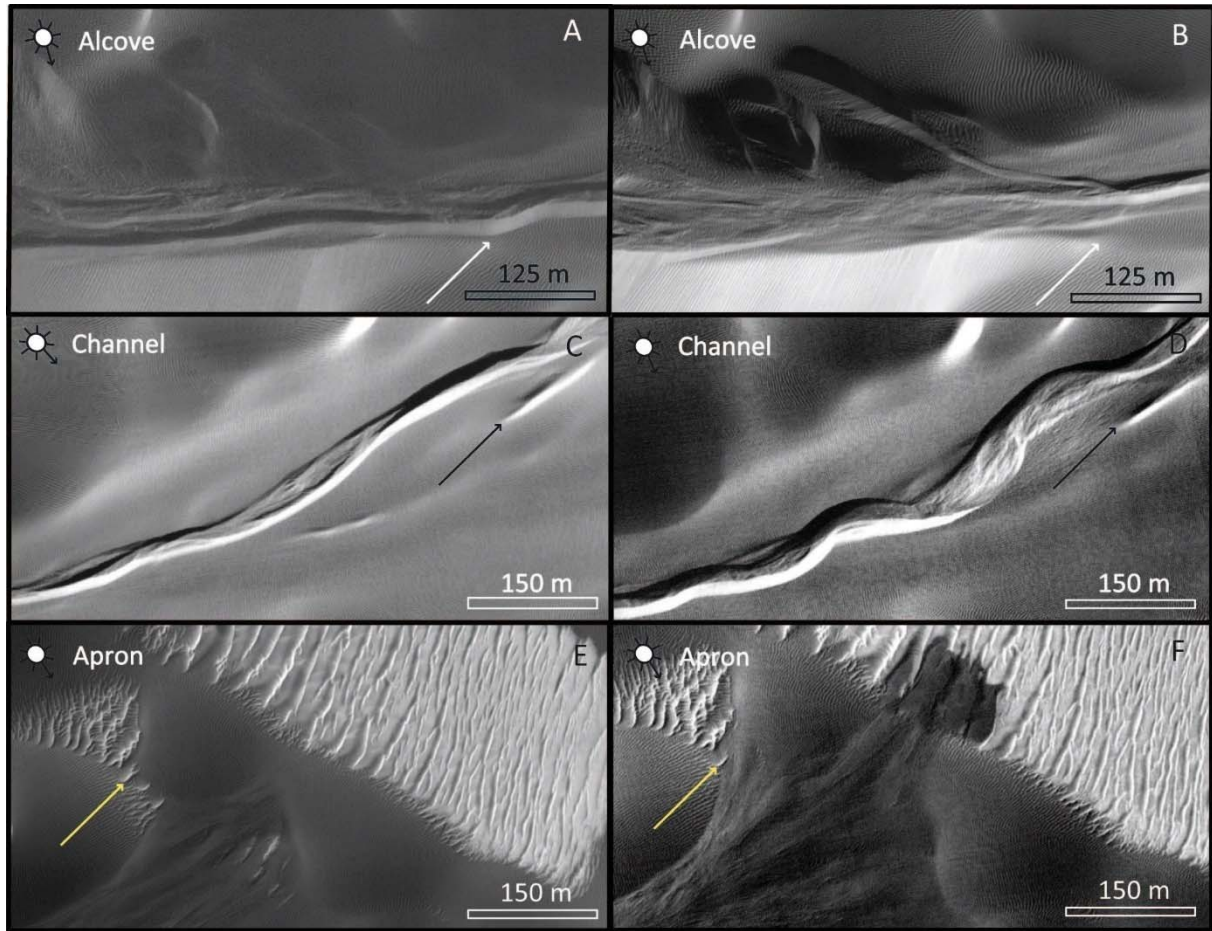
322 We find that only the activity in the sub-alcoves A_{4a} , A_{4b} and A_5 is temporally
323 correlated with the changes in the sinuosity of the main channel during MY29-33 (Fig.
324 5). In the next parts, we describe changes in the equator-facing and pole-facing
325 flanks separately, as they have distinctive types of activity.



326

327 Fig.5. Gully activity over 3 martian years (MY31-33). A) HiRISE image: ESP_046286_1300, L_s 199.8°,
328 MY31: in this reference image the channel is partly filled by sand (black circle). B) HiRISE image:
329 ESP_036910_1300, L_s 144.3°, MY32: the sub-alcove A_{4a} is active (green arrows), a channel is formed
330 (black oval) and material transported onto the debris apron. Subsequent events propagate the channel
331 on the debris apron. C) HiRISE image: ESP_037965_1300, L_s 188.6°, MY32: the sub-alcove A_5 is
332 active (green arrows), a channel is carved (black oval) and modifications occur at the end of the
333 channel and on the debris apron. The red arrows in sub-alcove A_5 indicate a failure scar, under which
334 there is material accumulation. Material has accumulated within the lower part of the channel, which
335 can be explained by the obstruction provided by the previous set of deposits, propagating channel fill
336 upstream. D) HiRISE image: ESP_046238_1300, L_s 167.0°, MY33: the material accumulated in the
337 sub-alcove A_5 is transported onto the channel and the debris apron. Material continues to accumulate
338 within the lower part of the channel, blocked by the previous deposits, propagating channel fill
339 upstream. White arrows show where modification of the channel morphology has occurred. Thin
340 arrows are reference points: red arrows for material accumulation, black arrows for material transport
341 onto the debris apron, and white arrows for changes in the channel morphology. Thick green arrows
342 indicate where there is activity in the alcove and channel of the gully. Black ovals highlight changes in

343 morphology in the area between the alcove and the beginning of the channel. White brackets show
344 multiple overlapping deposits.



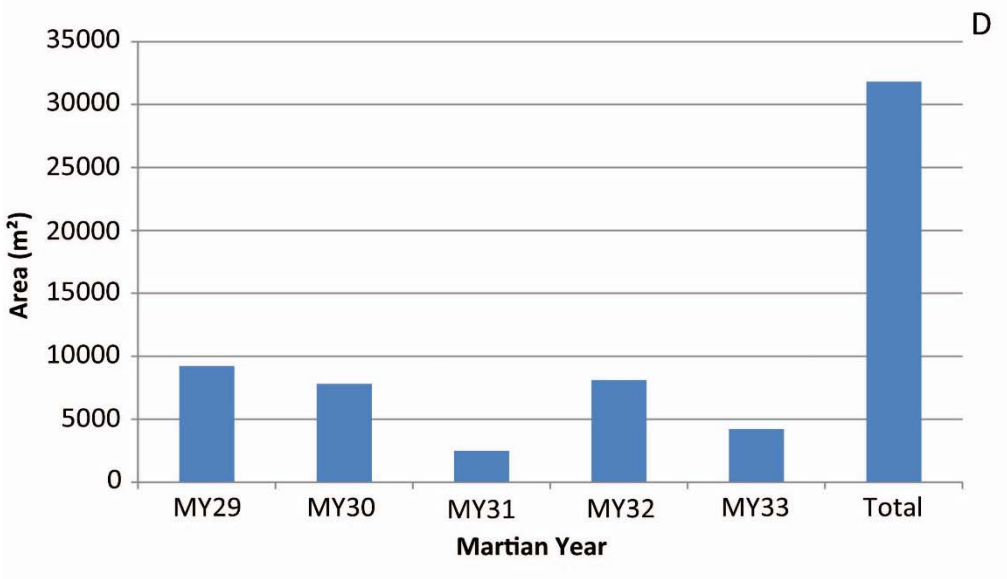
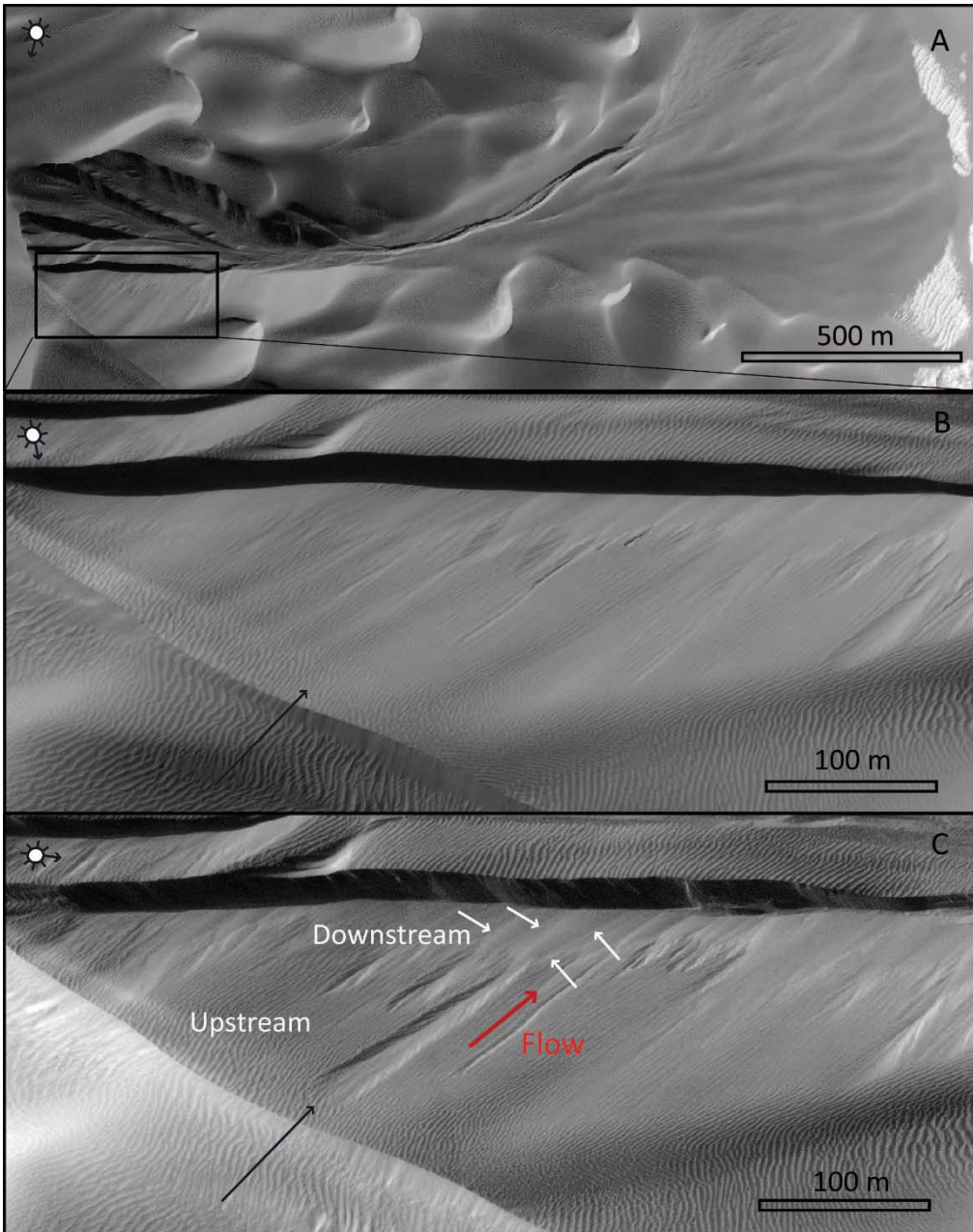
345
346 Fig. 6. Summary of main gully activity types represented by before-after pairs of images. (A-B) At the
347 transition between the alcove and the channel, sediment erosion and accumulation alternates, causing
348 channel formation, partial channel infilling or complete channel erasure. A) HiRISE image:
349 ESP_028972_1300, L_s 180.8° (MY32). B) HiRISE image: ESP_037965_1300, L_s 188.6° (MY32). (C-D)
350 Development of a more sinuous channel. C) HiRISE image: ESP_006648_1300 L_s 8.8° (MY29). D)
351 HiRISE image: ESP_037965_1300, L_s 188.6° (MY32). (E-F) Elongation of the debris apron deposits.
352 E) HiRISE image: ESP_034009_1300, L_s 41.8° (MY32). F) HiRISE image: ESP_037411_1300, L_s
353 164.5° (MY32). The white arrow shows a reference point between images A and B, the black arrow
354 between images C and D and the yellow arrow between images E and F.

355 3.3.1.1 Equator-facing flanks: material accumulation in the alcove

356 Sand material transport and accumulation was observed in sub-alcoves A_{4a} to
357 A_5 (Figs. 7; 5). Material transport is only observed on the equator-facing flanks (Figs.
358 7; 5C; Suppl. Material 3). On the equator-facing flanks of sub-alcoves A_{4b} to A_5 , small
359 discrete slope failures oriented toward NNE result in the transport of sand material
360 that is identifiable as accumulations on the alcove floors (Figs. 7ABC; 5C; Suppl.

361 Material 3). These failures comprise an alcove or scar and an apron, sometimes
362 connected by a depression, or channel (Figs. 7C; 5C; Suppl. Material 3). The total
363 area affected by these failures ranges between 2000 and 8000 m² and is highly
364 variable from one year to the next (Fig. 7D). During MY29-33, the cumulative area
365 affected by material transport and accumulation in the alcove attains 31 800 m² (Fig.
366 7D). An area of 14 800 m² is affected by material accumulation on the floor of the
367 sub-alcove A₅. The material initially accumulated in sub-alcoves A_{4b} to A₅ was
368 transported onto the debris apron of the gully (Fig. 5). This transport causes erosion
369 and deposition of sediment and the creation of a channel in the terminal part of the
370 alcove (Figs. Suppl. Material 3; 5ABC; 6AB). There was no observed accumulation of
371 material for MY29-33 in sub-alcoves A₁ to A₃ (Figs. 2E; 5), and no channel changes
372 were observed during their defrosting.

373



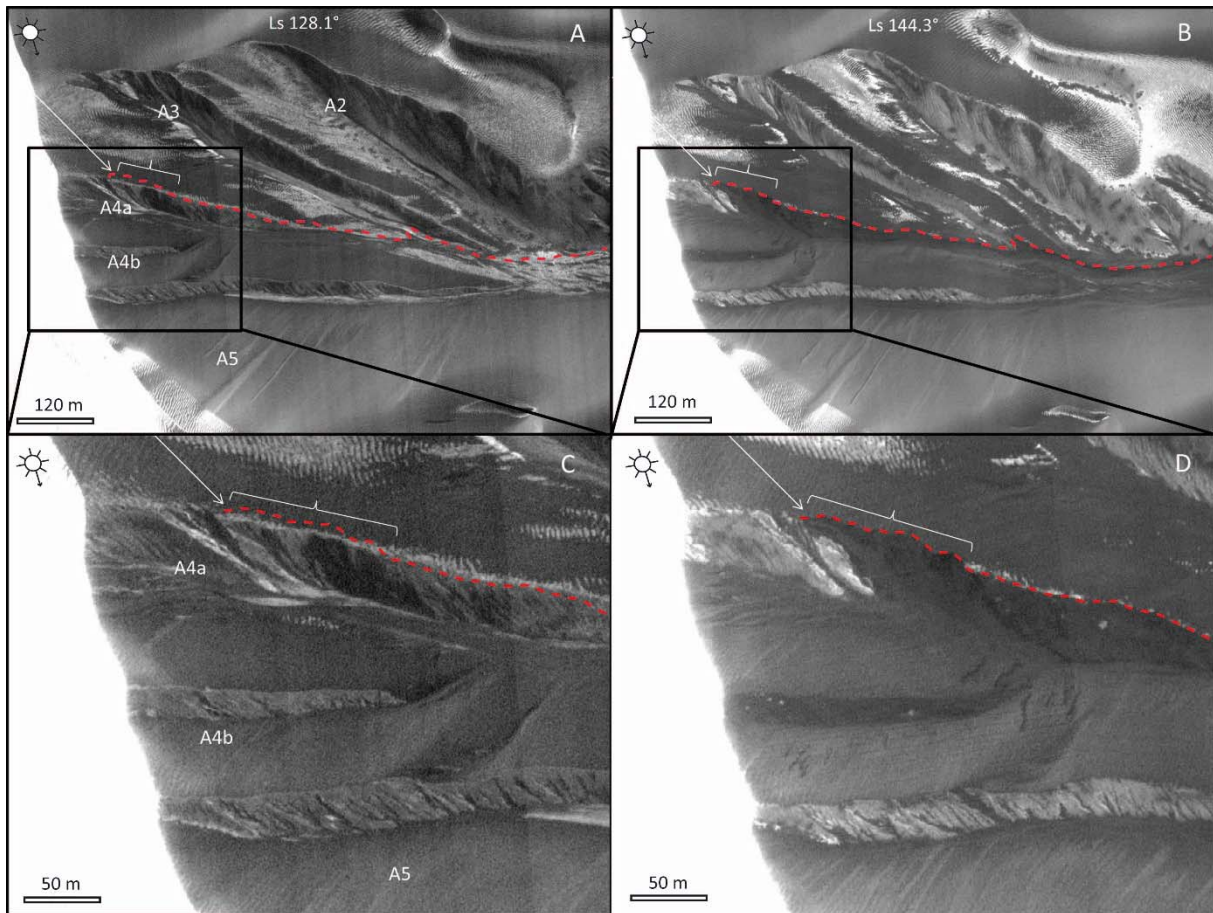
375 Fig. 7. A) Context view of the gully on the Matara Crater dunefield (HiRISE image: PSP_006648_1300
376 L_s 8.8°). B) and C) Detailed view of sub-alcoves A_{4b} and A₅, showing before and after examples of the
377 failures resulting in erosion of the flanks and accumulation on the alcove floor (HiRISE image:
378 PSP_006648_1300, L_s 8.8° MY29 and ESP_029394_1300, L_s 199.8° MY31). The black arrow
379 indicates a reference point and the white arrows the location of accumulated material. D) The total
380 area affected by the failures in the sub-alcoves A_{4a} and A₅ for MY29 to 33, including the erosional scar,
381 the transport zone and the deposited material.

382 **3.3.1.2 Pole-facing flanks: frost and collapse of material**

383 Seasonal frost deposits appear each year during the winter season on some
384 parts of the sinuous gully studied, but not everywhere. These deposits are visible on
385 HiRISE images. This ice can be observed on the alcove, specifically on the pole-
386 facing flanks of each sub-alcove (A₁ to A₅) (Figs. 8AC; 5B). For sub-alcoves A_{4a}, A_{4b}
387 and A₅, seasonal frost is only present on the pole-facing flank (Suppl. Material 2CD),
388 for the other sub-alcoves frost is also visible on the equator-facing flanks (Figs. 8AC;
389 5B). The appearance and disappearance of frost is generally gradual for the sub-
390 alcoves of this gully (Fig. 8), except for some events in sub-alcoves A_{4a}, A_{4b} and A₅
391 where the defrosting is sudden and contemporaneous with channel and apron
392 activity, described in Section 3.3.2. (Fig. 8). This sudden defrost coincides with the
393 collapse of part of the alcove flank (Fig. 8).

394 We observe alternation in the activity of the sub-alcoves A₄ and A₅ (Fig. 5), so the
395 source of the material driving changes downstream in the gully differs over time.

396



397

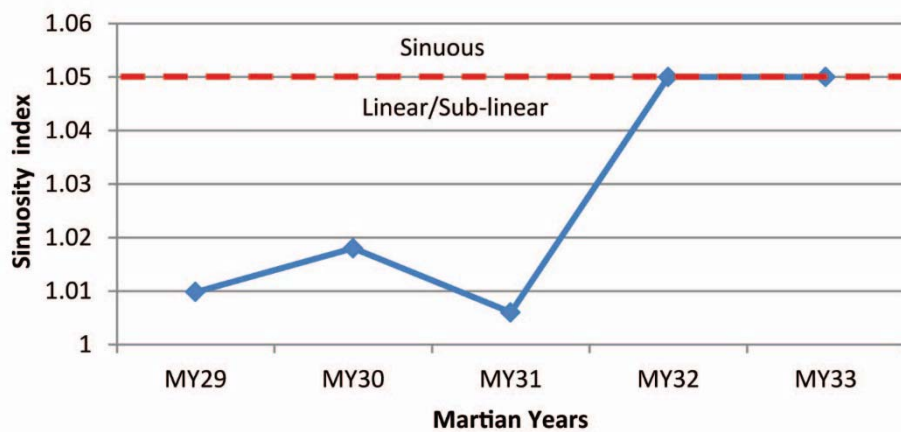
398 Fig. 8. Alcove activity. A) The gully alcove in the middle of winter; seasonal frost is observed mostly on
 399 the south-facing flanks of the alcoves, HiRISE image: ESP_036488_1300, L_s 128.1°. B) Collapse of
 400 one part of the sub-alcove A_{4a}. The seasonal frost disappears from pole-facing flank of the sub-alcove
 401 A_{4a} and material is transported toward the debris apron, HiRISE image: ESP_036910_1300, L_s 144.3°. C)
 402 Detailed view of sub-alcoves A_{4a} and A_{4b} from panel A. D) Detailed view of sub-alcoves A_{4a} and
 403 A_{4b} from panel B. The white arrow indicates a reference point, the white bracket shows the area of
 404 collapse visible in panels B and D, and the red dotted line shows the extent of the activity in sub-
 405 alcove A_{4a}: all parts of the slope below the line are affected by material collapse (changes are visible
 406 in panels B and D).

407 3.3.2 Channel and apron changes

408 3.3.2.1 Channel changes

409 We observed that channel sinuosity initiated and increased during MY29-33 in
 410 this gully system. The sinuosity of the channel is quantified using the sinuosity index
 411 “S” (Fig. 9). In our first observations during MY29 the channel was sub-linear with a
 412 sinuosity index of 1.0098 (Figs. 10A; 9). During MY30, one part of the channel was
 413 abandoned and the channel developed some curvature as indicated by an increase
 414 in the sinuosity index to 1.018 (Figs. 10B; 9). In MY31, the sinuous section developed

415 greater curvature and two terraces appeared on the inside of the bend. The sinuosity
 416 index reduced to 1.006 (Figs. 10C; 9). In MY32 four bends are visible and sinuosity
 417 increased reaching the maximum value of 1.05; (Figs. 10D; 9). Finally during MY33
 418 these bends migrate and part of the channel was abandoned. The sinuosity index
 419 remained stable at 1.05 (Figs. 10E; 9). The lateral bend migration rate is ~ 23 m/yr
 420 calculated on a baseline between $L_s 8.8^\circ$ in MY29 and $L_s 188.6^\circ$ in MY32. The width of
 421 the channel grew from 30 m in MY29 to more than 60 m in MY33.

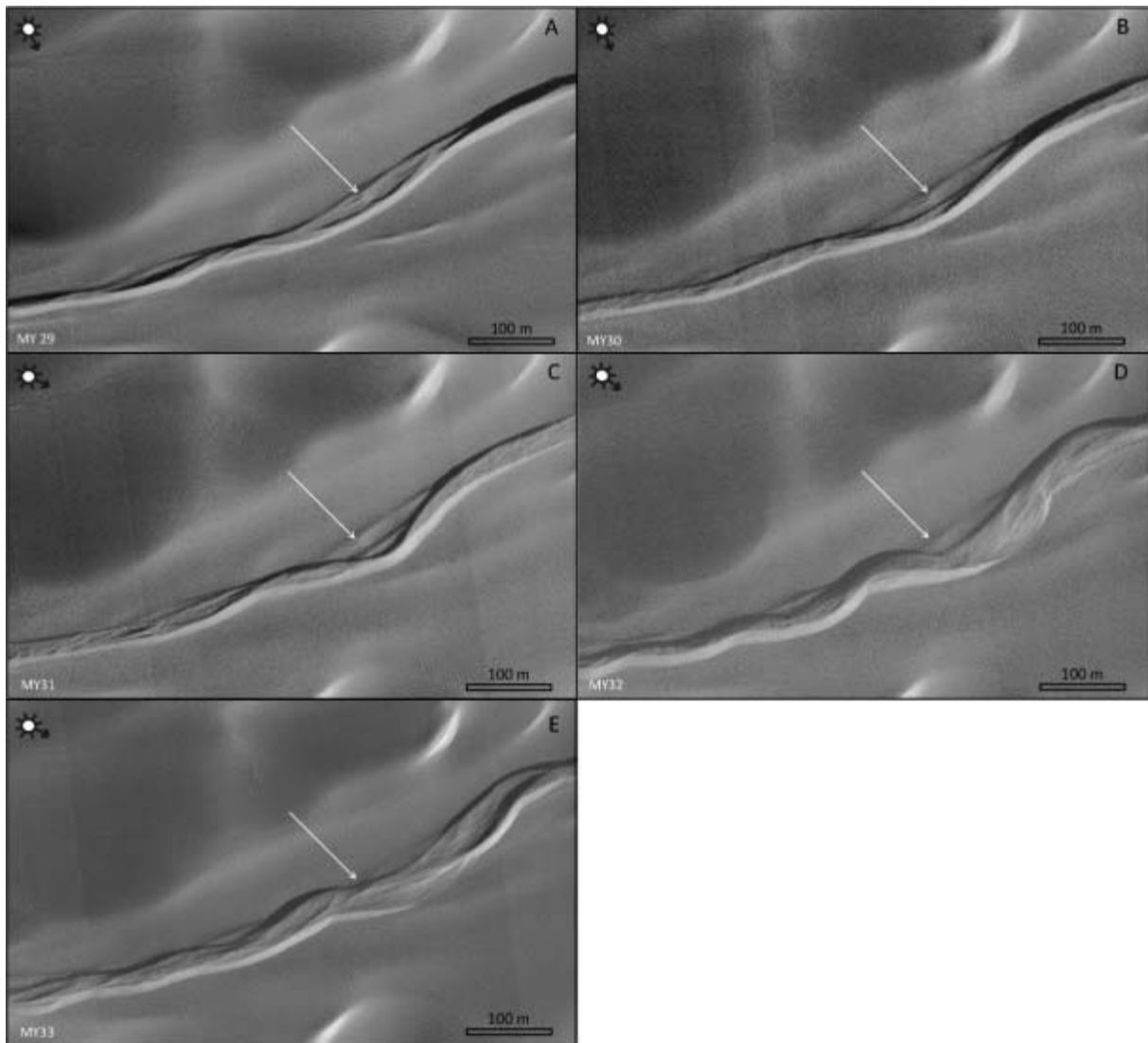


422

423 Fig. 9. Change in the sinuosity index of the channel over 5 martian years (MY29-33).

424

425 We observed an upstream propagation of the channel bends. We observed
 426 the formation of terraces with point bar deposits (Fig. 10BC) and their disappearance
 427 (Fig. 10DE), which demonstrates active erosion and deposition in the channel. We
 428 observed a cycle of transport and backfill. Each pulse of activity transports material
 429 downstream, resulting in the infill of the channel near the apron. As a consequence,
 430 the next pulse can be blocked by this obstacle and the channel infill propagates
 431 upstream (Fig. 5CD). Subsequent events can break through this infill and the cycle
 432 repeats (Fig. 5B). The channel extended more than 140 m in one single year (MY32)
 433 for a total length of 800 m (Figs.11A; 6F; 5B).



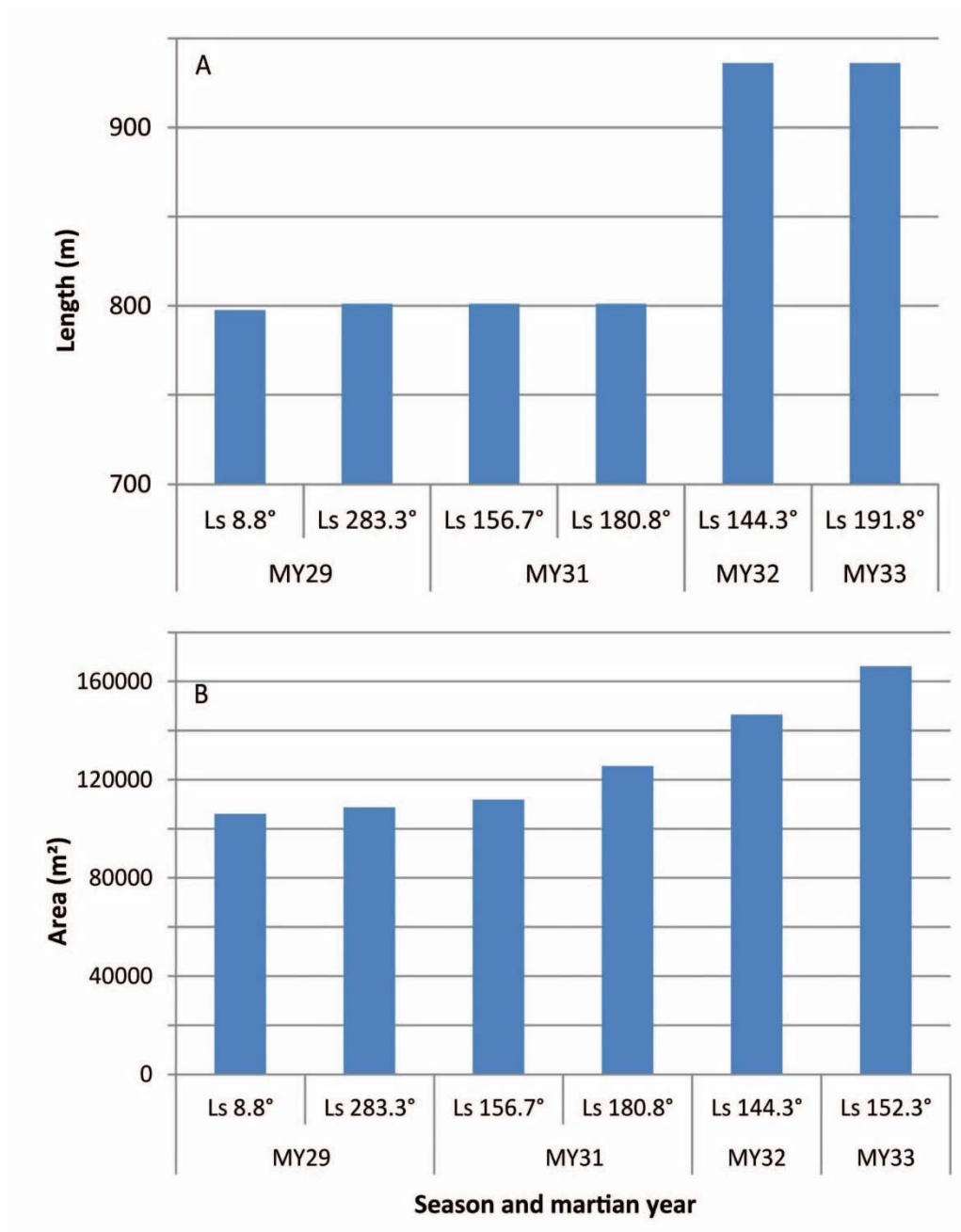
434

435 Fig. 10. Changes in the gully channel over 5 martian years (MY29-33). A) HiRISE image:
 436 PSP_006648_1300, L_s 8.8° (MY29), B) HiRISE image: ESP_020559_1300, L_s 198.9° (MY30), terrace
 437 formation with point bar deposits, C) HiRISE image: ESP_029394_1300, L_s 199.8° (MY31), terrace
 438 formation with point bar deposits, D) HiRISE image: ESP_037965_1300, L_s 188.6° (MY32), terrace
 439 erasure, sinuosity index of the channel reaches 1.05, E) HiRISE image: ESP_046853_1300, L_s 191.8°
 440 (MY33), terrace erasure, sinuosity index of the channel stable at 1.05. The white arrow shows a
 441 reference point and situates the point bar deposits.

442 **3.3.2.2 Debris apron changes**

443 The modification of the debris apron was characterized by measuring the
 444 length (Fig. 11A) and the area changes (Fig. 11B) of the new deposits. These
 445 changes happened at the same time as the channel changes documented above
 446 (Figs. 5AB; Suppl. Material 2AB). The apron deposits can extend by up to ~140
 447 meters over their previous extent in one martian year (Figs. 11A; 6EF; 5AB). MY32
 448 shows the most extensive activity on the gully apron in terms of length propagation

449 (Fig. 11A). Only the northern part of the apron was active over MY29-33 (Figs. 4D;
 450 5). We observed the development of multiple overlapping deposits (Fig. 5BCD).
 451 Between L_s 283.3° MY29 and L_s 144.3° MY32 the activity of the apron was
 452 characterized by the appearance of new deposits without any lengthening (Figs. 11A;
 453 5CD). An average 1.7×10^5 m² of the apron surface is affected by the gully activity
 454 during MY29-33 (Fig. 11B). This area represents around 20% of the total apron area
 455 (7.9×10^5 m²), suggesting such activity has been ongoing, perhaps on the order of
 456 decades.
 457



458

459 Fig. 11. A) Changes in the active apron length ($\pm 10\text{m}$). B) Changes in the active apron area (± 100
460 m^2) over 4 martian years. Image quality in MY30 did not allow us to make measurements on the debris
461 apron.

462 **3.4 Timing of activity**

463 **3.4.1 Timing of alcove activity (A_{4a} , A_{4b} and A_5)**

464 **3.4.1.1 Material accumulation (Equator-facing flanks)**

465 On the equator-facing flanks of the sub-alcoves A_{4a} , A_{4b} and A_5 , we observed
466 material transport and accumulation on the alcove floors (Figs. 7; 5C; Suppl. Material
467 3). During MY30, this activity occurred throughout the period spanning the beginning
468 of winter until the middle of spring (i.e., between $L_s 56.5^\circ$ and 249.9°) (Fig. 12A). For
469 MY31, the activity was observed between $L_s 168.8^\circ$ at the end of winter and $L_s 199.8^\circ$
470 at the beginning of spring (Fig. 12A). In MY32, it occurred at the end of winter
471 between $L_s 164.5^\circ$ and $L_s 176.4^\circ$ (Fig. 12A). For MY33, it started during the middle of
472 winter at $L_s 152.3^\circ$ and was still ongoing at the beginning of spring at $L_s 191.8^\circ$ (Fig.
473 12AE).

474 In general, material accumulation in the alcoves occurs between the beginning of
475 winter and the middle of spring (Fig. 12E). We did not observe seasonal frost on
476 HiRISE images at the location where the material transport occurs (Figs. 8AC; 5B;
477 Suppl. Material 3). This type of activity in the alcove is never observed during
478 summer and autumn in the time period studied, MY29-33 (Fig. 12AE). However, only
479 a few images are available between mid-spring and mid-autumn, which may bias our
480 observations. Moreover, we observe that this activity has a highly variable timing
481 from one martian year to the next (Fig. 12AE).

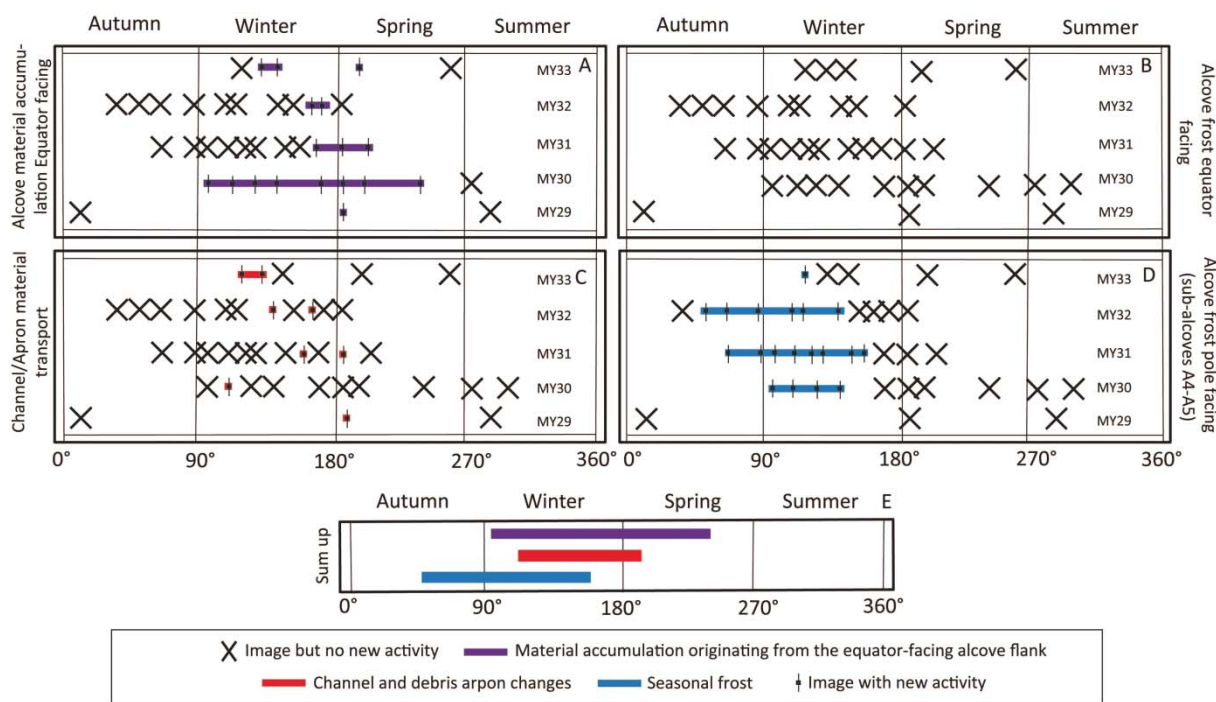
482 **3.4.1.2 Seasonal frost (Pole-facing flanks)**

483 Seasonal frost is only observed on the pole-facing flanks for sub-alcoves A_{4a} ,
484 A_{4b} and A_5 . This frost is visible from $L_s 95.2^\circ$ to $L_s 141.8^\circ$ during MY30, between L_s
485 67.5° and $L_s 156.7^\circ$ during MY31, between $L_s 56.4^\circ$ and $L_s 144.3^\circ$ during MY32 and
486 finally, from $L_s 149.7^\circ$ to $L_s 167.0^\circ$, during MY33 (Fig. 12D). So, for MY29-33
487 seasonal frost is temporally well constrained and observed between the middle of
488 autumn and the middle of winter, between $L_s 67.5^\circ$ and $L_s 167.0^\circ$ (Fig. 12DE). The
489 detailed presence of frost on sub-alcoves A_{4a} , A_{4b} and A_5 is presented in
490 Supplementary Material Fig. 2CD. No seasonal frost is observed on the equator-
491 facing flank of sub-alcove A_5 for MY29-33, where material transport and accumulation
492 is usually observed (Fig. 12B).

493 **3.4.2 Timing of the channel and the apron activity**

494 Changes in the channel and the apron are originate from sub-alcoves A_{4a}, A_{4b}
 495 and A₅. These changes occur contemporaneously at the beginning of winter, at L_s
 496 117.6° in MY30. During MY31, the changes occur between the middle of winter and
 497 the beginning of spring, i.e. between L_s 156.7° and L_s 180.8°. During MY31, the
 498 changes are observed in the middle of winter between L_s 144.3° and L_s 158.5°.
 499 Changes occur between L_s 149.7° and L_s 152.3° for MY33 (Fig. 12CE). When there is
 500 more than one pulse of activity per year, these pulses originate from different sub-
 501 alcoves (Figs. 5BC; Suppl. Material 2AB). We conclude that the activity of the
 502 channel and of the apron is well constrained and occurs each year from winter to the
 503 beginning of spring between L_s 117.6° and L_s 180.8° during MY29-33 (Figs. 12CE;
 504 Suppl. Material 2AB).

505



506

507 Fig. 12. A) Timing of material transport inside the alcove, including only sub-alcoves A_{4a}, A_{4b} and A₅
 508 where material accumulation on the floor of the alcoves can be identified, sourced from failures on the
 509 equator-facing flanks. B) Timing of presence of seasonal frost for sub-alcoves A_{4a}, A_{4b}, A₅ on their
 510 equator-facing flanks. C) Timing of activity for material transport from the alcove to the apron
 511 accompanied by changes in channel sinuosity. D) Timing of the presence of seasonal frost for sub-
 512 alcoves A_{4a}, A_{4b}, A₅ on their pole-facing flanks. Each line represents one martian year and each cross
 513 is a HiRISE image. E) Summary of the information presented in panels A-D.

514 **3.4.3 Timing synthesis**

515 Each year we observed: i) material transport from the equator-facing flanks of
516 the sub-alcoves A_{4a} , A_{4b} and A_5 to their floors, between the beginning of winter and
517 the middle of spring (Fig. 12AE), ii) seasonal frost on the pole-facing flanks of the
518 alcove between the middle of autumn and the end of winter (Figs. 12DE; Suppl.
519 Material 2CD), iii) sudden disappearance indicating collapse of the frost on pole-
520 facing alcove flanks contemporaneous with changes in the channel and debris apron
521 (Figs. 12; Suppl. Material 2). The activity observed in the channel and on the debris
522 apron can occur during winter up until the beginning of spring (Figs. 12CE; Suppl.
523 Material 2AB).

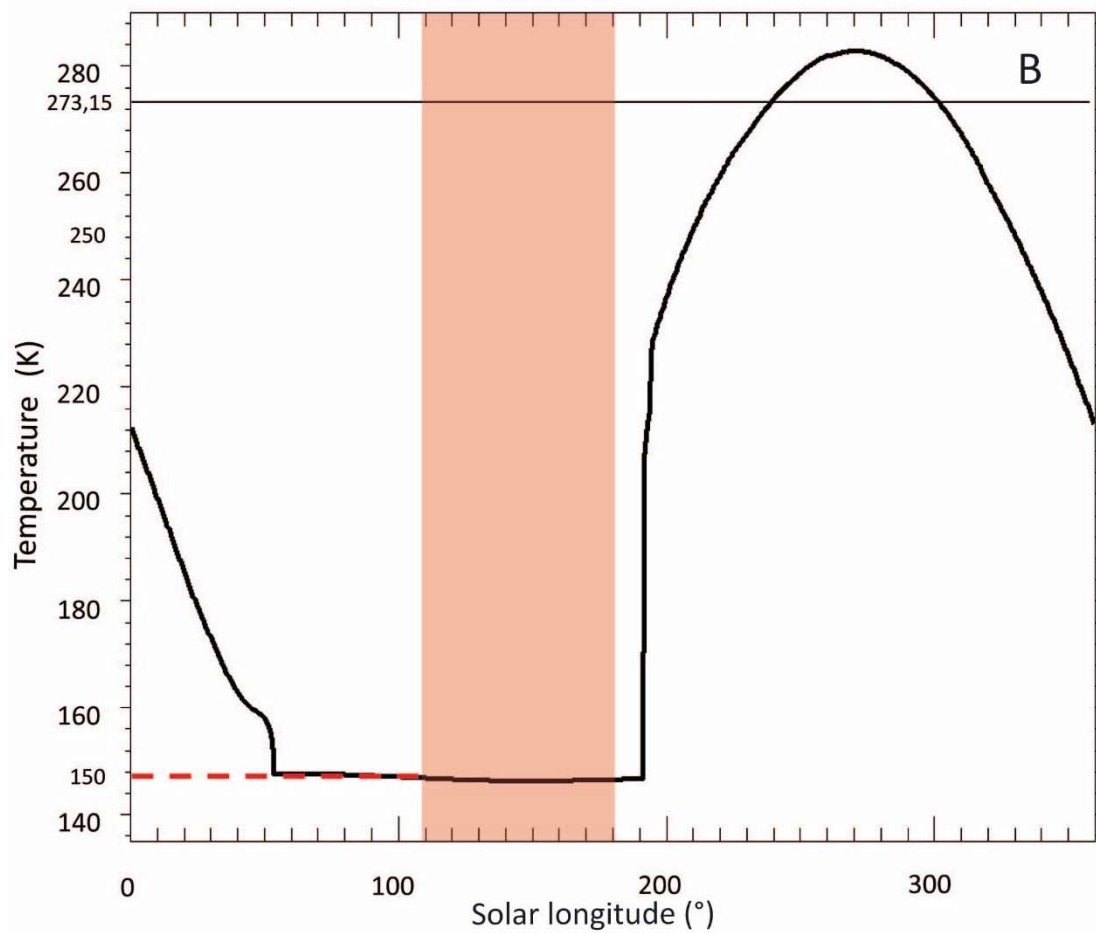
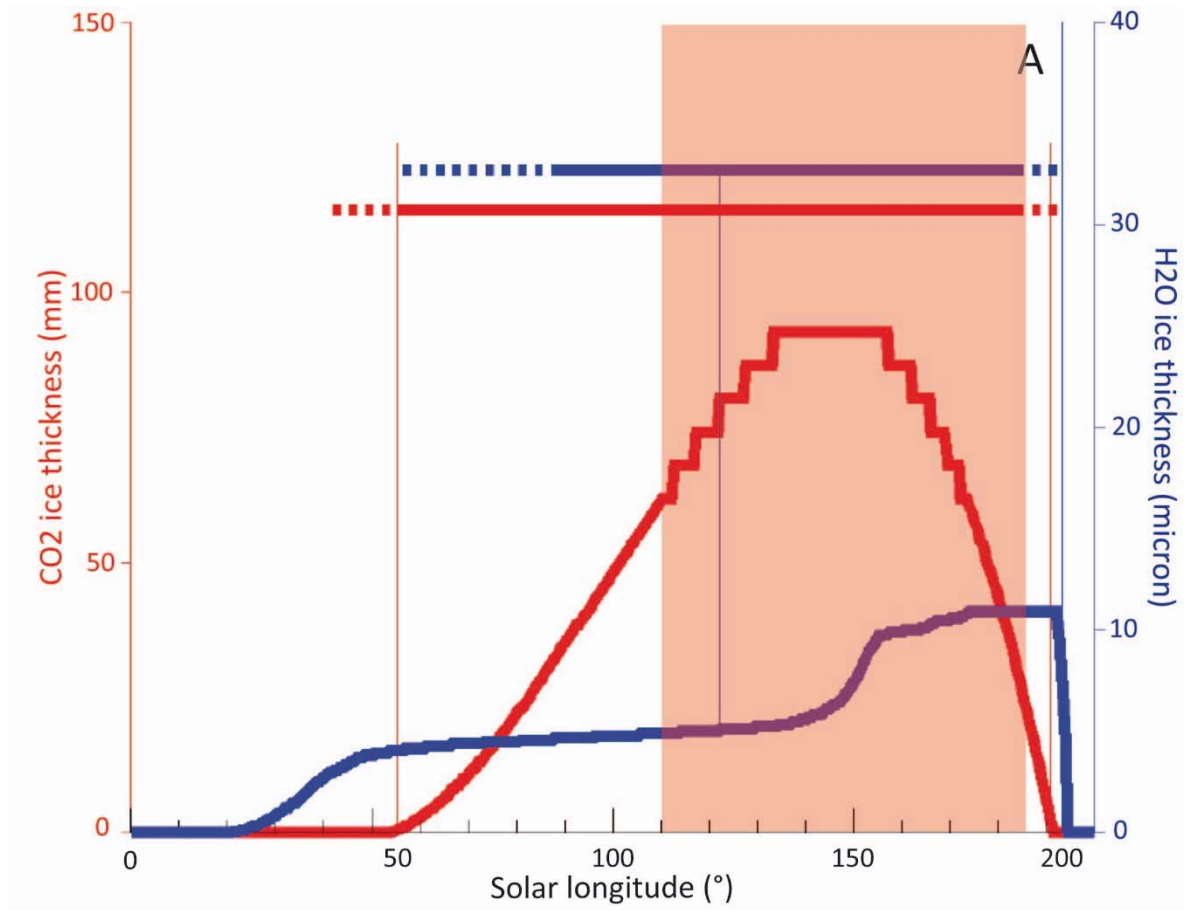
524 **3.5 Modeled temporal evolution in surface temperature and seasonal** 525 **frost composition and thickness**

526 **3.5.1 Seasonal frost deposits**

527 Seasonal frosts occur each year on the Matara Crater dune-gully, particularly
528 in the alcove and on the pole-facing flanks of the sub-alcoves A_{4a} to A_5 (Figs. 8AC;
529 5B). These sub-alcoves are the source of the material that then cause changes in the
530 channel sinuosity and changes on the debris apron. Defrosting of the seasonal ice
531 deposits is thought to play a role in present-day gully activity (e.g., Dundas et al.,
532 2012; 2015; 2017; Diniega et al., 2013) so, we studied frost composition and
533 thickness using a modelling approach calibrated with HiRISE and CRISM data (see
534 section 2.2). The results of the simulations for the pole-facing flank of the sub-alcove
535 A_5 are shown in Fig. 13. The simulations predict that CO_2 frost begins to deposit in
536 the middle of autumn at $L_s \sim 40\text{-}60^\circ$. The CO_2 ice thickness increases to a maximum
537 of 85-130 mm near mid-winter ($L_s 140^\circ\text{-}150^\circ$). After $\sim L_s 150^\circ$, the CO_2 ice thickness
538 decreases and the CO_2 frost totally disappears at $L_s \sim 180\text{-}190^\circ$ (Fig. 13A).

539 Our simulation suggests that H_2O ice is also present in the seasonal frost, but
540 in smaller quantities (i.e., $\sim 10\text{-}11 \mu\text{m}$ thickness). Such a low thickness of water ice is
541 close to the detection limits of near infrared spectroscopy of $\sim 5 \mu\text{m}$ (Vincendon et al.
542 2010b). The simulations predict that water ice first appears at $L_s \sim 20^\circ$ at the
543 beginning of autumn, while evidence for ice in the observations are found at $L_s > 80^\circ$
544 only, which is consistent with the predicted low thickness of water ice that remains
545 around $5 \mu\text{m}$ from $L_s 30^\circ$ to $L_s 150^\circ$ in the model (Fig. 13A). At $L_s 150^\circ$, the model
546 shows an increase in the H_2O ice thickness to $10\text{-}12 \mu\text{m}$ lasting until $L_s 195^\circ$, which is
547 supported by observations of ice over most of that period. At this point, the H_2O ice

548 thickness decreases reaching 0 μm at $L_s \sim 200^\circ$. In summary, H_2O ice is predicted to
549 be present between $L_s 20^\circ$ to $L_s 195^\circ - 200^\circ$, i.e., from the beginning of autumn to the
550 beginning of spring. Once CO_2 has disappeared, the model predicts that some water
551 ice remains for a few days (Fig. 13A), a phenomenon that is predicted to occur
552 frequently on Mars although it has never been observed, probably due to a lack of
553 appropriate timing of observations (Vincendon 2015).



555 Fig. 13. Numerical simulation results for the Matara Crater dunefield (49.5°S; 34.9°E) for pole-facing
556 flanks of the sub-alcove A₅ with 24° slope: A) Composition and thickness of the seasonal frost
557 predicted to be present. The red line shows the CO₂ ice frost thickness (mm) and the blue line shows
558 the H₂O ice thickness (μ). B) Modeled surface temperatures (predicted by the model at 2 pm local
559 time). Temperatures are calculated with a time step of 30 minutes over one martian year. The orange
560 area highlights the period during which channel and apron changes were observed (summarized in
561 Fig. 12).

562 **3.5.2 Surface temperature**

563 Simulations of surface temperature were performed in the same location
564 where frost composition and thickness simulations were performed (Fig. 13B). We
565 observed changes in the channel and apron between L_s 117.6° and L_s 180.8° (Fig.
566 12CE), a period where the alcove is covered by CO₂ ice and during which the model
567 predicts a temperature of about 145-150 K (Fig. 13B). The model shows that during
568 the few days (sols) following the disappearance of CO₂, and once the water ice has
569 disappeared, the temperature of the pole-facing flank quickly increases to reach
570 240K at L_s 200°. Note that these changes in frost and temperature do not concern
571 the adjacent, non-pole-facing, and thus warmer, areas of the alcove.

572 **4 Interpretation and discussion**

573 The transport of material from the alcove to the debris apron is
574 contemporaneous with: modifications on the alcove floor, the increase in channel
575 sinuosity, and the modification of the channel and the apron (Figs. 6; 5).

576 **4.1. Material accumulation and alternating source**

577 Two points seem necessary for the development of sinuosity: 1) material
578 accumulation on the floor of the alcoves of the gully and 2) the alternation of the
579 active sub-alcove.

580 The sub-alcoves A₁ to A₃ do not show any activity that can be linked to the
581 sinuosity development in the gully channel. We do not observe any material
582 accumulation in these sub-alcoves. Sub-alcoves A₄ to A₅ do show material
583 accumulation which is transported in winter through the channel and onto the debris
584 apron of the gully.

585 We do not think that the properties of the material into which the flow is
586 eroding is directly responsible for the development of sinuosity because there are
587 many non-sinuuous gullies observed on other sand dunes (Diniaga et al., 2010;

588 Pasquon et al., 2016). However, erosion of material is a necessary to explain terrace
 589 formation and suggests that the material must be sufficiently unconsolidated to be
 590 incorporated in the flow.

591 We observe alternating activity in sub-alcoves A₄ and A₅ (Fig. 5). The material
 592 transported through the channel and onto the debris apron of this gully does not
 593 originate from exactly the same area of the alcove from one active period to the next
 594 (Fig. 5). This could cause in homogeneities in the spatial distribution of erosion and
 595 deposition in the channel initiating the development of channel sinuosity.

596 4.2. Transport process

597 We hypothesize that the increase in channel sinuosity of the Matara Crater
 598 dune-gully is due to: 1) an alcove material contribution with alternation/variation of the
 599 alcove source location (A₄ to A₅) and 2) a flow process that produces landforms
 600 similar to those created via terrestrial hyper-concentrated flows, as outlined below.

601 To try to understand the processes behind the present-day activity in the gully
 602 on Matara Crater dunefield, we compare our observations with the properties of three
 603 different processes which are known to produce channel bends, or sinuosity on
 604 Earth: river meanders, hyper-concentrated flows and debris flow (Table 2).

Morphological observations of the gully on the Matara Crater dunefield	Terrestrial river meanders	Terrestrial hyper-concentrated flows	Terrestrial debris flows
Material accumulation on one side and erosion on the other side of the channel	X	X	-
No levees	X	X	-
Sinuosity migration	X	X	-
Formation mode: instantaneously	-	-	X
Point bar deposits and lateral migration	X	X	-
Evolution from straight to sinuous	X	X	-
Upstream accumulation	X	X	X
Significant amount of solid material	-	X	X

605 Table 2. Comparison between the sinuous gully studied on Mars and the behavior/morphology of three
606 others processes which can develop channel sinuosity on Earth (Leopold and Wolman, 1960; Hickin,
607 1974; Pierson, 1981; Allen, 1985; Williams, 1986; Johnson et Rodine, 1984; Coussot et Meunier,
608 1996; Allen, 1997). Crosses indicate that the terrestrial analogues possess similarities with the stated
609 properties for the gully on the Matara Crater dunefield and “-“ indicates dissimilarity.

610 Debris flow processes have been proposed as a possible formation
611 explanation of gullies on Mars (Costard et al., 2002; Mangold et al., 2003; Jouannic
612 et al., 2012; 2015). Table 2 shows that very few of the morphological attributes and
613 behavior of the gully on the Matara Crater dunefield are consistent with observations
614 of terrestrial debris flows. There are more morphological and behavioral similarities
615 with meandering rivers and hyper-concentrated flows. The formation mode of a
616 terrestrial meander is in a permanent flow of water. However, abundant liquid water
617 cannot exist under present-day martian conditions: the pressure, temperature and
618 humidity conditions are too low (Hecht, 2002), so we discount this formation process.

619 Hyper-concentrated flows seem to be the best potential analogue for the
620 activity observed in the sinuous gully on Matara Crater dunefield, because they have
621 the most similarities in Table 2. On Earth, hyper-concentrated flow is defined as a
622 two-phase flow of water and sediment, intermediate in concentration between normal
623 streamflow and debris flow or mudflow (Pierson, 2005). The suspended sediment
624 concentration ranges between 20 and 70% (Pierson, 2005; Allen, 1997). However,
625 such a mechanism requires large quantities of liquid water which are inconsistent
626 with present-day martian atmospheric conditions, as described above for meanders.
627 It is possible that the morphologies produced by a hyper-concentrated water flow
628 could also be produced by an alternative fluid, as discussed below.

629 **4.3. Role of CO₂**

630 Our observations of timing and location of the activity producing a sinuous
631 channel suggest that the activity is linked to the seasonal defrosting of CO₂ ice (Figs.
632 8; 12CDE; 13A; 5; Suppl. Material 2). However, the exact relation between CO₂ ice
633 and the numerous seasonal surface processes temporally linked to its defrosting on
634 Mars is not fully understood (e.g., Dundas et al., 2012; Harrison et al., 2015; Pasquon
635 et al., 2018).

636 Sublimation of seasonal CO₂ ice on martian dunes is thought to trigger the formation
637 of dark spots and dark flows (Kieffer, 2000; 2007; Piqueux et al., 2003; Kieffer et al.,

638 2006; Piqueux and Christensen, 2008). These morphologies have no measurable
639 topographic effect (Hansen et al., 2011; Raack et al., 2015). Sublimation of CO₂ ice
640 has also been associated with meter-scale topographic changes observed in “classic”
641 mid-latitude gullies (Pilorget and Forget, 2015; Vincendon, 2015; Dundas et al.,
642 2017). The feasibility of this process as an agent of topographic change has been
643 also been suggested by recent laboratory experiments showing that small amounts of
644 CO₂ frost deposited into a granular medium can cause granular flows on slopes >13°
645 under terrestrial gravity (Sylvest et al., 2015; 2018). However, these experiments did
646 not test whether the subsequent flow would have enough energy to move the bed
647 materials over low slopes for tens to hundreds of meters.

648 Our numerical simulations predict that CO₂ should be present on pole-facing alcove
649 flanks between L_s 40-60° and L_s 180-190° (the middle of autumn to the beginning of
650 spring) on the Matara Crater dunefield (Fig. 13A). The remobilization of the material
651 accumulated on the alcove floor is associated with collapse of the pole-facing alcove
652 flanks which happens at a time of year when our modeling predicts that the CO₂ ice
653 should be at its thickest (Figs. 8; 13A). The changes in channel and apron
654 morphology of the gully occur in winter between L_s 117.6° and L_s 180.8° when
655 seasonal frost is still observed (Fig. 12; Suppl. Material 2). The activity ends when the
656 CO₂ disappears (Fig. 12; Suppl. Material 2) and when the surface temperature of the
657 alcove increases from 145-150K to 210-220K (Fig. 13B). CO₂ gas could play a role in
658 transporting material in the channel and on to the debris apron. Based on our
659 observations, and on comparisons with terrestrial analogues in Table 2, we propose
660 that a hyper-concentrated flow, where the fluid is not constituted by liquid water, but
661 instead by CO₂ gas, could explain this gully activity. Specifically, after falling onto the
662 floor of the alcove, the CO₂ ice should sublimate vigorously via contact with the
663 relatively hot sand previously accumulated at the foot of the alcove. Exposed to more
664 solar insolation, this sand should have a temperature significantly higher than the
665 CO₂ ice sublimation temperature producing a high gas escape rate. This initial and
666 vigorous sublimation of the CO₂ ice triggers a CO₂ gas flow mixed with sand and
667 perhaps some ice and is the process responsible for the gully activity, the
668 development of sinuosity and for the new apron deposits (Table 2). The main activity
669 occurs during the winter and not at the end of winter when temperatures are warmer,
670 because at the end of winter CO₂ ice has almost entirely disappeared from the dune
671 surface and hence there would not be sufficient CO₂ ice to drive vigorous

672 sublimation. At the end of winter, the transport is limited by the reduced availability of
673 CO₂ ice, whereas at the beginning of winter this is not the case, even if the
674 temperature difference between the CO₂ ice and the hot sand could potentially
675 produce high sublimation rate.

676 Determining exactly how a mixture of sublimating CO₂ ice and sand can produce
677 landforms similar to those produced by hyper-concentrated water flows on Earth is a
678 detailed modelling exercise beyond the scope of this study. We acknowledge that
679 important physical differences exist between the fluids of water and CO₂ gas
680 including compressibility, density and buoyancy, which would lead to significant
681 differences in behavior.

682

683 **4.4. Conceptual model for the development of sinuous gully channels**

684 Based on our observations, we propose the following three-step conceptual
685 model for the development of sinuous gully channels (Fig. 14).

686 i) *Material accumulation at the foot of equator-facing alcove flanks (Fig. 14A).*

687 First, during Year N (section 3.3.1.2.), sand falls from equator-facing flanks estimated
688 to be at 24-26° slope in the sub-alcoves A_{4a}, A_{4b} and A₅ (Figs. 2E; 7; 5C; Suppl.
689 Material 1; 3)). The sand accumulates on the floor of the alcove during winter and
690 spring (Figs. 7; 12AE). This accumulation occurs preferentially during the middle of
691 winter and the early spring. Although for MY30 this activity is observed from early
692 winter to late spring (Fig. 12A). Around 31 800 m² or ~7% of the total area of the
693 alcove was resurfaced during MY29-33 (Fig. 7D). While no seasonal frosts were
694 observed on these slopes on HiRISE images (Fig. 12B), CRISM observations
695 indicate that CO₂ and H₂O ice cover most of the Matara Crater dunefield during mid-
696 winter, including equator-facing flanks, flat terrains, and extend to the bottom part of
697 equator-facing flanks with angles lower than 5-10° (Vincendon 2015). Seasonal ice is
698 thus probably very thin or located in the subsurface on the equator-facing flanks
699 where the activity occurs. However, sand material transport and accumulation on the
700 floor of the alcove is also observed at the end of spring (up to L_s 249.9° Fig. 12A),
701 despite the whole Matara Crater dunefield being entirely defrosted by L_s 192° (see
702 e.g., CRISM observation FRT #1C413). As a consequence, some of the observed
703 equator-facing flank material movements are very likely not related to seasonal frost.

704 This activity is never observed during summer and autumn, although the lack of
705 images at the end of spring and during summer during several years may bias our
706 interpretation. Overall, these observations support the idea that i) this activity is
707 seasonally favored, which may result from the role of temperature, ice, dust or wind
708 and ii) this activity can occur when seasonal ice is not present.

709 *ii) Seasonal frost deposition on pole-facing alcove flanks (Fig. 14B).*

710 Second, during Year N+1, seasonal frost mainly composed of CO₂ with some H₂O is
711 observed during the cold seasons of autumn and winter on the pole-facing flanks of
712 the alcove (Figs. 12DE; 13A). The seasonal CO₂ ice deposit is several orders of
713 magnitude thicker than the H₂O ice (Fig. 13A, mm compared to μm). CO₂ is not
714 present over the whole surface of the alcove, it is mainly located on the pole-facing
715 flank of each sub-alcove A₁ to A₅ in autumn and winter between L_s 40-60° and L_s 180-
716 190° (Figs. 13A; 8AC; 5B). The maximum thickness of CO₂ frost deposit occurs at L_s
717 ~140-150° (Fig. 13A).

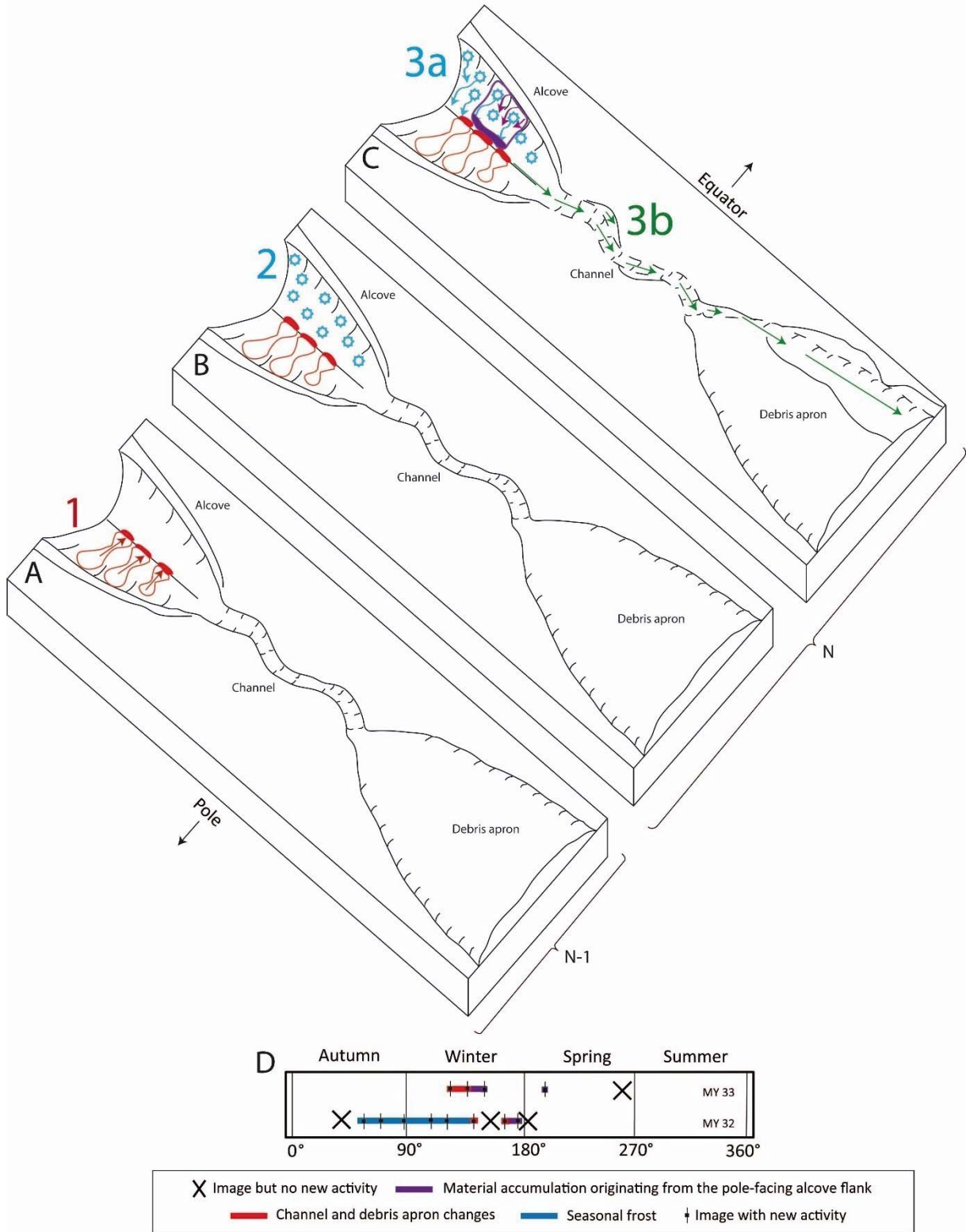
718 *iii) defrosting and development of channel sinuosity (Fig. 14C)*

719 Third, still during Year N+1, contemporaneously with the sudden collapse of seasonal
720 frost during the middle of winter on parts of the pole-facing flanks of sub-alcoves A_{4a}
721 to A₅, solid material is transported from the floors of the alcove to the debris apron
722 (Figs. 8; Suppl. Material 2). This timing is consistent with the retreat of the seasonal
723 frost deposits predicted by our simulations (Fig. 13). More precisely, we observed the
724 collapse of part of the slope of the alcove contemporaneously with the disappearance
725 of seasonal frost (Figs. 8; 12CDE; 13A; Suppl. Material 2). This collapse of sand
726 material on pole-facing flanks includes the seasonal CO₂ and H₂O frost present on
727 the same area (Fig. 8) incorporating them into the flow through the channel and onto
728 the apron.

729 There is a temporal correlation between the seasonal frost retreat and the
730 changes observed in the gully channel and on the apron (Figs.8; 12CDE; 13A; Suppl.
731 Material 2). The development of sinuosity in the channel is contemporaneous with the
732 sand remobilization from the floor of the sub-alcoves A_{4a}, A_{4b} and A₅ on to the debris
733 apron (Fig. 5BCD). After the sand accumulation on the floor of the sub-alcoves A_{4a} to
734 A₅, the material is evacuated toward the debris apron of the gully (Fig. 5CD).

735 Significant morphological changes of the debris apron can be observed such as an
736 elongation and increase in overall area (Figs. 11; 6EF; 5B). A process similar to
737 hyper-concentrated flows on Earth (Table 2) with an alternation of the alcove source
738 location could be responsible for the development of channel sinuosity and for the
739 new apron deposits. CO₂ gas mixed with sand, and likely some CO₂ and H₂O frost,
740 would constitute the flow from the alcove on to the debris apron. The defrosting of
741 seasonal CO₂ ice alone seems unable to cause channel and apron changes when
742 there is no material accumulation in the alcove.

743



744

745 Fig. 14. A) Material accumulation on the alcove floor sourced from the equator-facing part of the
 746 alcove during Year N represented by red shapes and arrows. B) Seasonal frost deposits on the pole-
 747 facing flanks in autumn and winter during Year N+1, represented by blue flakes, C) Sudden defrosting

748 of the seasonal frost deposits, remobilization and transport of material toward the debris apron with
749 development of channel sinuosity during Year N+1, represented by purple and green shapes and
750 arrows, D) Timing of activity: after material accumulation in the alcove occurs in MY32, we observe
751 development of channel sinuosity in MY33 together with deposition on the apron.

752 **5 Conclusions**

753 Here we describe in detail the present day development of a martian sinuous
754 gully over 5 martian years (MY29-33). Our aim was to better understand the
755 dynamics and the processes involved in developing gully channel sinuosity. Our
756 observations show:

757 - CO₂ frost deposits during autumn and winter (L_s 40-60° to L_s 180-190°) on
758 pole-facing alcove flanks in the gully on the Matara Crater dunefield with an
759 estimated ice thickness of ~10 cm.

760 - an accumulation of sand in the alcove, takes place during winter and spring
761 sourced by failures on the equator-facing flank. This material is later remobilized to
762 drive changes in the channel and apron morphology.

763 - material transport from the alcove floors to the debris apron concurrent with
764 channel morphology changes such as sinuosity development and new apron
765 deposits. This activity occurs every year and often coincides with the middle of
766 winter. It is contemporaneous with material collapse on the pole-facing alcove flank
767 and sudden disappearance of the seasonal CO₂ frost in the collapsed zone. We
768 hypothesize that the collapse of solid CO₂ onto the relatively warm loose sand
769 deposits on the alcove floor mixes the materials causing vigorous sublimation and
770 subsequent mobilization as a gas-supported flow.

771 - the development of channel sinuosity occurs over a timescale of 5 martian
772 years and rates of lateral migration is on average of ~ 23 m/yr (calculated over 3
773 MY).

774 A link between CO₂ defrosting and this gully activity is consistent with its
775 timing. We hypothesize that a flow composed of sand, CO₂ gas and ice together with
776 the contribution of material from alternating alcove sources can explain the
777 development of sinuous gully channels.

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784 **References**

785 Allen, J.R.L., 1985. Principles of Physical sedimentology. Georges Allen and Unwin,
786 London.

787 Allen, P., 1997. Earth Surface Processes, blackwell science ed.

788 Auld, K.S., Dixon, J.C., 2016. A classification of martian gullies from HiRISE imagery.
789 Planet. Space Sci. 131, 88-101. <http://dx.doi.org/10.1016/j.pss.2016.08.002>.

790 Balme, M., Mangold, N., Baratoux, D., Costard, F., Gosselin, M., Masson, P., Pinet,
791 P., Neukum, G. 2006. Orientation and distribution of recent gullies in the southern
792 hemisphere of Mars: Observations from High Resolution Stereo Camera/ Mars
793 Express (HRSC/MEX) and Mars Orbiter Camera/Mars Global Surveyor (MOC/MGS)
794 data. J. Geophys. Res. (Planets), 111 (E5). [http://dx.doi.org/](http://dx.doi.org/10.1029/2005JE002607E5)
795 [10.1029/2005JE002607E5](http://dx.doi.org/10.1029/2005JE002607E5).

796 Bandfield, J.L., 2002. Global mineral distributions on Mars. J. Geophys. Res. Planets
797 107 (E6), 5042. <http://dx.doi.org/10.1029/2001JE001510>.

798 Cedillo-Flores, Y., Treiman, A.H., Lasue, J., Clifford, S.M., 2011. CO₂ gas fluidization
799 in the initiation and formation of martian polar gullies. Geophys. Res. Lett. 38,
800 L21202. <http://dx.doi.org/10.1029/2011GL049403>.

801 Christensen, P.R., 2003. Formation of recent martian gullies through melting of
802 extensive water-rich snow deposits. Nature 422, 45-48.
803 <http://doi:10.1038/nature01436>.

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

807 Conway, S. J., & Balme, M. R., 2014. Decameter thick remnant glacial ice deposits on
808 Mars. *Geophysical Research Letters*, 41(15), 5402-5409.
809 <https://doi.org/10.1002/2014GL060314>.

810 Conway, S. J., Balme, M. R., Murray, J. B., Towner, M. C., Okubo, C. H., Grindrod,
811 P. M. 2011. The indication of martian gully formation processes by slope–area
812 analysis. *The Geological Society, London, Special publications*, 356(1), 171–201.
813 <https://doi.org/10.1144/SP356.10>.

814 Conway, S. J., Harrison, T. N., Soare, R. J., Britton, A. W., and Steele, L.J., 2017.
815 New slope-normalised global gully density and orientation maps for Mars. *The*
816 *Geological Society of London, Special publications*, 467.
817 <https://doi.org/10.1144/SP467.3>.

818 Conway, S. J., de Haas T. and Harrison, 2018. Martian gullies: a comprehensive
819 review of observations, mechanisms and insights from Earth analogues. *The*
820 *Geological Society of London, Special publications*, 467.
821 <https://doi.org/10.1144/SP467.14>.

822 Costard, F., Forget, F., Mangold, N., Peulvast, J.P., 2002. Formation of recent
823 Martian debris flows by melting of near-surface ground ice at high obliquity. *Planet.*
824 *Sci.* 295, 110-113. <http://dx.doi.org/10.1126/science.1066698>.

825 Cousot, P. and Meunier, M. 1996. Recognition, classification and mechanical
826 description of debris flows. *Earth Sci. Reviews* 40, 209-227. [http://doi:10.1016/0012-](http://doi:10.1016/0012-8252(95)00065-8)
827 [8252\(95\)00065-8](http://doi:10.1016/0012-8252(95)00065-8).

828 Di Achille, G., Silvestro, S., Ori, G.G., 2008. Defrosting processes on dark dunes:
829 new insights from HiRISE images at Noachis and Aonia Terrae, Mars. In: *Planetary*
830 *Dunes Workshop*, pp. 27-28.

831 Dickson, J., Head, J., Kreslavsky, M., 2007. Martian gullies in the southern mid-
832 latitudes of Mars: Evidence for climate-controlled formation of young fluvial features
833 based upon local and global topography. *Icarus* 188, 315-323.
834 <http://dx.doi.org/10.1016/j.icarus.2006.11.020>.

835 Diniega, S., Byrne, S., Bridges, N.T., Dundas, C.M., McEwen, A.S., 2010.
836 Seasonality of present-day martian dune-gully activity. *Geology* 38, 1047–1050.
837 <http://dx.doi.org/10.1130/G31287.1>.

838 Diniega, S., Hansen, C.J., McElwaine, J.N., Hugenholtz, C.H., Dundas, C.M.,
839 McEwen, A.S., Bourke, M.C., 2013. A new dry hypothesis for the formation of Martian
840 linear gullies. *Icarus* 225, 526-537. <http://dx.doi.org/10.1016/j.icarus.2013.04.006>.

841 Dundas, C.M., Bramson, A.M., Ojha, L., Wray, J.J., Mellon, M.T., Byrne, S., McEwen,
842 A.S., Putzig, N.E., Viola, D., Sutton, S., Clark, E., Holt, J.W. 2018. Exposed sub-
843 surface ice sheets in the Martian mid-latitudes. *Sciences*, 359, 199-201.
844 <http://doi.org/10.1126/science.aao1619>.

845 Dundas, C.M., Diniega, S., Hansen, C.J., Byrne, S., McEwen, A.S., 2012. Seasonal
846 activity and morphological changes in Martian gullies. *Icarus* 220, 124-143.
847 <http://dx.doi.org/10.1016/j.icarus.2012.04.005>.

848 Dundas, C.M., Diniega, S., McEwen, A.S., 2015. Long-term monitoring of martian
849 gully formation and evolution with MRO/HiRISE. *Icarus* 251, 244-263.
850 <http://dx.doi.org/10.1016/j.icarus.2014.05.013>.

851 Dundas, C.M., McEwen, A.S., Diniega, S., Byrne, S., Martinez-Alonso, S., 2010. New
852 and recent gully activity on Mars as seen by HiRISE. *Geophys. Res. Lett.* 37,
853 L07202. <http://dx.doi.org/10.1029/2009GL041351>.

854 Dundas, C. M., McEwen, A. S., Diniega, S., Hansen, C. J., Byrne, S., McElwaine, J
855 .N., 2017. The formation of gullies on Mars today. The Geological Society, London,
856 Special publications, 467. <https://doi.org/10.1144/SP467.5>.

857 Edwards, S.F., Liverpool, T.B., 1995. Dynamics of a Meandering River. *Phys. Rev.*
858 *Lett.* 75, 3016. <https://doi.org/10.1103/PhysRevLett.75.3016>.

859 Fenton, L. K., & Hayward, R. K., 2010. Southern high latitude dune fields on Mars:
860 Morphology, aeolian inactivity, and climate change. *Geomorphology*, 121(1-2), 98-
861 121. <https://doi.org/10.1016/j.geomorph.2009.11.006>.

862 Forget, F., Hourdin, F., Fournier, R., Hourdin, C., Talagrand, O., Collins, M., Lewis, S.
863 R., Read, P. L., Huot, J. P., 1999. Improved general circulation models of the martian

864 atmosphere from the surface to above 80 km. *Journal of Geophysical Research*
865 *Planets*, 104(E10), 24,155–24,175. <https://doi.org/10.1029/1999JE001025>.

866 Forget, G., Ferron, B., Mercier, H., 2008. Combining argo profiles with a general
867 circulation model in the north atlantic. Part 1: Estimation of hydrographic and
868 circulation anomalies from synthetic profiles, over a year. *Ocean Modelling*, 20(1), 1–
869 16. <https://doi.org/10.1016/j.ocemod.2007.06.001>.

870 Gaidos, E.J. 2001. Cryovolcanism and the Recent Flow of Liquid Water on Mars.
871 *Icarus* 153, 218-223. <http://doi:10.1006/icar.2001.6649>.

872 Gardin, E., Allemand, P., Quantin, C., Thollot, P., 2010. Defrosting, dark flow
873 features, and dune activity on Mars: Example in Russell crater. *J. Geophys. Res.*
874 115, 1–9. <http://dx.doi.org/10.1029/2009JE003515>.

875 Hauber, E., Reiss, D., Ulrich, M., Preusker, F., Trauthan, F., 2011. Landscape
876 evolution in Martian mid-latitude regions: insights from analogous periglacial
877 landforms in Svalbard. *The Geological Society of London, Special Publications*, 356.
878 <https://doi.org/10.1144/SP356.7>.

879 Hansen, C.J., Bourke, M., Bridges, N.T., Byrne, S., Colon, C., Diniega, S., Dundas,
880 C., Herkenhoff, K., McEwen, A., Mellon, M., Portyankina, G., Thomas, N.2011.
881 Seasonal erosion and restoration of Mars' northern polar dunes. *Science* 331, 575–
882 578. <http://dx.doi.org/10.1126/science.1197636>.

883 Harrison, T.N., Osinski, G.R., Tornabene, L.L., Jones, E., 2015. Global
884 documentation of gullies with the Mars Reconnaissance Orbiter Context Camera and
885 implications for their formation. *Icarus* 252, 236–254.
886 <http://dx.doi.org/10.1016/j.icarus.2015.01.022>.

887 Hartmann, W. K., 2001. Martian seeps and their relation to youthful geothermal
888 activity. *Space Sci. Reviews* 96, 405-410. http://doi:10.1007/978-94-017-1035-0_15.

889 Hayward, R.K., Fenton, L.K., Titus, T.N., 2014. Mars Global Digital Dune Database
890 (MGD3): Global dune distribution and wind pattern observations. *Icarus* 230, 38–46.
891 <http://dx.doi.org/10.1016/j.icarus.2013.04.011>.

892 Hecht, M. H. (2002), Metastability of liquid water on mars, *Icarus*, 156(2), 373–386.
893 <https://doi.org/10.1006/icar.2001.6794>.

894 Heldmann, J. H., Mellon, M. T. 2004. Observations of martians gullies and
895 constraints on potential formation mechanisms. *Icarus* 168, 285-304.
896 <http://dx.doi.org/10.1016/j.icarus.2003.11.024>.

897 Heldmann, J. L., Toon, O. B., Pollard, W. H., Mellon, M. T., Pitlick, J., McKay, C. P.,
898 and Andersen, D. T. 2005. Formation of Martian gullies by the action of liquid water
899 flowing under current Martian environmental conditions. *J. Geophys. Res.* 110,
900 E05004. <http://doi:10.1029/2004JE002261>.

901 Herkenhoff, K.E., Vasavada, A.R., 1999. Dark material in the polar layered deposits
902 and dunes on Mars. *J. Geophys. Res.* 104 (E7), 16487-16500.
903 <http://dx.doi.org/10.1029/1998JE000589>.

904 Hickin, E., 1974. The development of meanders in natural river-channel, *American*
905 *Journal of Science*, 274, 414–442. <https://doi.org/10.2475/ajs.274.4.414>.

906 Hoffman, N., 2002. Active Polar gullies on Mars and the Role of Carbon Dioxide.
907 *Astrobiology* 2, 313-323. <http://doi:10.1089/153110702762027899>.

908 Hugenholtz, C.H. 2008. Frosted granular flow: A new hypothesis for mass wasting in
909 martian gullies. *Icarus* 197, 65-72. <http://dx.doi.org/10.1016/j.icarus.2008.04.010>.

910 Ishii, T., Sasaki, S., 2004. Formation of recent martian gullies by avalanches of CO₂
911 frost. *Lunar Planet. Sci.* 35. Abstract 1556.

912 Johnson, A., Rodine, J., 1984. Debris flow, Slope instability, pp. 257–361.

913 Jouannic, G., Gargani, J., Conway, S.J., Costard, F., Balme, M.R., Patel, M.R.,
914 Massé, M., Marmo, C., Jomelli, V., Ori, G.G., 2015. Laboratory simulation of debris
915 flows over sand dunes: Insights into gully-formation (Mars). *Geomorphology* 231,
916 101–115. <http://dx.doi.org/10.1016/j.geomorph.2014.12.007>.

917 Jouannic, G., Gargani, J., Costard, F., Massé, M., Bourgeois, O., Carter, J., Schmidt,
918 F., Marmo, C., Ori., G., Nachon, M., Pasquon, K., 2018. Morphological
919 characterization of landsforms produced by springtime seasonal activity on Russell

920 dune (Mars), The Geological Society, London, Special publications.
921 <https://doi.org/10.1144/SP467.16>.

922 Jouannic, G., Gargani, J., Costard, F., Ori, G.G., Marmo, C., Schmidt, F., Lucas, A.,
923 2012. Morphological and mechanical characterization of gullies in a periglacial
924 environment: The case of the Russell crater dune Mars. *Planet.Space. Sci.* 71, 38-
925 54. <http://dx.doi.org/10.1016/j.pss.2012.07.005>.

926 Kereszturi, A., Möhlmann, D., Berczi, S., Ganti, T., Kuti, A., Sik, A., Horvath, A.,
927 2009. Recent rheologic processes on dark polar dunes of Mars: Driven by interfacial
928 water? *Icarus* 201, 492-503. <http://dx.doi.org/10.1016/j.icarus.2009.01.014>.

929 Kieffer, H. H., 2000. Annual punctuated CO₂ slab-ice and jets on Mars. 2nd Int. Conf.
930 Mars Polar Sci. Abstract 4095.

931 Kieffer, H.H., 2007. Cold jets in the Martina polar caps, *J. Geophys. Res.* 112.
932 E08005. <http://dx.doi.org/10.1029/2006JE002816>.

933 Kieffer, H.H., Christensen, P.R., Titus, T.N., 2006. CO₂ jets formed by sublimation
934 beneath translucent slab ice in Mars seasonal south polar ice cap. *Nature* 442, 793-
935 796. <http://dx.doi.org/10.1038/nature04945>.

936 Knauth, J.P., Burt, D.M., 2002. Eutectic brines on Mars: Origin and possible relation
937 to young seepage features. *Icarus* 158, 267-271.
938 <http://dx.doi.org/10.1006/icar.2002.6866>.

939 Kossacki, K. J., Markiewicz, W. J., 2004. Seasonal melting of surface water ice
940 condensing in martian gullies. *Icarus* 171, 272-283.
941 <https://doi.org/10.1016/j.icarus.2004.05.018>.

942 Lee, P., Cockell, C. S., Marinova, M. M., McKay C. P., Rice, J. W., 2001. Snow and
943 Ice Melt Flow Features on Devon Island, Nunavut, Arctic Canada as Possible
944 Analogs for Recent Slope Flow Features on Mars. *Lunar and Planetary Science*
945 Conference 32 (abstract 1809).

946 Lemmon, M. T., Wolff, M. J., Bell, J. F., Smith, M. D., Cantor, B. A., Smith, P. H.
947 2015. Dust aerosol, clouds, and the atmospheric optical depth record over 5 mars

948 years of the mars exploration rover mission. *Icarus*, 251, 96–111.
949 <https://doi.org/10.1016/j.icarus.2014.03.029>.

950 Leopold, L. B., and Wolman, M. G., 1960. River meanders, *Geological Society of*
951 *America Bulletin*, 71(6), 769–793. [https://doi.org/10.1130/0016-](https://doi.org/10.1130/0016-7606(1960)71[769:RM]2.0.CO;2)
952 [7606\(1960\)71\[769:RM\]2.0.CO;2](https://doi.org/10.1130/0016-7606(1960)71[769:RM]2.0.CO;2).

953 Malin, M.C., Edgett, K.S., Posiolova, L.V., McColley, S.M., NoeDobrea, E.Z., 2006.
954 Present-Day Impact Cratering Rate and Contemporary Gully Activity on
955 Mars. *Science* 314, 1573. <http://doi10.1126/science.1135156>.

956 Malin, M.C., Edgett, K.S., 2000. Evidence for recent groundwater seepage and
957 surface runoff on Mars. *Sciences* 288, 2330-2335.
958 <http://dx.doi.org/10.1126/science.288.5475.233>.

959 Mangold, N., Costard, F. Forget. F., 2003. Debris flows over sand dunes on Mars:
960 Evidence for liquid water, *J. Geophys. Res.*, 108 (E4), 5027.
961 <http://dx.doi.org/10.1029/2002JE001958>.

962 Mangold, N., Mangeney, A., Migeon, V. Ansan, V., Lucas, A., Baratoux, D., Bouchut,
963 F., 2010. Sinuous gullies on Mars: Frequency, distribution, and implications for flow
964 properties. *J. Geophys. Res.* 115, E11001. <http://dx.doi.org/10.1029/2009JE003540>.

965 Massé, M., Conway, S.J., Gargani, J., Patel, M.R., Pasquon, K., McEwen, A., Carpy,
966 S., Chevrier, V., Balme, M., Ojha, L., Vincendon, M., Poulet, F., Costard, F.,
967 Jouannic, G., 2016. Transport processes induced by metastable boiling water under
968 Martian surface conditions. *Nature geosc.* 9, 425-428. <http://doi:10.1038/NGEO2706>.

969 McEwen, A. S. et al., 2010. The High Resolution Imaging Science Experiment
970 (HiRISE) during MRO's Primary Science Phase (PSP). *Icarus* 205, 2-37.
971 <http://dx.doi.org/doi:10.1016/j.icarus.2009.04.023>.

972 McEwen, A. S., et al. (2007), Mars Reconnaissance Orbiter's High Resolution
973 Imaging Science Experiment (HiRISE), *Journal of Geophysical Research: Planets*,
974 112(E5). <https://doi.org/10.1029/2005JE002605>.

975 Mellon, M.T., Feldman, W.C., Prettyman, T.H., 2004. The presence and stability of
976 ground ice in the southern hemisphere of Mars. *Icarus* 169, 324–340.
977 <https://doi.org/10.1016/j.icarus.2003.10.022>.

978 Mellon, M.T., Philips, R.J., 2001. Recent gullies on Mars and the source of liquid
979 water. *J.Geophys.Res.*106 (E10) 23165-23179. <http://doi:10.1029/2000JE001424>.

980 Miyamoto, H., Dohm, J. M., Baker, V. R., Beyer, R. A., Bourke, M., 2004. Dynamics
981 of unusual debris flows on martian sand dunes, *Geophysical Research Letters*,
982 31(13). <https://doi.org/10.1029/2004GL020313>.

983 Murchie, S. L., et al. 2004, CRISM (Compact Reconnaissance Imaging Spectrometer
984 for Mars) on MRO (Mars Reconnaissance Orbiter), *Instruments, Science, and*
985 *Methods for Geospace and Planetary Remote Sensing*, vol. 5660, pp. 66–78,
986 International Society for Optics and Photonics. <http://doi.org/10.1117/12.578976>.

987 Musselwhite, D.S., Swindle, T.D., Lunine, J.I., 2001. Liquid CO₂ breakout and the
988 formation of recent small gullies on Mars. *Geophys. Res. Lett.* 28, 1283-1285.
989 <http://doi:10.1029/2000GL012496>.

990 Ojha, L., Wilhelm, M. B., Murchie, S. L., McEwen, A. S., Wray, J. J., Hanley, J.,
991 Massé, M., and Chojnacki, M., 2015. Spectral evidence for hydrated salts in recurring
992 slope lineae on Mars, *Nature Geoscience*, 8(11), 829–
993 832. <http://dx.doi.org/10.1038/ngeo2546>.

994 Paige, D.A., Keegan, K.D., 1994. Thermal and albedo mapping of the polar regions
995 of Mars using Viking thermal mapper observations: 2. South polar region. *J.*
996 *Geophys. Res.* 99 (E12), 25993-2601. <http://dx.doi.org/10.1029/93JE03429>.

997 Pasquon , K., Gargani, J., Massé, M., Conway, S .J., 2016. Present-day formation
998 and seasonal evolution of linear dune gullies on Mars. *Icarus* 274, 195-210.
999 <http://dx.doi.org/10.1016/j.icarus.2016.03.024>.

1000 Pasquon, K., Gargani, J., Nachon, M., Conway, S. J., Massé, M., Jouannic, G.,
1001 Balme, M. R., Costard, F., Vincendon, M., 2018. Are different martian gully
1002 morphologies due to different processes on the kaiser dune field ? *The Geological*
1003 *Society of London, Special publication*, 467. <https://doi.org/10.1144/SP467.13>.

1004 Pierson, T. C., 2005. Hyperconcentrated flow—transitional process between water
1005 flow and debris flow. *Debris-flow hazards and related phenomena*, Springer, 159-
1006 202.

1007 Pierson, T. C., 1981. Dominant particle support mechanisms in debris flows at
1008 Mt. Thomas, New Zealand, and implications for flow mobility. *Sedimentology*, 28(1), 49–
1009 60. <https://doi.org/10.1111/j.1365-3091.1981.tb01662.x>.

1010 Pilorget, C., Forget, F., 2015. Formation of gullies on Mars by debris flows triggered
1011 by CO₂ sublimation. *Nature Geosc.* 9, 65-69. <http://dx.doi.org/10.1038/NGEO2619>.

1012 Piqueux, S., Byrne, S., Richardson, M., 2003. Sublimation of Mars southern seasonal
1013 CO₂ ice cap and the formation of spiders. *J. Geophys. Res.* 108 (E8) 5084.
1014 <http://dx.doi.org/10.1029/2002JE002007>.

1015 Piqueux, S., Christensen, P.R., 2008. North and south sub-ice gas flow and venting
1016 of the seasonal caps of Mars: A major geomorphological agent. *J. Geophys. Res.*
1017 *Planets* 113 (E6). <http://dx.doi.org/10.1029/2007JE003009>.

1018 Raack, J., Reiss, D., Appéré, T., Vincendon, M., Ruesch, O., Hiesinger, H., 2015.
1019 Present-day seasonal gully activity in a south polar pit (Sisyphi Cavi) on Mars. *Icarus*
1020 251, 226-243. <http://dx.doi.org/10.1016/j.icarus.2014.03.040>.

1021 Reiss, D., Jaumann, R., 2003. Recent debris flows on Mars: Seasonal observations
1022 of the Russell Crater dunefield. *Geophys. Res. Lett.* 30 (6):060000–1.
1023 <http://dx.doi.org/10.1029/2002GL016704>.

1024 Reiss, D., Erkeling, G., Bauch, K.E. and Hiesinger, H. 2010. Evidence for present day
1025 Gully on the Russell crater dunefield, Mars. *Geophys. Res. Lett.* 37, L06203.
1026 <http://dx.doi.org/10.1029/20090421192>.

1027 Schorghofer, N., Edgett, K.S., 2006. Seasonal surface frost at Low latitudes on Mars.
1028 *Icarus* 180, 321–334. <http://dx.doi.org/10.1016/j.icarus.2005.08.022>.

1029 Shinbrot, T., Duong, N.H., Kwan, L., Alvarez, M.M., 2004. Dry granular flows can
1030 generate surface features resembling those seen in martian gullies. *Proc. Natl. Acad.*
1031 *Sci.* 101, 8542-8546. [http://doi: 10.1073/pnas.0308251101](http://doi:10.1073/pnas.0308251101).

1032 Smith, D. E., Zuber, M. T., Neumann, G. A. 2001. Seasonal Variations of Snow
1033 Depth on Mars. *Science*, 294, 2141–2146.
1034 <http://dx.doi.org/10.1126/science.1066556>.

1035 Spiga, A., Forget, F., 2008. Fast and accurate estimation of solar irradiance on
1036 martian slopes. *Geophysical Research Letters*, 35(15).
1037 <https://doi.org/10.1029/2008GL034956>.

1038 Sylvest, M.E., Conway, S.J., Patel, M.R., Dixon, J., Barnes, A., 2015. Laboratory
1039 observations of mass wasting triggered by sublimation of condensed CO₂ frost under
1040 Martian conditions. *Lunar Planet.Sci.* 46. Abstract 2667.

1041 Sylvest, M. E., Dixon, J.C., Conway, S.J., Patel, M.R., McElwaine, J.N., Hagermann,
1042 A., Barnes, A, 2018. CO₂ sublimation in Martian gullies: laboratory experiments at
1043 varied slope angle and regolith grain sizes. The Geological Society, London, Special
1044 publications, 467. <https://doi.org/10.1144/SP467.11>.

1045 Thomas, P., 1982. Present wind activity on Mars - Relation to large latitudinal zoned
1046 sediment deposits. *J. Geophys. Res.* 87, 9999-10008.
1047 <http://dx.doi.org/10.1029/JB087iB12p09999>.

1048 Treiman, A.H., 2003. Geologic setting of martian gullies: implications for their origins.
1049 *J. Geophys. Res.* 108 (E4), 8031. <http://doi:10.1029/2002JE001900>.

1050 Vincendon, M., Mustard, J., Forget, F., Kreslavsky, M., Spiga, A., Murchie, S.,
1051 Bibring, J-P., 2010a. Near-tropical subsurface ice on Mars. *Geophys. Res. Lett.* 37,
1052 L01202. <http://dx.doi.org/10.1029/2009GL041426>, 2010.

1053 Vincendon, M., Forget, F., Mustard, J., 2010b. Water ice at low to mid-latitudes on
1054 Mars. *J. Geophys. Res.* 115, E10001. <http://dx.doi.org/10.1029/2010JE003584>,
1055 2010.

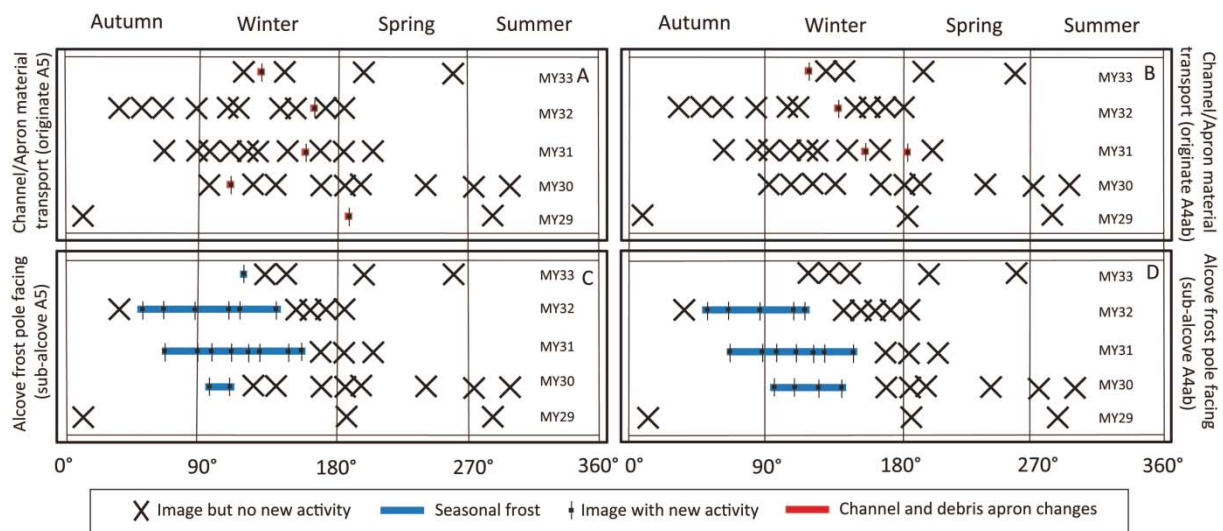
1056 Vincendon, M. 2015. Identification of Mars gully activity types associated with ice
1057 composition. *J. Geophys. Res. Planets*, 120.
1058 <http://dx.doi.org/doi:10.1002/2015JE004909>.

- 1059 Védie, E., Costard, F., Font, M., and Lagarde, J., 2008. Laboratory simulations of
1060 martian gullies on sand dunes, *Geophysical Research Letters*, 35(21).
1061 <https://doi.org/10.1029/2008GL035638>.
- 1062 Williams, G.P. 1986. River meanders and channel size. *Journal of Hydrology*, 88,
1063 147-164. [https://doi.org/10.1016/0022-1694\(86\)90202-7](https://doi.org/10.1016/0022-1694(86)90202-7).
- 1064 Williams, K.E., Toon, O.B., Heldmann, J.L., Mellon, M.T., 2009. Ancient melting of
1065 mid-latitude snowpacks on Mars as a water source for gullies. *Icarus* 200, 418-425.
1066 <http://dx.doi.org/10.1016/j.icarus.2008.12.013>.
- 1067 Ward, A. W., Doyle, K. B., 1983. Speculation on Martian north polar wind circulation
1068 and the resultant orientations of polar sand dunes. *Icarus* 55, 420-431.
1069 [http://dx.doi.org/10.1016/0019-1035\(83\)90112-4](http://dx.doi.org/10.1016/0019-1035(83)90112-4).

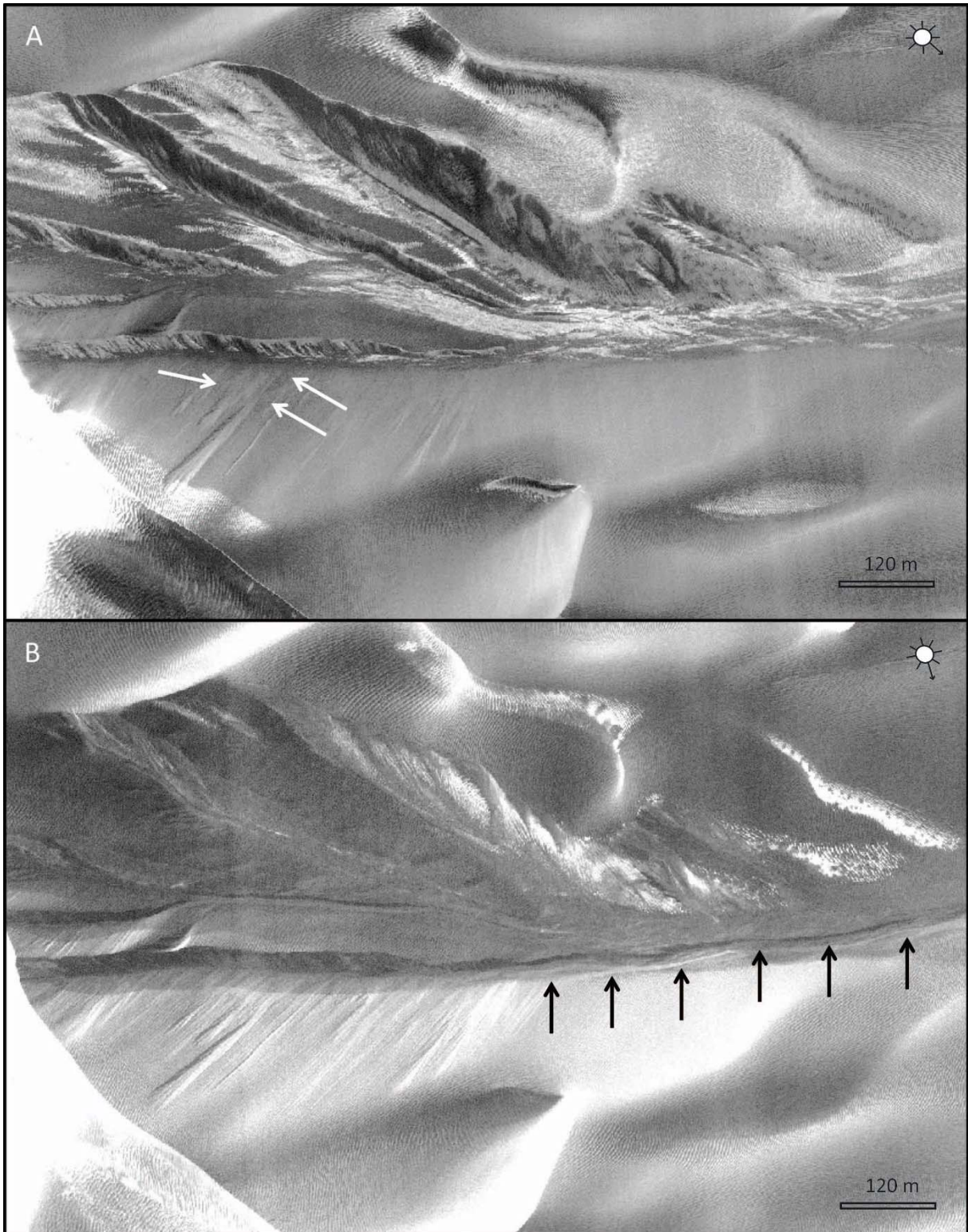
Supplementary material

Sub-alcove	Pole facing slope (°)	Equator facing slope (°)
A1	22.4	19.5
A2	22.5	18.6
A3	23.8	21.0
A4a	24.2	25.0
A4b	22.6	25.6
A5	23.8	26.3
average	23.2	22.7

Suppl. Material 1. Slopes of the sub-alcoves.



Suppl. Material. 2. A) Timing of presence of seasonal frost for sub-alcove A₅ on pole facing slopes. B) Timing of presence of seasonal frost for sub-alcoves A_{4a}, A_{4b} on pole facing slopes, C) Timing of activity for material transport from the sub-alcove A₅ to the apron synchronous with sinuosity development, D) Timing of activity for material transport from the sub-alcoves A_{4a}, A_{4b} to the apron synchronous with sinuosity development. Each line represents one martian year and each cross (or vertical line) is a HiRISE image.



Suppl. Material 3. Alcove activity: A) material accumulation on equator facing slope (white arrow) (HiRISE image: ESP_027838_1300, Ls 134.4°), B) transport of material accumulated on the equator facing slope toward the debris apron. Erosion of a channel on the floor of the alcove (black arrows) (HiRISE image: ESP_028405_1300, Ls 156.7°).