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

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

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

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

46 **1** Introduction

47

1.1 Context and objective

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

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

Dundas et al., 2010; 2012; 2015; 2017; Raack et al., 2015; Jouannic et al., 2012; 61 Pasquon et al., 2016, 2018), including reports of the development of channel 62 sinuosity (Dundas et al., 2017). The timing of this present-day activity is generally 63 constrained to the autumn to early spring when CO_2 ice is present on the surface. 64 Although Vincendon (2015) found that only H₂O ice was present during some of the 65 reported activity and Pasquon et al. (2016) found that linear gullies on sand dunes 66 are only active as the last CO₂ frost is removed, conditions cited as particularly 67 favorable for water ice melt (Kossacki and Markiewicz, 2004). 68

Here we perform detailed analysis of the development and migration of a sinuous channel observed over 5 martian years (MY29-33) of a gully located on the dunefield of Matara Crater (49.5°S; 34.9°E). The aim of this study is to better understand the processes leading to the development of channel sinuosity and the role of volatiles H_2O and CO_2 in developing this morphology.

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1.2 Martian gullies

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

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

Some gullies are still active today and the timing of their activity suggests that 100 they are triggered by seasonal processes (e.g., Dundas et al., 2010; Pasquon et al., 101 2016). Seasonal processes have been generally attributed to the defrosting of CO₂ 102 (e.g., Dundas et al., 2012; 2015; 2017). CO₂ is omnipresent on Mars: when the 103 temperature decreases in winter, deposits of solid CO₂ and a small quantity of water 104 ice can accumulate at the surface from direct condensation of the atmosphere in 105 contact with the cold surface or through precipitation of ice crystals from the cold 106 107 atmosphere. During winter, such deposits i) cover all surfaces above $\sim 60^{\circ}$ latitude, ii) are discontinuous from 40° to 60° latitude (Schorghofer and Edgett, 2006; Vincendon 108 109 et al., 2010b; Diniega et al., 2013), and iii) are limited to pole-facing slopes nearer the equator (Vincendon et al., 2010b; Dundas et al., 2015; 2017). These deposits can be 110 up to meters in thickness near the poles (Smith et al., 2001), but are generally sub-111 centimeter thickness at lower latitudes (Vincendon, 2015). Most of this frost is 112 composed of CO_2 that can reach a few centimeters in thickness (Diniega et al., 2013; 113 Dundas et al., 2015), and H₂O is a minor component estimated to be of the order of 114 micrometers in thickness (Kereszturi et al., 2009; Gardin et al., 2010; Vincendon et 115 116 al., 2010b).

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

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

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





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

than 30% of solid material. Hyper-concentrated flows can have an intermediate state
 between turbulent stream flows and laminar viscous debris flows (e.g., Allen, 1997).

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

179

1.4 Gully on Matara Crater dunefield

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

190 **2 Methods**

191 **2.1 Morphology**

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

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

One HiRISE Digital Terrain Model (DTM) is available for the studied sinuous 212 213 qully. This DTM was produced from images ESP 022115 1300 and ESP 022392 1300 by the HiRISE team and enable topographic measurements 214 better than 25 cm of relative vertical precision (McEwen et al., 2007). Slope angles 215 were estimated by taking a topographic profile along the line of steepest decent and 216 217 making a linear fit over the area of interest.

To estimate the erosion and the deposition volume of the Matara dune-gully we used the topographic reconstruction method of Conway and Balme (2014) which consists of estimating the initial topography prior to the gully formation. In brief, we used the topographic contours either side of the gully to estimate the position of the contours across the dune before the gully formed. These contours are then used as the input to a Natural Neighbor interpolation to produce a gridded elevation dataset. This estimated topography is then subtracted from the real topography to estimate the overall volumes of deposition and erosion. Given the irregular topography of the dune, the errors are likely larger than in Conway and Balme (2014). Therefore in order to estimate the potential errors on this calculation, we linearly connected the contours either side of the gully and re-performed our analysis – we used the difference between these two volumes as an estimate of the magnitude of error.

230

2.2 Simulation of surface temperature and frost occurrence

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

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

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

The model outputs are:

- The masses of CO_2 and H_2O ice accumulated on the ground as a function of L_S : these masses are converted to thicknesses using densities of 1.62. 10³ and 0.92.10³ kg.m⁻³ respectively.
- 251

- The temperature of the surface every half an hour.

Model parameters used for the numerical simulation are given in Table1. Model parameters such as CO_2 ice albedo and ground ice depth are tuned, similarly to Vincendon et al. (2010), to fit the model to the observations of ice previously reported from near-IR spectroscopy (Vincendon 2015) as well as to the frost occurrence as
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
sand	CO ₂ ice	H₂O ice	ground	ice	(m.s ⁻¹)	ground	ground ice	(change with L _s)	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

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

262 **3 Results**

263

3.1 Overall morphology of the gully with channel sinuosity

The gully studied is located on the eastern part of the Matara Crater dunefield 264 (49.5°S; 34.9°E) (Fig. 2). The dunefield is comprised of transverse dunes and is 16 265 km across with a low albedo typical of dunes of Mars (Thomas, 1982). The 266 investigated gully is composed of an alcove, a channel, and an apron (Fig. 2D) and 267 measures almost 2700 meters in length (Fig. 2D). The alcove covers a surface area 268 of 3.7 x 10⁵ m² and is constituted by 6 sub-alcoves that converge toward the channel. 269 These different sub-alcoves are numbered A_1 , A_2 , A_3 , A_{4a} , A_{4b} and A_5 in Fig. 2E. The 270 channel covers a surface area of 3 x 10^4 m², is ~1000 meters long with a maximum 271 width of 60 m, and has several channel bends. The area of the apron is larger than 272 that of the alcove with a total area of 7.9 x 10⁵ m². We estimated a volume of alcove 273 erosion of 6 x 10⁶ m³ (+/- 4 x 10⁶ m³) and an apron deposit of 8 x 10⁶ m³ (+/- 4 x 10⁶ 274 m³) (Fig. 3). Within the bounds of the error these two volumes are balanced. In 275 MY29-33 1/5 of the area of the apron experienced changes (Fig. 4D). 276



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



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

287 **3.2 Slopes and cross-sections**

Slopes measurements on cross sections and longitudinal profiles were made 288 using the HiRISE DTM. The mean slope of the sinuous gully is ~13°. The alcove has 289 a slope of ~16°, the channel ~13° and the active part of the apron ~10°. The 290 longitudinal cross-section of the gully is slightly concave (Fig. 4A). Two transversal 291 cross-sections are presented: i) at the top of the alcove (Fig. 4B), ii) at the end of the 292 channel (Fig. 4C). The alcove can be separated into different sub-alcoves that we 293 have called: A₁, A₂, A₃, A_{4a}, A_{4b} and A₅ (Fig. 2E) which have different slope angles 294 (Fig. Suppl. Material 1). The morphology of the alcove and its constituent sub-alcoves 295 is asymmetric. For example, in the case of the sub-alcove A₅ the length of the 296 equator-facing flank is greater than that of the pole-facing flank (Fig. 4B). 297 298 Nevertheless, the average slopes of the opposing sub-alcove flanks are similar: the 6 pole-facing flanks of the sub-alcoves have an average slope angle of 22.8° and the 299 equator-facing flanks have an average slope of 23.2° (Fig. Suppl. Material 1). 300



301

Fig. 4. Topographic profiles of: A-A') along the gully length, B-B') across the upper part of the alcove (the slope along the line of steepest decent of A_{5} , A_{4a} , A_{3} sub-alcoves are marked), C-C') across the lower end of the channel. D) Location of the topographic profiles on the image of the gully (HiRISE image: PSP_006648_1300, L_s 8.8°). Note that vertical exaggeration accentuates some of the slope differences and the slope angles quoted on the cross-profiles are not necessarily measured in the same plane as the displayed profile.

308

3.3 Evolution in the gully morphology

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

313 3.3.1 Alcove changes

The alcove of this gully is composed of 6 different sub-alcoves that converge towards the channel: A_1 , A_2 , A_3 , A_{4a} , A_{4b} and A_5 (Fig. 2E). The cross-section in Fig. 4B illustrates the typical topographic configuration of these sub-alcoves. During MY29-33, we observed activity in different sectors of the alcove (Figs. 5ABC; Suppl. Material 2AB). Part of the alcove is considered "active" when a change in the morphology is observed. These changes due to erosion or deposition are easily observable at the transition between the alcove and the channel of the gully (Figs.
Suppl. Material 3; 5ABC; 6AB).

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



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327 Fig.5. Gully activity over 3 martian years (MY31-33). A) HiRISE image: ESP 046286 1300, L_s 199.8°, MY31: in this reference image the channel is partly filled by sand (black circle). B) HiRISE image: 328 329 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 on the debris apron. C) HiRISE image: ESP_037965_1300, L_s 188.6°, MY32: the sub-alcove A₅ is 331 332 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 A₅ 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 upstream. D) HiRISE image: ESP 046238 1300, L_s 167.0°, MY33: the material accumulated in the 336 337 sub-alcove A₅ is transported onto the channel and the debris apron. Material continues to accumulate within the lower part of the channel, blocked by the previous deposits, propagating channel fill 338 339 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 onto the debris apron, and white arrows for changes in the channel morphology. Thick green arrows 341 342 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

Fig. 6. Summary of main gully activity types represented by before-after pairs of images. (A-B) At the 346 347 transition between the alcove and the channel, sediment erosion and accumulation alternates, causing channel formation, partial channel infilling or complete channel erasure. A) HiRISE image: 348 ESP_028972_1300, L_s 180.8° (MY32). B) HiRISE image: ESP_037965_1300, L_s 188.6° (MY32). (C-D) 349 350 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, Ls 41.8° (MY32). F) HiRISE image: ESP_037411_1300, Ls 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

Sand material transport and accumulation was observed in sub-alcoves A_{4a} to A₅ (Figs. 7; 5). Material transport is only observed on the equator-facing flanks (Figs. 7; 5C; Suppl. Material 3). On the equator-facing flanks of sub-alcoves A_{4b} to A_5 , small discrete slope failures oriented toward NNE result in the transport of sand material that is identifiable as accumulations on the alcove floors (Figs. 7ABC; 5C; Suppl.

Material 3). These failures comprise an alcove or scar and an apron, sometimes 361 connected by a depression, or channel (Figs. 7C; 5C; Suppl. Material 3). The total 362 area affected by these failures ranges between 2000 and 8000 m² and is highly 363 variable from one year to the next (Fig. 7D). During MY29-33, the cumulative area 364 affected by material transport and accumulation in the alcove attains 31 800 m² (Fig. 365 7D). An area of 14 800 m² is affected by material accumulation on the floor of the 366 sub-alcove A_5 . The material initially accumulated in sub-alcoves A_{4b} to A_5 was 367 transported onto the debris apron of the gully (Fig. 5). This transport causes erosion 368 and deposition of sediment and the creation of a channel in the terminal part of the 369 alcove (Figs. Suppl. Material 3; 5ABC; 6AB). There was no observed accumulation of 370 material for MY29-33 in sub-alcoves A_1 to A_3 (Figs. 2E; 5), and no channel changes 371 were observed during their defrosting. 372

373



Fig. 7. A) Context view of the gully on the Matara Crater dunefield (HiRISE image: PSP_006648_1300 L_s 8.8°). B) and C) Detailed view of sub-alcoves A_{4b} and A_5 , showing before and after examples of the failures resulting in erosion of the flanks and accumulation on the alcove floor (HiRISE image: PSP_006648_1300, L_s 8.8° MY29 and ESP_029394_1300, L_s 199.8° MY31). The black arrow indicates a reference point and the white arrows the location of accumulated material. D) The total area affected by the failures in the sub-alcoves A_{4a} and A_5 for MY29 to 33, including the erosional scar, the transport zone and the deposited material.

382

3.3.1.2 Pole-facing flanks: frost and collapse of material

Seasonal frost deposits appear each year during the winter season on some 383 parts of the sinuous gully studied, but not everywhere. These deposits are visible on 384 HiRISE images. This ice can be observed on the alcove, specifically on the pole-385 facing flanks of each sub-alcove (A₁ to A₅) (Figs. 8AC; 5B). For sub-alcoves A_{4a}, A_{4b} 386 and A₅, seasonal frost is only present on the pole-facing flank (Suppl. Material 2CD), 387 for the other sub-alcoves frost is also visible on the equator-facing flanks (Figs. 8AC; 388 5B). The appearance and disappearance of frost is generally gradual for the sub-389 alcoves of this gully (Fig. 8), except for some events in sub-alcoves A_{4a} , A_{4b} and A_5 390 where the defrosting is sudden and contemporaneous with channel and apron 391 activity, described in Section 3.3.2. (Fig. 8). This sudden defrost coincides with the 392 collapse of part of the alcove flank (Fig. 8). 393

We observe alternation in the activity of the sub-alcoves A_4 and A_5 (Fig. 5), so the 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, Ls 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°. 402 C) 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 A4a: 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

We observed that channel sinuosity initiated and increased during MY29-33 in this gully system. The sinuosity of the channel is quantified using the sinuosity index "S" (Fig. 9). In our first observations during MY29 the channel was sub-linear with a sinuosity index of 1.0098 (Figs. 10A; 9). During MY30, one part of the channel was abandoned and the channel developed some curvature as indicated by an increase in the sinuosity index to 1.018 (Figs. 10B; 9). In MY31, the sinuous section developed greater curvature and two terraces appeared on the inside of the bend. The sinuosity index reduced to 1.006 (Figs. 10C; 9). In MY32 four bends are visible and sinuosity increased reaching the maximum value of 1.05; (Figs. 10D; 9). Finally during MY33 these bends migrate and part of the channel was abandoned. The sinuosity index remained stable at 1.05 (Figs. 10E; 9). The lateral bend migration rate is ~ 23 m/yr calculated on a baseline between L_s 8.8° in MY29 and L_s 188.6° in MY32. The width of the channel grew from 30 m in MY29 to more than 60 m in MY33.



422



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



434

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

442

3.3.2.2 Debris apron changes

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

(Fig. 11A). Only the northern part of the apron was active over MY29-33 (Figs. 4D; 449 5). We observed the development of multiple overlapping deposits (Fig. 5BCD). 450 Between L_s 283.3° MY29 and L_s 144.3° MY32 the activity of the apron was 451 characterized by the appearance of new deposits without any lengthening (Figs. 11A; 452 5CD). An average 1.7×10^5 m² of the apron surface is affected by the gully activity 453 during MY29-33 (Fig. 11B). This area represents around 20% of the total apron area 454 (7.9 x 10⁵ m²), suggesting such activity has been ongoing, perhaps on the order of 455 decades. 456

457



458

Fig. 11. A) Changes in the active apron length (+/-10m). B) Changes in the active apron area (+/-100
m²) over 4 martian years. Image quality in MY30 did not allow us to make measurements on the debris
apron.

462 **3.4 Timing of activity**

463 **3.4.1** Timing of alcove activity (A_{4a}, A_{4b} and A₅)

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

On the equator-facing flanks of the sub-alcoves A_{4a} , A_{4b} and A_5 , we observed 465 material transport and accumulation on the alcove floors (Figs. 7; 5C; Suppl. Material 466 3). During MY30, this activity occurred throughout the period spanning the beginning 467 of winter until the middle of spring (i.e., between L_s 56.5° and 249.9°) (Fig. 12A). For 468 MY31, the activity was observed between $L_s168.8^\circ$ at the end of winter and $L_s199.8^\circ$ 469 470 at the beginning of spring (Fig. 12A). In MY32, it occurred at the end of winter between L_s 164.5° and L_s 176.4° (Fig. 12A). For MY33, it started during the middle of 471 winter at L_s 152.3° and was still ongoing at the beginning of spring at L_s 191.8° (Fig. 472 12AE). 473

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

482

3.4.1.2 Seasonal frost (Pole-facing flanks)

Seasonal frost is only observed on the pole-facing flanks for sub-alcoves A_{4a}, 483 A_{4b} and A_5 . This frost is visible from L_s 95.2° to L_s 141.8° during MY30, between L_s 484 67.5° and L_s 156.7° during MY31, between L_s 56.4° and L_s 144.3° during MY32 and 485 finally, from L_s 149.7° to L_s 167.0°, during MY33 (Fig. 12D). So, for MY29-33 486 seasonal frost is temporally well constrained and observed between the middle of 487 autumn and the middle of winter, between $L_s 67.5^\circ$ and $L_s 167.0^\circ$ (Fig. 12DE). The 488 detailed presence of frost on sub-alcoves A_{4a} , A_{4b} and A_5 is presented in 489 Supplementary Material Fig. 2CD. No seasonal frost is observed on the equator-490 facing flank of sub-alcove A₅ for MY29-33, where material transport and accumulation 491 is usually observed (Fig. 12B). 492

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

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

505



506

Fig. 12. A) Timing of material transport inside the alcove, including only sub-alcoves A_{4a} , A_{4b} and A_5 where material accumulation on the floor of the alcoves can be identified, sourced from failures on the equator-facing flanks. B) Timing of presence of seasonal frost for sub-alcoves A_{4a} , A_{4b} , A_5 on their equator-facing flanks. C) Timing of activity for material transport from the alcove to the apron accompanied by changes in channel sinuosity. D) Timing of the presence of seasonal frost for subalcoves A_{4a} , A_{4b} , A_5 on their pole-facing flanks. Each line represents one martian year and each cross is a HiRISE image. E) Summary of the information presented in panels A-D.

514 3.4.3 Timing synthesis

Each year we observed: i) material transport from the equator-facing flanks of 515 the sub-alcoves A_{4a}, A_{4b} and A₅ to their floors, between the beginning of winter and 516 the middle of spring (Fig. 12AE), ii) seasonal frost on the pole-facing flanks of the 517 alcove between the middle of autumn and the end of winter (Figs. 12DE; Suppl. 518 Material 2CD), iii) sudden disappearance indicating collapse of the frost on pole-519 facing alcove flanks contemporaneous with changes in the channel and debris apron 520 (Figs. 12; Suppl. Material 2). The activity observed in the channel and on the debris 521 apron can occur during winter up until the beginning of spring (Figs. 12CE; Suppl. 522 Material 2AB). 523

5243.5Modeled temporal evolution in surface temperature and seasonal525frost composition and thickness

526 3.5.1 Seasonal frost deposits

Seasonal frosts occur each year on the Matara Crater dune-gully, particularly 527 in the alcove and on the pole-facing flanks of the sub-alcoves A_{4a} to A_5 (Figs. 8AC; 528 5B). These sub-alcoves are the source of the material that then cause changes in the 529 channel sinuosity and changes on the debris apron. Defrosting of the seasonal ice 530 deposits is thought to play a role in present-day gully activity (e.g., Dundas et al., 531 2012; 2015; 2017; Diniega et al., 2013) so, we studied frost composition and 532 thickness using a modelling approach calibrated with HiRISE and CRISM data (see 533 section 2.2). The results of the simulations for the pole-facing flank of the sub-alcove 534 A₅ are shown in Fig. 13. The simulations predict that CO₂ frost begins to deposit in 535 the middle of autumn at $L_s \sim 40-60^\circ$. The CO₂ ice thickness increases to a maximum 536 of 85-130 mm near mid-winter (L_s 140°-150°). After ~ L_s 150°, the CO₂ ice thickness 537 decreases and the CO₂ frost totally disappears at $L_s \sim 180-190^\circ$ (Fig. 13A). 538

Our simulation suggests that H₂O ice is also present in the seasonal frost, but 539 in smaller quantities (i.e., ~10-11 µm thickness). Such a low thickness of water ice is 540 close to the detection limits of near infrared spectroscopy of ~ 5 μ m (Vincendon et al. 541 2010b). The simulations predict that water ice first appears at $L_s \sim 20^\circ$ at the 542 beginning of autumn, while evidence for ice in the observations are found at $L_s > 80^\circ$ 543 only, which is consistent with the predicted low thickness of water ice that remains 544 around 5 μ m from L_s 30° to L_s 150° in the model (Fig. 13A). At L_s 150°, the model 545 shows an increase in the H₂O ice thickness to 10-12 μ m lasting until L_s 195°, which is 546 547 supported by observations of ice over most of that period. At this point, the H₂O ice

thickness decreases reaching 0 μ m at L_s ~200°. In summary, H₂O ice is predicted to be present between L_s 20° to L_s 195°- 200°, i.e., from the beginning of autumn to the beginning of spring. Once CO₂ has disappeared, the model predicts that some water ice remains for a few days (Fig. 13A), a phenomenon that is predicted to occur frequently on Mars although it has never been observed, probably due to a lack of appropriate timing of observations (Vincendon 2015).



Fig. 13. Numerical simulation results for the Matara Crater dunefield (49.5°S; 34.9°E) for pole-facing flanks of the sub-alcove A_5 with 24° slope: A) Composition and thickness of the seasonal frost predicted to be present. The red line shows the CO₂ ice frost thickness (mm) and the blue line shows the H₂O ice thickness (μ). B) Modeled surface temperatures (predicted by the model at 2 pm local time). Temperatures are calculated with a time step of 30 minutes over one martian year. The orange area highlights the period during which channel and apron changes were observed (summarized in Fig. 12).

562 3.5.2 Surface temperature

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

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.

The sub-alcoves A_1 to A_3 do not show any activity that can be linked to the sinuosity development in the gully channel. We do not observe any material accumulation in these sub-alcoves. Sub-alcoves A_4 to A_5 do show material accumulation which is transported in winter through the channel and onto the debris 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-sinuous gullies observed on other sand dunes (Diniega 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.

We observe alternating activity in sub-alcoves A_4 and A_5 (Fig. 5). The material transported through the channel and onto the debris apron of this gully does not originate from exactly the same area of the alcove from one active period to the next (Fig. 5). This could cause in homogeneities in the spatial distribution of erosion and 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 (A_4 to A_5) and 2) a flow process that produces landforms 500 similar to those created via terrestrial hyper-concentrated flows, as outlined below.

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

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

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

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

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

629 **4.3. Role of CO₂**

Our observations of timing and location of the activity producing a sinuous channel suggest that the activity is linked to the seasonal defrosting of CO_2 ice (Figs. 8; 12CDE; 13A; 5; Suppl. Material 2). However, the exact relation between CO_2 ice and the numerous seasonal surface processes temporally linked to its defrosting on Mars is not fully understood (e.g., Dundas et al., 2012; Harrison et al., 2015; Pasquon et al., 2018).

Sublimation of seasonal CO_2 ice on martian dunes is thought to trigger the formation of dark spots and dark flows (Kieffer, 2000; 2007; Piqueux et al., 2003; Kieffer et al.,

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

648 Our numerical simulations predict that CO₂ should be present on pole-facing alcove flanks between $L_s 40-60^\circ$ and $L_s 180-190^\circ$ (the middle of autumn to the beginning of 649 650 spring) on the Matara Crater dunefield (Fig. 13A). The remobilization of the material accumulated on the alcove floor is associated with collapse of the pole-facing alcove 651 652 flanks which happens at a time of year when our modeling predicts that the CO₂ ice should be at its thickest (Figs. 8; 13A). The changes in channel and apron 653 654 morphology of the gully occur in winter between L_s 117.6° and L_s 180.8° when seasonal frost is still observed (Fig. 12; Suppl. Material 2). The activity ends when the 655 CO₂ disappears (Fig. 12; Suppl. Material 2) and when the surface temperature of the 656 alcove increases from 145-150K to 210-220K (Fig. 13B). CO₂ gas could play a role in 657 transporting material in the channel and on to the debris apron. Based on our 658 659 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 instead by CO₂ gas, could explain this gully activity. Specifically, after falling onto the 661 floor of the alcove, the CO₂ ice should sublimate vigorously via contact with the 662 relatively hot sand previously accumulated at the foot of the alcove. Exposed to more 663 solar insolation, this sand should have a temperature significantly higher than the 664 665 CO₂ ice sublimation temperature producing a high gas escape rate. This initial and vigorous sublimation of the CO₂ ice triggers a CO₂ gas flow mixed with sand and 666 667 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, because at the end of winter CO₂ ice has almost entirely disappeared from the dune 670 671 surface and hence there would not be sufficient CO₂ ice to drive vigorous sublimation. At the end of winter, the transport is limited by the reduced availability of CO_2 ice, whereas at the beginning of winter this is not the case, even if the temperature difference between the CO_2 ice and the hot sand could potentially produce high sublimation rate.

Determining exactly how a mixture of sublimating CO_2 ice and sand can produce landforms similar to those produced by hyper-concentrated water flows on Earth is a detailed modelling exercise beyond the scope of this study. We acknowledge that important physical differences exist between the fluids of water and CO_2 gas including compressibility, density and buoyancy, which would lead to significant differences in behavior.

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- 683

4.4. Conceptual model for the development of sinuous gully channels

Based on our observations, we propose the following three-step conceptual 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 to be at 24-26° slope in the sub-alcoves A_{4a} , A_{4b} and A_5 (Figs. 2E; 7; 5C; Suppl. 688 689 Material 1; 3)). The sand accumulates on the floor of the alcove during winter and spring (Figs. 7; 12AE). This accumulation occurs preferentially during the middle of 690 691 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 observed on these slopes on HiRISE images (Fig. 12B), CRISM observations 694 indicate that CO₂ and H₂O ice cover most of the Matara Crater dunefield during mid-695 winter, including equator-facing flanks, flat terrains, and extend to the bottom part of 696 equator-facing flanks with angles lower than 5-10° (Vincendon 2015). Seasonal ice is 697 thus probably very thin or located in the subsurface on the equator-facing flanks 698 where the activity occurs. However, sand material transport and accumulation on the 699 floor of the alcove is also observed at the end of spring (up to $L_s 249.9^{\circ}$ Fig. 12A), 700 despite the whole Matara Crater dunefield being entirely defrosted by L_s 192° (see 701 e.g., CRISM observation FRT #1C413). As a consequence, some of the observed 702 equator-facing flank material movements are very likely not related to seasonal frost. 703

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

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

Second, during Year N+1, seasonal frost mainly composed of CO₂ with some H₂O is 710 observed during the cold seasons of autumn and winter on the pole-facing flanks of 711 712 the alcove (Figs. 12DE; 13A). The seasonal CO_2 ice deposit is several orders of 713 magnitude thicker than the H_2O ice (Fig. 13A, mm compared to μm). CO_2 is not present over the whole surface of the alcove, it is mainly located on the pole-facing 714 flank of each sub-alcove A_1 to A_5 in autumn and winter between $L_s 40-60^\circ$ and $L_s 180-$ 715 190° (Figs. 13A; 8AC; 5B). The maximum thickness of CO₂ frost deposit occurs at L_s 716 ~140-150° (Fig. 13A). 717

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

There is a temporal correlation between the seasonal frost retreat and the changes observed in the gully channel and on the apron (Figs.8; 12CDE; 13A; Suppl. Material 2). The development of sinuosity in the channel is contemporaneous with the sand remobilization from the floor of the sub-alcoves A_{4a} , A_{4b} and A_5 on to the debris apron (Fig. 5BCD). After the sand accumulation on the floor of the sub-alcoves A_{4a} to A_5 , the material is evacuated toward the debris apron of the gully (Fig. 5CD).

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

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

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

752 **5 Conclusions**

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

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

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

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

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

A link between CO_2 defrosting and this gully activity is consistent with its timing. We hypothesize that a flow composed of sand, CO_2 gas and ice together with the contribution of material from alternating alcove sources can explain the development of sinuous gully channels.

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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 A_5 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 A_5 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°).