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1 **Martian gullies: a comprehensive review of observations, mechanisms and the insights from Earth**  
2 **analogues**

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## 13 Abstract

14 Upon their discovery in 2000, martian gullies were hailed as the first proof of recent (<a few Ma)  
15 flowing liquid water on the surface of a dry desert planet. Many processes have been proposed to  
16 have formed martian gullies, ranging from liquid-water seepage from aquifers, melting of snow, ice  
17 and frost, to dry granular flows, potentially lubricated by CO<sub>2</sub>. Terrestrial analogues have played a  
18 pivotal role in the conception and validation of gully-formation mechanisms. Comparison with the  
19 terrestrial landscape argues for gully formation by liquid-water debris flows originating from surface  
20 melting. However, limited knowledge of sediment transport by sublimation is a critical factor in  
21 impeding progress on the CO<sub>2</sub>-sublimation hypothesis. We propose avenues towards resolving the  
22 debate: a) laboratory simulations targeting variables that can be measured from orbit, b)  
23 applications of landscape-evolution models, c) incorporation of the concept of sediment  
24 connectivity, d) using 3D fluid-dynamic models to link deposit morphology and flow rheology, and e)  
25 more intense exchange of techniques between terrestrial and planetary geomorphology, including  
26 quantitative and temporal approaches. Finally, we emphasize that the present may not accurately  
27 represent the past and martian gullies may have formed by a combination of processes.

## 28 1. Introduction

29 This review provides an overview of the research done on martian gullies since their discovery by  
30 Malin and Edgett (2000), providing the backdrop to the papers in this special issue. The review  
31 specifically highlights how the use of terrestrial analogues has provided insight into the formation  
32 mechanisms of martian gullies. The study of martian gullies has been steeped in analogy to  
33 terrestrial landforms from the very beginning – starting with their naming as “gully” (Malin and  
34 Edgett, 2000). This name was chosen in reference to their resemblance to “spur and gully”  
35 morphology on Earth, rather than referring to the terrestrial definition of gully as “a water-made  
36 cutting, usually steep-sided with a flattened floor” (Mayhew, 2015) which is “deep enough (usually  
37 >0.5 m) to interfere with, and not to be obliterated by, normal tillage operations”  
38 (<https://www.soils.org/publications/soils-glossary>). In making our descriptions we use terms  
39 derived from terrestrial geomorphology to describe the characteristics of martian gullies, which  
40 inevitably are rooted in the terminology used in the description of fluvial catchments and may  
41 suggest a fluvial origin. We attempt to make a reasonable balance between using process-neutral  
42 terms (which if taken to extremes are so generic as to be unhelpful) and terms that inevitably invoke  
43 a given process.

44 We start by providing a comprehensive review of the observational data collected on martian gullies.  
45 Following this, we summarise their proposed formation mechanisms, along with the range of Earth  
46 analogues that have been used to gain insight into martian gully formation. Within Earth analogues  
47 we include scaled physical laboratory simulations, which we argue play a similar role to flume  
48 experiments in understanding terrestrial geomorphic processes (e.g., Paola et al., 2009). We then  
49 undertake a short critical assessment of the limitations of such analogies and highlight future  
50 avenues and challenges for research as a result of this review and discussions at the second Mars  
51 gullies workshop held in London, June 2016.

## 52 2. Review of key observations of martian gullies

### 53 2.1 Morphology

54 Martian gullies are composite landforms that comprise an alcove, channel and depositional fan (also  
55 referred to as apron in the martian literature; Malin and Edgett, 2000). They can be up to several  
56 kilometres in length, and their length seems to be controlled by the length of the hillslope available  
57 (Hobbs et al., 2017, 2013). Alcove zones can span up to a kilometre cross-slope (Bridges and Lackner,  
58 2006; Conway et al., 2015a; Heldmann et al., 2007; Heldmann and Mellon, 2004; Yue et al., 2014).  
59 They occur in a wide range of settings mostly in the mid-latitudes and sometimes polar regions,  
60 ranging from the walls and central peaks of impact craters to valley walls, hills, dunes, and polar pits  
61 (e.g., Balme et al., 2006; Malin and Edgett, 2000). The main requirement for their occurrence being  
62 the availability of steep slopes exceeding ~20-30° (Conway et al., 2017, 2017, e.g., 2015a; Dickson et  
63 al., 2007; Reiss et al., 2009a). Gullies can occur singularly, but they usually occur in groups and can  
64 span whole hillslopes (Figure 1: e, g-i, l). Sites with gullies number nearly 5000, and it is estimated  
65 therefore that tens of thousands of gullies exist on Mars (Harrison et al., 2009).

66 What follows is a generic description of gullies on Mars, placing emphasis on their most commonly  
67 observed morphological features, while also summarising the wide variation in morphology  
68 observed in martian gullies. We begin our morphologic descriptions with so called “classic” gullies,  
69 which are the most abundant (98% of the database of Harrison et al., 2015) and show the widest  
70 variation, then follow with descriptions of two uncommon, but remarkable gully-types: linear dune  
71 gullies (33 sites globally, 0.6%; Pasquon et al., 2016) and polar-pit gullies (1% of Harrison et al., 2015)  
72 (Figures 1e and 1g, respectively).

73 Gully-alcoves are generally theatre-shaped depressions, whose upslope extent is located at the  
74 hillcrest or mid-slope within the hillslope on which they are located. They can be incised into the  
75 bedrock, often exposing numerous metre-scale boulders, or into slope-side deposits, such as the  
76 latitude dependant mantle (LDM) or sand (e.g., Aston et al., 2011; de Haas et al., 2018, 2015a, 2013;  
77 Núñez et al., 2016b). The LDM is believed to be an ice-rich mantling unit of which the most recent  
78 layers were deposited during climate excursions, which happened in the last few millions of years  
79 (see Section 2.3). Some variations in gully source material are related to host-crater age, and lead to  
80 contrasting gully-alcove morphology (de Haas et al., 2018).

81 Alcoves often lead to chutes in which channels are developed, and these channels then lead onto  
82 the depositional debris fan, or apron. Here, as in the terrestrial literature, we make a distinction  
83 between “channels” and “chutes”. We define channels as erosional incisions which should indicate  
84 the bankfull level of the fluid and therefore can be taken to represent a single “event” (Figure 2d).  
85 Chutes, on the other hand, are analogous to valleys in lowland geomorphology, they are erosional  
86 incisions representing the ensemble of erosional events and do not represent bankfull conditions. It  
87 should be noted, however, that incised channels cannot always be reliably identified and hence the  
88 confusion between chutes and channels in the martian gully literature, which is likely related to the  
89 rapid reworking of the martian surface. Where chutes are classified as channels, this can lead to  
90 poor application of terrestrial geomorphologic laws developed for channels. Channels extend from  
91 within the alcove and onto/across the depositional zone. It has been stated in the literature that  
92 gully channels become narrower in downslope direction (Hartmann et al., 2003), but in fact it is  
93 usually the incised chutes that narrow downslope. In many cases the upper part of martian gullies  
94 lacks a true alcove as described above – the upper escarpment, or break in slope is missing. Such  
95 gullies are usually characterised by a source area where many small channels emerge gradually from  
96 rocky hillslopes and come together to form a single chute (Figures 2e, f). Gilmore and Phillips (2002)  
97 initially reported the origin of gully-channels at outcropping bedrock layers. However, with higher  
98 resolution images in many cases it can be seen that the channels originate (often as barely  
99 distinguishable rills) above the bedrock layer (Dickson and Head, 2009) (Figure 2f).

100 Downslope of the alcoves, at the point where deposition dominates over erosion due to lower  
101 gradients, a depositional fan is present. These can be wide cone-shaped deposits of sediments,  
102 which originate at the apex where the chute intersects with the hillslope (e.g., Figures 1j, 1m, 2b).  
103 Similar to alluvial fans on Earth, these deposits “fan out” from the apex in planview and have a  
104 convex cross-slope curvature. Such gully-fans are often dissected by entrenched, steep-walled,  
105 channels. Both primary and secondary channels (the latter being abandoned, formerly active,  
106 channel systems), can often be identified on gully-fan surfaces (Figure 2c). The fans of adjacent  
107 gullies can merge downslope forming a bajada, a continuous deposit at the foot of the hillslope.  
108 Additionally, many other gullies lack wide, fan-shaped deposits, but have more restricted deposits,  
109 which are longer in the downslope direction than they are wide. These deposits can be digitate in  
110 shape, or indistinctly blend into the surrounding terrain.

111 Figure 2

112 Polar-pit gullies (Figure 1g) are notable not only for their high-latitude location, but they also have a  
113 distinctive morphology and morphometry. This type of gully is only found in south polar pits, which  
114 form the only steep topography at latitudes poleward of 60°S (Conway et al., 2017). These pits are  
115 believed to be formed by collapse of the terrain induced by sub-glacial volcanism (Ghatan and Head  
116 III, 2002). The gullies incised into the walls of these polar pits are characterised by regularly-spaced  
117 rounded alcoves which often reach the top of the slope and when they do, on their inner slopes are  
118 comprised of metre to decametre-scale rounded boulders. The base of the alcove sometimes leads

119 into a chute and the deposits more often than not form a bajada of continuous fan-deposits.  
120 Channels are slightly sinuous and lead out onto the fan, where sometimes other channel segments  
121 can also be seen. Many studies, however, do not distinguish these gullies from classic gullies  
122 elsewhere on Mars (e.g., Auld and Dixon, 2016).

123 Linear dune gullies (Fig. 1e) are the most uncommon and distinctive subtype of martian gullies. They  
124 are only found on dark sandy slopes, either dune slip-faces or sand-covered slopes in the southern  
125 hemisphere (Figures 1a, e, f) (Pasquon et al., 2016). They are dominated by a long parallel-sided  
126 leveed channel, which varies little in width along its length. This channel either directly follows the  
127 hillslope gradient, or possesses some considerable sinuosity (Pasquon et al., 2016). The alcove is  
128 rarely wider than the channel and is often comprised of poorly expressed tributary rills. The channel  
129 terminates downslope abruptly and the “apron” is simply comprised of the bounding levee, although  
130 in some cases the channel is perched (an erosional landform within the depositional landform)  
131 (Jouannic et al., 2015). Channel terminations can be in form of pit-chains, or can be surrounded by  
132 pits. The longest examples are found on the extraordinary Russell Crater megadune (Gardin et al.,  
133 2010; Jouannic et al., 2017; Reiss et al., 2010a; Reiss and Jaumann, 2003), which rises to 500 m in  
134 height (Gardin et al., 2010). As for classic gullies their length seems to be limited by the size of the  
135 hillslope available. They often occur alongside gullies with a “classic” morphology (Figures 1a, e, f)  
136 and there are some cases where intermediate forms can be found.

137 Typically gully alcove slopes on Mars exceed 20° (Conway et al., 2015a; Dickson et al., 2007;  
138 Heldmann et al., 2007; Heldmann and Mellon, 2004), while gully-fan slopes range from 5° to 25°  
139 (Conway et al., 2015a, Gulick et al., 2018; Kolb et al., 2010), with channels spanning the whole range  
140 of slopes. Conway et al. (2015b) found that gullies whose alcoves extend up to and erode into the  
141 bedrock of a crater wall tend to have the steepest alcove and apron slopes (>23° and >20°  
142 respectively). Polar-pit gullies are distinctive as they tend to have lower alcove and debris apron  
143 slopes (<25° and <12°, respectively) compared to the population as a whole. Pasquon et al. (2016)  
144 reported alcove slopes for linear gullies of 14-25° and mean slopes of 9-17° along the whole profile,  
145 which are consistent with the general population of martian gullies.

146 As with any classification system, there are forms that do not fit neatly into the descriptions  
147 provided above. In the most generic sense martian gullies are a form of gravity-driven mass wasting  
148 system, where material is removed from the top and transported towards the base of the hillslope.  
149 However, they are distinguishable from simple fall-deposits (scree, talus or colluvium) by the  
150 presence of the transport channel and/or chute as pointed out by Malin and Edgett (2000) and the  
151 presence of a depositional fan below the dynamic angle of repose (Kokelaar et al., 2017). Hence, it  
152 has generally been acknowledged that a channel is the essential attribute for identifying a martian  
153 gully (e.g., Balme et al., 2006). Alcoves (with a spur and gully morphology) are common in bedrock  
154 escarpments across Mars and the Moon (Dickson and Head, 2009; Sharpton, 2014) (Figure 3).  
155 Hillslopes that are contiguous with those hosting well-developed gullies can themselves show  
156 morphologies that without the context of their neighbours, would not necessarily be classified as  
157 gullies (Figure 4). These slopes have poorly developed and discontinuous channels, which have  
158 limited sinuosity trending directly downslope. Such features are also found in isolation, often in the  
159 equatorial regions of Mars (Auld and Dixon, 2016; Rummel et al., 2014) (Figure 4c) and have usually  
160 been omitted from global-scale catalogues of martian gullies (e.g., Harrison et al., 2015). Treiman  
161 (2003) classified some equatorial features as gullies, such as alcoves with aprons in the calderas of  
162 the Tharsis volcanoes and the light-toned layered mounds in Candor Chasma (Figure 4a). These  
163 equatorial features have channels—a downslope trending linear depression - yet they lack the steep  
164 banks and morphological complexity of their mid-latitude counterparts and more closely resemble

165 terrestrial dry mass movement chutes (refer to Section 3.1), and hence have not been classified as  
166 gullies.

167 As discussed in more detail in the following section, gullies have small-scale morphologies indicating  
168 many episodes of deposition and erosion. In addition, relict versions of whole gully-landforms have  
169 also been reported. In order to be identifiable as relict gullies, some aspect of the channel has to be  
170 identifiable strengthened by identification of associated relict fan and/or alcove.

171 Figures 3 and 4

## 172 2.2 Detailed Morphology

173 The arrival of the HiRISE instrument in orbit around Mars in 2006 which returns 0.25-0.5 cm/pix  
174 images of the martian surface (Alfred S. McEwen et al., 2007) has allowed the morphology of  
175 martian gullies to be catalogued in great detail. Here we describe commonly observed metre- to  
176 decametre-scale features associated with the channels and depositional parts of gullies.

177 The chutes and channels of gullies can be highly sinuous (Figures 1e, 5a) (Arfstrom and Hartmann,  
178 2005; Mangold et al., 2010). Many authors report both v-shaped incisions (e.g., Dickson and Head,  
179 2009; Hobbs et al., 2013), and tributary organisation of channels/chutes (e.g., Malin and Edgett,  
180 2000; Morgan et al., 2010). Terraced cutbacks and longitudinal bars (Figure 5c) (Schon and Head,  
181 2009) and more rarely levees (Figure 5b) (Hugenholtz, 2008a; Johnsson et al., 2014; Lanza et al.,  
182 2010; Levy et al., 2010; Sinha et al., 2018) have also been reported as attributes of gully-channels. In  
183 systems with well-developed fans the chute and base of the alcove can become back-filled with  
184 sediment. In these sediment-choked systems channels tend to be discontinuous and braided within  
185 the confining chutes (A. S. McEwen et al., 2007), good examples of this are seen in Gasa Crater  
186 (Figure 5d). Braiding of channels is also seen on the fans and in shallow upslope tributary systems  
187 (Gallagher et al., 2011; Levy et al., 2009).

188 Figure 5

189 Digitate deposits, either as part of a fan or on their own, are often reported to characterise the  
190 terminal part of martian gullies (Dickson and Head, 2009) (Figure 6a,b). Deposits often “spill over”  
191 the sides of channels (Stewart and Nimmo, 2002), but deposits are also re-incised by channels. A  
192 distributary organisation of channels is associated with gully-deposits (A. S. McEwen et al., 2007) and  
193 metre-sized boulders can be common on their depositional surfaces (de Haas et al., 2015d; A. S.  
194 McEwen et al., 2007). Sometimes distinct depositional lobes are also observed with high relative  
195 relief (Johnsson et al., 2014; Lanza et al., 2010; Levy et al., 2010; Sinha et al., 2018) (Figure 6a). The  
196 surfaces of martian gully-fans can often be divided into segments with different ages, based on  
197 cross-cutting relationships and morphological differences between segments (de Haas et al., 2015d,  
198 2013; Johnsson et al., 2014; Schon et al., 2009a). This observation shows that gullies form in multiple  
199 episodes, i.e. separated by enough time to have been modified by other processes, rather than in  
200 one event (Schon and Head, 2011) (Figure 6c). This assertion is also supported by the presence of  
201 terraces within gully-chutes. The surfaces of gully-fans are in many instances heavily degraded (de  
202 Haas et al., 2015d; Dickson et al., 2015), mainly by weathering and wind erosion, but also they may  
203 be covered by LDM deposits. Gully channels can be crossed by fractures within the LDM and  
204 superpose other similar fractures (Dickson et al., 2015) (Figure 6d). As a result, gully-fan surface  
205 morphology is often dominated by secondary, post-depositional, processes. Interpretation of the  
206 primary formation processes of gullies based on fan surface characteristics may be misleading for



207 the often long-inactive martian gullies, and interpretation of surface morphology should be  
208 approached with care (de Haas et al., 2015d).

209 Because the channel and associated deposits are the parts of the gully-landform that have the least  
210 relative relief it has the poorest preservation potential, making relict gullies hard to substantiate.  
211 Dickson et al. (2015) identified inverted gully channels in >500 sites poleward of 20°S. These ridges  
212 are present on pole-facing slopes between 40°S and 50°S and are likely being revealed from under  
213 the LDM. Dickson et al. (2015) further report the burial of whole gully-systems beneath LDM and  
214 present two examples of this. Many other authors report apparently infilled alcoves next to distinct  
215 or active gully-systems (e.g., Auld and Dixon, 2016; Christensen, 2003; de Haas et al., 2018; Hoffman,  
216 2002), which they interpret as relict gully-systems.

### 217 2.3 Associated landforms

218 Martian gullies do not occur in isolation, but in association with, and often with superposition  
219 relationships to, a range of other morphologic features, which we briefly summarise here (in order  
220 of descending size). Of the same order of scale or larger than martian gullies are viscous flow  
221 features (Squyres, 1978) which encompass a wide range of features, of which the subtype glacier like  
222 forms (GLF) (Hubbard et al., 2011; Souness et al., 2012; Souness and Hubbard, 2012) are the most  
223 similar in scale to gullies. Martian gullies occur in the same latitude band as GLF and crater-filling VFF  
224 (Levy et al., 2014), and recent work has shown that gullies tend to be sparse where Lobate Debris  
225 Aprons (a large subtype of VFF) and GLFs are dense (Conway et al., 2017). From surface morphology  
226 and topography alone VFF are believed to be debris covered glaciers (e.g., Mangold, 2003a; Morgan  
227 et al., 2009; Squyres, 1979) and radar data have confirmed that the ice under the debris is almost  
228 pure (Plaut et al., 2009). Gullies are sometimes observed adjacent to or topographically above such  
229 features (Figures 1d & i), but rarely intersect them. Gullies only occur in ~12% of craters filled with  
230 VFF despite occupying the same latitude band. Spatulate depressions or arcuate ridges are thought  
231 to represent the end moraines of now ablated GLFs (Hartmann et al., 2014) and often occur at the  
232 foot of gully-systems (Arfstrom and Hartmann, 2005; Berman et al., 2005; de Haas et al., 2018; Head  
233 et al., 2008) (Figure 7c,e). Gully-fans superpose these arcuate ridges and sometimes form on their  
234 downslope scarps (Figure 7d).

235 In Utopia Planitia and the Agyre region of Mars (Pearce et al., 2011; Soare et al., 2017, 2007) gullies  
236 occur in close association with hundred-metre-scale polygonised depressions that are linked to the  
237 ablation of excess ice, so-called thermokarst or scalloped depressions (Figure 8c). Similarly Soare et  
238 al. (2014b) found that hundred-metre-scale mounds they interpreted to be caused by ice-heave  
239 (pingos) also occurred in association with gullies in the Argyre region (Figure 8d).

240 Figures 7 and 8

241 Many gullies are intimately associated with the LDM (Aston et al., 2011; de Haas et al., 2018, 2015a;  
242 Dickson et al., 2015) and dissected LDM (Milliken et al., 2003; Mustard et al., 2001). The LDM is  
243 characterised by a terrain draping unit which infills decametre to hundred-metre topographic lows  
244 and smooths the topography at high latitudes (Kreslavsky and Head, 2002). It is often associated  
245 with polygonally patterned ground at the metre to decametre scale, which is thought to be caused  
246 by thermal contraction in ice cemented soil (Levy et al., 2009; Mangold, 2005). Initially the term  
247 “pasted-on terrain” was used to refer to the polygonally patterned terrain into which gullies are  
248 incised (Christensen, 2003), but this has later been incorporated into the catch-all term of “LDM”.  
249 Although an in-depth discussion of the LDM is beyond the scope of this paper, it should be noted  
250 that: multiple generations of LDM deposits are thought to exist (e.g., Schon et al., 2009b), and



251 although the LDM is generally attributed to airfall deposits of ice nucleated on atmospheric aerosols  
252 (Kreslavsky and Head, 2002), some aspects of the LDM argue for ice enrichment through freeze-thaw  
253 cycling (Soare et al., 2017). Several lines of evidence (aside from the crack-morphology) have led  
254 most researchers to agree that polygonally patterned ground indicates ice-rich terrain, including:  
255 newly-formed impact craters discovered with CTX have been found by CRISM and HiRISE to have  
256 excavated subsurface water ice (Byrne et al., 2009), in-situ discovery of ice associated with  
257 polygonally patterned ground by the Phoenix lander (Mellon et al., 2009) and the spatial correlation  
258 between high ice content as inferred from the neutron spectrometer data and polygonally patterned  
259 ground (e.g., Mangold, 2005).

260 Not all gullies are found in association with LDM, yet a large proportion are - Levy et al. (2009) report  
261 just over 50% of gullies in their survey (all HiRISE images 30–80° north and south latitude) are  
262 associated with polygonally patterned ground. Polygonal patterns are found on the inner slopes of  
263 alcoves and chutes of gullies as well as in the terrain the gullies incise (Figure 9b). Their fan deposits  
264 superpose polygonally patterned ground and sometimes relict fan deposits show polygonisation  
265 (Figure 9c). Volume-balance arguments indicate substantial volatile loss in gully-systems incised into  
266 this type of terrain (Conway and Balme, 2014; Gulick et al., 2018), implying excess ice in the ground  
267 at these locations. The lowest latitudinal limit of gullies coincides with the edge of the dissected LDM  
268 (Milliken et al., 2003), but also the lowest latitude extension of VFF (Levy et al., 2014). Head et al.  
269 (2003) noted that the LDM superposes crater-bound VFF, yet the LDM may superpose gullies and  
270 also be dissected by gullies (Dickson et al., 2015). Hillslopes with pasted-on material or LDM are  
271 often associated with arcuate ridges at the base of the slope, but also smaller-scale landforms  
272 informally termed “washboard terrain” encompassing parallel series of across-slope trending  
273 fractures thought to represent crevasses (Arfstrom and Hartmann, 2005; Dickson et al., 2015;  
274 Hubbard et al., 2014) (Figure 9d).

275 Landforms intimately associated with periglacial conditions (those conducive to freeze-thaw cycling  
276 in the ground) have been reported to occur in close proximity to, or in association with, martian  
277 gullies. These landforms are generally on the metre- to decametre-scale and the frequency of their  
278 association with gullies numbers in the tens, rather than in the hundreds, as for the features  
279 mentioned above. Cross-cutting and intimate association has been reported between gullies and (1)  
280 lobate forms (including stone garlands), which are attributed to solifluction processes where the top  
281 part of the soil profile creeps downslope due to repeated thawing (Gallagher et al., 2011; Gallagher  
282 and Balme, 2011; Johnsson et al., 2012; Soare et al., 2014a) (Figure 10d), and (2) sorted stone stripes  
283 where clasts are gathered at the edge of convection cells in the soil caused by freeze-thaw cycling  
284 (Gallagher et al., 2011) (Figure 10e). Gullies are also reported to occur in close proximity to other  
285 sorted patterned grounds, including sorted stone circles and nets and rubble piles (Balme et al.,  
286 2013; Barrett et al., 2017; Gallagher et al., 2011).

287 Finally gullies are often found on the same slopes as recurring slope lineae (RSL) (e.g., Dundas et al.,  
288 2017a; McEwen et al., 2011; Ojha et al., 2015), which are downslope propagating dark streaks  
289 typically a few metres to tens of metres wide and hundreds of metres long (Figure 10f). They only  
290 occur on the steepest slopes and originate at rock outcrops in terrains that have high thermal inertia  
291 (interpreted to have low dust cover). Their behaviour distinguishes them from other mass wasting  
292 phenomena; they grow during the hottest times of the year, fade during the cold season and reoccur  
293 at the same (or nearly the same) place each year (Grimm et al., 2014; Stillman and Grimm, 2018).  
294 RSL generally occur superposed on gully alcoves. No change in relief is associated with RSL so they  
295 are thought to transport only small amounts of sediment (if any). Some RSL propagate over sandy  
296 fans and occasionally slumps are also found on these fans, but their relation to RSL remains unclear

297 (Chojnacki et al., 2016; Ojha et al., 2017). RSL are also found on steep slopes without gullies, most  
298 notably those in Valles Marineris (Chojnacki et al., 2016; McEwen et al., 2014; Stillman et al., 2017).

299 Figures 9 and 10

## 300 2.4 Global trends

301 Gullies are found on steep slopes poleward of  $\sim 30^\circ$  in each hemisphere (Harrison et al., 2015) (Figure  
302 11). Between latitudes of  $30^\circ$  and  $40^\circ$  pole-facing gullies are strongly dominant, whereas from  $40^\circ$  to  
303 the pole gullies are mostly equator-facing but also exist in other orientations. Gullies are found  
304 across all elevations on Mars, but are notably absent within their general latitudinal distribution  
305 from the Tharsis bulge and the Hellas basin (Dickson et al., 2007; Heldmann et al., 2007; Heldmann  
306 and Mellon, 2004). The latter is due to the absence of steep slopes and the former seems to be an  
307 effect of surface thermal inertia (Conway et al., 2017). The general paucity of gullies in the northern  
308 hemisphere can be directly attributed to the lack of steep slopes in that hemisphere (Conway et al.,  
309 2017).

310 Figure 11

311 Although their morphology varies widely (Figure 1), there seems to be no distinctly identifiable  
312 trends in gully-morphology with latitude and/or orientation (Balme et al., 2006). An obvious  
313 exception to this general rule are the polar-pit gullies. There are hints in the literature as to gullies  
314 with different degradation states having different latitudes/orientations, but this remains to be fully-  
315 substantiated. Bridges and Lackner (2006) and Heldmann et al. (2007) did note that gullies in the  
316 northern hemisphere were more degraded in appearance than those in the southern hemisphere.  
317 Morgan et al. (2010), Raack et al. (2012) and Levy et al. (2009) reported that for the southern  
318 hemisphere equator-facing gullies seemed more degraded than the pole-facing ones.

## 319 2.5 Compositional data

320 Harrison et al. (2015) showed that gullies are more prevalent on terrains classified as high thermal  
321 inertia, interpreted as being low dust, low albedo, with grainsizes between 60 $\mu$ m and 3mm (Jones et  
322 al., 2014; Putzig et al., 2005). Harrison et al. (2017) found that fans associated with active gullies in  
323 Gasa Crater have higher thermal inertia than other gully fans, yet lower thermal inertia than talus  
324 slopes. The hyperspectral imaging system CRISM has been used to examine the composition of the  
325 materials in and around gullies (Allender and Stepinski, 2018, 2017; Barnouin-Jha et al., 2008; Núñez  
326 et al., 2016a) and suggested that: (1) gullies are hosted on a wide range of geological materials, (2) in  
327 some cases gullies expose underlying rock and move it downslope, (3) many other gullies show no  
328 spectral difference from their surroundings and (4) there is no systematic association between  
329 hydrated minerals and gullies even in the new light-toned deposits near gullies. Heldmann et al.  
330 (2010) used CRISM data and also confirmed that recent light-toned deposits in Penticton Crater have  
331 no spectral differences to surrounding material. It should be noted that the lack of systematic  
332 observations of hydrated or brine spectral signals in gullies does not mean these materials are  
333 absent (Massé et al., 2014) - hydrated signatures rapidly disappear under martian conditions and a  
334 spectral signal can easily be obscured by a surface coating of millimetres of dust, which is highly-  
335 abundant and pervasive on Mars.

336 Fan et al. (2009) investigated the relative water content of four gully sites compared to their  
337 surrounding areas and found that the gully sites had elevated water contents by using statistical  
338 analysis of OMEGA hyperspectral data. Dickson and Head (2009) used colour HiRISE images to

339 identify the seasonal accumulation of frost in the alcoves and channels of two gully systems and in  
340 one case they used CRISM to confirm its composition as water ice. Vincendon (2015) reported both  
341 seasonal water ice and CO<sub>2</sub> ice in association with active gullies. Dundas et al. (2017b) also find from  
342 HiRISE image data that active gullies are commonly associated with seasonal ice deposits.  
343 Sometimes these ices are observed in the alcoves of generally equator-facing gullies, but the frost is  
344 located on pole-facing sections of their alcoves (Figure 12). These results are in general accordance  
345 with those obtained for surfaces on Mars in general. Carrozzo et al. (2009) observe from OMEGA  
346 data that low latitude ice condensation occurs preferentially on shadowed (i.e. pole-facing at the  
347 present day) slopes between 30°S and 30°N. Kuzmin et al. (2009) used TES thermal inertia data to  
348 map water ice at the surface and report widespread water ice condensation on the surface occurring  
349 in winter between 40-50°S and 40-50°N, particularly in the northern hemisphere which is consistent  
350 with spectral observations (Appéré et al., 2011).

351 Figure 12

## 352 2.6 Temporal context (age and activity)

353 Gullies are geologically very young landforms that formed within the last few million years. This is  
354 inferred from the conspicuous absence of superposed impact craters on gullies (e.g., Malin and  
355 Edgett, 2000), superposition relationships with polygons, dunes and transverse aeolian ridges (e.g.,  
356 Malin and Edgett, 2000; Reiss et al., 2004), their occurrence in young impact craters that formed  
357 within the last few million years (Conway et al., 2018a; de Haas et al., 2018, 2015b; Johnsson et al.,  
358 2014) and the presence of secondary craters related to recent crater impacts as marker horizons on  
359 gully-lobes (Schon et al., 2009a). Geologically young gully deposits are present in both very young  
360 and very old host craters (< 1 Ma to > 1 Ga), and their size is unrelated to host-crater age (de Haas et  
361 al., 2018; Grotzinger et al., 2013). While the spatial distribution of martian gullies has been  
362 extensively studied and quantified, their temporal evolution is poorly understood. Documenting the  
363 temporal evolution of gully systems was already noted as one of the main outstanding questions and  
364 avenues for advancement regarding the understanding of martian gullies by Dickson and Head  
365 (2009), yet very few papers have addressed this topic since then. De Haas et al. (2018) show that  
366 after their formation in fresh craters, gullies may go through repeated sequences of (1) LDM  
367 deposition and reactivation and (2) glacier formation and gully removal (Conway et al., 2018a),  
368 followed by the formation of new gully systems. In general, gullies in host craters that are younger  
369 than a few Ma have not been affected by LDM or glaciation (type 1), gullies in host craters of a few  
370 Ma to a few tens of Ma have been affected by LDM but not by glaciation (type 2), and gullies in host  
371 craters of more than a few tens of Ma have been affected by both LDM and glaciation (type 3).  
372 These various types of history are reflected in the gully morphology: type 1 gullies have large alcoves  
373 with rough surfaces that cut into bedrock and extent up to the top of the crater rim (Figure 1l; 2b);  
374 type 2 gullies are similar but are visually softened by a veneer of LDM deposits (Figure 1h,k; 9a); type  
375 3 gullies lay within the former extent of glaciers, as indicated by the presence of, for example  
376 arcuate ridges and sublimation till, and have elongated, v-shaped, alcoves that often do not extend  
377 all the way up to the crater rim (Figure 7b,e; 8b).

378 Repeat imaging of martian gullies has revealed that mass transport is occurring within these systems  
379 at the present-day (Diniaga et al., 2010; Dundas et al., 2017b, 2015a, 2012a, 2010a; Malin et al.,  
380 2006; A. S. McEwen et al., 2007; Pasquon et al., 2016; Raack et al., 2015; Reiss et al., 2010a; Reiss  
381 and Jaumann, 2003). Activity within gullies on dark sandy substrates in the southern hemisphere is  
382 particularly remarkable with both “classic” and “linear” gully sites showing some kind of mass  
383 transport every Mars year. In this issue Pasquon et al. (2017) show that the timing and nature of the  
384 activity of the classic gullies on dark sand dunes differs from that of linear dune gullies. Classic dune  
385 gullies are generally active in local winter (Diniaga et al., 2010; Pasquon et al., 2017) and their

386 activity is characterised by smaller metre-scale slumps into the chute/alcove and large alcove-  
387 clearing events which leave upstanding deposits on the debris fan (Pasquon et al., 2017). Linear  
388 dune gullies are active as the seasonal surface frost finally sublimates from the surface (~Ls 200°,  
389 early spring) and their activity is characterised by the elongation of channels, appearance of new pits  
390 and appearance of new channels. Linear gullies with no changes are also observed. Volume balance  
391 arguments dictate that entire linear gully systems can be produced on the order of tens of Mars  
392 years (likely slightly longer for the large systems on the Russell megadune) and classic gullies on the  
393 order of hundreds of Mars years (Pasquon et al., 2017). Hence it is likely these dune gully systems  
394 are a product of the present-climate system. It is also worth-noting that the north polar dune fields  
395 are also remarkably active, yet the timing and character of this activity differs from the southern  
396 hemisphere (Diniaga et al. 2017). Here, alcove-fan systems only tens to hundreds of metres in length  
397 form on dune slip faces in autumn or early winter. Their formation seems to be linked to the first  
398 deposits of the seasonally CO<sub>2</sub> ice. Channels are occasionally visible at the limit of resolution, hence  
399 why these features are not usually classed as martian gullies.

400 Polar-pit gullies are also more active than classic gullies elsewhere (Hoffman, 2002; Raack et al.,  
401 2015). Their activity is characterised by the gradual progression of relatively dark sediment deposits  
402 over the seasonal ices during the latter part of winter. These dark deposits are visible as topographic  
403 relief once the ice has been removed. Not all polar-pit gullies are active at once, which lead Raack et  
404 al. (2015) to surmise that the process must be supply limited, rather than environment limited.

405 Activity in classic gullies was first documented in the form of “bright white deposits” in Mars Orbiter  
406 Camera data (Malin et al., 2006). These deposits appear on the depositional apron of the gully, have  
407 a digitate outline, no detectable relief, and no distinct source zone (Figure 13b). Since then repeat  
408 images by HiRISE have detected movements that appear both “bright” and “dark” in the red channel  
409 (Figure 13a,b) and can have various colour hues including “blue” and “yellow”. These movements  
410 include deposits with no detectable relief, but also deposits with upstanding lobate edges containing  
411 boulders (Figure 13c), evacuation of sediment infilling channels and in one case the incision of a new  
412 channel (Dundas et al., 2017b, 2015a, 2012a, 2010a) (Figure 13d). Activity is rarer in the northern  
413 hemisphere and so far none of the observed modifications have engendered any detectable  
414 alteration in relief (Dundas et al., 2017b). Source areas for these movements cannot usually be  
415 identified, although occasionally failure scars are present. Crown fractures have been identified in  
416 the alcoves of Gasa crater (Okubo et al., 2011), where the gullies are particularly active (Dundas et  
417 al., 2017b), suggesting slope instability as a trigger for movement. Because activity in classic gullies is  
418 so sporadic there are only ~40 examples where timing can be constrained to within less than 3  
419 months and the activity tends to occur in winter during defrosting at that latitude (Dundas et al.,  
420 2017b). Whether these observations of activity in classic gullies represent the process that forms the  
421 whole gully-landform is currently under debate.

422 Figure 13

### 423 3. Review of proposed martian gully formation mechanisms and their 424 terrestrial analogues

425 Multiple models have been put forth in an attempt to understand how geologically youthful gully  
426 features could have formed on Mars. Our view of martian gullies has improved over time since their  
427 initial discovery thanks to long-term monitoring and higher resolution data, which is reflected by the  
428 wealth of data on their morphology and spatial distribution presented above. Accordingly, the  
429 models of formation that have been put forth have evolved over time as well. Terrestrial analogy has  
430 played a key role in developing these formation models and also in testing them against

431 observations. It was the analogy to systems on Earth carved by liquid water that sparked the initial  
432 controversy about gully-formation as corroborated by the flurry of comments on the initial discovery  
433 paper (Doran and Forman, 2000; Hoffman, 2000; Knauth et al., 2000; Saunders and Zurek, 2000).  
434 The reason this claim was so controversial and remains so, is that our understanding of Mars’  
435 surface environment dictates that liquid water should not be thermodynamically stable – it should  
436 only be present in its gaseous or solid forms (Hecht, 2002; Richardson and Mischna, 2005). Climate  
437 models have shown liquid water could be transiently stable, but the locations where this is predicted  
438 do not match with the locations of gullies (e.g., Richardson and Mischna, 2005; Stillman et al., 2014).  
439 Authors have therefore proposed that landforms resembling terrestrial water-carved landforms  
440 could be formed on Mars by other fluids, or even without fluids – a concept termed “equifinality”.  
441 One of the reasons that multiple hypotheses for formative mechanisms are conceptually viable is the  
442 steepness of the relief and the instability of surface materials under steep gradients. Hence, any  
443 appreciable applied force might be capable of causing bulk flows. It is now generally accepted that  
444 gullies are formed by a fluid, presently thought to be H<sub>2</sub>O or CO<sub>2</sub>. In this section we first summarise  
445 the arguments which show that gullies on Mars are not formed by a completely dry granular flow.  
446 We then go on to present the arguments made in favour of liquid-water mechanisms and the  
447 models outlining the origin for this water. Finally we outline the arguments made in favour of CO<sub>2</sub>-  
448 based-fluids for gully formation. Each of these sections will emphasise the role that terrestrial  
449 analogues have played in developing these working hypotheses.

### 450 3.1 Dry granular flow

451 Treiman (2003) proposed entirely dry flow as the agent behind martian gully formation based on the  
452 difficulty of sustaining liquid water under recent climate conditions. He explained the leveed channel  
453 morphology of martian gullies with reference to the terrestrial analogues of pyroclastic flows and  
454 dry snow avalanches, as examples of natural dry granular flows (Figure 14a,b). However, McClung  
455 and Shaerer (2006) note that “dry snow avalanches tend to travel in straight lines rather than being  
456 deflected by topography, such as gullies”. Observations of snow avalanches by Kochel and Trop  
457 (2008) as Mars analogues in the Wrangell Mountains in Alaska also point to some differences:  
458 avalanches have very straight, wide channels, with broad levees, the terminal deposit is often  
459 square-lobate showing no digitate break-offs. These landforms are similar in morphology to those  
460 produced by dry granular flow in experiments (e.g., Félix and Thomas, 2004; Kokelaar et al., 2014)  
461 (Figure 14c-e) and numerical modelling (Gueugneau et al., 2017). There is also disagreement in  
462 terrestrial literature as to whether dry granular flow models are even valid for snow avalanches,  
463 which almost inevitably involve some phase-changes (e.g., Gauer et al., 2008; Hutter et al., 2005;  
464 Naaïm et al., 2003; Platzler et al., 2007) and wet snow avalanches can behave like and have a similar  
465 morphology to debris flows (Bartelt et al., 2012)(covered in the next section). The same is true for  
466 pyroclastic flows, which are fluidised by hot pressurised gas in the pore space (either trapped on  
467 catastrophic collapse of the ash column and/or continually produced from the hot volatile volcanic  
468 products) (e.g., Mellors et al., 1988; Siebert et al., 1987; Sparks and Wilson, 1976). We will come  
469 back to the pyroclastic analogy within our discussion concerning the fluidisation by CO<sub>2</sub> gas evolved  
470 by sublimation (Section 3.3.3).

471 Figure 14

472 Shinbrot et al. (2004) also supported a dry granular flow model based on the fact that both martian  
473 gullies and dry mass movement features on terrestrial sand dune slip faces (Figure 14g-i) both have  
474 leveed channels (e.g., Sutton et al., 2013a). Shinbrot (2004; 2007) used a spinning disc to simulate  
475 the lower cohesion induced by lower gravity and generated features with wide, shallow channels  
476 and gentle lateral levees (Figure 14). However, other authors have found that martian gullies in the  
477 detail are morphologically distinct from dry features on Earth and dry mass movement features



478 elsewhere on Mars (Figure 3), as detailed below. Martian gullies show evidence for flows that divert  
479 around an obstacle and re-integrate after passing it (i.e., braided), which requires a certain flow  
480 thickness, viscosity and fluidity which according to our present knowledge is not achievable in dry  
481 flows even under low gravity (Brusnikin et al., 2016). Dry granular flows do not behave in this  
482 manner unless they are sufficiently thick and fine-grained such that Van der Waals forces are many  
483 orders of magnitude larger than intergranular friction and grain weight (Campbell, 1990; Derjaguin  
484 et al., 1975; Johnson et al., 1971). Conway and Balme (2016) compared the morphometries of the  
485 catchments of martian gullies to dry mass wasting features on Earth (talus slopes), on the Moon and  
486 unguilled crater walls on Mars and found that martian gullies were statistically dissimilar from these  
487 nominally “dry” landforms. The runout of dry granular flows should not extend very far beyond  
488 slopes greater than the dynamic angle of repose ( $\sim 20^\circ$ ; Kleinhans et al., 2011; Pouliquen, 1999)  
489 which has been confirmed to be the case for dry avalanches on the Moon (Kokelaar et al., 2017) yet  
490 the majority of martian gully-fans are shallower than this. Conway et al., 2015a, measured a median  
491 slope of  $14^\circ$  for 67 gully-fans and Kolb et al. (2010) concluded 72% of the 76 fans they studied were  
492 likely emplaced by fluidised flows. It should be noted that Pelletier et al. (2008) and Kolb et al. (2010)  
493 found that the new bright deposits reported by Malin et al. (2006) in Penticton and Hale craters  
494 occur on steep enough slopes to be attributed to dry granular flows. The general consensus among  
495 the Mars gully community today is that gullies do not form via an entirely dry granular flow  
496 mechanism, although dry mass movement processes could occur within pre-existing gullies today  
497 (Harrison et al., 2015). Dry granular flows remain a reasonable mechanism for spur and gully  
498 landforms, which often lack channels/chutes.

## 499 3.2 Liquid water gullies

500 Martian gullies are similar to terrestrial analogue landforms carved by water on a number of levels,  
501 which has lead researchers to propose a number of water-related flow processes for their genesis. It  
502 should be noted that the ubiquity of precipitation involvement, directly or indirectly, in such  
503 analogues makes extrapolation to Mars somewhat questionable. In the first part of this section we  
504 discuss the arguments that have been made in favour of each of these water-based flow processes  
505 in light of their terrestrial analogues (Section 3.2.1). Whether or not similar landforms can be  
506 produced by other non-water flow processes will be discussed in Section 3.3. Following this we  
507 discuss the possible origins of this water along with their terrestrial analogues (Sections 3.2.2 to  
508 3.2.5).

### 509 3.2.1 Fluvial flow, debris flow, slushflow, brines and other exotic fluids

510 The involvement of water in the formation of martian gullies has from the start been driven by their  
511 similarity to terrestrial water-generated landforms. On Earth the two main flow processes  
512 responsible for the downslope transport of sediment are fluvial flows and debris flows. When we  
513 refer to fluvial flows we mean flows in which the sediment concentration is sufficiently low that the  
514 fluid behaves like a Newtonian fluid and sediment entrainment solely occurs via shear stress exerted  
515 on the bed by the fluid – generically referred to as the stream power law (e.g., Hack, 1957; Sklar and  
516 Dietrich, 1998; Whipple and Tucker, 1999). Debris flows on the other hand are flows where the  
517 sediment to water ratio, typically  $\sim 20$ -60% water by volume (Costa, 1984; Iverson, 1997; Pierson,  
518 2005), is sufficiently high that the rheology of the fluid changes and it behaves more like a bingham  
519 plastic, or a viscous fluid (e.g., Ancey, 2007; Iverson, 2014, 1997). Steep first order catchments on  
520 Earth are often dominated by debris flow processes, which leave an identifiable morphological  
521 fingerprint on the landscape (Jackson et al., 1987; Lague and Davy, 2003; Mao et al., 2009).  
522 Slushflow is a special kind of debris flow where some of the clastic material is replaced by ice (André,  
523 1990; Decaulne and Saemundsson, 2006; Nyberg, 1989; Rapp, 1960). In the most general sense  
524 brines can replace water in both fluvial flows and debris flows, so could also be a component of the  
525 sediment transport in martian gullies. In addition there is a range of more “exotic” processes that

526 cannot occur on Earth have been revealed in scaled-physical models in the laboratory, which could  
527 be active in martian gullies. In the following sections we will discuss these different sediment  
528 transport processes, how they have been applied to martian gullies and the relevant terrestrial  
529 analogues.

### 530 *Fluvial flow*

531 Once produced, liquid water has been shown by multiple authors to have a residency time of up to a  
532 few hours on the martian surface under the temperature and pressure conditions of both the  
533 present and the geologically recent past (e.g., Carr, 1983; Haberle et al., 2001; Hecht, 2002;  
534 Heldmann, 2005; McKay and Davis, 1991). This duration combined with the evidence for multiple  
535 events required to form martian gullies leaves plenty of scope for water to form martian gullies.

536 There are uncountable numbers of erosion-deposition systems on Earth that comprise the generic  
537 elements of a source alcove, a transportation channel and depositional apron/fan, especially if no  
538 scale or slope constraints are imposed. In searching for kilometre-scale systems in which only 1<sup>st</sup> or  
539 2<sup>nd</sup> order catchments are developed as for martian gullies it becomes clear that in many cases the  
540 depositional part of any given terrestrial system has been removed by other parts of the hydraulic  
541 system (located in the sea, or a lake, or eroded by a trunk river). This fact alone indicates that  
542 martian gully systems are water-starved compared to those on Earth and do not form part of a  
543 larger connected hydraulic system.

544 Terrestrial gullies formed by fluvial flow comparable in scale and structure to those on Mars have  
545 been reported from a wide variety of sites with a large range of climatic settings (Table 1), ranging  
546 from cold or hot deserts to relatively humid mountain environments. In addition to the planview  
547 similarity between fluvial terrestrial gullies and martian gullies, authors have noted similarity in  
548 catchment properties (Conway and Balme, 2016), long-profiles (Conway et al., 2015b; Hobbs et al.,  
549 2017; Yue et al., 2014), cross-sectional properties (Yue et al., 2014), fan-slopes, channel organisation  
550 and channel features such as streamlining, terracing and braiding (Gallagher et al., 2011; Kumar et  
551 al., 2010; Reiss et al., 2011). Note, however, that features such as terraces are also common on  
552 terrestrial debris-flow fans (Figure 15e-h).

### 553 Figure 15

554 Following from these similarities several authors have used terrestrial inspired fluvial erosion models  
555 to infer the discharge and therefore the amount of water required to form gullies (Heldmann et al.,  
556 2005; Hobbs et al., 2014; Parsons and Nimmo, 2010). These models are based on knowledge  
557 obtained via field or experimental data on Earth in fluvial fluid flows with low sediment content and  
558 link channel geometries to flow discharge.

### 559 *Debris flow*

560 Debris flow analogue sites for martian gullies are dominantly located in arid, periglacial, or glacial  
561 climates. Many authors have noted the key characteristics (Figure 16): (1) lateral levees (2) lobate or  
562 digitate deposits and (3) poorly-sorted gravel or coarser sized sediments as deposits (Costard et al.,  
563 2007a; Hartmann et al., 2003; Kochel and Trop, 2008; Reiss et al., 2009a), which are attributes often  
564 seen in martian gullies. Heldmann et al. (2010) drew an analogy between mudflows in the Atacama  
565 and the new light-toned deposits on Mars (Malin et al., 2006). They found the higher albedo  
566 mudflow was a smooth deposit, with 90% fines compared to 78% fines in the surrounding material  
567 and that the deposit and surrounding material were spectrally indistinguishable – thus a viable  
568 hypothesis for the origin of the light-toned martian gully-deposits. In contrast, the Atacama debris



569 flows described by Oyarzun et al. (2003) have very marked topographic effects and form an elevated  
570 digitate fan deposit and a channel with lateral levees, similar to those described in glacial and  
571 periglacial environments.

572 Figure 16

573 Multiple types of morphometric analyses which reference terrestrial data have already been applied  
574 to martian gullies, and they imply predominant gully-formation by debris flows. They include, slope-  
575 area relations (Conway et al., 2011b; Lanza et al., 2010), gully width-depth relations (Yue et al.,  
576 2014), channel sinuosity (Mangold et al., 2010), the short length of gullies (Heldmann et al., 2005)  
577 and the often steep depositional slopes of the fans ( $>15^\circ$ ) (e.g., Conway et al., 2015a; Dickson et al.,  
578 2007; Heldmann and Mellon, 2004; Lanza et al., 2010; Levy et al., 2010). These analyses are in  
579 contrast to many analyses of surficial morphology suggesting a formation by fluvial flows (e.g.,  
580 Heldmann and Mellon, 2004; Reiss et al., 2011, 2009a). All these studies make strong references to  
581 Earth analogues in order to define the morphometric properties distinctive to debris flows. The fact  
582 that martian gullies bear resemblance to terrestrial systems carved by fluvial flows and by debris  
583 flows is not surprising, because firstly systems on Earth (and likely Mars) are polygenetic and  
584 secondly, as detailed below primary formation processes can be masked by secondary ones.

585 Terrestrial studies inform us that effectiveness of secondary modification depends on the ratio  
586 between the characteristic time scales to build morphology by primary deposition and to modify  
587 morphology by secondary processes (de Haas et al., 2014). Alluvial fans whereon the return periods  
588 of primary geomorphic activity are low and/or whereon secondary processes are highly effective are  
589 therefore most susceptible to secondary modification. In extremely dry environments where rates of  
590 geomorphic activity are low, such as in terrestrial deserts and on Mars, surfaces are often modified  
591 by secondary processes. Secondary modification of alluvial fan surfaces can result from multiple  
592 processes, such as wind erosion, fluvial erosion and weathering (Blair and McPherson, 2009, 1994;  
593 de Haas et al., 2015d, 2015b, 2014, 2013). Which of these processes dominate secondary reworking  
594 differs between sites. On Earth, for example, de Haas et al. (2014) describe a debris-flow fan in the  
595 Atacama desert with a surface that has primarily been reworked by weathering and fluvial runoff.  
596 This fan is relatively wind-sheltered, however, and many other fan surfaces in terrestrial deserts are  
597 heavily modified by wind (e.g., Anderson and Anderson, 1990; Blair and McPherson, 2009; de Haas  
598 et al., 2015d, 2014; Morgan et al., 2014). Inactive parts of alluvial fans in the high-arctic, periglacial,  
599 environment of Svalbard are also prone to secondary modification (de Haas et al., 2015c). Here,  
600 secondary reworking mainly results from snow avalanches, weathering and periglacial conditions in  
601 the topsoil resulting in the formation of patterned ground, solifluction lobes and hummocks on  
602 inactive fan surfaces. The origin of long-inactive and modified fans can be determined by  
603 sedimentological analysis of stratigraphic exposures, because reworking is superficial and barely  
604 recorded in the subsurface (Blair and McPherson, 2009, 1994; de Haas et al., 2014). Wind scour can  
605 be an aid in revealing such stratigraphic relationships.

606 Figure 17

607 Similar to terrestrial fan systems, the morphological signatures of the primary processes forming  
608 martian gullies may thus have been removed and/or masked by secondary processes (Figure 17).  
609 High-resolution HiRISE images ( $\sim 0.25$  m/pix) enable the recognition of large boulders and large-scale  
610 stratigraphic layering in sedimentary outcrops on Mars, and thereby sedimentological subsurface  
611 analyses. Sedimentological analysis of outcrops in gully-fans in 51 HiRISE images widely distributed  
612 over the southern mid-latitudes shows that the sedimentology visible in incised sections of many

613 gullies is consistent with debris-flow sedimentology as observed on Earth (de Haas et al., 2015d). The  
614 great majority (96%) of outcrop exposures in gully-fans fed by catchments which mainly comprise  
615 bedrock and thus host boulders, contain sedimentological evidence for debris-flow formation. These  
616 exposures contain many randomly distributed large boulders (>1 m) suspended in a finer matrix and  
617 in some cases lens-shaped and truncated layering. This may explain the long-lasting discrepancy  
618 between morphometric analyses that imply gully formation by debris flows (e.g., Conway et al.,  
619 2011b; Lanza et al., 2010; Mangold et al., 2010) and frequent observations of fan surfaces lacking  
620 clear debris-flow morphology, suggesting formation by fluvial flows (e.g., Dickson and Head, 2009;  
621 Levy et al., 2010; Reiss et al., 2011).

622 In a similar fashion as for fluvial flows, authors have used terrestrial relationships between channel  
623 geometries and discharge/flow velocity for debris flow dynamics to infer the water content and  
624 associated reservoir-size for martian gullies (Jouannic et al., 2012; Levy et al., 2010; Mangold et al.,  
625 2010; Miyamoto et al., 2004). Further, by using terrestrial knowledge of the size-frequency and  
626 sediment concentrations of debris flows not only can the water-reservoir be estimated, but also the  
627 timing and cadence of gully-activity (de Haas et al., 2015b).

### 628 *Slushflows and other exotic fluids*

629 Both slushflows and icy debris flows have been proposed for martian gullies inspired by their  
630 observation on Earth (Auld and Dixon, 2017; Kochel and Trop, 2008) (Figure 18). Icy debris flows  
631 have the same morphological attributes as debris flows, but some of the transported solids are ice –  
632 this leads to a small amount of deflation of the deposits post-deposition (Kochel and Trop, 2008).  
633 The deposits of such flows are similar to those of wet snow avalanches (Figure 18), but for wet snow  
634 avalanches the only remaining morphology is a low concentration clasts (Decaulne et al., 2013; e.g.,  
635 Decaulne and Sæmundsson, 2010; Laute and Beylich, 2013) (Figure 18h) that through repeated  
636 action can result in a recognisable avalanche debris cone (de Haas et al., 2015c) (Figure 18g). On  
637 Earth these cones are built by a combination of processes (Luckman, 1992; Stoffel et al., 2006), so  
638 the contribution of avalanches to the sediment budget can be hard to ascertain. Slushflows are  
639 somewhat similar to debris flows in that they contain a low amount of liquid water compared to  
640 solids, however those solids are not just sediments but relatively large quantities of snow and ice (>  
641 70%). This leads to a number of differences with debris flows, they can initiate on slopes as low as  
642 10° (Elder and Kattelmann, 1993) (Figure 18a), and although they can have lateral levees, the  
643 deposits tend to be chaotic with no clearly defined downslope boundary (Larocque et al., 2001). Like  
644 debris flows they can occur in a hillslope or torrent-fan system (Figure 18b). Physical scale  
645 experiments under terrestrial atmospheric conditions have been performed by Auld and Dixon  
646 (2017), and showing that slushflow could account for some of the erosional and depositional  
647 features of martian gullies. Auld and Dixon (2017) allowed a mixture of liquid and ice to run over an  
648 erodible sediment bed, so the concentration of sediment approaches that for an icy debris flow,  
649 rather than a slushflow which has a lower sediment concentration and less topographic relief than  
650 an icy debris flow.

651 For icy debris flows, avalanches and slushflows, there should be substantial ice content within the  
652 deposited debris. This high volatile content could account for some of the features of martian  
653 gullies, including the slope-orthogonal fractures (Figures 6d and 9d) and the presence of thermal  
654 contraction polygons on the debris fans (Figure 9c). However, ice exposed at the surface of Mars  
655 would also sublime and therefore martian gully-fans should also show signs of sublimation,  
656 including disruption of surface textures, pitting and possibly collapse-structures, which are not  
657 systematically observed.

658 Figure 18 and 19

659 Scaled physical models have been used to explore the effects of the martian atmospheric pressure  
660 on the sediment transport capacity of liquid water. Martian surface air pressure and temperature  
661 are generally below the triple point of water and this means water is transient and unstable – often  
662 termed metastable (Hecht, 2002) and therefore boils. Frozen soil conditions lead to reduced  
663 infiltration, which can lead to both overland flow and debris flow processes at much lower discharge  
664 than if the soil was above freezing (Conway et al., 2011a; Gabet, 2000; Jouannic et al., 2015; Védie et  
665 al., 2008) (Figure 19a-c). Laboratory simulation experiments have shown that boiling leads to three  
666 processes that are not experienced by water flows on Earth (Herny et al., 2018; Massé et al., 2016;  
667 Raack et al., 2017): grain saltation at the flow boundary, granular avalanches triggered by the  
668 saltation and gas production and finally sediment levitation (Figure 19d). All three processes can act  
669 together to lead to much more efficient sediment transport than the equivalent for stable water and  
670 no terrestrial field analogues exist for these sediment transport mechanisms.

#### 671 *Depressed freezing temperatures*

672 The potential influence of brines on the morphology of water-eroded features has not been  
673 addressed in great detail via terrestrial analogy. In their studies of the Antarctic Dry Valleys  
674 Marchant and Head (2007) noted that the water flowing in streams could be saline, but did not  
675 remark on any influence this had on the morphology of the system compared systems developed  
676 with non-saline water. Similarly Harris et al. (2007), Lyons et al. (2005) and in arctic Canada Pollard  
677 et al. (1999) noted springs were forming channels with saline waters yet did not make a full  
678 morphological analogy to martian gullies or a comparison to pure water springs. Levy et al. (2011)  
679 did study the morphology of saline water tracks in the Antarctic Dry Valley, but noted their relief was  
680 weak. Salts are not the only mechanism through which the freezing point of water can be depressed.  
681 Water inside the pore space of sediments can exist in a supercooled state (Kereszturi and Appéré,  
682 2014; Kereszturi and Rivera-Valentin, 2012; K. J. Kossacki and Markiewicz, 2004; Oyarzun et al.,  
683 2003). Water in a porous medium can have freezing points as low as 233 K (-40°C) (Cahn et al., 1992;  
684 Maruyama et al., 1992) without excessive salinity due to the presence of a kinetic barrier, preventing  
685 crystallization in pore spaces where the kinetic energy is considerably lowered (Morishige and  
686 Kawano, 2000). However, to our knowledge no cases have been reported terrestrially where such  
687 interstitial water can trigger downslope sediment flows. Highly concentrated acidic water, such as  
688 that suggested by results from the MER-A and B rovers, can also result in a freezing point much  
689 lower than that of pure water (e.g., Squyres et al., 2006). Using a scaled-physical model Benison et  
690 al. (2008) examined the sediment transport capacity of acidic solutions and found that because  
691 these solutions were more dense and viscous than pure water they carved deeper and narrower  
692 channels yet still produced generically gully-like features. They noted that these solutions could also  
693 form isolated pits in the sediment bed.

694 In principle, the sediment erosion and, transport processes caused by a brine should have similar  
695 mechanisms to those caused by pure water, as long as the brine is sufficiently dilute to remain in the  
696 Newtonian regime. A similar argument can be made for debris flow processes occurring with brines.  
697 However, landscape-scale features with high solute concentrations are limited to hot springs on  
698 Earth (e.g., Fouke et al., 2000) and to a lesser extent rare overland flow events in deserts where salt  
699 has had time to accumulate at the surface (e.g., Callow, 2011). The effect of brines on geomorphic  
700 processes has to our knowledge not been isolated. An expectation from terrestrial geomorphology is  
701 that because we have a good knowledge of the physical processes that govern erosion and  
702 deposition by water that account for fluid viscosity, fluid and particle densities and gravitational  
703 acceleration, it should be relatively simple to transfer this knowledge to brines and then to other  
704 worlds (Grotzinger et al., 2013; Julien, 2010). Although recent low gravity work has started to throw  
705 doubt on this expectation (Kuhn, 2014).

### 706 3.2.2 Release of water at high to moderate obliquity

707 The bottom-up and top-down gully-formation mechanisms described in following Sections (3.2.4-  
708 3.2.6) share a common final water release mechanism: freeze and thaw under the different climate  
709 conditions experienced at high to moderate orbital obliquity on Mars. Mars has an axial tilt which  
710 has a much greater amplitude of oscillation than that of the Earth ( $23^\circ \pm 10^\circ$  in the last 5Ma compared  
711 to  $23^\circ \pm 1$  for the Earth, Figure 20), due to the lack of a large stabilising Moon (Laskar et al., 2004;  
712 Laskar and Robutel, 1993). Variations in axial tilt on the Earth are a component of “Milankovitch  
713 cycles” that are known to strongly influence climate, including mean annual surface temperatures  
714 and volatile distribution (Berger, 1988). Mars’ stronger variation in axial tilt is therefore assumed to  
715 have a commensurately stronger influence on its climate (Forget et al., 2006; Head et al., 2003), with  
716 Head et al. (2008) making a direct comparison to glacial-interglacial cycles on Earth. At higher orbital  
717 obliquity the polar caps receive more insolation in summer and can be completely destabilised,  
718 redistributing their volatiles via the atmosphere to the lower latitudes, resulting in a more vigorous  
719 atmospheric circulation, higher atmospheric pressure and humidity (e.g., Dickson, 2014; Madeleine  
720 et al., 2014). These changes in atmospheric conditions bring Mars’ surface much closer to the triple  
721 point making freeze-thaw cycling and transient liquid water more likely (e.g., Costard et al., 2002;  
722 Richardson and Mischna, 2005).

723 Figure 20

724 This mechanism enables authors to reconcile the observations that mid-latitude gullies are  
725 dominantly pole-facing and that higher latitude gullies have a weaker equator-facing preference, as  
726 these are the places where insolation conditions are expected to favour melt. Costard et al. (2002)  
727 initially invoked orbital obliquities of  $45^\circ$  or more (which last occurred more than 5 Ma ago) to  
728 account for these trends. The Costard model finds that the only locations on Mars that would  
729 experience daily mean temperatures higher than the melting point for ice (273 K) are the mid to high  
730 latitudes on pole-facing slopes, where gullies are indeed observed. However, the Costard model  
731 does not predict the observed onset of equator-facing gullies poleward of  $40^\circ$  latitude (Conway et  
732 al., 2017). More recent studies have shown that more moderate obliquities of  $30\text{-}35^\circ$  which  
733 occurred in the last hundreds of thousands of years can provide good matches to these orientation  
734 observations (Conway et al., 2018b; Williams et al., 2009), but invoke much shallower melting  
735 conditions.

### 736 3.2.3 Release of groundwater from aquifers

737 The shallow aquifer hypothesis was first proposed by Malin and Edgett (2000), and then expanded  
738 upon by Mellon and Phillips (2001) and Goldspiel and Squyres, (2011). This model involves an aquifer  
739 confined by an impermeable rock layer and dry overlying regolith (to provide thermal insulation)  
740 lying upslope from a ridge. At a point close enough to the surface toward the ridge where ground ice  
741 is stable, an ice plug forms. Obliquity-induced freeze-thaw cycles lead to increased fluid pressure  
742 within the aquifer, eventually fracturing the ice plug and allowing water from the aquifer to burst  
743 out of the side of the slope and run downhill, forming a gully. Goldspiel and Squyres, (2011)  
744 concluded this model could only function if the aquifer were briney, or had high permeability (like  
745 that of gravel) or high initial temperature (high geothermal heat flux).

746 Another flavour of this model was proposed by Gaidos (2001) where a deep aquifer is confined by an  
747 impermeable rock layer on the bottom and the cryosphere (Clifford, 1993) on the top. Decreasing  
748 heat flow in the subsurface leads to expansion of the cryosphere, pressurizing the confined aquifer  
749 to the point of fracturing the cryosphere. The liquid water from the aquifer then travels upward  
750 through the fractures due to increased pore pressure until low vertical stresses or failure of the  
751 surrounding rock occur, at which point the water begins moving laterally and a sill of liquid water

752 forms. If the sills reach the surface on a slope, the water is expelled and gullies form. Hartmann et al.  
753 (2003) proposed a shallow aquifer formed by localized geothermal melting of ground ice. Debris  
754 flows would then triggered either by direct rapid release of water to the surface or by saturation-  
755 induced failure. The fact that water travels along impermeable layers in the subsurface and exits at  
756 cliff faces in Iceland (Decaulne et al., 2005; Hartmann et al., 2003), and gully-like forms were located  
757 downslope was used as a direct support for their hypothesis.

758 Grasby et al. (2014) reported on landforms resembling martian gullies (alcove-channel-apron) being  
759 formed by springs fed by a sub-permafrost groundwater circulation system in the Canadian high  
760 arctic (Figure 21). This goes one step further than other authors who used terrestrial analogues to  
761 demonstrate that springs can bring water to the surface in environments considered as analogous to  
762 Mars in the high arctic and Antarctica (Andersen et al., 2002; Harris et al., 2007; Heldmann et al.,  
763 2005; Lyons et al., 2005) and did not attempt to draw a morphological analogy. Coleman et al. (2009)  
764 used a scaled physical model to simulate gullies formed by emergence of water from an  
765 underground aquifer. Their experiments were performed in sand under terrestrial temperature and  
766 pressure and they concluded that gully-like landforms could be produced by aquifer flow at the base  
767 of a cliff.

768 Figure 21

769 Observations of gullies occurring at rock outcrops and at consistent heights below local highs (e.g.,  
770 Gilmore and Phillips, 2002; Heldmann and Mellon, 2004; Marquez et al., 2005) used as support for  
771 the aquifer hypothesis have since been shown to be an artefact of imaging quality, or far from  
772 systematic (with the majority of gully systems extending to the highest local elevation). The shallow  
773 aquifer model cannot easily account for the occurrence of gullies on isolated central peaks and  
774 massifs (e.g., Balme et al., 2006) and recharge mechanisms are problematic without invoking a deep-  
775 cryosphere connection. However, invoking a deep-cryosphere creates the additional problem that  
776 seeps should also be observed on surfaces other than steep hillslopes. Neither the Mars Advanced  
777 Radar for Subsurface and Ionosphere Sounding (MARSIS) nor SHARAD have detected evidence for  
778 shallow aquifers on Mars (Nunes et al., 2010). Despite these difficulties, this model has recently  
779 been revived to account for the occurrence of possibly water- or brine- animated “recurring slope  
780 lineae” (Stillman et al., 2017, 2016).

781 Finally terrestrial analogues have also been used to argue against the groundwater hypothesis.  
782 Treiman (2003) uses terrestrial analogues to argue that the geological structure of craters is  
783 unsuitable for directing seeps to the surface – the layers dip away from the inner crater wall  
784 (Kenkmann et al., 2014). Secondly, the observation that gullies occur across a wide range of bedrock  
785 geologies which should have widely varying permeability makes a universal aquifer hypothesis  
786 unlikely. Earth, which is a similarly geologically complex planet, does not host such integrated  
787 groundwater systems.

788 As pointed out by Baker (2001), based on global trends in gully distribution and orientation alone it  
789 is hard to rule-out the groundwater hypothesis because the source of the water is hidden and the  
790 release mechanism is the same as that proposed for the melt-based hypotheses. Despite the many  
791 convincing arguments against this hypothesis only in situ investigation could completely rule-out  
792 aquifers as a source of water in martian gullies.



### 793 3.2.4 Melting of near-surface ground ice

794 A few different models of melting of near-surface ground ice to produce gullies have been proposed.  
795 In the model of Costard et al. (2002), warming of the surface at an obliquity of 45° lasts long enough  
796 for the temperature wave to penetrate far enough to melt ground ice. The meltwater then saturates  
797 the regolith and produces debris flows once critical shear stress is reached. Gilmore and Phillips  
798 (2002) on the other hand propose a model where water from melting ground ice percolates through  
799 the regolith until encountering an impermeable layer, at which point it travels laterally along the  
800 layer until it exits at the surface where the layers are exposed, such as in a crater or valley wall.  
801 However, this model suffers the structural problems raised for the aquifer models (Section 3.2.3).

802 Costard et al. (2007a, 2002) cited debris flows which they inferred to be produced via melting of  
803 ground ice in Greenland as terrestrial analogues in support of this hypothesis. Védie et al. (2008) and  
804 Jouannic et al. (2015, 2012) point to the formation of the active layer (defrosted upper portion of  
805 permafrost) as key in forming this kind of mass flow on martian sand dunes. Studies by Hooper and  
806 Dinwiddie (2014) and Hugenholtz (2007) in the Great Kobuk Sand Dunes Alaska and southwestern  
807 Saskatchewan, Canada and have shown that debris flows can be initiated by melting of niveo-aeolian  
808 (wind-driven snow) within sand dunes. Gallagher and Balme (2011) noted the similarity in terms of  
809 morphology and landform assemblage between retrogressive thaw on Earth (Figure 22) and gullies  
810 in the northern hemisphere of Mars. However, the wide, shallow depressions with minimal  
811 channelized flow of typical terrestrial retrogressive thaw slumps is dissimilar to most martian gullies.  
812 Yet as shown by Figure 22, such failures could be an initiation point, or component of the sediment  
813 cascade in martian gullies.

814 Figure 22

815 Terrestrial landscapes with gullies where active-layer formation is key to the morphogenesis of the  
816 component landforms have also been used to support this model of gully formation. One of the  
817 often cited case studies is Svalbard (Balme et al., 2013; Hauber et al., 2011a, 2011b; Johnsson et al.,  
818 2012; Reiss et al., 2011) where thaw is central to forming solifluction lobes, sorted patterned ground  
819 and pingos, and debris flows may be triggered by active-layer detachment (de Haas et al., 2015c).  
820 The landscape also contains debris covered glaciers and polygonally-patterned ground, which  
821 although not related to thaw attest to the ice-enrichment of the surface environment. These authors  
822 identify each of these landscape elements on Mars, where they also highlight the similar spatial  
823 arrangement and scale of the landforms. Gallagher and Balme (2011) did not draw on a specific  
824 terrestrial analogue, but referred extensively to terrestrial landscapes and the interrelation typically  
825 reported between landforms to build the case that gullies in high northern latitudes may be formed  
826 by processes analogous to retrogressive thaw slumping. Soare et al. (2017, 2014a, 2014b, 2007) have  
827 used landscapes in the Tuktoyaktuk peninsula, northern Canada, to argue that martian gullies are an  
828 element of a landscape resulting from freeze-thaw cycling, which also includes, high-centred  
829 polygons, pingos and thermokarst depressions (Figure 23).

830 Figure 23

831 In order for this hypothesis to be valid melting needs to be possible in the top metres of the ground  
832 on Mars. Modelling by Mellon and Phillips (2001) showed that the depth of the 273 K isotherm is  
833 always above the depth of any near-surface ground ice that might exist at these latitudes, under  
834 both present-day conditions and under past conditions at high obliquity. Similarly Kreslavsky et al.  
835 (2008) examined the orbital conditions which would permit an active-layer to form and concluded  
836 that these conditions last occurred >5 Ma, hence do not provide a good explanation for martian

837 gullies. Further, Mellon and Phillips (2001) also found that temperatures high enough to melt ice  
838 would only be attained if the ice were composed of 15–40% salts. Melting due to the presence of  
839 salts is also inconsistent with the latitudinal distribution of gullies, as they would be expected to  
840 form at all latitudes over a range of obliquity regimes in this case (Mellon and Phillips, 2001). If the  
841 process that initially formed gullies is responsible for the activity we observe today, the Costard et al.  
842 (2002) model cannot be invoked as gullies are active at Mars' current obliquity. Any models  
843 involving melting at or near the surface would also imply that gully activity would be expected in  
844 summer (as is the case for terrestrial snowmelt-initiated debris flows in Iceland, which peak in the  
845 summer (de Haas et al., 2015c; Decaulne and Sæmundsson, 2007; Rapp, 1986)), and the seasonal  
846 constraints of all of the new gully flows known to have formed within a single Mars year  
847 demonstrate that they are forming in autumn, winter, or very early spring (Diniega et al., 2010;  
848 Dundas et al., 2015, 2012, 2010; Harrison et al., 2009). If the present-day activity in gullies is  
849 separate from their initial formation mechanism, however, then these issues do not pose a problem  
850 for the ground-ice model as it could be valid during periods of higher obliquity.

### 851 3.2.5 Melting of snow

852 Melting of snow as the genesis of gullies was first proposed by Lee et al. (2002) and Hartmann et al.  
853 (2003) based on the resemblance of martian gullies to those on Devon Island and Iceland,  
854 respectively, created by snowmelt (Figure 24a,b). Christensen (2003) (later expanded by Williams et  
855 al., 2009) invoked snowmelt by proposing that gullies were created by melting of dust-covered  
856 snowpacks that formed at high to moderate obliquity ( $\sim 35^\circ$ ), remnants of which are preserved as  
857 LDM deposits on gullied crater walls today. Head et al. (2008) also proposed a model involving  
858 surface meltwater, in which the last glaciation of Mars resulted in debris-covered glaciers forming  
859 against the poleward-facing walls and on the floors of mid-latitude craters. When the climate  
860 changed, the glaciers stopped accumulating and flowing, leaving alcoves exposed on the crater  
861 walls. Residual surface ice and snow in these alcoves then melted to form gullies. Schon et al. (2012)  
862 advocates this model based on the correlation between the calculated age of one particular gully  
863 they studied and the emplacement time of dust-ice covered mantling deposits. The presence of  
864 intimate relationship between glaciers and gullies is further supported by de Haas et al. (2018), who  
865 show that glacial activity often removes gully deposits (leaving only the crown of the gully-alcoves  
866 exposed) but that gullies subsequently rapidly form within the formerly glaciated crater wall  
867 (Conway et al., 2018a). The support and caveats of these models are the same as those discussed in  
868 the previous section on melting of ground ice.

### 869 Figure 24

870 Overland flow of water sourced from snow meltwater in the dry valleys of Antarctica produces many  
871 of the features associated with gullies on Mars: channel sinuosity, v-shaped incision, lateral levees  
872 (although their topographic expression is small) and fan-shaped deposits. Marchant and Head  
873 (2007), amongst others, argue that the cold dry climate of the Antarctic dry valleys makes them a  
874 particularly suitable analogue for Mars, which very few other terrestrial analogues can match. In this  
875 location, gully alcoves are observed to form traps for windblown snow and ice, otherwise known as  
876 nivation hollows (e.g., Christiansen, 1998; Dickson et al., 2007; Lee et al., 2004). Because of the  
877 aridity of the dry valleys, there are usually high concentrations of salt at the surface, which cause any  
878 water flow to be salty (Marchant and Head, 2007). The authors argue that this could also be the case  
879 on Mars and would favour gully formation via snowmelt. The assemblage of landforms found  
880 alongside gullies in the Dry Valleys, including notably polygonally-patterned ground and glacial  
881 landforms has also been used to support this environmental analogue as a process analogue to  
882 gullies and their associated landforms on Mars (Levy et al., 2009; Marchant and Head, 2007) (Figure  
883 24c).



884 Védie et al. (2008) performed scaled physical experiments designed to simulate the formation of  
885 Russell Crater's linear dune gullies under ambient Earth pressure and low temperature (Figure 19).  
886 They found that snowmelt as a water-source did not produce morphologies distinct from other  
887 water sources (perched aquifer, melting of ground ice). A similar conclusion was reached by Sinha et  
888 al. (2018) who compared debris flows generated by snowmelt in the arid Himalaya to gullies with  
889 similar morphology on Mars. These studies imply that snowmelt is hard to distinguish from other  
890 near-surface sources of water by morphology alone and hence it would be difficult to detect its  
891 influence in the formation of martian gullies.

### 892 3.2.6 Melting of H<sub>2</sub>O frost

893 Kossacki and Markiewicz (2004) investigated whether gullies could have formed from seasonal  
894 melting of accumulated H<sub>2</sub>O frost under favourable pressure and wind speed conditions. In this  
895 model, H<sub>2</sub>O frost transitions to the liquid phase after the complete removal of the overlying CO<sub>2</sub> frost  
896 layer (which deposits atop H<sub>2</sub>O frost seasonally on Mars). CO<sub>2</sub> frost can remain on crater walls into  
897 late spring. Once insolation increases above a certain intensity (in late spring/early summer), the last  
898 CO<sub>2</sub> frost sublimates away, which could result in the rapid heating (and melting) of the underlying  
899 H<sub>2</sub>O frost. The presence of salts within the water ice could aid in lowering the melting temperature  
900 and favour this process. The estimated maximum volume of liquid that could be generated by this  
901 melting is <0.2–0.55 kg/m<sup>2</sup> depending on latitude, which Kossacki and Markiewicz (2004) state is not  
902 enough to generate any surface flow, but could affect the cohesive properties of the surface layer of  
903 the slope. With an average water-vapour abundance of only ~10 precipitable micrometres in the  
904 current martian atmosphere (Jakosky and Barker, 1984; Jakosky and Farmer, 1982), other authors  
905 have also argued that frost accumulation and subsequent melting would likely not be significant  
906 enough to saturate the regolith to the point of slope failure, but rather the dampening would lead to  
907 increased cohesion (e.g., Dundas et al., 2015). The darkening of the surface by this dampening has  
908 been hypothesised to be the origin of RSL on Mars (McEwen et al., 2011), where downslope  
909 percolation of small amounts of water explain the gradual growth of these relatively dark features. A  
910 terrestrial analogue for this kind of water percolation was reported by Levy et al. (2011) in the form  
911 of water tracks in Antarctica. These water tracks are saline and supplied by melting snow, pore-ice  
912 and ground ice. They have also been used as analogies for martian linear gullies on dark sand dunes—  
913 where a dark halo is observed to appear at the same time as new/modified gully-tracks (Jouannic et  
914 al., 2017). Pasquon et al. (2016) termed these dark halos “RDF” or Recurrent Diffusing Flows.  
915 Jouannic et al. (2017) also use an unusual example of snowmelt on a glacier as a process analogue  
916 for the formation of new “perennial rills” within these RDF, however they leave open the question of  
917 which fluid is involved.

918 Recent scaled physical models under Mars pressures have revealed that the metastable nature of  
919 water on Mars means that more sediment transport could occur than might be expected from stable  
920 water (Herny et al., 2018; Massé et al., 2016; Raack et al., 2017). Therefore, the main argument  
921 against the meltwater hypothesis – that melting surface frost cannot produce enough water for  
922 surface flow – may be somewhat ameliorated if these processes are indeed active.

923 The argument that frosts are too thin (because of the low atmospheric humidity) to explain the size  
924 of martian gullies, has some potential counter-arguments, as follows. Water vapour abundance in  
925 the martian atmosphere is highly variable, dependent upon the time of day, season, and local  
926 conditions (e.g., Tamppari and Lemmon, 2014). Due to its low concentration in the atmosphere and  
927 its variability, modelling the distribution of water vapour in the past is challenging (e.g., Madeleine  
928 et al., 2014; Steele et al., 2017), particularly under high obliquity when the water cycle is predicted  
929 to be more intense (e.g., Haberle et al., 2003). Hence, it is challenging to make any solid statements  
930 about frost availability at martian gully sites in the past. Further, present-day measurements of

931 water vapour from orbit are likely unrepresentative of transient and local surface conditions, which  
932 would be sufficient to generate small amounts of melt, as argued in the RSL literature (Chojnacki et  
933 al., 2016; McEwen et al., 2014). Wind redistribution of seasonal frosts could also increase the local  
934 thicknesses of frosts, somewhat analogously to the melting of snow hypothesis discussed in the  
935 previous section. Equally the distribution of surface frosts is highly sensitive to small variations in  
936 topography, so despite the general prediction that frost should not accumulate on equator-facing  
937 slopes as they are never deeply shadowed (Schorghofer and Edgett, 2006), observations of frost are  
938 made on equator-facing slopes (Dundas et al., 2017b) (Figure 12). Terrestrial analogy dictates that  
939 only episodic optimal conditions are required and they can produce significant landscape change  
940 (Levy, 2015; Marchant and Head, 2007).

### 941 3.3 CO<sub>2</sub> related mechanisms

942 Carbon dioxide is the major constituent of the martian atmosphere and condenses onto the surface  
943 at the high latitudes every winter. Its sublimation in the spring is believed to be responsible for  
944 sediment transport in the form of “spiders” (e.g., Kieffer et al., 2006; Piqueux et al., 2003a;  
945 Portyankina et al., 2010) and dark spots and flows on polar dunes (e.g., Gardin et al., 2010; Kereszturi  
946 et al., 2009; Kossacki and Markiewicz, 2014). CO<sub>2</sub> frost is known to extend continuously from the  
947 pole to latitudes of 50° in mid-winter (e.g., Piqueux et al., 2015) and is found on steep pole-facing  
948 slopes from latitudes from 50° to 30° (Vincendon et al., 2010b). Hence, its geographical distribution  
949 matches that of gullies and the timing of recent gully-activity in martian winter matches with its  
950 presence. The polar-pit gullies and classic dune gullies are the only examples where the tight  
951 constraint on timing leaves CO<sub>2</sub> as the only unambiguous candidate to account for the sediment  
952 movements observed in these systems. However, as discussed in Section 2.1, polar-pit gullies are  
953 somewhat different from the majority of gully systems, so the processes that form them may differ  
954 from those active in other gully systems.

955 Based on the timing of observed present-day gully activity (generally in winter coinciding with  
956 periods when CO<sub>2</sub>-frost is on the ground), a CO<sub>2</sub>-based process for gully formation is favoured by  
957 Diniega et al. (2010), Dundas et al. (2017b, 2015a, 2012a, 2010a), Pasquon et al. (2016) and Raack et  
958 al. (2015). A CO<sub>2</sub>-related process is supported by the observation of a higher level of activity in the  
959 south polar-pit gullies (Raack et al., 2015) compared to those in the mid-latitudes, as more frost is  
960 deposited on slopes at higher latitudes. South polar pits should host ~1 m of CO<sub>2</sub> frost accumulation  
961 in winter (Hoffman, 2002), which is significantly more than lower latitude gullies, where microns of  
962 accumulation are predicted (Vincendon et al., 2010a). However, CO<sub>2</sub> frost has not been detected  
963 spectroscopically at latitudes equatorward of ~34°S (Vincendon et al., 2010b), and present-day gully  
964 activity has been observed at latitudes as low as 29°S. Dundas et al. (2015) do note that CO<sub>2</sub> frost  
965 processes might simply be the dominant driver of activity within pre-existing gullies today, and not  
966 the process by which they initially formed.

967 In the following sections we will present the various CO<sub>2</sub>-driven mechanisms of gully-formation that  
968 have been proposed. We start with liquid CO<sub>2</sub> which has now been rejected on the grounds of  
969 thermodynamics, but is presented here because the authors used terrestrial analogues to support  
970 their arguments. We then present mechanisms that involve the gravitational displacement of solid  
971 CO<sub>2</sub> with or without the evolution of CO<sub>2</sub> gas. Finally we detail the mechanisms that primarily involve  
972 the transport of sediment by gas evolved from CO<sub>2</sub> sublimation.

#### 973 3.3.1 Release of liquid CO<sub>2</sub> from shallow aquifers

974 Musselwhite et al. (2001) proposed that martian gullies formed via the outbreak of liquid CO<sub>2</sub> from  
975 near-surface “aquifers”. In this model, similar to the shallow groundwater model of Malin and Edgett

976 (2000) described in Section 3.2.2, liquid CO<sub>2</sub> builds up in an aquifer behind a dry ice “dam” that  
977 forms at the point in the subsurface where liquid CO<sub>2</sub> is no longer stable. Seasonal and/or obliquity  
978 cycle driven heating weakens the dry ice “dam”, eventually resulting in the rapid release of liquid  
979 CO<sub>2</sub> to the surface. Upon reaching the surface, the CO<sub>2</sub> would rapidly vaporise, forming a gas-  
980 supported flow that entrained rock and ice, carving a gully as it moved downhill. The authors argue  
981 for CO<sub>2</sub> over H<sub>2</sub>O as the gully-carving agent on Mars, because CO<sub>2</sub> is the most abundant volatile on  
982 the planet. This model was quickly dismissed due to the difficulty in both accumulating and  
983 sustaining significant amounts of either condensed CO<sub>2</sub> or CO<sub>2</sub> clathrate-hydrate in the martian crust  
984 (Stewart and Nimmo, 2002). Stewart and Nimmo (2002) state that gas-supported flows of this  
985 nature would have velocities much too high to create morphologies observed in martian gullies, and  
986 would be expected to result in forms more like terrestrial pyroclastic flows than the fluvial/debris  
987 flow forms of gullies (Stewart and Nimmo, 2002). Therefore, they used the dissimilarity of a  
988 terrestrial landform to martian gullies in order to counter the hypothesis proposed by Musselwhite  
989 et al. (2001). They particularly point to the visual dissimilarity between the deposits of the Mt. St.  
990 Helen’s pyroclastic flows and the depositional fans of martian gullies (Figures 6 and 14).

### 991 3.3.2 CO<sub>2</sub> frost avalanches, blocks and frosted granular flow

992 Ishii and Sasaki (2004) proposed that avalanches of solid CO<sub>2</sub> frost could gradually carve gullies over  
993 time by “scratching” into the surface as chunks of frost fell during periods of sublimation (i.e., spring  
994 into summer). Frost avalanches have also been proposed as gully formation/evolution mechanisms  
995 by some authors based on HiRISE observations of frost-dust avalanches on a north polar scarp  
996 (Russell et al., 2008) and the hypothesis of Costard et al. (2007b) that “dark streaks” observed over  
997 frost in gullies are dry avalanches. However, present-day CO<sub>2</sub> frost avalanches on scarps of the  
998 northern polar layered deposits have not been observed to form any gully-like features (Russell et  
999 al., 2008). Because these avalanches do not involve a volatile phase their behaviour and morphology  
1000 should be similar to that of dry granular flows and therefore this model has been discounted on the  
1001 same grounds (see Section 3.1).

#### 1002 Figure 25

1003 A different type of sublimation-induced CO<sub>2</sub> ice avalanching has been suggested as the formation  
1004 mechanism behind linear dune gullies, such as those on the dunes in Russell Crater (Diniega et al.,  
1005 2013). In this model (originally proposed by Hansen et al. (2011) for mass-movement features on the  
1006 north polar erg of Mars), blocks of CO<sub>2</sub> ice dislodge from the top of the dune in springtime due to  
1007 sublimation induced by solar heating. The blocks then travel downslope, levitating on a cushion of  
1008 CO<sub>2</sub> gas, carving leveed linear channels. The authors use a field-simulation analogue to support their  
1009 hypothesis, where the authors placed decametre-scale sublimating blocks of CO<sub>2</sub> ice on terrestrial  
1010 dunefields (Figure 25) and produced similar narrow leveed channels (and terminal pits). These pits  
1011 have also been reproduced in laboratory simulations with sublimating blocks of CO<sub>2</sub> ice (Mc Keown  
1012 et al., 2017). As discussed in Sections 2.1 and 2.6, the peculiar morphology and precise timing of the  
1013 activity of linear gullies suggests that their formation process is different from the other martian  
1014 gullies, so this mechanism has not been applied to the general population of gullies.

#### 1015 Figure 26

1016 Hugenholtz (2008b) proposed frosted granular flow as a gully formation mechanism on Mars based  
1017 on terrestrial observations (Figure 26). Frosted granular flow is a rare type of mass movement on  
1018 Earth where clasts are lubricated by thin frost coatings, facilitating downslope movement. They tend  
1019 to occur in the fall and spring when the air temperature oscillates around freezing (273 K) at times of

1020 relatively high humidity on snow-free surfaces (Hétu et al., 1994; Hétu and Gray, 2000). Hétu et al.  
1021 (1994) noted four conditions required for frosted granular flow: (1) unconsolidated sediment easily  
1022 mobilized downslope, (2) a slope gradient at or near the angle of repose in the source region, (3)  
1023 frost accumulation on the unconsolidated grains, and (4) a trigger for mass movement (on Mars this  
1024 could be, for example, rockfall (Hétu et al., 1994), point-source defrosting (Costard et al., 2007b),  
1025 vapour-induced instability (Hoffman, 2002), or avalanching of CO<sub>2</sub> frost (Ishii and Sasaki, 2004)).  
1026 Locations of repeated flows typically either follow pre-existing channels or, when diverted by  
1027 obstacles, create new channels. Grains ranging in size from fine-grained sand (~0.0007 cm) to large  
1028 clasts (20 cm) can be mobilized by these flows on slopes as low as ~25°; however, frosted granular  
1029 flows predominantly transport gravel-sized grains (Hétu and Gray, 2000; Hugenholtz, 2008b). As for  
1030 debris flows, kinetic sieving results in accumulation of large clasts at the flow margins and surface of  
1031 frosted granular flows. Frosted granular flows are reported to exhibit levees, straight to sinuous  
1032 channels, concave profiles, and digitate terminations (Hétu et al., 1994; Hétu and Gray, 2000), which  
1033 are similar to debris flows. Seasonal H<sub>2</sub>O frost accumulates as far north as 13°S in the winter  
1034 (Vincendon et al., 2010a), and early morning frost has been observed on the ground by the  
1035 Opportunity rover at 2°S (Landis, 2007), covering the entire latitude range where gullies are found in  
1036 the southern hemisphere. Hugenholtz (2008b) proposes that CO<sub>2</sub> frost rather than water ice frost  
1037 may be the lubricating mechanism for frosted granular flows on Mars. However, this seems unlikely  
1038 because only thin diurnal night time CO<sub>2</sub> frost has been detected at latitudes lower than ~34°S  
1039 (Piqueux et al., 2016; Vincendon et al., 2010b). Additionally, CO<sub>2</sub> frost does not accumulate in the  
1040 mid- to high-latitudes in areas that are never deeply shadowed at any point in the year (Schorghofer  
1041 and Edgett, 2006), and gullies are found on equator-facing slopes where CO<sub>2</sub> frost is not predicted to  
1042 accumulate. In addition, frosted granular flow seems unlikely as a principle driver for gully formation  
1043 based on their morphology. The morphology of frosted granular flow channels and deposits are very  
1044 similar to that of classic granular flows described in Section 3.1 and lack the morphological  
1045 complexity shown by typical martian gullies, including tributary networks, deep incisions,  
1046 streamlined forms and terraces (Figures 2, 5, 6).

### 1047 3.3.3 CO<sub>2</sub> gas-fluidized flow

1048 Hoffman (2002) and Cedillo-Flores et al (2011) proposed that gullies in at least Mars' polar regions,  
1049 such as those in the south polar pits of Sisyphi Cavi, formed by fluidization of aeolian sediment  
1050 deposited atop CO<sub>2</sub> frost once the frost begins to sublime in springtime (Figure 27). This model  
1051 requires a slope covered with CO<sub>2</sub> frost, which is then subsequently mantled by sediment, sand, or  
1052 dust via aeolian transport from adjacent non-frosted slopes. The frost layer rapidly sublimates due to  
1053 heating of the overlying lower-albedo material. This introduces instability to the slope, triggering  
1054 mass movement. Mechanical heating as the material moves downslope generates more CO<sub>2</sub> vapour,  
1055 acting as a lubricant to allow the mass to behave like a fluid and carving a channel. This model differs  
1056 from that of Musselwhite et al. (2001) in that it only invokes surface CO<sub>2</sub> ice based on the  
1057 aforementioned thermodynamic difficulty in sustaining CO<sub>2</sub> ground ice on Mars.

1058 Figure 27

1059 Recent activity within polar pit gullies coincides with periods of defrosting (Hoffman, 2002; Raack et  
1060 al., 2015), which has led to the suggestion that CO<sub>2</sub> defrosting is capable of initiating mass  
1061 movement of the underlying sediment (rather than sediment deposited atop it). Hoffman (2002)  
1062 suggests that the closest terrestrial analogue to this sort of gas-fluidized flow is a density flow, and  
1063 presents submarine turbidity channels for their morphological similarity to martian gullies, where  
1064 the submarine landforms display sinuous channels (Figure 28) and distributary fans.

1065 Figure 28

1066 Following along the same lines, Pilorget and Forget (2016) propose a model where CO<sub>2</sub> ice  
1067 condenses onto the surface in autumn, gradually forming a continuous slab. Sublimation at the base  
1068 of the slab ice occurs due to differential solar heating of the underlying regolith, because the slab ice  
1069 is relatively transparent to sunlight. Some of the resulting CO<sub>2</sub> gas diffuses into the regolith, trapped  
1070 between impermeable permafrost and the overlying CO<sub>2</sub> slab ice. In mid-winter, CO<sub>2</sub> ice begins to  
1071 condense in pore spaces within the upper few centimetres of the underlying regolith. Pressure  
1072 builds up to a point where the CO<sub>2</sub> gas ruptures the overlying ice, forming jets of CO<sub>2</sub> gas that could  
1073 destabilize the slope and cause a fluidized debris flow. This was inspired by the model of sub-slab  
1074 sublimation which has been proposed for the formation of south polar spiders (Kieffer et al., 2006;  
1075 Piqueux et al., 2003b). Pilorget and Forget (2016) describe this type of gas-supported flow as being  
1076 akin to a terrestrial pyroclastic flow (Figure 14). They note that not every “eruption” of CO<sub>2</sub> gas  
1077 would be expected to generate a gully, but multiple eruptions in the same place could occur due to  
1078 re-condensation, leading to repeated events within an individual gully system. In fact, in the case of  
1079 the Russell Crater dune gullies, their model predicts eruptions on a daily basis from L<sub>s</sub> 150–205°,  
1080 which coincides with the appearance of dark flows, but not linear gully activity (Jouannic et al., 2017;  
1081 Pasquon et al., 2017). One of the prerequisites for this model is the presence of a CO<sub>2</sub> ice slab, which  
1082 is not expected at the mid-latitude sites where the majority of active gullies are located and is not  
1083 easily applicable to gullies on equator-facing slopes in the mid-latitudes, where CO<sub>2</sub> if present is  
1084 likely to be spatially discontinuous and thin (Conway et al., 2018b; Dundas et al., 2017b).

1085 As argued by Hoffman (2002), density currents, such as pyroclastic flows and submarine turbidity  
1086 currents are the nearest analogy for sediment transport by sublimating CO<sub>2</sub>. Numerical models have  
1087 shown that pyroclastic flows on Earth behave like dense granular flows and produce a broad central  
1088 linear channel with lateral levees and terminal lobes (Félix and Thomas, 2004; Mangeney et al.,  
1089 2007). Terrestrial laboratory experiments of fluidization of dry material with CO<sub>2</sub> gas (Cedillo-Flores  
1090 et al., 2008; Sylvest et al., 2018, 2016) similarly produce features morphologically similar to dry sand  
1091 flows on terrestrial dunes, as the gas rapidly escapes (Figure 14). Further work is needed to ascertain  
1092 whether CO<sub>2</sub> sublimation can produce long-lived fluidisation and therefore morphologies similar to  
1093 martian gullies. It has been hypothesised that the repeated action of discrete granular flows can  
1094 produce connected networks (Shelef and Hilley, 2016) and complex channel geometries as seen in  
1095 martian gullies and terrestrial equivalents. As stated by Hoffman (2002) “quantitative diagnostic  
1096 criteria must be developed to distinguish between the morphologies produced by subaerial flows  
1097 and those of density flows”.

### 1098 3.4 Summary of gully formation mechanisms

1099 Since their discovery, many processes, often based on terrestrial analogues, have been proposed by  
1100 a variety of authors to understand the formation of gullies on Mars. Hypothesized geomorphic flow  
1101 processes range from completely dry to various types of water- and CO<sub>2</sub>-lubricated flows. To fully  
1102 understand gully formation, these processes need to be able to account for activity in gullies at the  
1103 present-day as well as during past, higher-obliquity, conditions.

1104 At present, dry flows have been ruled out as a predominant gully-forming mechanisms, because of  
1105 the typical gully-fan slopes, which are well below the dynamic angle of repose, and gully morphology  
1106 that is inconsistent with dry-flow morphology. Present-day gully activity is intimately linked to CO<sub>2</sub>-  
1107 defrosting, and therefore CO<sub>2</sub> likely plays a role in the formation of many present-day flows.  
1108 However, this process is not able to account for the distribution of the full gully population, such as  
1109 gullies on equator-facing mid-latitude slopes. Liquid water should not be thermodynamically stable  
1110 under current martian conditions, and therefore is unlikely to account for present-day gully activity.  
1111 On the other hand, during periods of higher-obliquity in the past, climate models predict that snow  
1112 and ice should have been stable down to ~30° of latitude, consistent with the global distribution of



1113 gullies. Moreover, under these conditions snow and ice was likely able to melt, and thereby form  
1114 gullies.

1115 In short, as extensively discussed above, there is no single gully-formation mechanism that is  
1116 consistent with all the observations of the full gully-population on Mars. Like on Earth, it is therefore  
1117 likely that multiple processes operate within gullies, and that the predominant mechanism could  
1118 change over time, under changing atmospheric conditions as a result of variations in orbital forcing.

## 1119 4. The role of Earth analogues in gully-research

### 1120 4.1 Earth analogues: their advantages and their limitations

1121 A full review of the usefulness of Earth analogues in planetary science is outside the scope of this  
1122 review and we refer interested readers to more detailed works on this topic (e.g., Baker, 2014). Here  
1123 we discuss particular issues that have arisen repeatedly during our review of the martian gully  
1124 literature. Earth analogues have been intensely used to construct working hypotheses regarding the  
1125 processes and fluids that lead to gully formation on Mars. Different types of terrestrial analogy have  
1126 been used and we have pulled-out these general themes, where most papers on martian gullies use  
1127 one or more of these approaches:

- 1128 • Plan-view morphology at the landscape-scale or feature-scale
- 1129 • Three-dimensional (3D) or plan-view morphometry
- 1130 • Environmental analogues
- 1131 • Landscape assemblages
- 1132 • Physical scale experiments
- 1133 • Empirical laws from terrestrial studies

1134 Out of these types of analogues the ones that rely on planview morphology are the most  
1135 controversial, because of equifinality, whereby similar landforms can be produced by widely  
1136 different processes (Chorley, 1962). A case in point is that pyroclastic flows have been interpreted to  
1137 be both similar and unlike martian gullies by different authors (Sections 3.1 and 3.3.3) (Pilorget and  
1138 Forget, 2016; Stewart and Nimmo, 2002; A. H. Treiman, 2003). The fact that widely different  
1139 processes can result in leveed channels with lobate terminal deposits on Earth (including debris  
1140 flows, lava flows, and pyroclastic flows; Figure 29), suggests that various physical processes can be  
1141 responsible for a similar morphology. However, once the morphometry, upslope landforms, and  
1142 landscape setting of these lobate deposits are taken into account the similarity with the alternative  
1143 landform is reduced (Baker, 2017). Hence, using a combination of morphological and morphometric  
1144 similarities at a range of spatial scales can establish a more robust analogy (Mutch, 1979;  
1145 Zimbelman, 2001) and is an approach that has been adopted by many researchers working on  
1146 martian gullies. To build a successful analogy, full similarity over a range of scales and processes is  
1147 not required, i.e., not every aspect of the target landscape needs to be reproduced (e.g., climate,  
1148 geology, soil, topography). In the case of martian gullies, Antarctica is the nearest environmental  
1149 analogue (low temperatures and humidity; e.g., Marchant and Head, 2007), Iceland forms a better  
1150 geological analogue (basalt bedrock; Hartmann et al., 2003), and impact craters form the best  
1151 analogue in terms of topographic and structural setting (e.g., Osinski et al., 2006) and all of these  
1152 have been used to gain fruitful insights into martian gully formation.

1153 Figure 29

1154 The debate over carbon dioxide as an active agent of morphological change in martian gullies  
1155 highlights one of the potential limitations of Earth analogy. That is, can we successfully argue that  
1156 liquid water is involved in martian gullies by using Earth analogues if we cannot provide the counter-  
1157 point of landscapes created by CO<sub>2</sub> sublimation, or at least gas-supported flows? In this case are  
1158 terrestrial analogues helpful at all, or simply misleading? Analogy (Hesse, 1966) can still be useful:  
1159 although not providing definitive explanations, it does provide a source of hypotheses that move  
1160 geological research into productive lines of inquiry (Gilbert, 1896). We argue that for terrestrially  
1161 rare or unknown processes, further progress can be made by using numerical modelling and scaled  
1162 physical models (which we consider here as a subtype of terrestrial analogy). Laboratory  
1163 experiments can be used to determine if the physical processes governing sediment transport by  
1164 CO<sub>2</sub> sublimation are indistinguishable from those driven by water as the interstitial fluid. Substantial  
1165 work is required, however, to both properly understand the physics that govern these processes and  
1166 then to appropriately scale up the processes observed in the laboratory to assess if they can indeed  
1167 produce the landforms we observe.

1168 Establishing a terrestrial analogue allows us to exploit the depth of knowledge on that process in  
1169 order to respond to Mars-specific questions. For example, based on an analogy between fluvial and  
1170 martian gullies, Parsons and Nimmo (2010) and Hobbs et al. (2014) applied empirical terrestrial  
1171 relationships between discharge and fluvial channel dimensions to estimate the water required to  
1172 form martian gullies. Yet, success of empirical approaches depends on whether the empirical  
1173 parameters are inherently terrestrial. Recent work in low gravity parabolic flights has highlighted, for  
1174 example, that the empirical drag coefficient used when estimating the settling velocity of particles in  
1175 a flow, is dependent on gravity, when previously it was believed to be independent (Kuhn, 2014).  
1176 Therefore, particles under martian gravity settle more quickly and have a much narrower  
1177 distribution in settling velocities (for a given range of particle shapes and sizes) than would be  
1178 predicted by applying the empirical settling velocity. Nevertheless applying terrestrial empirical laws  
1179 can give important insights into gully formation and evolution, as long as interplanetary differences  
1180 are carefully considered.

#### 1181 4.2 Future directions

1182 The work reviewed in this paper shows that terrestrial analogues have played an important role in  
1183 martian gully research. We consider transporting both terrestrial analogies in terms of both  
1184 landscape-process interpretation, but also in terms of the methodologies used to interpret the  
1185 formative environment, as a fruitful avenue that should continue to be exploited in future martian  
1186 gully research. We have also identified five further avenues where we think further research could  
1187 yield important insights.

1188 Terrestrial experience tells us that separating individual landscape-forming processes from one  
1189 another is disingenuous. For instance, fluvial flows can evolve into debris flows via gradual  
1190 incorporation of loose debris downslope (firehose effect, or bulking; Coe et al., 2008; Godt and Coe,  
1191 2007). Erosion of bedrock is typically limited during fluvial or debris flow events in steep catchments,  
1192 landslide processes are a common prerequisite for making sediment available in catchments (Benda  
1193 and Dunne, 1997) and the bedrock is initially weakened by weathering (Matsuoka and Murton,  
1194 2008; Phillips, 2005). Those loose sediments are then removed by debris flow or fluvial processes,  
1195 the efficiency of such sediment cascades is defined as “connectivity” (e.g., Cavalli et al., 2013). We  
1196 advocate that progress can be made in martian gully research by considering the landform as a  
1197 series of sediment cascades and the connectivity of the landscape as a whole system (Bennett et al.,  
1198 2014; Heckmann and Schwanghart, 2013). In considering the cascade of sediments relatively little  
1199 work has focussed on establishing terrestrial analogues and understanding the processes in the  
1200 erosional part of martian gullies (i.e., the alcoves). A notable exception is the study by Okubo et al.



1201 (2011) who examined the potential triggers of landslides in alcoves to supply sediment to martian  
1202 gullies in Gasa crater. However, these authors did not consider the fate of the sediments post-  
1203 failure. The increasing availability of high resolution digital elevation models of martian gullies is  
1204 opening up the opportunity to study the connectivity and sediment cascades from source to sink  
1205 using both morphological and morphometric techniques.

1206 The increasing availability of digital elevation models of martian gullies also offers another  
1207 opportunity – the possibility of employing landscape evolution models to understanding gully  
1208 formation. Such an approach has been applied in the study of the degradation of martian impact  
1209 craters via fluvial systems driven by rainfall (Howard, 2007). However, this approach has yet to be  
1210 applied to martian gullies. Martian gullies are ripe for this application because of two recent  
1211 innovations: 1) the increasing use of synthetic DEMs as a starting point for landscape evolution  
1212 models (Hillier et al., 2015), allowing gullies to be simulated in undisturbed topography and 2) the  
1213 recognition that landscape evolution models can be driven by stochastic discrete flow events (Shelef  
1214 and Hilley, 2016), rather than flow driven by continuous variables. The use of landscape evolution  
1215 models could help us to explore the age of gullies, the climate drivers and the expected sedimentary  
1216 packages relevant for understanding the rock record on Mars.

1217 Similarly, there is a wide range of advanced 2D to 3D numerical models that are used simulate dry  
1218 and wet sediment-gravity flows on Earth over realistic topography (e.g., debris flows, grain flows and  
1219 snow avalanches) (Christen et al., 2010, 2007; Iverson and George, 2014; Mergili et al., 2017; O'Brien  
1220 et al., 1993). Such models can correct for martian gravity, and in combination with high-resolution  
1221 DEMs, be used to infer the initiation and flow conditions that led to the formation of deposits on  
1222 martian gully-fans. Such analyses could shed new light on the palaeoclimatic conditions leading to  
1223 gully formation. Yet, despite their great potential, only Pelletier et al. (2008) used one such model,  
1224 FLO-2D, to infer the volumetric water content in a recent flow deposits in a crater in the Centauri  
1225 Montes region. An important application of such models would be distinguishing between fluvial,  
1226 debris flow and gas supported flows based on the extent and thickness of the observed deposits.

1227 Scaled-physical models are another area where we think that significant progress can be made in  
1228 understanding the processes that form martian gullies. Lapotre et al. (2017) highlighted that natural  
1229 water flows on Earth cover a narrow range of fluid densities, viscosities, and grain densities and they  
1230 inevitably occur under terrestrial gravity, which means that the effects of these different parameters  
1231 on flow behaviour is hard to assess from terrestrial observations alone. Laboratory experiments  
1232 allow us to vary such parameters. In addition, certain physical processes can be isolated and studied  
1233 in detail in order to understand the basic underlying mechanics. The relative importance of the  
1234 driving variables can be assessed experimentally (in terms of rates, frequency and magnitude) and  
1235 the physical equations can be used to explore the parameter space guiding future laboratory work.  
1236 Gravity can be adjusted via the use of parabolic flights and has been used to study granular flows  
1237 under martian gravity (Kleinhans et al., 2011), but has not yet been extended to fluidised flows. The  
1238 study of sediment transport by CO<sub>2</sub> sublimation is in its infancy and is of particular importance for  
1239 breaking the impasse between liquid water vs CO<sub>2</sub> for forming and modifying gullies. The potential  
1240 role of brines and metastable fluids in sediment transport on Mars is also an area where significant  
1241 work remains. An important area for future work will be using experiments to place limits on slope  
1242 angles and grainsizes for deposition and erosion caused by different transport mechanisms, which  
1243 can then be compared to slope and grainsize observations of martian gullies. Laboratory simulations  
1244 exploring how volatiles such as CO<sub>2</sub> and water vapour interact with the martian regolith and respond  
1245 to changes in surface temperatures are also needed to understand the processes involved in  
1246 triggering the sediment cascades we observe in martian gullies. Laboratory studies also present the  
1247 advantage of being able to study the dynamic component of sediment transport, which is severely

1248 lacking on Mars where the gap between images can be several sols, but is usually at least several  
1249 months.

1250 The formative processes of gullies and their spatial distribution has been extensively studied and  
1251 quantified (e.g., Balme et al., 2006; Dickson et al., 2007; Harrison et al., 2015; Heldmann and Mellon,  
1252 2004; Kneissl et al., 2009), while only few studies have addressed their temporal evolution (de Haas  
1253 et al., 2018, 2015b; Dickson et al., 2015). Focusing on the temporal evolution of gullies is an  
1254 important avenue of future research, as the dominant formative mechanism of gullies may change  
1255 over time and because gullies may interact with other processes over time. Recent work by de Haas  
1256 (2018, 2015b) shows that crater dating provides a promising tool for unravelling gully formation  
1257 mechanisms as long as the considered temporal resolution is large enough to be resolved via crater  
1258 counting.

## 1259 5. Conclusions

1260 In this review we have summarised the main hypotheses proposed for martian gully formation and  
1261 the role that Earth analogues have played in conceiving and developing these hypotheses. There  
1262 remains a debate in the community between the role of CO<sub>2</sub> and liquid water in forming gullies.  
1263 Using terrestrial analogy alone, liquid water is the most plausible candidate, yet current  
1264 modifications in gullies occur at times of year when surface liquid water is unlikely. Sediment  
1265 transport by sublimating CO<sub>2</sub> lacks a terrestrial analogue, hence it is difficult to judge whether the  
1266 morphology of all martian gullies could be produced by this mechanism. Knowledge from Earth tells  
1267 us that landforms are not made by a single processes and that these processes can vary in space and  
1268 in time. Hence, we believe that the present processes in gullies likely do not accurately represent  
1269 those active in the past. An urgent effort is required to ascertain the sediment transport capacity of  
1270 CO<sub>2</sub> supported flows on Mars and its resulting landforms to make progress.

1271 We find that on balance terrestrial analogies are useful for understanding the complexity and  
1272 interplay of processes involved in creating gullies on Mars – such insights are difficult to obtain from  
1273 either remote sensing, numerical modelling, or laboratory studies alone. We emphasise that caution  
1274 should be taken in applying these analogies taking into consideration the important environmental  
1275 differences between Earth and Mars.

1276 We highlight six particular areas where we think progress can be made in Mars gully research in the  
1277 near future:

- 1278 • Laboratory simulations using scaled-physical models, focusing specifically on exploring  
1279 variables that can be observed from orbit.
- 1280 • The use of landscape evolution models which are specifically adapted to recent and past  
1281 martian climate.
- 1282 • Application of the concept of sediment connectivity, with specific emphasis on the insights  
1283 that can be gained from the erosional landforms of martian gullies with reference to Earth  
1284 analogues.
- 1285 • Application of advanced 2D and 3D numerical sediment-gravity flow models, to back  
1286 calculate the conditions leading to observed gully deposits.
- 1287 • Cross-fertilisation of concepts and methodologies used in terrestrial geomorphology to the  
1288 study of martian gullies.

1289 • Quantitative analyses of the temporal evolution of martian gullies, and the identification and  
1290 exploration of terrestrial analogues representative for martian gullies during different time  
1291 periods.

1292 The activity of Martian gullies extends from the present day back to the last few million years, and  
1293 they are geographically widespread. Therefore, understanding the processes that shape them has  
1294 the potential to unlock the secrets of Mars' recent and past climate, hydrosphere and habitability.

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2269 **Figure Captions**

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2271 **Figure 1:** Example images of gullies on Mars with context images. North is up unless indicated  
2272 otherwise. The scales in images b-d and o-s are the same as indicated in a. For images e-n all scale  
2273 bars are 200 m. (a) Southern part of Kaiser Crater dunefield in CTX image D07\_030133\_1330, black  
2274 boxes indicate locations of panels e and f. (b) Part of the wall of one of the polar pits in Sisyphi Cavi  
2275 in CTX image B10\_013598\_1092 with black box indicating the location of panel g. (c) Part of Nirgil  
2276 Vallis in CTX image F08\_038957\_1517 with black box indicating the location of panel h. (d) 12-km-  
2277 diameter crater in Acidalia Planitia, CTX image F21\_043861\_2326 with black box indicating the  
2278 location of panel i. (e) Linear dune gullies on a dune in Kaiser crater with frost visible in upper-left  
2279 corner, HiRISE image ESP\_028788\_1325 at Ls 173°. (f) A classic gully also on Kaiser Crater dunefield  
2280 with a new deposit outlined by a bright halo, HiRISE image ESP\_027944\_1325 at Ls 139°. (g) Gullies  
2281 on the wall of a polar pit in Sisyphi Cavi, HiRISE image ESP\_049531\_1090. (h) Gullies on the wall of  
2282 Nirgil Vallis, HiRISE image ESP\_038957\_1515. (i) Gullies originating at bedrock layer on the inner wall  
2283 of an impact crater, HiRISE image ESP\_045193\_2325. (j) A gully system spanning ~4 km in length  
2284 with large tributary catchment in HiRISE image ESP\_013894\_1410. (k) Gully which does not extend  
2285 up to the slope crest in HiRISE image ESP\_014312\_1320. (l) Gullies extending into alcoves incised  
2286 into the bedrock of Galap crater in HiRISE image PSP\_003939\_1420. (m) Gullies entirely contained  
2287 within deposits of the LDM in HiRISE image PSP\_002514\_1420. (n) Gullies surrounded by pitted  
2288 ground in the LDM in HiRISE image ESP\_026097\_2310. (o) Part of the wall of a 19-km-diameter  
2289 crater in Terra Sirenum in CTX image B11\_013894\_1412 with black box indicating the location of  
2290 panel j. (p) Mesa in Nereidum Montes in CTX image B12\_014312\_1323 with black box indicating the  
2291 location of panel k. (q) Galap Crater in Terra Sirenum in CTX image B09\_012971\_1421 with black box  
2292 indicating the location of panel l. (r) Inner wall of Bunnik Crater in Terra Sirenum in CTX image  
2293 P04\_002659\_1418 with black box indicating the location of panel m. (s) Inner wall of Lyot Crater in  
2294 CTX image D19\_034800\_2310 with black box indicating the location of panel n. HiRISE image credit:  
2295 NASA/JPL/University of Arizona. CTX image credit: NASA/JPL-Caltech/MSSS.

2296 **Figure 2:** Alcove zones of gullies on Mars. (a) An individual gully located within LDM inside an impact  
2297 crater on a south-facing slope in the rim materials of the Argyre Impact Basin. The alcove of this gully  
2298 is comprised of a single incision or chute. HiRISE image ESP\_013850\_1415. (b) Gasa crater whose rim  
2299 hosts numerous gully alcoves incised into the bedrock. Location of panel c is given by the black box.  
2300 HiRISE image ESP\_014081\_1440. (c) Detail of chutes and channels emerging from the alcoves in Gasa  
2301 Crater onto the fans below. Discontinuous secondary channels can be identified on the fan as well as  
2302 primary channels which are still connected to the chutes and alcoves. (d) A gully incised into LDM,  
2303 where the channels are located within a chute. The chute walls have mass wasting scars. HiRISE  
2304 image PSP\_005616\_1440. (e) A gully-system where the alcoves are poorly defined topographically,  
2305 but instead comprise many coalescing rills which come together to form the primary channels  
2306 midslope. HiRISE image ESP\_022685\_1400. (f) Gullies on a crater wall which appear to originate at  
2307 bedrock outcrops, yet on closer inspection rills can be seen above the outcrops upslope of their  
2308 parent gullies. HiRISE image PSP\_006261\_1410. (g-i) context images for panels d-f using the same  
2309 HiRISE images. HiRISE image credit: NASA/JPL/University of Arizona.

2310 **Figure 3:** Spur and gully morphology on Mars and the Moon. (a) Inner wall of Dawes crater on the  
2311 Moon, with spur and gully features identified by Kumar et al. (2013) in LROC NA image M175104387.  
2312 (b) Wall of Noctis Labyrinthus on Mars, showing extensive evidence of aeolian activity in the form of  
2313 ripples on the talus slope, HiRISE image ESP\_028805\_1725. (c) Inner wall of a ~6 km impact crater at  
2314 2°S in Libya Montes, showing tongues of granular material extending downslope, HiRISE image  
2315 ESP\_014412\_1780. (d) Inner wall of a 21-km-diameter central pit crater, mentioned in the pristine  
2316 crater catalogue of Tornabene et al. (2018), where the dark slope streaks originating at the top of  
2317 the talus slope are thought to be triggered by a recent rockfall. HiRISE image PSP\_010037\_1965.  
2318 HiRISE image credit: NASA/JPL/University of Arizona. LROC image credit: NASA/GSFC/Arizona State  
2319 University.

2320 **Figure 4:** Gully-like landforms at equatorial latitudes (a-c) and adjacent to mid-latitude gully-systems  
2321 (d-f) on Mars. (a) Alcove into an interior layered deposit in Ganges Chasma with associated fan of  
2322 dark sediments, HiRISE image ESP\_032324\_1715. (b) Inner wall of a 5-km-diameter crater at 14°S,  
2323 with linear incisions (channels) and associated fans on the crater wall, HiRISE image  
2324 ESP\_046433\_1655. (c) An isolated alcove-channel-fan system within an 800-m-diameter crater  
2325 superposed on an ancient valley leading northwards into the Isidis Basin at 2°S, HiRISE image  
2326 ESP\_036987\_1825. (d) Alcove-channel-fan systems on the west-facing wall of Istok Crater adjacent  
2327 to a series of well-developed gullies (Johnsson et al., 2014), HiRISE image PSP\_006837\_1345. (e)  
2328 Alcove-channel-fan systems on a north-facing wall within Asimov Crater, where south-facing gullies  
2329 are abundant (Morgan et al., 2010), HiRISE image ESP\_016657\_1330. (f) Alcove-channel-fan systems  
2330 on a west-facing portion of Hale Crater's rim adjacent to large well-developed gully systems (Kolb et  
2331 al., 2010), HiRISE image ESP\_012597\_1435. HiRISE image credit: NASA/JPL/University of Arizona.

2332



2333 **Figure 5:** Martian gully channel features. (a) Highly-sinuuous gully channels highlighted by black  
2334 arrows in HiRISE image PSP\_003464\_1380. (b) Channels with well-developed lateral levees in Istok  
2335 crater highlighted by black and white arrows in HiRISE image PSP\_006837\_1345. (c) Terraces in a  
2336 gully-fan channel in Gasa crater highlighted by black arrows in HiRISE image ESP\_014081\_1440. (d)  
2337 Braided channel pattern on a gully-fan surface in Gasa crater in HiRISE image ESP\_014081\_1440. (e-  
2338 g) context images for panels a-d. HiRISE image credit: NASA/JPL/University of Arizona.

2339 **Figure 6:** Depositional features and cross-cutting relationships, indicating martian gully formation  
2340 over multiple flow events. (a-b) Multiple superposed channels with lateral levees ending in well-  
2341 defined lobate deposits on gully-fans in Hale crater (after Reiss et al., 2011) and Istok crater (after  
2342 Johnsson et al., 2014), respectively. Panel a: HiRISE image PSP\_006822\_1440, panel b: HiRISE image  
2343 PSP\_006837\_1345. (c) Cross-cutting channels and gully-fan sectors of different ages on a gully-fan in  
2344 Artik crater (after de Haas et al., 2013 and; Schon and Head, 2011) (HiRISE image  
2345 ESP\_012314\_1450). (d) Gully-fan deposits predating and postdating fractured washboard terrain  
2346 (after Dickson et al., 2015) (HiRISE image PSP\_005943\_1380). HiRISE image credit:  
2347 NASA/JPL/University of Arizona.

2348 **Figure 7:** The relationship between arcuate ridges and martian gullies. (a) Overview of a ridge in  
2349 Nereidum Montes with arcuate ridges downslope of gullies on its eastern flank. HiRISE image  
2350 ESP\_022685\_1400 overlain on CTX image G11\_022685\_1402. (b) Overview of a 9-km-diameter  
2351 crater in Terra Sirenum, containing a “Viscous Flow Feature”, with gullies upslope of arcuate ridges  
2352 on its pole-facing wall. HiRISE image ESP\_022108\_1410 overlain on CTX image B07\_012337\_1408. (c)  
2353 Detailed view of gullies upslope of a complex of arcuate ridges, whose fans superpose the terrain  
2354 hosting the ridges. Location of panel d is indicated by the black box. (d) Small gully-like landforms on  
2355 the scarps of the arcuate ridges. (e) Detailed view of the gullies upslope of the arcuate ridges, where  
2356 the gully fans appear to be backfilling the spatulate depression behind the ridges. HiRISE image  
2357 credit: NASA/JPL/University of Arizona. CTX image credit: NASA/JPL-Caltech/MSSS.

2358 **Figure 8:** The relationship between gullies and scalloped depressions and pingo-like-mounds. The  
2359 scale indicated in panel a is the same in b, idem for c and d. North is up in all panels. (a) A 9-km-  
2360 diameter crater in Utopia Planitia reported by Soare et al. (2007) containing gullies and scalloped  
2361 depressions. HiRISE image ESP\_016113\_2305. (b) Pingo-like mounds and gullies on a massif in the  
2362 Nereidum Montes reported by Soare et al. (2014b). HiRISE image ESP\_020720\_1410. (c) Detailed  
2363 view of scalloped depression located downslope of the gullies, with polygonised floor and steep,  
2364 cusped margins particularly on the pole-facing slope. (d) Detailed view of the pingo-like mounds,  
2365 where the right-hand example has a collapsed summit and both have fissures at their summits.  
2366 HiRISE image credit: NASA/JPL/University of Arizona.

2367 **Figure 9:** Relation between gullies and LDM deposits. (a) Gullies with and without LDM cover in  
2368 Domoni crater (HiRISE image ESP\_016213\_2315) (after de Haas et al., 2018). (b) Polygonal ground in  
2369 gully-alcoves in Langtang crater (HiRISE image ESP\_023809\_1415) (after de Haas et al., 2018). (c)  
2370 Polygons on an inactive gully-fan lobe (HiRISE image PSP\_002368\_1275) (after Levy et al., 2009). (d)  
2371 Washboard terrain superposing old gully-fan deposits, while being covered by younger gully-fan  
2372 deposits (HiRISE image PSP\_005943\_1380 see also Figure 6d) (after Dickson et al., 2015). HiRISE  
2373 image credit: NASA/JPL/University of Arizona.



2374 **Figure 10:** The relationship between gullies and lobes, patterned ground and RSL. (a) Gullies in  
2375 Ruhea Crater in HiRISE image ESP\_023679\_1365, black box marks location of d. (b) Gullies in a 20-  
2376 km-diameter crater in Acidalia Planitia, HiRISE image ESP\_045997\_2520 overlain on CTX image  
2377 B01\_010077\_2520, where black box marks the location of e. (c) Gullies on the central mounds of  
2378 Lohse crater in HiRISE image PSP\_006162\_1365, where black box marks the location of f. (d) Lobes  
2379 on the terraces in the chute walls of gullies and on the surrounding terrains as first reported in  
2380 Johnsson et al. (2018). (e) Stripes between the gully fans first reported in Fig. 12 Gallagher et al.  
2381 (2011). Inset box shows that clasts make up the lower albedo parts of the stripes. (f) RSL in the  
2382 alcoves of gullies, first reported in Fig. 14 of Ojha et al. (2014). HiRISE image credit:  
2383 NASA/JPL/University of Arizona. CTX image credit: NASA/JPL-Caltech/MSSS.

2384 **Figure 11:** Global gully trends on Mars. (a) Map showing the orientation of gullies and their relation  
2385 to the occurrence of steep slopes, data from Conway et al. (2017). Red colour indicates gullies are  
2386 100% pole-facing, blue 100% equator-facing and yellow 50-50%. Darker shades are the locations  
2387 where there are more steep slopes and lighter shades, fewer. In detail the number of pixels with 20°  
2388 slopes derived from projection-corrected MOLA data was counted inside a 250 km moving window,  
2389 which was then normalised by the true area of that moving window. The cutoff between the two  
2390 shades is  $3 \times 10^{-3}$  steep pixels per km<sup>2</sup>. MOLA hillshaded relief is in the background for context. (b)  
2391 Comparison between the location of gullies (black-white), large glacier like forms (blue) and the  
2392 roughness boundary of Kreslavsky and Head (2000) as an orange dashed line, thought to represent  
2393 the equatorward limit of the LDM. Number of gully sites per km<sup>2</sup> of steep slope are given in black  
2394 and white, where black is >250 and white is <250. The glacier like forms are compiled from the  
2395 catalogues of Souness et al. (2012), van Gasselt (2007) and Levy et al. (2014). MOLA hillshaded relief  
2396 is in the background for context. (c) Histograms showing the latitudinal distribution of glacier like  
2397 forms (Lineated Valley Fill – LVF, Concentric Crater Fill – CCF, Lobate Debris Aprons – LDA all from  
2398 Levy et al., 2014), dissected Latitude Dependant Mantle (LDM) from Milliken et al. (2003), slope-  
2399 normalised gully density from Conway et al. (2018b) and raw counts of gullies from Harrison et al.  
2400 (2015). LVF, CCF and LDA are given as number of landforms per 1° latitude bin. Dissected LDM is  
2401 given as the percentage of MOC images per 2.5° latitude bin. Gullies are given as the mean number  
2402 of sites per steep slope and counts in 5° latitude bins.

2403 **Figure 12:** Frost visible in equator-facing and pole-facing alcoves of gullies in a 12-km-diameter  
2404 crater located in the northern hemisphere in Acidalia Planitia. (a) Overview in HiRISE image  
2405 ESP\_052090\_2450 overlain on CTX image P18\_007995\_2448. (b) Frost in the equator-facing alcove  
2406 (black arrows), but on the facets of the alcove that do not face directly south. (c) Frost in the pole-  
2407 facing alcove (black arrows), located at the most sheltered positions. HiRISE image credit:  
2408 NASA/JPL/University of Arizona. CTX image credit: NASA/JPL-Caltech/MSSS.

2409 **Figure 13:** Present-day activity in martian gullies. Images have been selected to best highlight the  
2410 new morphology so are not necessarily the closest in time. For each row the leftmost image is the  
2411 “before” image. The middle image is the “after” image, which is the same image used in the  
2412 overview panel located on the far right. (a) A new dark flow, which is superposed on seasonal frost  
2413 on the crater wall making it particularly visible even though the slope is in shadow. HiRISE images  
2414 ESP\_022688\_1425 (before) and ESP\_027567\_1425 (after and overview). (b) New relatively light  
2415 toned deposits on a gully-fan, highlighted by black arrows in the middle panel. HiRISE images  
2416 ESP\_014368\_1435 (before) and ESP\_031919\_1435 (after and overview). (c) New massive deposit on  
2417 the fan of a gully in Galap Crater, outlined in middle pane by arrows, this new deposit is lobate and  
2418 contains boulders. HiRISE images PSP\_003939\_1420 (before) and ESP\_032078\_1420 (after and  
2419 overview). (d) A newly incised channel branching off a pre-existing gully, highlighted by black arrow.  
2420 HiRISE images ESP\_013115\_1420 (before) and ESP\_032011\_1425 (after and overview). HiRISE image  
2421 credit: NASA/JPL/University of Arizona.

2422 **Figure 14:** Dry mass wasting features. (a) Dry powder avalanches in the European Alps taken from  
2423 the European Avalanche Warning Services  
2424 ([http://www.avalanches.org/eaws/en/includes/glossary/glossary\\_en\\_all.html](http://www.avalanches.org/eaws/en/includes/glossary/glossary_en_all.html)). Hillslope length is  
2425 approximately several hundred metres. (b) Deposits from 17th October (light grey) and 7th August  
2426 pyroclastic flows at Mount Saint Helens, Figure 294 from Lipman and Mullineaux (1981). Lobe widths  
2427 on the order of several tens of metres. (c) Experimental granular flows, where numbers across the  
2428 top denote percentage of fines (white 150–250  $\mu\text{m}$  ballotini) in natural sand (300–355  $\mu\text{m}$  quartz).  
2429 Adapted from Figure 4 of Kokelaar et al. (2014). Top-down photos of a 29° inclined plane where the  
2430 mixture was dropped to give initial velocity. (d) Deposits of experimental granular flow of  
2431 microbeads released onto an inclined plane at 25° as described in Félix and Thomas (2004), photo  
2432 credit Nathalie Thomas. Lobe width  $\sim$ 8 cm. (e-f) Two views of a leveed channel created by an  
2433 experimental granular flow of microbeads released onto an inclined plane at 25°, experiments  
2434 described in Félix and Thomas (2004). In panel e the distance between the levees is  $\sim$ 17cm and in  
2435 panel f there is a 10 cm interval between the lines. Photos courtesy of Nathalie Thomas. (g) Granular  
2436 flow deposits at the foot of the scree slope on the western face of Hafnarfjall in Iceland. The channel  
2437 width is approximately 2 m. Photo taken by S.J. Conway . (h) Dune slip face avalanche on a dune in  
2438 the Namib desert near Walvis Bay, avalanche is approximately 50cm long. Photo taken by S.J.  
2439 Conway. (i) Experimental slip face avalanche on a slope of 34° with a mean sand of diameter of 277  
2440  $\mu\text{m}$ . Taken from Figure 2 of Sutton et al. (2013b). Avalanche is approximately 2 m long. (j) Granular  
2441 flow under simulated low gravity conditions (spinning disk), taken from Figure 1 of Shinbrot et al.  
2442 (2004). Copyright (2004) National Academy of Sciences.



2443 **Figure 15:** Terraces and braided morphology in gullies on Earth. (a-d) Fluvial fans in the periglacial  
2444 environment of Svalbard, showing braided channel morphology, terraces and cut banks. Panels a  
2445 and c show a fan in Adventdalen, panels b and d show a fan in Bjørndalen (see also de Haas et al.,  
2446 2015c). Source: HRSC-AX orthoimages from DLR (German Aerospace Centre), see Hauber et al.  
2447 (2011a) for details. (e-f) Hillshaded images of debris-flow and fluvial fan in the arid Saline Valley  
2448 (Mojave Desert, USA). Panels e and h show terraces and cut banks on a debris-flow fan, panel f  
2449 shows braided channel morphology on an adjacent fluvial fan. Source: EarthScope Southern &  
2450 Eastern California Lidar Project ([www.opentopography.org](http://www.opentopography.org)).

2451 **Figure 16:** Debris-flow deposits on Earth. (a) Debris-flow lobe deposit on a fan surface in periglacial  
2452 environment of Svalbard. (b) Debris-flow lobe deposit in the Chilean hyperarid Atacama Desert (from  
2453 Figure 2 of de Haas et al., 2015d). (c) Debris-flow channel with clearly-defined lateral levees on  
2454 Svalbard. This channel is connected to the lobe shown in panel a. (d) Debris-flow channel with well-  
2455 defined levees on the Dolomite Fan in the Mojave Desert (USA).

2456 **Figure 17:** Secondary, post-depositional, modification of fan surfaces on Earth, masking the original  
2457 depositional morphology. (a) Debris-flow fan surfaces covered by aeolian sand, in the Atacama  
2458 Desert, Chile (from Figure 11 of de Haas et al., 2015d). (b) Polygonal ground on top of a debris-flow  
2459 fan surface in Svalbard (from Figure 15 of de Haas et al., 2015c). (c) Hummocks on top of a fluvial fan  
2460 surface in Svalbard (from Figure 15 of de Haas et al., 2015c). (d) Detail of the fan shown in panel a.  
2461 (e) Detail of polygonal ground on fan in panel b (from Figure 15 of de Haas et al., 2015c). (f) Detail of  
2462 hummocky ground on fan in panel c (from Figure 15 of de Haas et al., 2015c). (g) Desert pavement  
2463 on top of a debris flow fan surface in Nevada (USA) (from Blair and McPherson, 1994). (h) Fluvial  
2464 channels on a debris-flow fan surface in the Atacama Desert, Chile, as a result of secondary runoff;  
2465 person for scale is 1.85 m tall (from Figure 11 of de Haas et al., 2015d). (i) Broken down clast on the  
2466 surface of a debris-flow fan as a result of salt weathering in the Atacama Desert, Chile (from Figure 7  
2467 of de Haas et al., 2014).

2468 **Figure 18:** Geophysical flows involving ice on Earth. (a) Low gradient slushflow cutting across  
2469 Snøheim road in Norway taken from  
2470 [https://reccoprofessionals.files.wordpress.com/2011/05/slush\\_flow\\_no.jpg](https://reccoprofessionals.files.wordpress.com/2011/05/slush_flow_no.jpg) (b) Gully dominated by  
2471 slushflow processes on the northwest flank of Mount Saint-Pierre, Québec (Canada) studied by Hétu  
2472 et al. (2017) and taken from Figure 15 of the same paper – person for scale. (c) Cirque at McCarthy  
2473 Creek, Wrangell St. Elias National Park, Alaska studied by Kochel and Trop (2008), right fan is  
2474 dominated by avalanche processes and the left one by icy debris flows, taken from Figure 2A of  
2475 Kochel and Trop (2008). (d) Icy debris flow on the left fan shown in panel c, where its length is  
2476 approximately 50m taken from Figure 13A of Kochel and Trop (2008). (e) The fan on the right of  
2477 panel c with a fresh wet snow avalanche deposit showing lateral levees and lobate snout. The  
2478 avalanche deposit is approximately 200 m in length. Taken from Figure 8B of Kochel and Trop (2008).  
2479 (f) Wet snow avalanche deposit Vallée de la Sionne in Switzerland showing complex morphologies,  
2480 including lateral levees and overbank deposits, taken from Figure 1 of Bartelt et al. (2012). House in  
2481 top right for scale. (g) Snow avalanche dominated debris fans in in Longyeardalen, Svalbard after  
2482 Figure 7c of de Haas et al. (2015c). (h) Isolated boulders deposited by snow avalanches in Erdalen,  
2483 Norway, taken by A. Decaulne on 27 August 2010. The largest rocks in the foreground are  
2484 approximately 30 cm across.

2485 **Figure 19:** Physical scale models of martian gullies. (a) Sediment transport engendered by liquid  
2486 water over fine sand at 14° slope under low pressure (~7mbar) and low sediment temperature (-  
2487 25°C) reported in Conway et al. (2011a). Water at the base of the flow has frozen solid and the flow  
2488 propagated over a lens of frozen, saturated sediment. Bubbles formed by boiling were frozen into  
2489 this mixture as the flow progressed. Tray is 1 m in length. Photo taken by S.J. Conway. (b) Sediment  
2490 transport engendered by liquid water over an active-layer of several millimetres deep formed in  
2491 saturated frozen fine sand at 14° slope under low pressure (~7mbar) reported in Jouannic et al.  
2492 (2015). Bubbles visible across the surface are formed by gas produced within the sediment by  
2493 boiling. Tray is 1 m in length. Photo taken by G. Jouannic. (c) Figure 4 from Védie et al. (2008)  
2494 showing channels on a sloping active-layer formed in a frozen bed of silt caused by pulses of water  
2495 from a perched aquifer. Top of the slope is 55 cm across and the experiments were performed under  
2496 terrestrial pressure. (d) Sediment transport engendered by liquid water over fine sand at 20° slope  
2497 under low pressure (~9mbar) and elevated sediment temperature (~25°C) reported in Raack et al.  
2498 (2017) and Herny et al. (2018). White arrow points to sediment displaced by dry avalanches  
2499 triggered by grain saltation at the flow front and black arrow saturated pellets levitated on cushions  
2500 of gas released by boiling. Tray is 1 m in length. Photo taken by C. Herny.



2501 **Figure 20:** Martian and terrestrial obliquity during the past 10 Ma (Laskar et al., 2004), along with  
2502 estimated maximum gully ages. Maximum gully ages based on crater impact ages: Istok crater  
2503 (Johnsson et al., 2014), Gasa crater (Schon et al., 2009a), Roseau crater (de Haas et al., 2018), Galap  
2504 crater (de Haas et al., 2015a). Maximum gully age based on superposition relationship with Nirgal  
2505 Vallis dune field from Reiss et al. (2004).

2506 **Figure 21:** Gullies as a result of aquifer seepage at Ice River, Nunavut, Canadian High Arctic. (a)  
2507 Satellite image overview of the zone containing the gullies with box indicating the location of panel  
2508 b. Image credit Quickbird-2 © 2011 DigitalGlobe, Inc. (b) Detail of the gullies. Image credit Quickbird-  
2509 2 © 2011 DigitalGlobe, Inc. (c) Oblique aerial view taken from Figure 4A of Grasby et al. (2014).

2510 **Figure 22:** Active-layer detachment on Earth and potentially on Mars. (a) Gullies and candidate  
2511 active-layer detachments (indicated by white arrows and boxes) in Yaren crater as seen in HiRISE  
2512 image ESP\_024086\_1360 (after Johnsson et al., 2018). (b) Detail of shallow landslides from possible  
2513 active-layer detachments in the lower gully-alcove. (c) Possible active-layer detachment scars in the  
2514 upper alcove. (d) Active-layer detachment slides in Hanaskogdalen, Svalbard (from Hauber et al.,  
2515 2011a). (e) Photograph of two active-layer detachment slides in panel d (from Figure 12 of de Haas  
2516 et al., 2015c). (f) Active-layer detachment on a steep slope near Svea, Svalbard (from de Haas et al.,  
2517 2015c). HiRISE image credit: NASA/JPL/University of Arizona.

2518 **Figure 23:** Periglacial landform assemblage in northern Canada. (a) High centred polygonally  
2519 patterned ground, Tuktoyaktuk Coastlands, with meltwater visible in polygon troughs, taken from  
2520 Figure 14 of Soare et al. (2014a), polygons are ~20-50 m across. (b) Alases or thermokarstic  
2521 depressions (Tuktoyaktuk Coastlands) surrounded by polygonally patterned ground, taken from  
2522 Figure 2 of Soare et al. (2015). The thermokarst lake in the background is ~100 m across. (c) Cross  
2523 section through a polygon margin revealing the ice-wedge (~2.5 m across at the top), Tuktoyaktuk  
2524 Coastlands, taken from Figure 13 of Soare et al. (2014a). (d) Ibyuk Pingo with Split Pingo in the  
2525 background, Northwest Territories, Canada, taken from Figure 7 of Soare et al. (2014b).

2526 **Figure 24:** Gullies on Earth generated by snowmelt. (a) Satellite images of the gullies shown in panel  
2527 b. Image credit GeoEye-1 © 2013 DigitalGlobe, Inc. (b) Debris flows in Jameson Land, Greenland,  
2528 which occurred by the infiltration of melting snow during the summer season, taken from Figure  
2529 10.4 in Costard et al. (2007a). (c) Debris flow on the slopes above Ísafjörður in NW Iceland triggered  
2530 by rapid snowmelt in 1999 (Track #1 of Decaulne et al., 2005), photo taken by John Murray in 2007.  
2531 (d) Gullies studied by Levy et al. (2009) in Wright Valley, Antarctica. Polygonal patterned ground  
2532 visible on the plateau and the depositional fans. Image credit GoogleEarth, DigitalGlobe.

2533 **Figure 25:** Sliding sublimating CO<sub>2</sub>-ice blocks down dunes as analogues for martian linear gullies,  
2534 frames captured from the video included as Supplementary video 4 in Diniega et al. (2013), where  
2535 block is released over a 20° slope on Kelso Dunes, California, person at dune brink for scale. Black  
2536 arrows point to block at each time-step labelled t1 to t4.



2537 **Figure 26:** Hillslopes with frosted granular flow in the St. Pierre river valley in Québec, investigated  
2538 initially by Hétu and Vandelac (1989) and Hétu et al. (1994) and reported as a terrestrial analogue by  
2539 Hughenholtz (2008a). (a) Overview of the hillslopes with debris flows and talus slope with frosted  
2540 granular flow and (b) zoom showing the talus slope. (c) Photo from of the talus slope taken by taken  
2541 by Maxime Chevalier. Panels a and b modified from Harrison et al. (2015) with image credit: Google  
2542 Earth/CNES/Spot and c taken by Maxime Chevalier from Harrison (2016).

2543 **Figure 27:** CO<sub>2</sub> gas-lubricated flow model from Figure 6 of Hoffman (2002). (A) Sunlight (black  
2544 arrows) penetrates through the surface CO<sub>2</sub> frost and warms the underlying regolith. This causes the  
2545 frost layer to sublimate at its base, destabilizing the slope and generating an avalanche. (B) A  
2546 mixture of the CO<sub>2</sub> frost, gas, and entrained debris move downslope, with the frost continuing to  
2547 degas and generating a vapour-lubricated flow.

2548 **Figure 28:** Submarine gullies and canyons. Data from the USGS showing the bathymetry of the Los  
2549 Angeles, California Margin surveyed between 1996 and 1999 and detailed in Gardner and Dartnell  
2550 (2002).

2551 **Figure 29:** Channelized deposits from different processes on different planetary surfaces, scale bars  
2552 are 50 m in all cases. (a) Debris flow deposits in Svalbard, image credit DLR HRSC-AX campaign. (b)  
2553 Lava flows on Tenerife, aerial image courtesy of IGN, Plan Nacional de Ortofotografía Aérea de  
2554 España. (c) Self-channelling pyroclastic deposits at Lascar volcano, Chile, Pléiades image. (d)  
2555 Depositional lobes in Istok crater on Mars, where channels (likely from debris flows) are formed as  
2556 part of the depositional fans, HiRISE image PSP\_007127\_1345. (e) Fingering granular flows on the  
2557 Moon, likely self-channelling dry granular flows (Shinbrot, 2007), LROC image M167036896. (f)  
2558 Lobate deposit and associated channel on the Moon, perhaps from impact melt or ejecta processes,  
2559 LROC image M143676946. HiRISE image credit: NASA/JPL/University of Arizona. LROC image credit:  
2560 NASA/GSFC/Arizona State University.

**Table 1:** Summary of Earth analogues used for comparison to martian gullies, including the climate and which gully formation model they have been used to support. The analogues are listed by continent and then by site (in descending latitude) and grouped by team where appropriate.

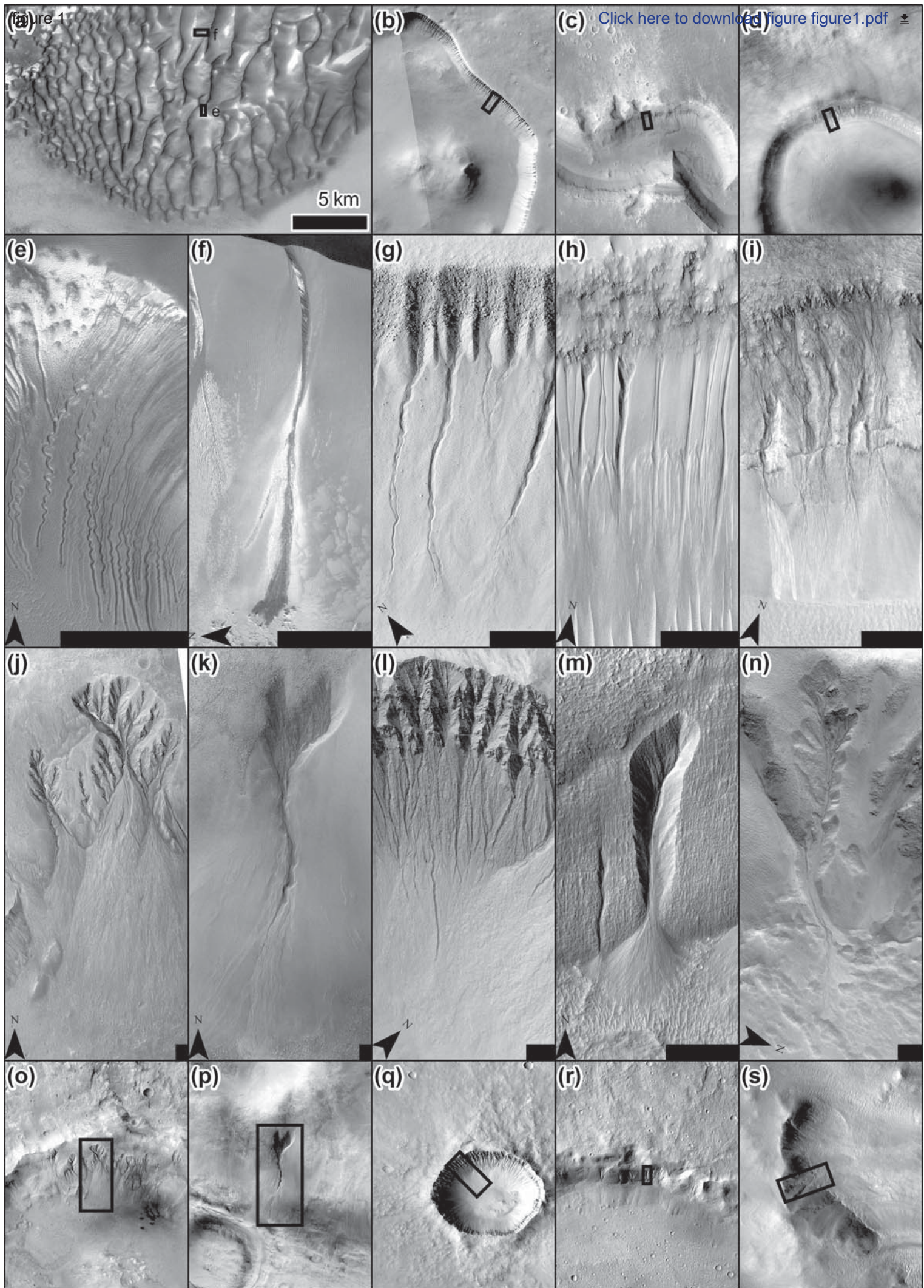
Continent	Authors	Location(s)	Climate type	Ground conditions	Process	Trigger	In support of:
Antarctica	Marchant and Head (2007), Dickson and Head (2009), Levy et al. (2009, 2007), Dickson et al. (2018, 2007), Morgan et al. (2007)	McMurdo Dry Valleys	hyper-arid cold polar desert	permafrost at 35-45 cm	pure water flow	insolation	surface melt, influence of brines, no rain, snow drifting
Antarctica	Harris et al. (2007)	McMurdo Dry Valleys			groundwater and surface flow of brines		shallow groundwater
	Lyons et al. (2005)				groundwater seep	melting of subsurface	iceshallow groundwater
Antarctica	Hauber et al. (2018)	Northern Victoria Land	hyper-arid cold polar desert	permafrost	debris flows, percolation	meltwater	meltwater from ice and/or snow, highlight as analogue
S. America	Heldmann et al. (2010)	Atacama desert, Chile	arid desert	dry	debris flows	rare rain event	fluvial processes
S. America	Oyarzun et al. (2003)	Atacama, Chile, Road from Copiapo' to Maricunga	arid desert	dry	mudflow		water in gullies from the surface or groundwater
S. America	de Haas et al. (2015d, 2014)	Atacama Desert coast, northern Chile	arid desert	dry	debris flow	rare rain events	role of secondary modification on fan morphology
S. America	Conway and Balme (2016)	Quebrada de Camarones, Atacama, Chile	arid desert	dry	dry rockfalls	unknown	counter-example for water hypotheses from morphometrics
S. America	Pacifici (2009)	Santa Cruz region, Argentinean Patagonia	arid steppe highlands	proglacial deposit, unknown if ice			highlight as an analogue
S. America	Pilorget and Forget (2016)	Lascar, Chile	desert	dry	pyroclastic	volcanic eruption	CO <sub>2</sub>
S. America	Stewart and Nimmo (2002)						Counter-example, support instead water hypotheses
N. America	Costard et al. (2007a, 2002)	Jameson Land, E. Greenland	dry periglacial	thick permafrost, 1 m	active-layer debris flows	melting permafrost	melting in the near surface
N. America	Lee et al. (2006, 2002, 2001)	Devon Island, High Arctic; valleys and Haughton impact	polar desert climate	talus	debris flows	all temperature triggered (very transient)	surface snowmelt
				talus	snow gullies	snow gullies, surface snowmelt	
N. America	Oskinski et al. (2006)	Arctic Canada		permafrost			highlight as an analogue
N. America	Andersen et al. (2002)	Axel Heiberg Island, Canada	polar desert climate	permafrost 600 m thick	brine flow from groundwater		groundwater
N. America	Heldmann et al. (2005)	Axel Heiberg Island, Canada		permafrost	brine flow from groundwater		brines

Continent	Authors	Location(s)	Climate type	Ground conditions	Process	Trigger	In support of:
N. America	Grasby et al. (2014)	Ellesmere Island, Nunavut, Canadian High Arctic	polar desert	permafrost	fluvial	spring	groundwater
N. America	Soare et al. (2018, 2014a, 2014b, 2007)	Tuktoyaktuk, NWP, Canada	thermokarst - degraded permafrost areas	permafrost and substantial segregated ice lenses	long term temperature increase and thaw	possibly insolation triggered snowmelt, or permafrost melting	melting near surface
N. America	Hugenholz et al. (2007)	Bigstick Sand Hills - southwestern Saskatchewan, Canada	continental	permafrost	debris flow	snowmelt and niveo-aeolian	melt
N. America	Hugenholz (2008b)	St. Pierre valley, Gaspé region, Québec	continental, humid	talus, possible permafrost	frosted granular flow	temperature oscillations around freezing	frosted granular flow
N. America	Kochel and Trop (2008)	Wrangell Mountains, Alaska	supraglacial	substantial snow and ground ice on debris fans	icy debris flow	rainfall	generic process analogue
N. America	Conway et al. (2011b) Conway and Balme (2016)	St Elias Mountains, Alaska	Periglacial	talus, discontinuous permafrost	rockfalls	unknown	counter-example for water hypotheses from morphometrics
N. America	Hooper and Dinwiddie (2014)	Great Kobuk Sand Dunes, Alaska	subarctic		debris flow, fluvial	snowmelt and niveo-aeolian	near surface melt
N. America	Conway et al. (2015b, 2011b) Conway and Balme (2016)	St. Front Range, Colorado	mountainous periglacial	talus	debris flow	unknown	water hypotheses from morphometrics
N. America	de Haas et al. (2015d)	Panamint Valley, Death Valley, California	desert		Debris flow, secondary aeolian modification		role of secondary modification on fan morphology
N. America	Conway et al. (2015b, 2011b) Conway and Balme (2016)	San Jacinto Fault, Death Valley, Lucerne Valley and Anderson Dry Lake, California	desert	dry	fluvial	precipitation	water hypotheses from morphometrics
N. America	Eyles and Daurio (2015)	Ubehebe Crater, Death Valley, California	desert	dry porous volcanic products	fluvial gullies associated with protalus ramparts		highlight as an analogue in terms of snow-driven processes
N. America	Kumar et al. (2010), Yue et al. (2014) Conway and Balme (2016)	Meteor Crater, Arizona	arid, wetter in past	dry	fluvial and debris flow	rainfall, snowmelt and springs	water hypotheses, debris flow
Europe & N. America	Tretman (2003)	Adventdalen, Svalbard; Ashcroft, Colorado			snow avalanches		dry granular flow
Europe	Reiss et al. (2011, 2010b, 2009b), Hauber et al. (2011a, 2011b, 2009), Johnsson et al. (2014, 2012), Conway and Balme (2016)	Svalbard, Norway	arctic desert	permafrost	fluvial and debris flow		water hypotheses, meltwater, snowmelt fluvial, debris flow, influence of freeze-thaw cycles, landscape assemblage in periglacial environment



Continent	Authors	Location(s)	Climate type	Ground conditions	Process	Trigger	In support of:
Europe	Hartmann et al. (2003)	Esja Plateau, Iceland	periglacial	ground sometimes frozen	debris flow	snowmelt, connected to drainage,	water hypotheses
Europe	Conway et al. (2015b, 2011b) Conway and Balme (2016)	Westfjords & Tindastöll, Iceland fjordlands, periglacial		talus	debris flow	Snowmelt, heavy precipitation	water hypotheses from morphometrics
Europe	Mangold et al. (2003b)	Southern French Alps	alpine	talus	debris flows		debris flow
Europe	Marquez et al. (2005)	La Gomera, Canary Islands	warm and wet	no ice, dry talus with calcrete	fluvial	aquifer outflow	groundwater
	Conway et al. (2015b)						water hypotheses from morphometrics
Oceania	Hobbs et al. (2014)	Island Lagoon near Woomera, Australia	semi-arid		fluvial	overland flow	water and dry
		Pasture Hill, New Zealand	periglacial		fluvial	frost processes, rain, snowmelt	
	Hobbs et al. (2013)	Lake George escarpment, Australia	arid		surficial runoff		water and LDM melt
	Hobbs et al. (2015)	all three of the above					water and melt
	Hobbs et al. (2016)	Cooma, Australia	arid		runoff	rainfall	
Asia	Komatsu et al. (2014)	Lonar Crater, India	tropical savanna	humid soils	debris flow, fluvial	groundwater and overland flow	highlight as an analogue
Asia	Xiao et al. (2017)	Qaidam Basin, Tibetan Plateau (NW China)	high elevation desert		fluvial	rainfall	highlight as an analogue
Asia	Anglés and Li (2017)	Qaidam Basin, Tibetan Plateau (NW China)	high elevation desert				overland flow or melt
Asia	Sinha et al. (2018)	Ladakh Himalaya	high elevation desert	talus and alluvial fans	debris flow	snowmelt	debris flow from snowmelt
Asia	Yue et al. (2014) Wang et al. (2013)	Xiuyan Crater, NE China	humid, continental	humid soils	fluvial	precipitation	water hypotheses and dry processes
Several	Hugenholtz and Tseung 2007	Escuer fan in central Spanish Pyrenees, intense thawing of frozen sand Canada, New Zealand, beach sand fans triggered by groundwater, Spain base of cliffs with ephemeral groundwater.			debris flow dominated alluvial fans		debris flow







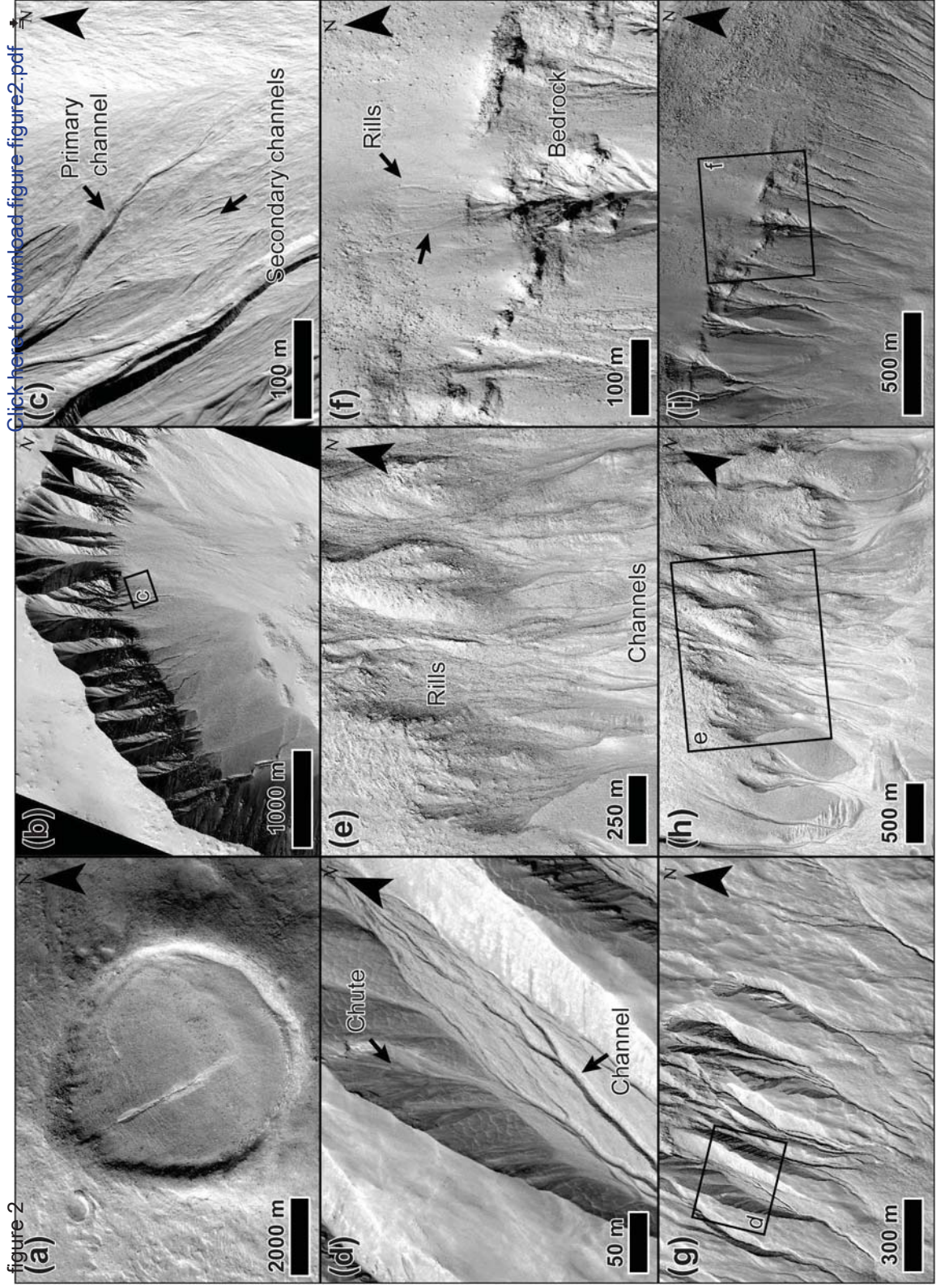


figure 2

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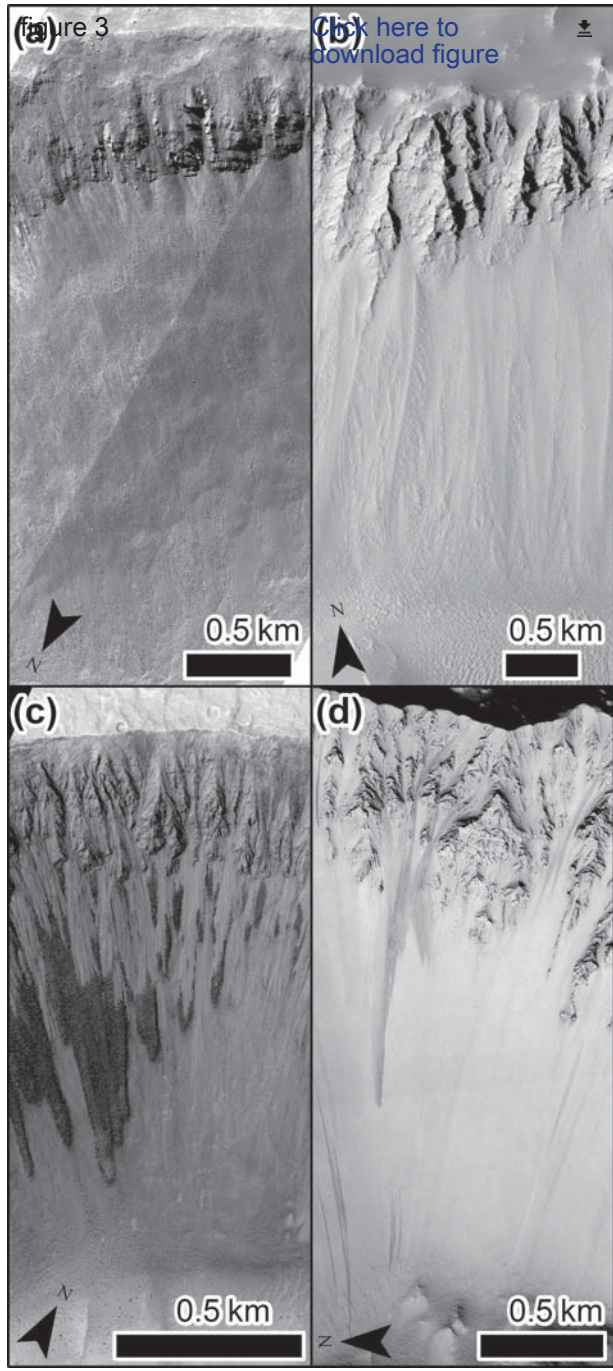




Figure 4

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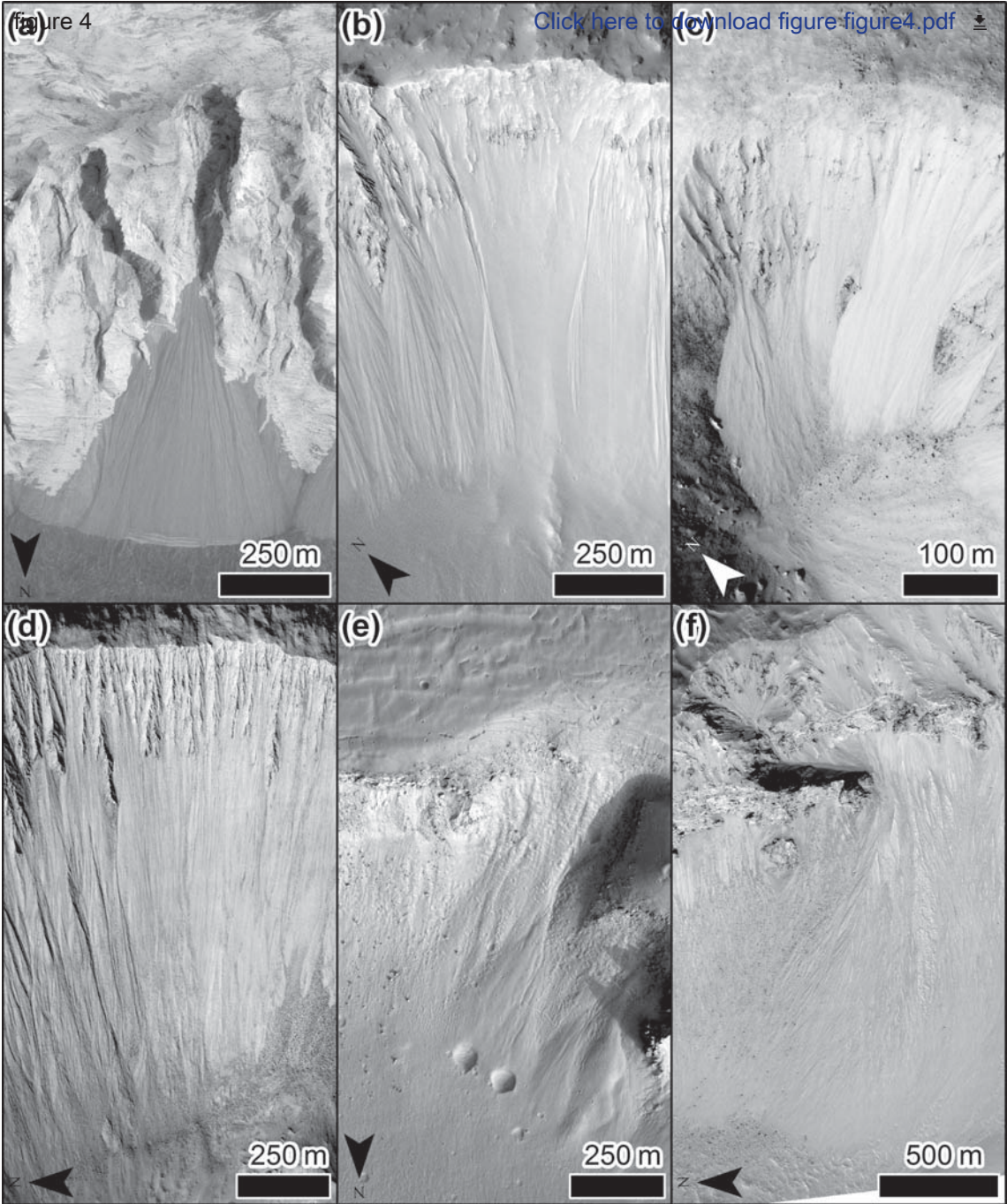
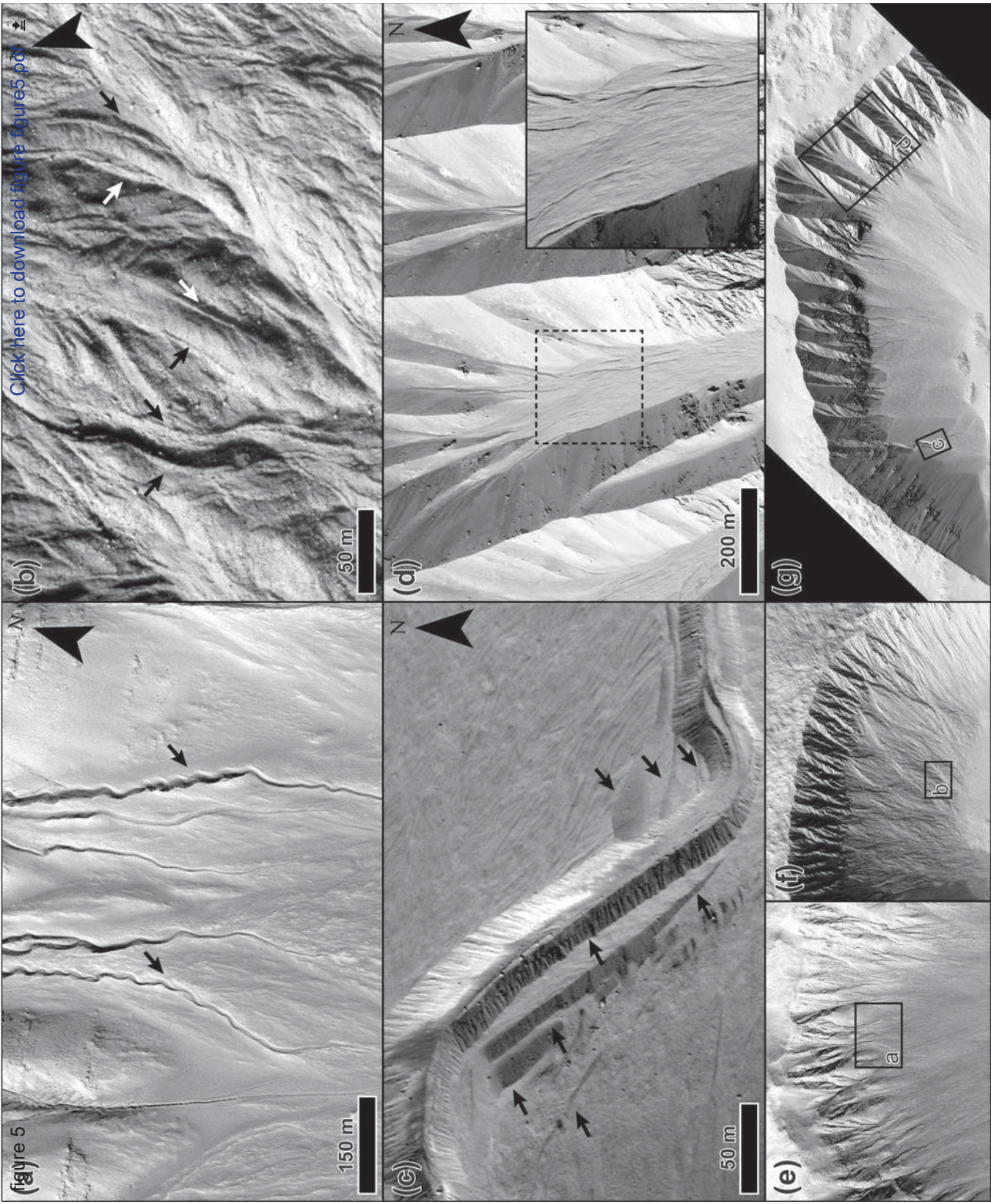




figure 5



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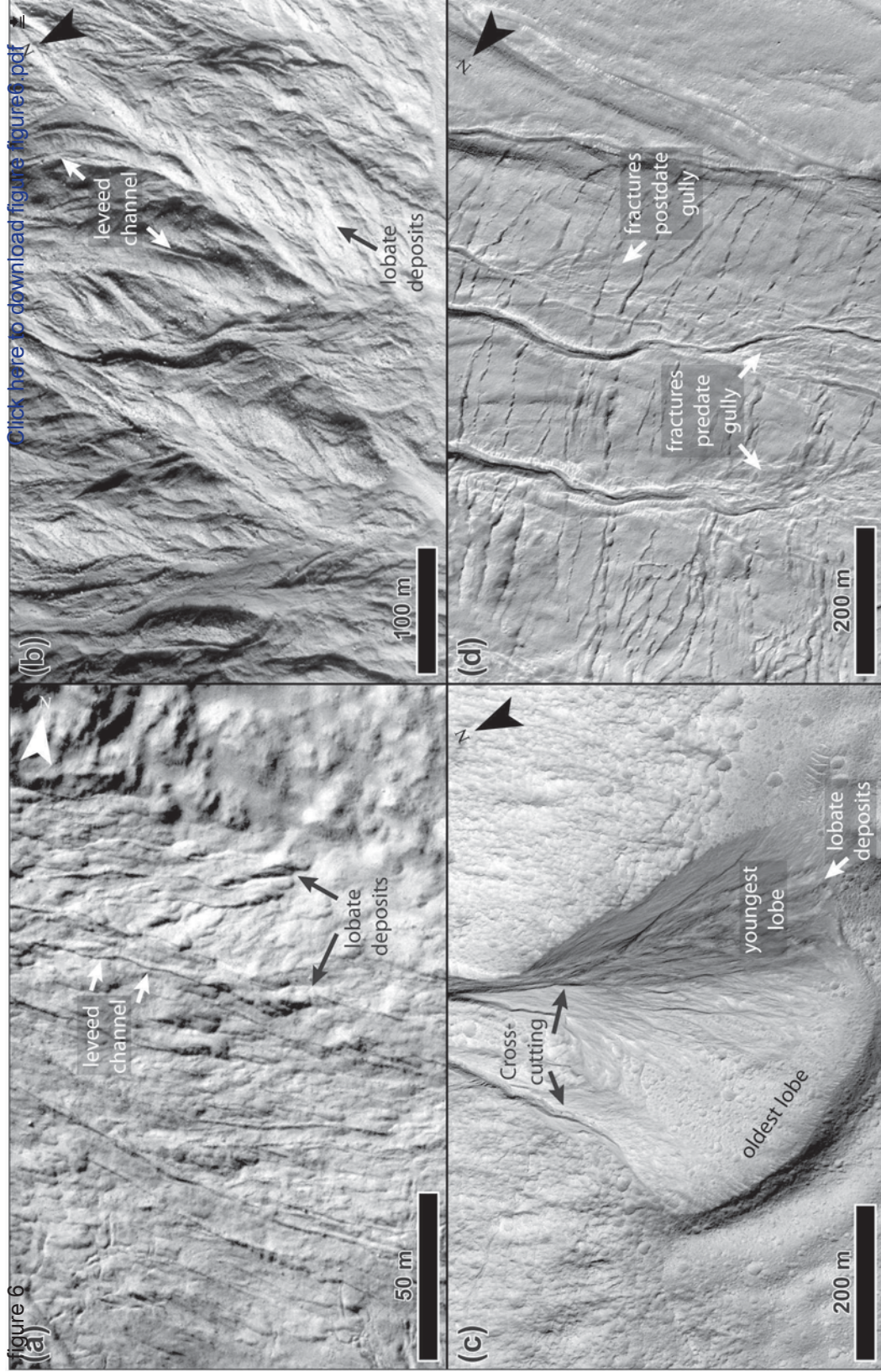
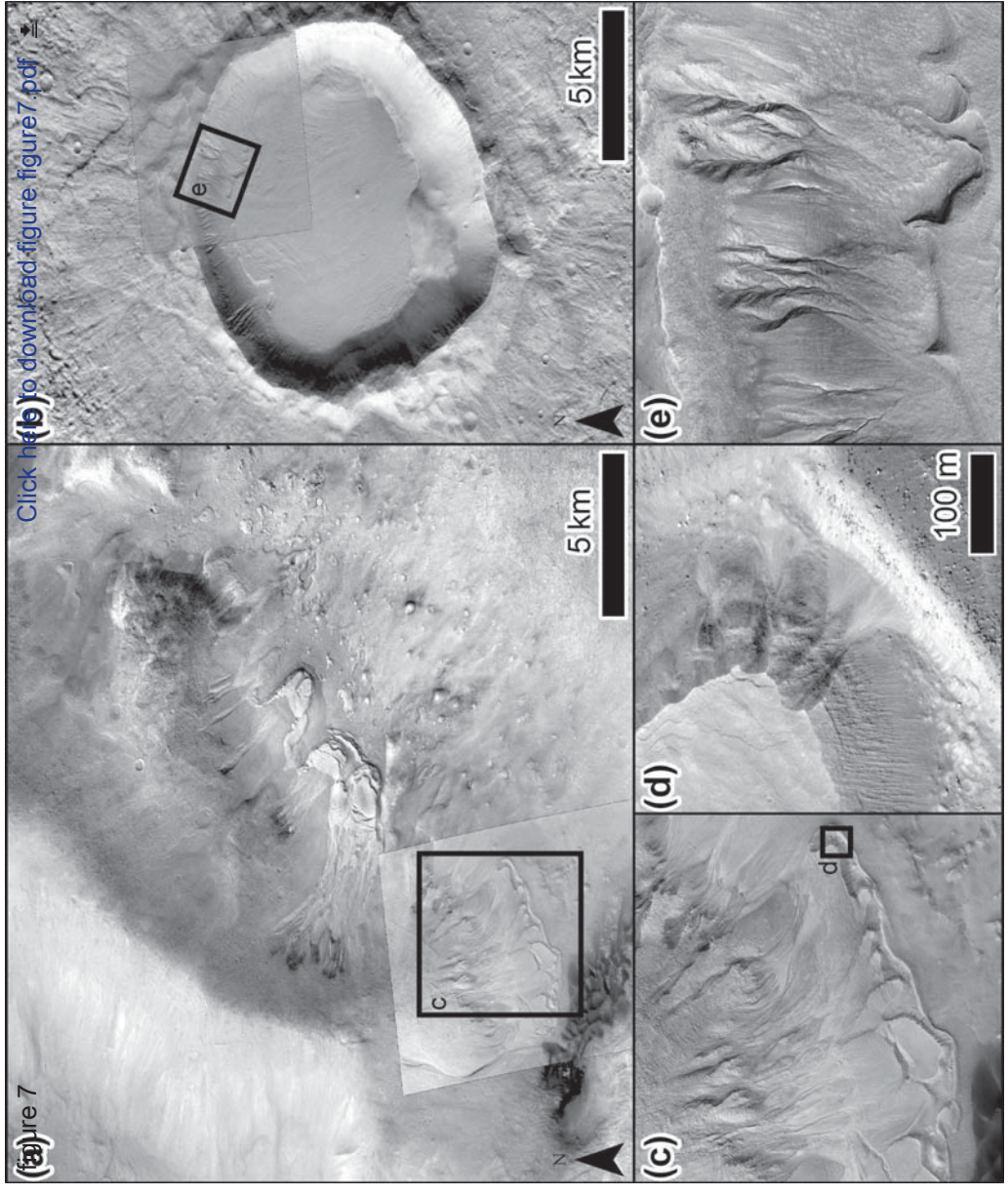


figure 6

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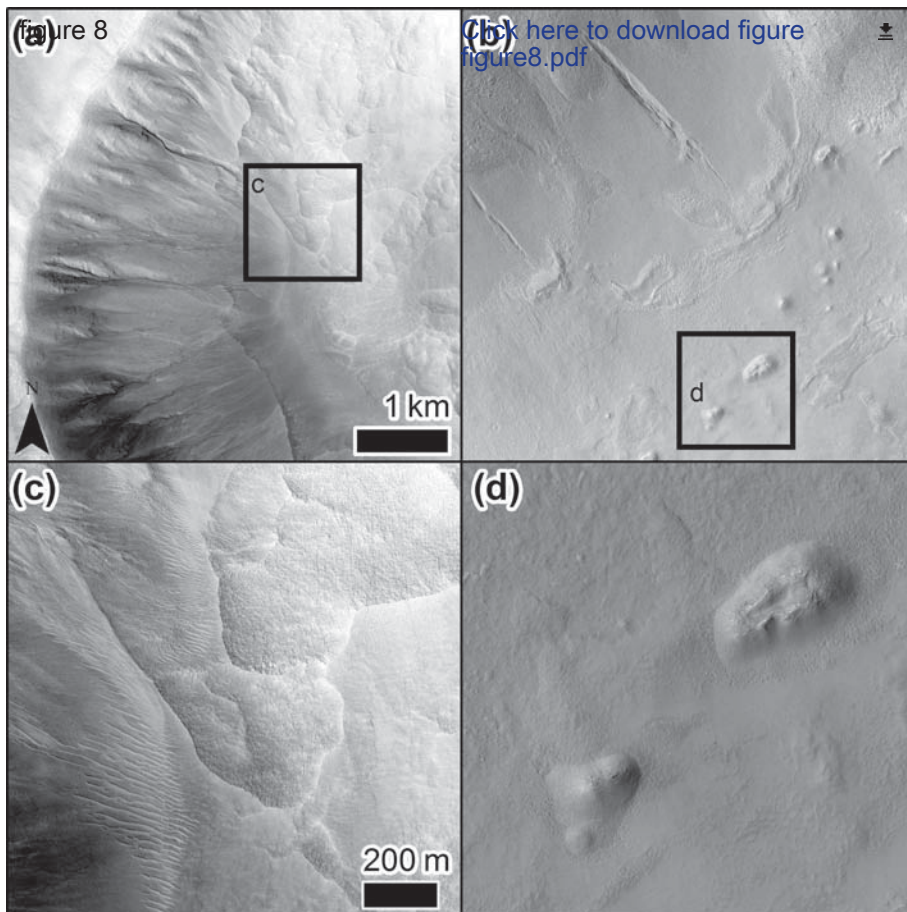
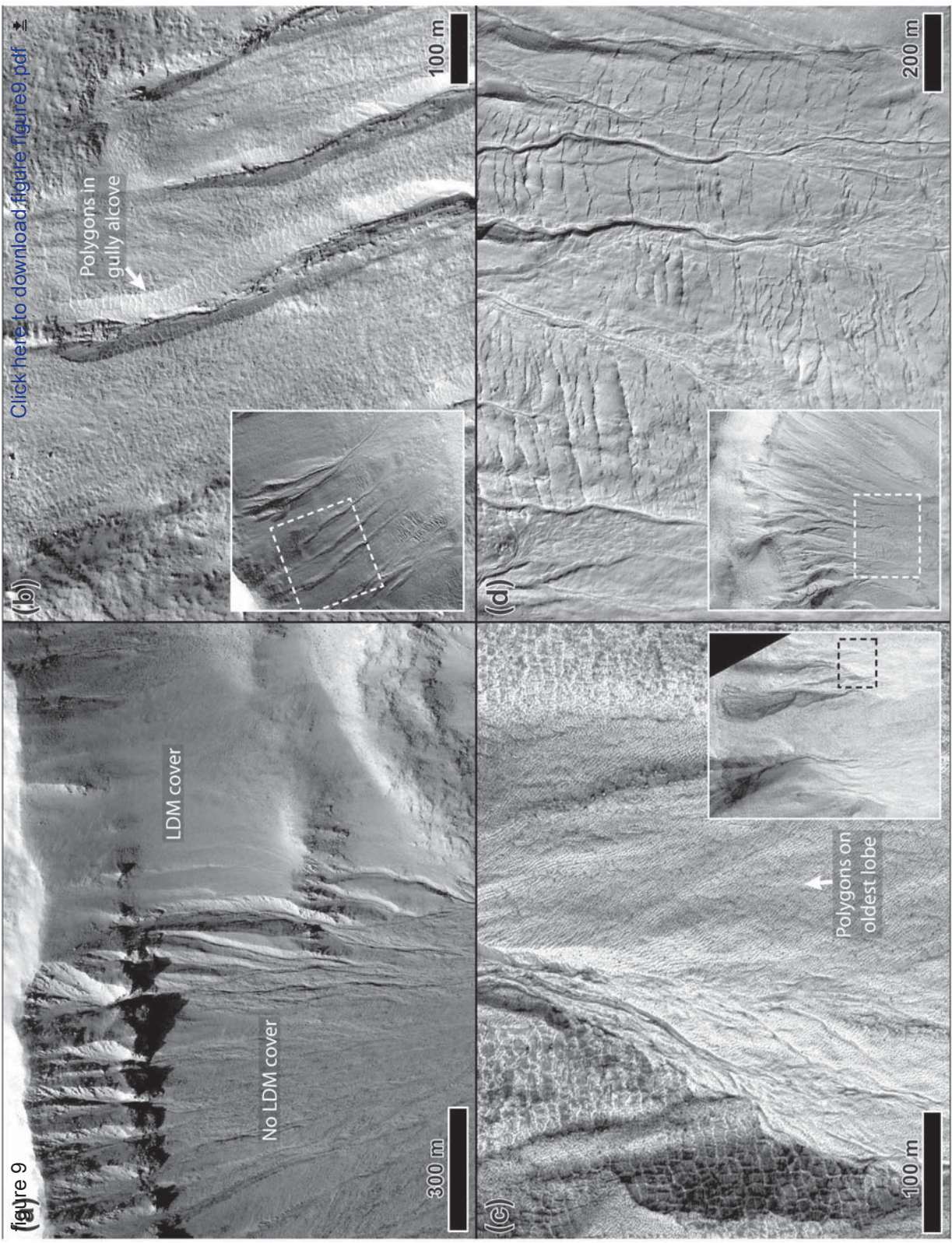


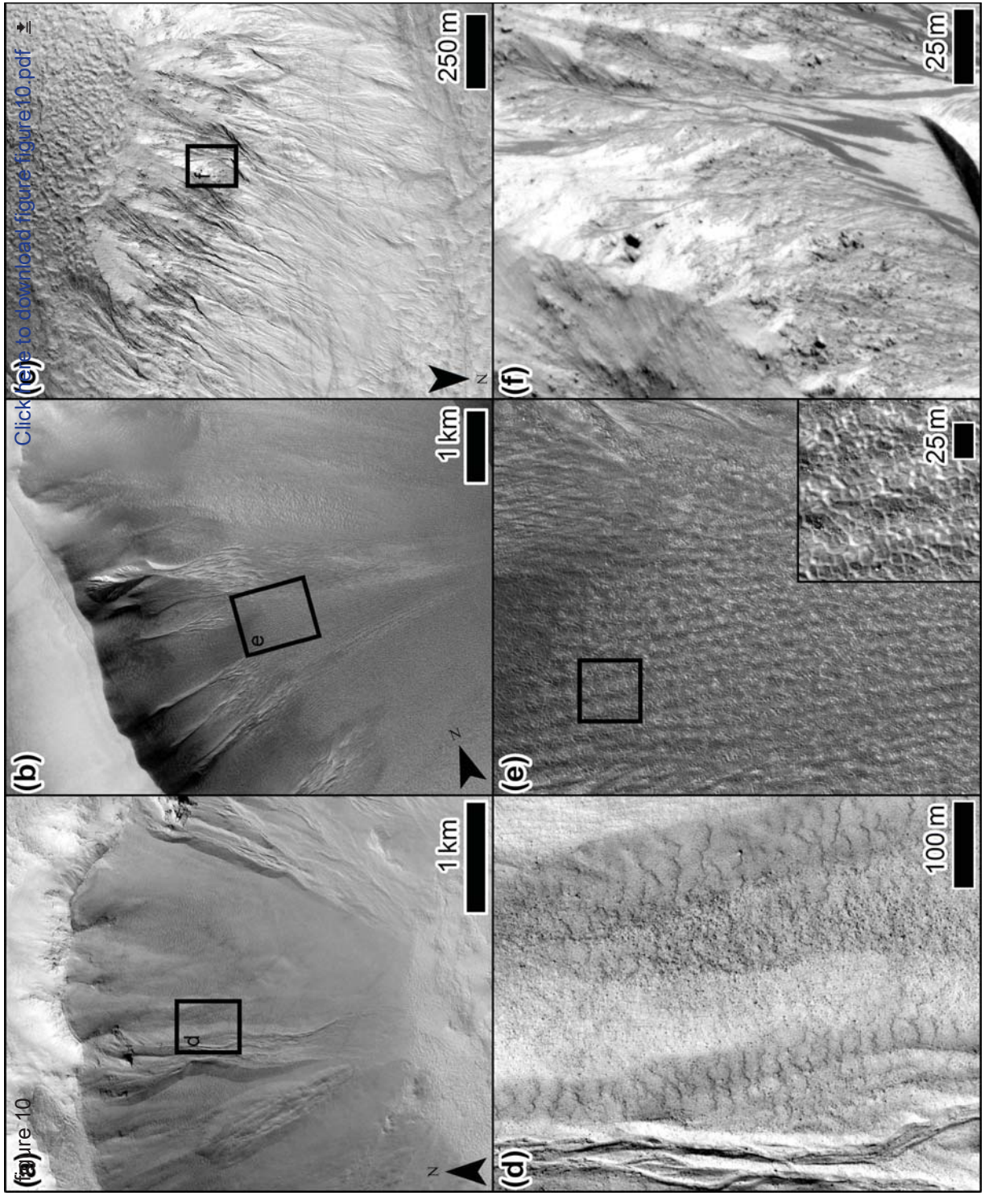


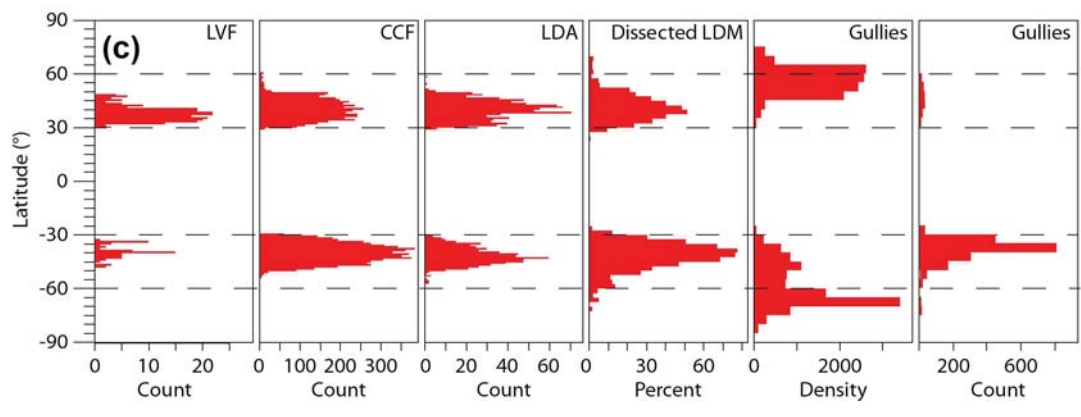
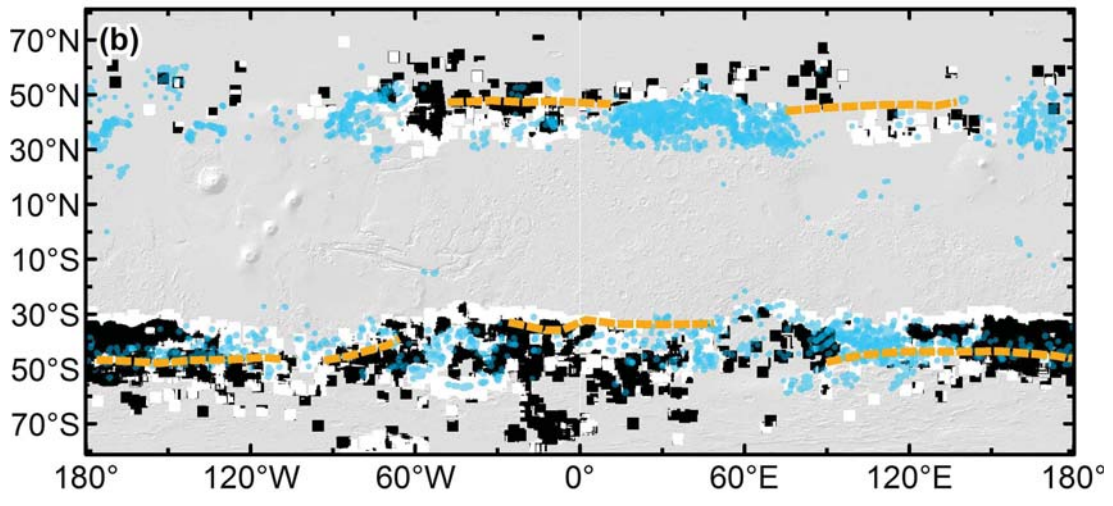
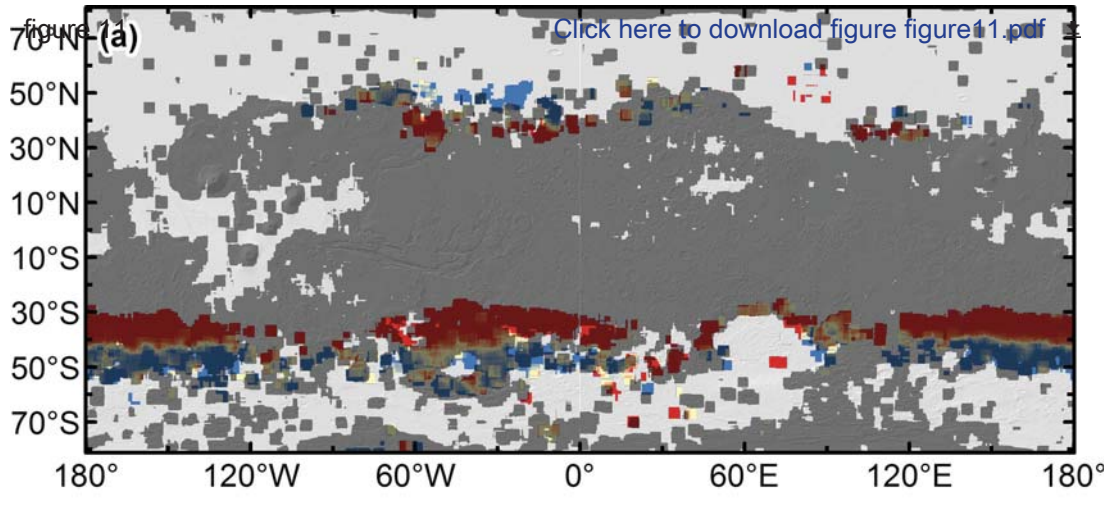
figure 9



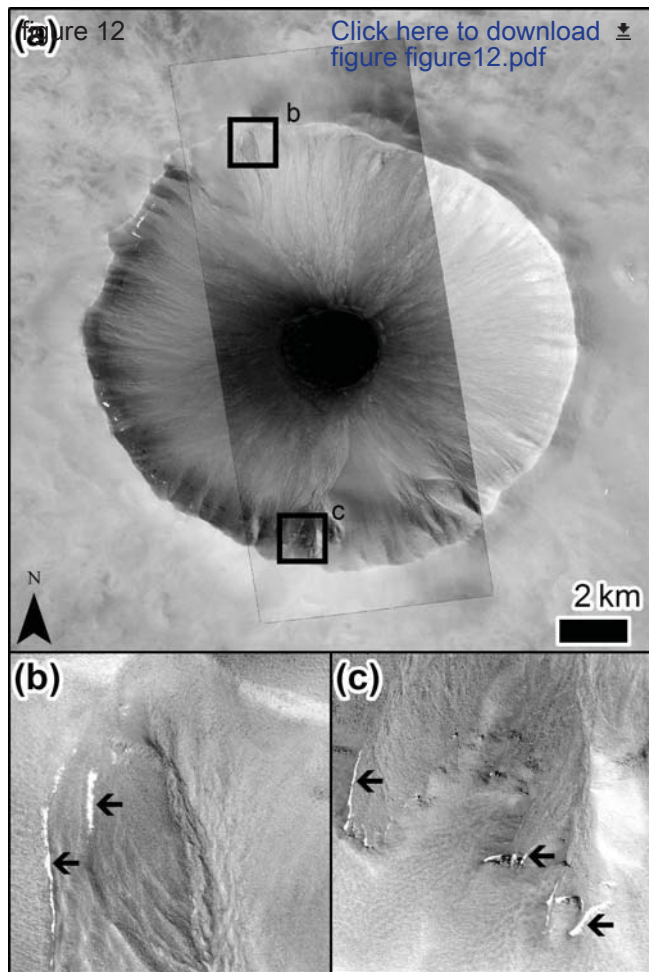
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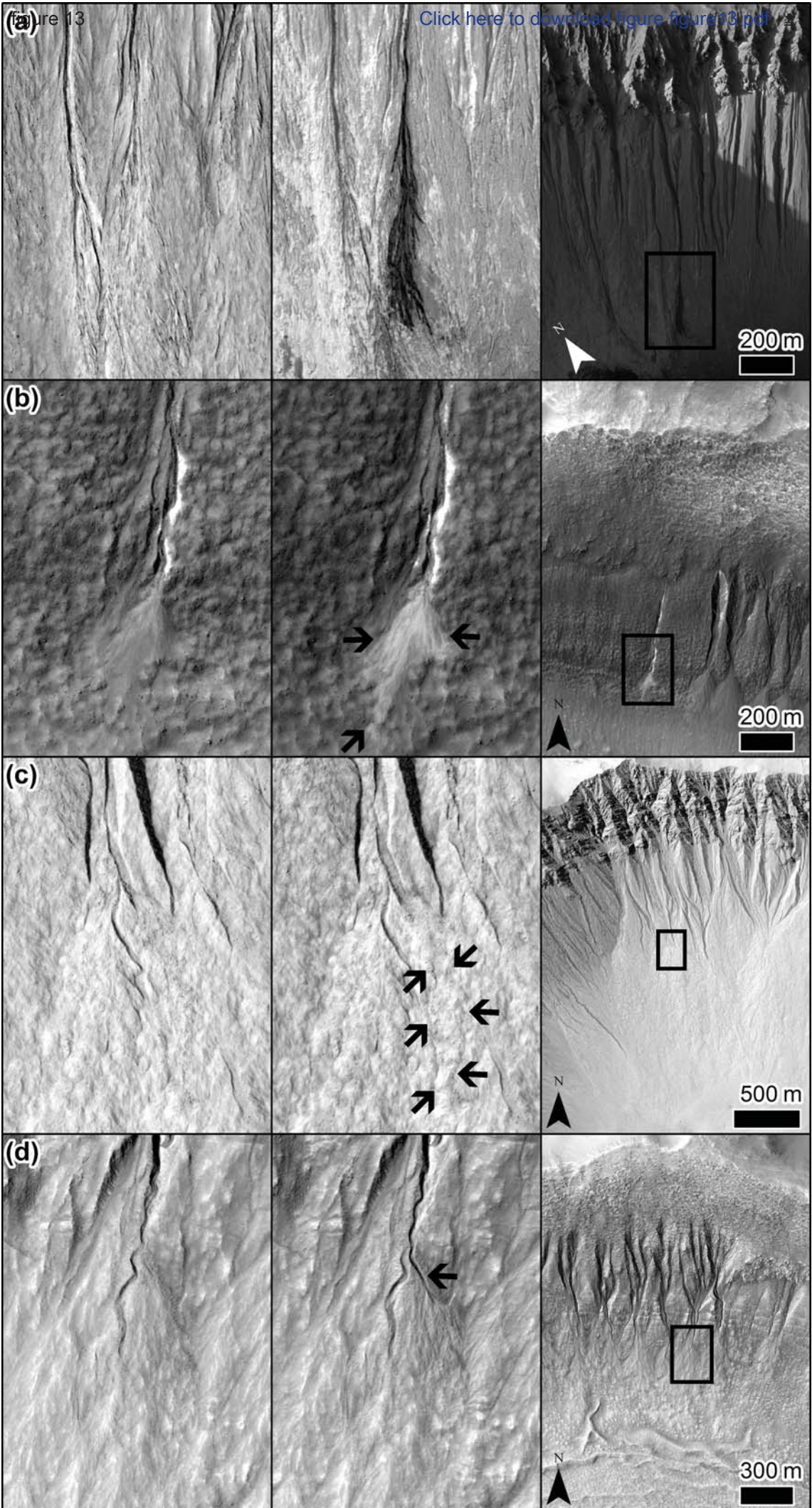
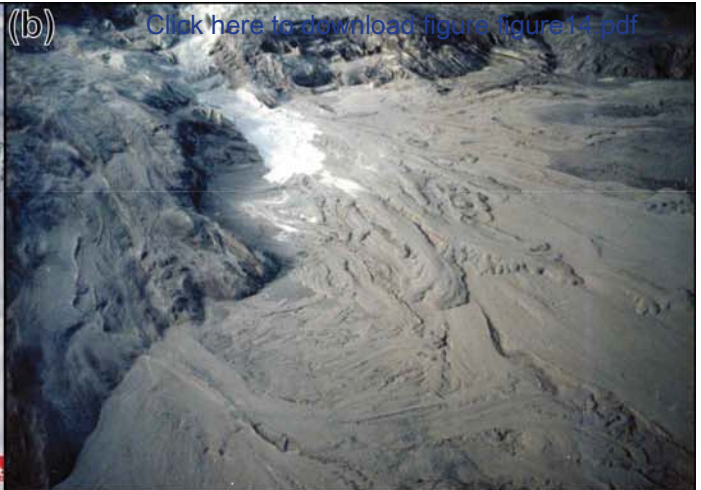
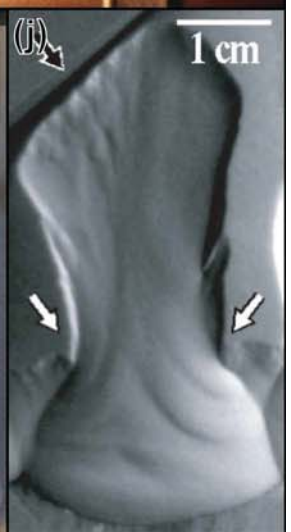
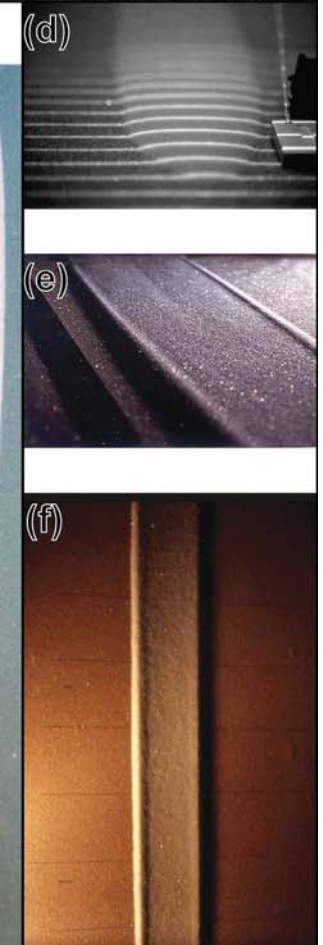
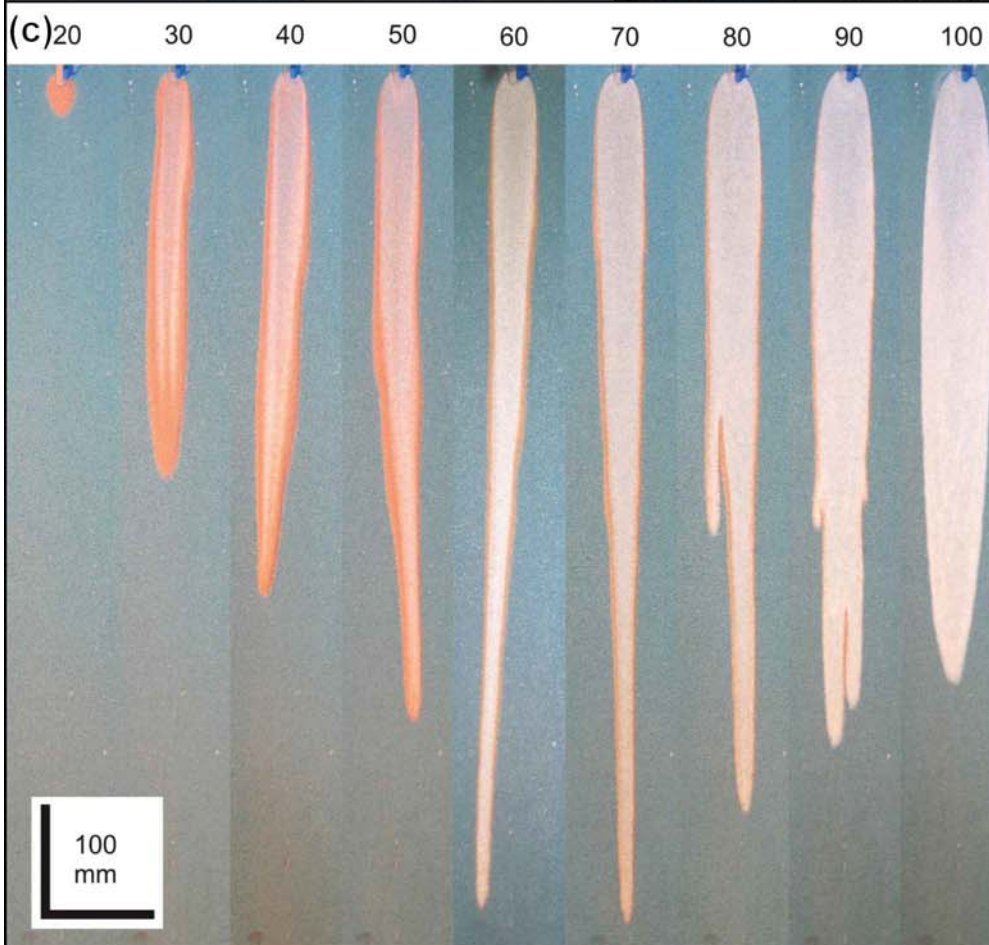




Figure 14



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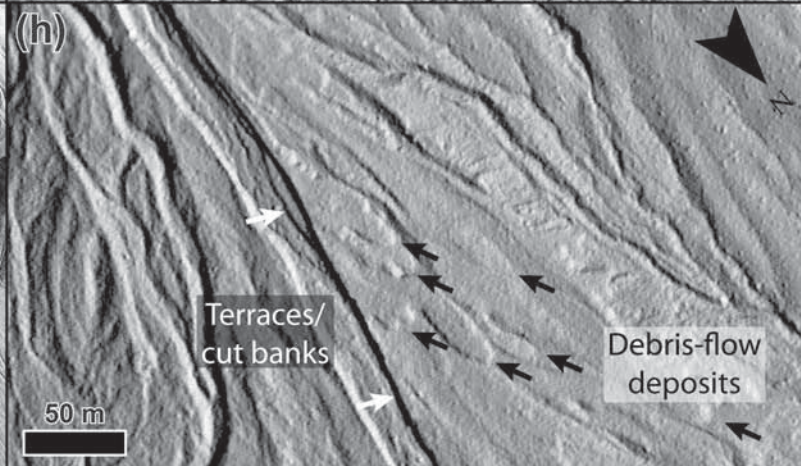
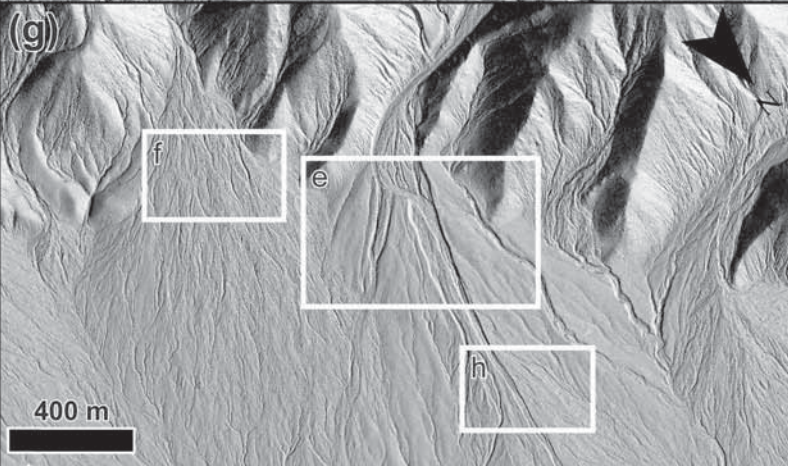
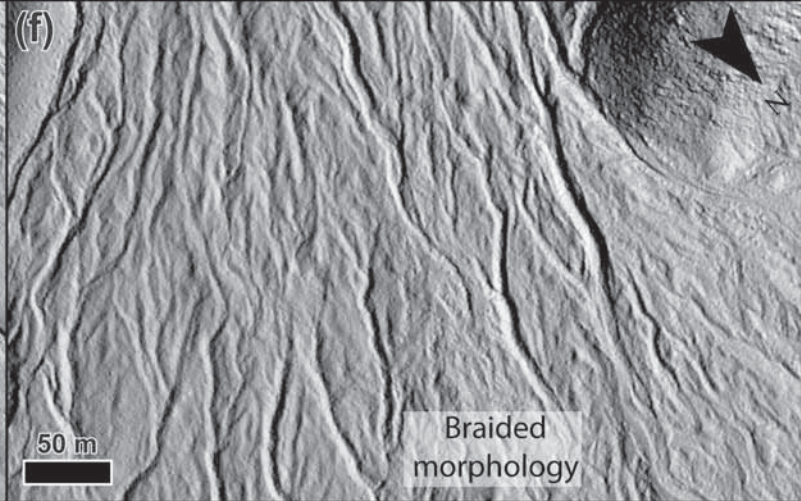
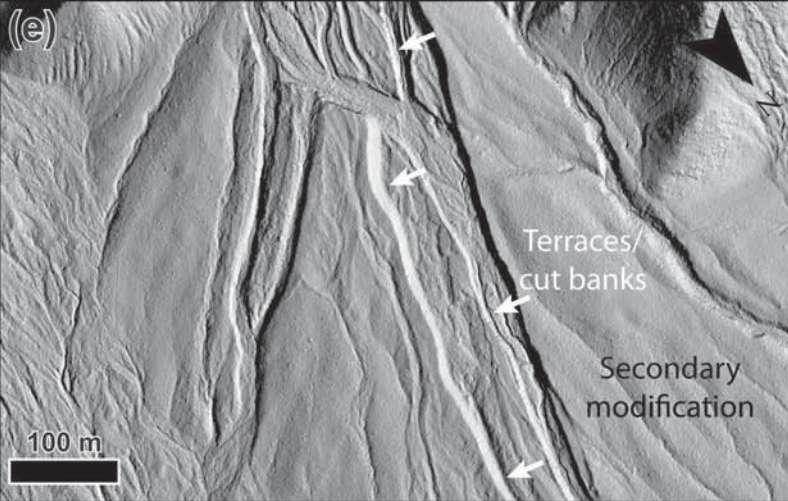
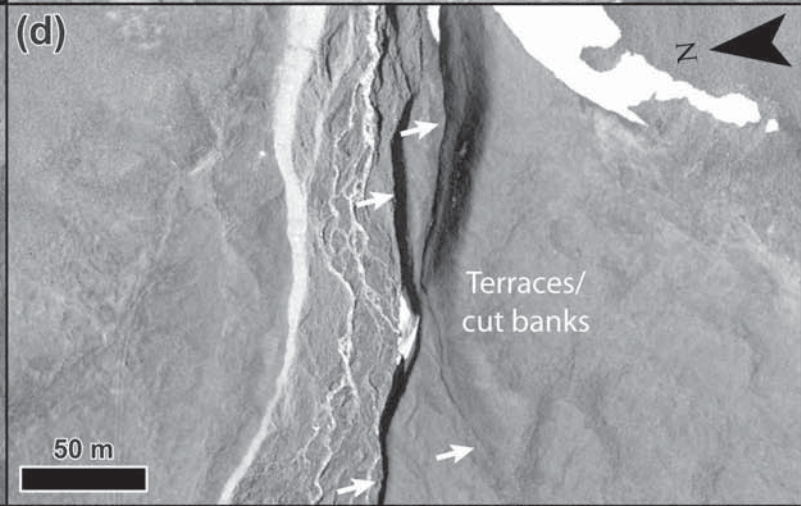
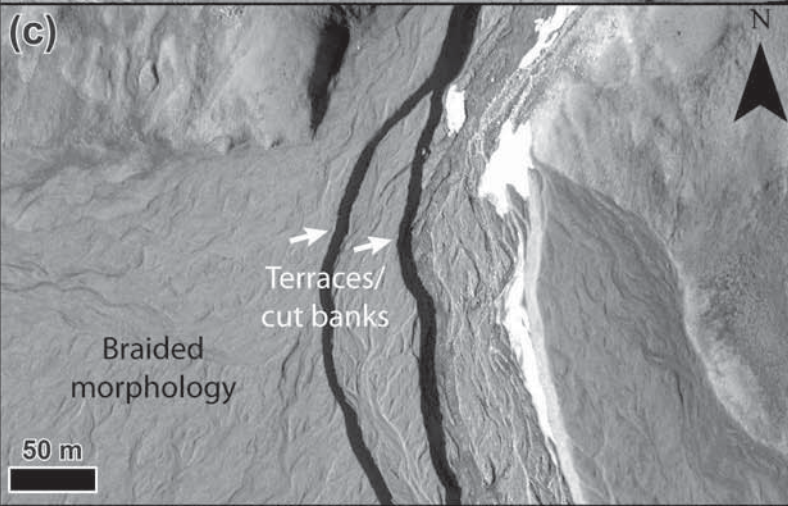
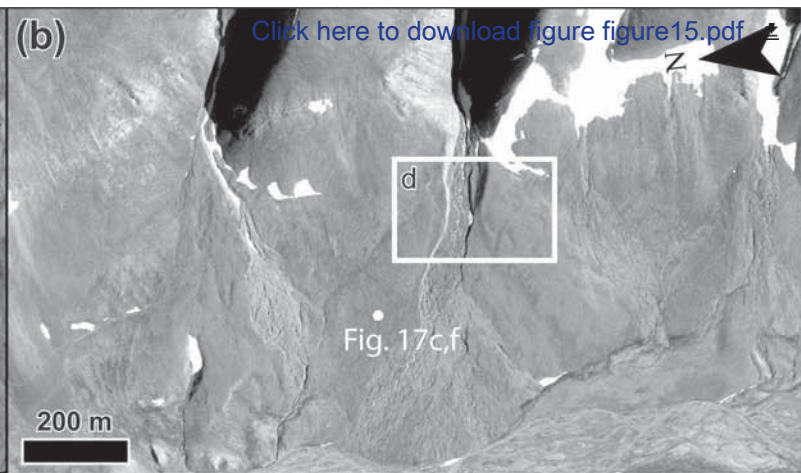
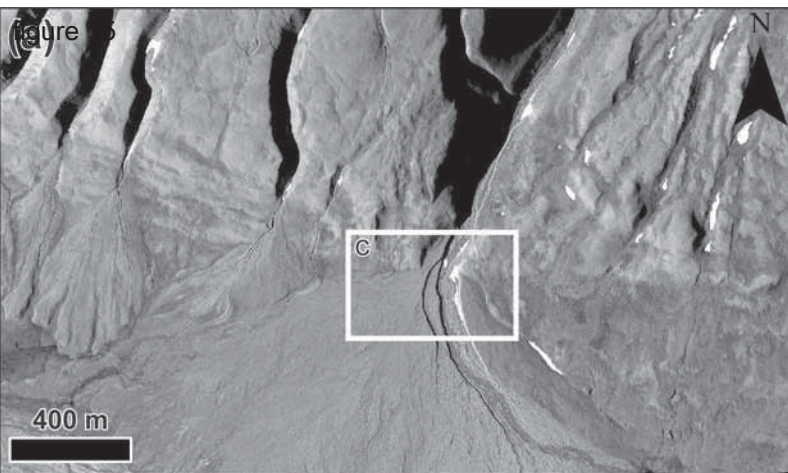
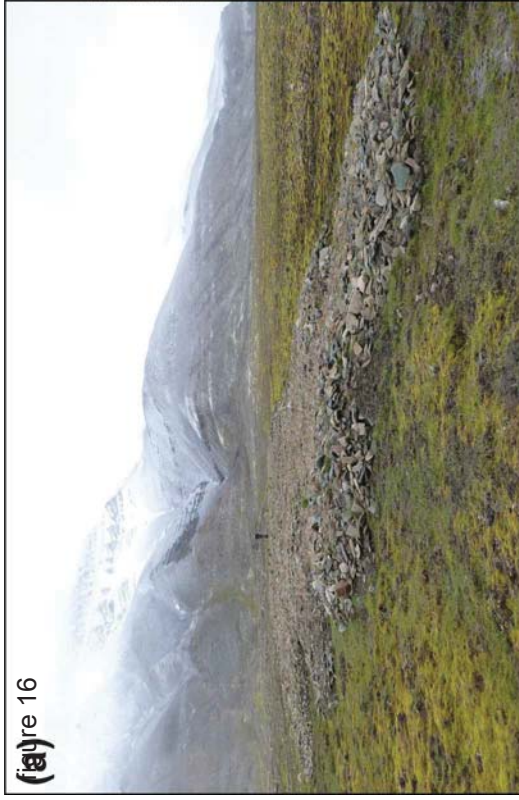




figure 16



(c)



(b)

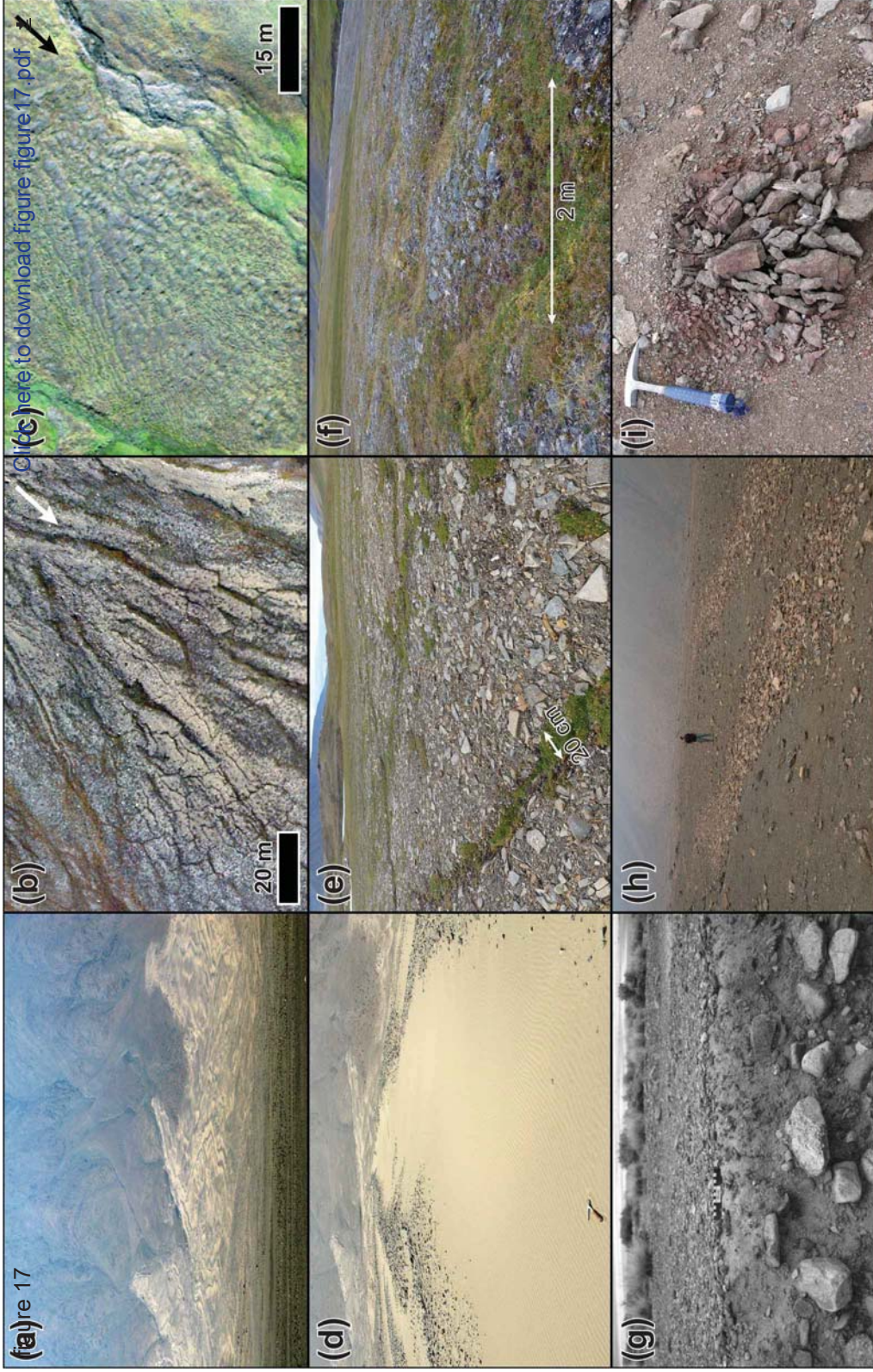
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(d)



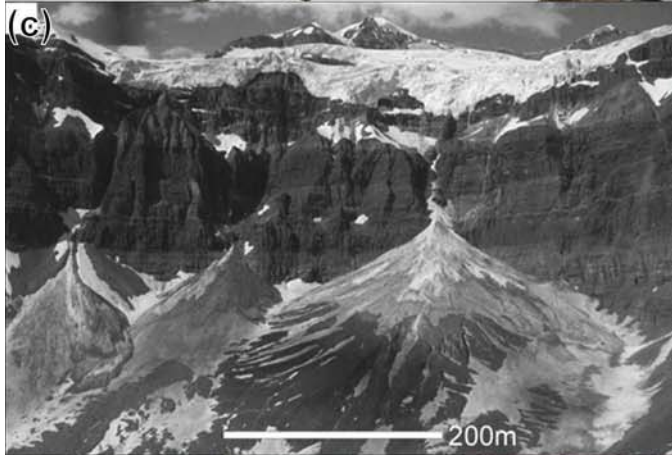
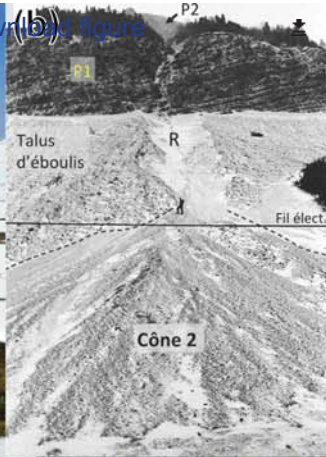




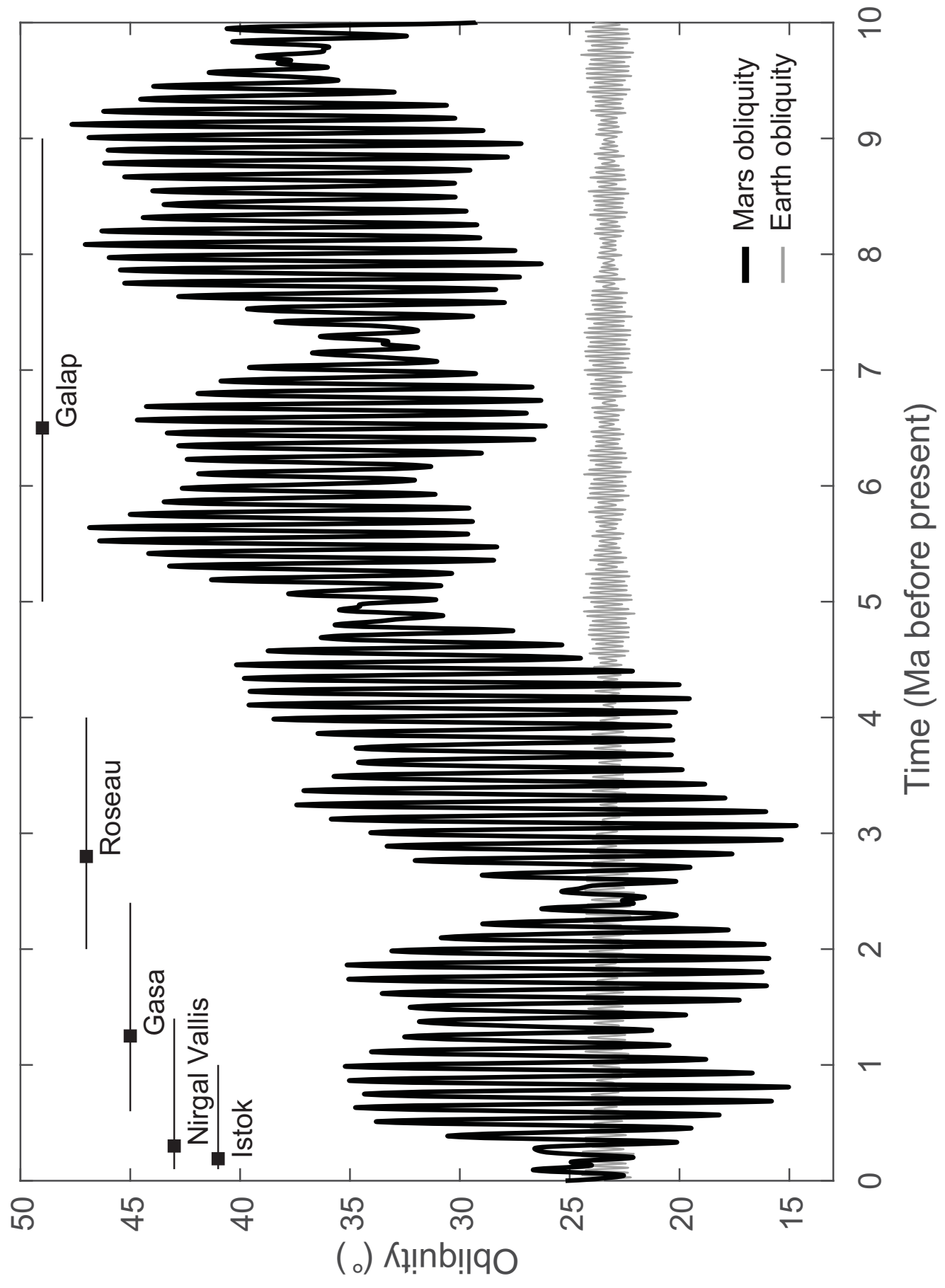


(a) Figure 18

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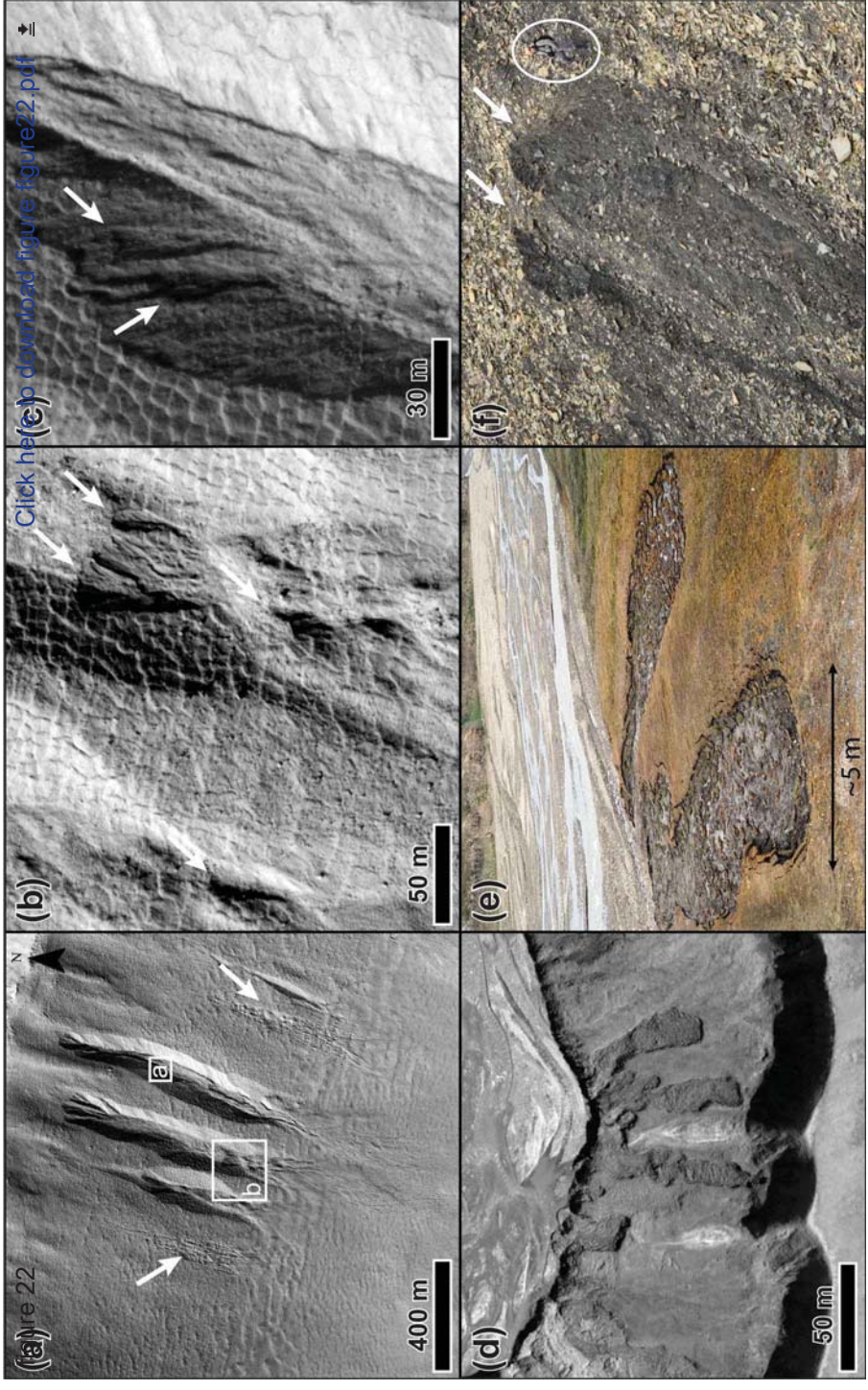














(a) Figure 23



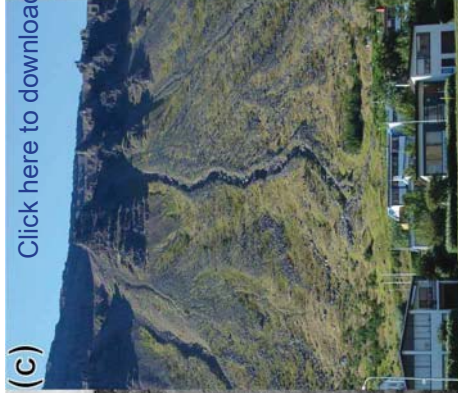
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figure23.pdf

(c)



(d)





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