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Renaldo Gastineau, Susan Conway, Andreas Johnsson, Jana Eichel, Nicolas Mangold, et al.. Small-scale lobate hillslope features on Mars: A comparative 3D morphological study with terrestrial solifluction lobes and zebra stripe lobes. *Icarus*, 2020, 342, pp.113606. 10.1016/j.icarus.2019.113606 . hal-02499008

HAL Id: hal-02499008

<https://hal.science/hal-02499008>

Submitted on 21 May 2020

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Small-scale lobate hillslope features on Mars: A comparative 3D morphological study with terrestrial solifluction lobes and zebra stripe lobes

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25 **Key points**

26

- 27 1. Small scale lobes (SSL) on Mars share more morphometric characteristics with terrestrial
28 solifluction lobes than zebra stripe lobes from seismic shaking in the Atacama Desert.
- 29
- 30 2. Martian SSL only occur on slopes greater than $\sim 10^\circ$, a constraint not observed for lobes on
31 Earth and could be due to differences in material properties or thermal regime.
- 32
- 33 3. Martian SSL differ from terrestrial ones in two other ways: they can have larger dimensions
34 and they tend to occur near the top of the slope as opposed to the bottom.

35 Abstract

36 Small-scale lobes (SSL) observed at the surface of Mars are thought to be the result of solifluction.
37 Hence, their existence has important implications for our understanding of recent climate history, the
38 distribution of thaw liquids and its geomorphic effects, as water is believed not to have been recently
39 stable at the martian surface. These small-scale lobes are limited to sloping terrains and often occur
40 alongside polygonal patterned ground attesting to the presence of ice in the environment. In this study,
41 we perform a comparative 3D morphometric analysis of the lobes on Mars with terrestrial analogues.
42 We use data from High Resolution Imaging Science Experiment (HiRISE) camera in order to create
43 Digital Terrain Models (DTMs) on Mars at 1 m/pix. For the terrestrial analogues, we use DTMs and
44 orthophotos from five periglacial environments with solifluction lobes and from one site with lobate
45 features found in the Atacama Desert. The lobate features in the Atacama are found within features
46 called “zebra stripes”, which are apparently unique to the Atacama and are now generally accepted
47 to be the result of seismic shaking. We show that SSL on Mars overlap morphometrically with
48 terrestrial solifluction lobes, and are less similar to zebra stripe lobes. The majority of martian SSL
49 occur below the angle of repose which demonstrates that a dry fall mechanism cannot be responsible
50 for their formation and that lubrication of the subsurface is required. We found that martian SSL only
51 occur on slopes greater than $\sim 10^\circ$, a constraint not observed for terrestrial solifluction lobes nor zebra
52 stripe lobes in Atacama. We hypothesise that this apparent constraint does not result from the lowered
53 gravity on Mars, but instead from differing soil properties and/or thermal regime between Mars and
54 Earth which affects the slope at which creep can initiate. We cannot rule out a role of CO_2 sublimation
55 in lobe-formation based on our terrestrial measurements.

56 **Keywords:** Mars; Surface activity; Periglacial processes; Terrestrial analogues; 3D analysis

58 1. Introduction

59 Solifluction landforms, in the form of downslope oriented lobes, are common in cold-climate
60 environments on Earth. Mars is currently a cold hyper-arid desert planet where contemporary liquid
61 water may be extremely localized and rare (e.g., Ojha et al., 2015). Lobate hillslope features, similar
62 in morphology to terrestrial solifluction lobes have been observed on Mars (Mangold, 2005;
63 Gallagher et al., 2011; Hauber et al., 2011; Johnsson et al., 2012; Balme et al., 2013; Johnsson et al.,
64 2018). These landforms, termed “Small-Scale Lobes” (SSL), are interpreted to have been formed by
65 solifluction processes due to their morphological similarity to solifluction lobes on Earth (Fig. 1;
66 Gallagher et al., 2011; Johnsson et al., 2012).

67 We identified a new terrestrial environment where lobate forms are observed on sloping terrain and
68 could therefore provide an alternative mechanism to solifluction as an explanation for martian SSL.
69 In the Atacama Desert, lobate forms visible in aerial images on small hills, have been attributed to
70 the action of salts (Beatty, 1983), overland flow (Owen et al., 2013), and seismic shaking (May et al.,
71 2019). This desert is the driest on Earth, which is one of the closest analogues for the current martian
72 climate. One of the main problems facing the solifluction interpretation of SSL on Mars is the fact
73 that extensive thaw is not thought to have been possible in the last 1 Ga (e.g., Kreslavsky et al., 2008).
74 Hence, if a landform similar to SSL can be found in a dry terrestrial environment, it could provide a
75 possible solution to this problem. The lobes are found within zebra stripes in Atacama, whose origin
76 is not fully understood, but is now generally accepted to be the result of seismic shaking (May et al.,
77 2019). As seismic shaking from impacts or marsquakes is becoming recognised as a potential element
78 in martian landscape evolution (Roberts et al., 2012; Brown and Roberts, 2019; Kumar et al., 2019),
79 this forms a potentially interesting alternative formation mechanism for martian SSL.

In this study, we performed a comparative morphometric analysis of SSL on Mars, terrestrial periglacial solifluction lobes and the Atacama lobate forms. Previous works relied on plan-view measurements and observations of martian SSL such as the study of the distribution of small-scale lobes using HiRISE images, or their relationship to other possible ground ice-related landforms such as gullies, polygonally patterned ground, and stripes (Gallagher et al., 2011; Johnsson et al., 2012; Nyström and Johnsson, 2014; Johnsson et al., 2018). Here, we add topographic context and quantitative 3D analysis of these landforms. These are the first large systematic 3D measurements of these features. For this we used data from HiRISE to create DTMs (Digital Terrain Models). For the terrestrial analogues, we used DTMs and orthophotos from Svalbard (Adventdalen), Greenland (Carlsberg Fjord), Sweden (Hödj), the French Alps (Termignon), Iceland (Tindastóll), and the Atacama Desert (Antofagasta). The aim of the study is to use both the new topographic information and comparison with an alternate terrestrial lobate form to assess whether the solifluction interpretation for the martian SSL should be maintained. If the small-scale lobes observed on Mars are indeed the result of solifluction, their existence has important implications for our understanding of recent climate history, the distribution of thaw liquids near the surface, its geomorphic effects and implications for Special Regions for planetary protection (Rummel et al., 2014).

1.1. Small-scale lobes on Mars

Mars has abundant ground ice from the mid- to high latitudes as shown by GRS (Gamma Ray Spectrometer on Mars Odyssey) (Boynton et al., 2002; Pathare et al., 2018), radar (Mouginot et al., 2010; Bramson et al., 2015; Stuurman et al., 2016) and imaging datasets of fresh craters exposing ice (Byrne et al., 2009; Dundas et al., 2014). In particular the ubiquitous presence of polygonally patterned ground at latitudes higher than $\sim 55^\circ$ and discontinuously between 30° and 55° is thought to represent the thermal contraction of these ground ice deposits (Mangold et al., 2004; Levy et al., 2009). 98% of martian SSL are found adjacent to, and sometimes superposed on, polygonally patterned ground (Nyström and Johnsson, 2014). If martian SSL are formed by solifluction then they could indicate thaw of this ground ice in the recent past. In support of this hypothesis is the rare observation of ploughing boulders associated with martian SSL (Fig. 2; Johnsson et al., 2018), which on Earth, are intimately associated with solifluction (French, 1976; Ballantyne and Harris, 1994; Ballantyne, 2001). The latitude dependence of SSL orientation also suggests a climatic driver in their formation. SSL are limited to sloping terrain and mainly observed in the northern hemisphere (e.g., Johnsson et al., 2018; Barrett et al., 2018). The southern hemisphere has more steep slopes (Kreslavsky and Head, 2003), so the relative paucity of SSL is not clearly understood, but could be linked to hemispherical differences in surface properties (Johnsson et al., 2018). Mid-latitude (55° to 65°) SSL have a pole-facing preference whereas high-latitude (65° to 80°) ones tend to have an equator-facing preference (Nyström and Johnsson, 2014).

In the arid climate of present-day Mars, the production of liquid water is still a point of debate, and is considered to be slightly more probable in the recent past (e.g., Richardson and Mischna, 2005). This is because Mars has undergone recent climatic shifts due to the variations in its orbital parameters. Contrary to the Earth which is stabilized by the Moon, the obliquity of Mars, currently equal to 25.2° , changes by approximately 20° on a 100 ka cycle (Laskar et al., 2004). According to modelling by Kreslavsky et al., (2008), conditions favouring the formation of an active layer (a thawed layer atop the permafrost) could have last been reached between 10 and 5 Ma.

SSL have been studied by several authors using HiRISE images (Gallagher et al., 2011; Johnsson et al., 2012; Nyström and Johnsson, 2014; Johnsson et al., 2018). As reported by Nyström and Johnsson, (2014), 48% of martian SSL occur in craters that also host gullies. SSL superpose gullies (Gallagher and Balme, 2011) suggesting their age to be equivalent to those of gullies (i.e. the last few Ma; Reiss

et al., 2004; Schon et al., 2009; De Haas et al., 2015). Whether gullies are caused by flowing liquid water/brine or CO₂ sublimation triggered flows is a current point of debate (e.g., Conway et al., 2018). Their intimate association with martian SSL suggests that the two landforms are likely to be linked as a landform assemblage, i.e. formed by related processes (Gallagher et al., 2011). Liquid water could be favoured by the presence of perchlorates in the regolith, which were found at the Phoenix site. Perchlorates are molecules which have a eutectic point at 240K, that maintain water in a liquid state at temperatures below its freezing point (Pestova et al., 2005; Marion et al., 2010). Sublimation of CO₂ frost (Sylvest et al., 2016) is not currently favoured to explain martian SSL, because lobes at the foot of the slope are hard to explain as they are lower than the dynamic angle of friction which limits mass wasting processes (Johnsson et al., 2012, 2018). However, the distribution of seasonal CO₂ matches with the observed latitudinal distribution of martian SSL and a recent study has revealed active rock motion associated with SSL and the seasonal CO₂ ice deposits (Dundas et al., 2019).

Finally martian SSL are often associated with landforms that resemble terrestrial sorted patterned ground (Johnsson et al., 2012, 2018), which are found in environments with active freeze-thaw cycling. The patterns are outlined by increased concentrations of clasts and can take the form of piles, nets, polygons, circles or stripes depending on the clast concentration and surface slope (Kessler and Werner, 2003). Such patterns have been reported on Mars (Soare et al., 2016; Barrett et al., 2017) and are found in proximity to SSL (Gallagher et al., 2011; Johnsson et al., 2018).

1.2. An overview of lobe-producing processes on Earth

Mass wasting is defined as the downslope movement of soil/rock induced by gravity. Mass wasting encompasses a number of processes, which can operate together or separately (e.g., Selby, 1982) (Fig. 3a). However, not many of these processes produce lobes. Solifluction processes are known to produce lobes whereas soil creep on its own does not, as shown by field observations (Fig. 3a). Commonly, soil creep is described as the process of downslope soil movement driven by a range of processes (Heimsath and Jungers, 2013) such as moisture and/or temperature fluctuations, dissolution and recrystallization of salts (Pawlik and Šamonil, 2018). Solifluction, on the other hand, refers to slow downslope movement of water-saturated debris or soils (Gallagher et al., 2011) by cyclic freezing and thawing of water (e.g., Matsuoka, 2001).

Solifluction can be divided into four processes (Matsuoka, 2001). 1) Frost creep is a ratchet-like downslope movement due to a normal frost heave followed by thaw and near vertical settling (Fig. 3b). Frost creep is divided into diurnal and annual frost creep depending on the timescale over which the soil has undergone the freeze-thaw cycle. The timescale of the freezing affects the depth of the movement, for example diurnal frost creep mainly affects the first centimetres of the soil (Matsuoka, 1998) whereas annual frost creep affects a few decimetres (Smith, 1988). 2) Needle ice creep is special kind of diurnal frost creep, occurring when superficial surface debris is lifted perpendicular to the surface by ice needles and then falls again vertically on thawing (Li et al., 2018). 3) Gelifluction occurs on thaw when self-compaction leads to high pore-water pressures resulting in plastic deformation of the soil (Fig. 3b; Harris et al., 2008). 4) When conditions of two-sided freezing occur, there is an additional process called “plug-like” flow in cold permafrost conditions. In this case, the whole active layer is set in motion (Matsuoka, 2001). Morphologically, solifluction lobes can be divided into stone- and turf-banked lobes. However, this morphometric classification does not imply a difference in process forming the lobe. It is likely that vegetation (and animals) strongly influence creep processes and thereby also landform development and morphometry (Eichel et al., 2017). Turf-

169 banked lobes have, for example, a higher sediment thickness and a lower surface velocity than
170 vegetation-free lobes (stone-banked lobes) (Matsuoka, 2001; Harris et al., 2008).

171 Debris flows are another lobe producing process (Draebing and Eichel, 2018). Debris flows are rapid
172 mass movements of mixtures of sediment (40-50%) and water moving under gravity (Iverson, 1997)
173 and deposit lateral levees as well as terminal lobes of unsorted materials. Draebing and Eichel, (2018)
174 compared former debris flow lobes reworked by solifluction with solifluction lobes and only found
175 slight geomorphic differences, with reworked debris flow lobes possessing a more half-moon-like
176 shape while solifluction lobes were more tongue-shaped. However, lobes developed from debris flow
177 lobes have steep catchment areas and a debris flow origin can be deduced from their context (e.g. foot
178 of proximal moraines or alluvial fan; De Haas et al., 2015; Draebing and Eichel, 2018). We do not
179 examine this particular lobe-forming process in any further detail as we consider similar
180 environmental conditions are required as those that form solifluction lobes *sensu stricto*.

181

182 **2. Study sites**

183 **2.1. On Mars**

184 We studied sites containing two types of martian SSL, sorted lobes or clast-banked lobes which have
185 a distinct clast-rich front, and non-sorted lobes where the lobate shape is visible because of the relief
186 (Gallagher et al., 2011; Johnsson et al., 2012). They are thought to be analogous to stone-banked and
187 turf-banked lobes on Earth based on their shape, respectively (Fig. 4; Benedict, 1976). Based on the
188 dataset presented in Johnsson et al. (2012, 2018) and the location of HiRISE images, 36 stereo pairs
189 hosting SSL were identified from which DTMs could be made (see Table 1 and Fig. 5 for their
190 locations). Seven stereo pairs were processed into DTMs in the northern hemisphere and one in the
191 southern hemisphere. All of the sites are located on crater walls where sloping terrains are present.
192 The craters range from 1.8 to 16.6 km in diameter, and they are all simple bowl-shaped craters. Seven
193 of the craters also contain gullies and six of the craters also have polygonally patterned ground (Table
194 2). Only the crater at site L_63_292 contains any appreciable infill in the form of dark-toned aeolian
195 dunes. The relatively young age of these craters is attested by their easily identifiable ejecta blankets,
196 which have few superposed impact craters.

197 **2.2. On Earth: solifluction lobes**

198 Five terrestrial analogues with solifluction lobes have been included in this study: Svalbard
199 (Adventdalen), Greenland (Carlsberg Fjord), Sweden (Hödj), the French Alps (Termignon) and
200 Iceland (Tindastóll) (Fig. 6 and Table 3). These sites are all in periglacial environments, which are
201 defined as an environment where the phenomena of freezing and thawing and associated permafrost
202 related processes occur (French, 1976; Slaymaker, 2011). In this study, we include sites where
203 solifluction lobes are found in the northern hemisphere, and each site has a different climatic context,
204 soil properties, vegetation type and geology (Table 3). Thus, our terrestrial analogues represent a
205 varied sample of the possible types of solifluction lobes found on Earth.

206 **2.3. On Earth: zebra stripe lobes in the Atacama Desert**

207 In the Atacama Desert, lobate-shaped in plan-view are observed despite it being one of the driest
208 places on Earth (Clarke, 2006; Owen et al., 2013). It is unlikely, however, that they are formed by
209 solifluction, so provide an alternate Earth analogue for comparison to martian SSL. The Atacama
210 Desert extends from southern Peru to northern Chile with rainfall of ~2 mm/year, making this desert
211 the driest on Earth (Clarke, 2006). Thus, it is often used as an analogue for the current climate of

212 Mars (Catling et al., 2010). Lobate features have been reported on hillslopes in the Atacama and
213 similar lobes have not been reported from any other desert on Earth to our knowledge. They are found
214 within “zebra stripes”, so called because of the contrast between the darkly-varnished gravels and the
215 light-coloured, salt-rich soil (Fig. 7). Initially, these features were attributed to salt heave (Beaty,
216 1983), later reinterpreted to be due to ancient overland flow events (Owen et al., 2013) and most
217 recently attributed to seismic shaking (May et al., 2019).

218 Beaty, (1983) was the first author to mention zebra stripes in the literature, calling them “tiger
219 stripes”. He proposed that they are formed due to the shrinking and swelling of the ubiquitous salts
220 in the soil. This process occurs when the soil undergoes repeated cycles of thermal and/or desiccation
221 induced contraction and expansion of salt minerals (Buck et al., 2006). Over a long period ($\sim 10^6$
222 years) these processes could form salt wedges and patterned ground (Buck et al., 2006) somewhat
223 equivalent to ice lenses and ice wedge polygons formed in periglacial terrains on Earth. Owen et al.
224 (2013) further studied zebra stripes and concluded that rare pluvial events causing overland flow
225 could explain the grain-sorting observed within the zebra stripes on hillslopes in the Atacama.

226 A new study has re-examined the formation of this landform (May et al., 2019). They showed, based
227 on UAV-derived photos that the frontal part of zebra stripes have a distinct boundary, which is almost
228 contour-parallel yet consists of multiple bulges which look like downslope-facing lobes. They found
229 a remarkable similarity in shape between the lobes developed in zebra stripes and deposits developed
230 in experiments examining the process of segregation-induced granular fingering. They propose a
231 combination of seismic shaking (Matmon et al., 2015) and instantaneous dry granular free surface
232 flows as the key mechanism for zebra stripe formation. They also found that the lobes developed in
233 zebra stripes in their study area have width and length ranging from 1 to 3 m, and 10 to 30 m
234 respectively, and that they form on slopes ranging from 10 to 20°.

235

236 3. Approach

237 Images from the HiRISE camera on the Mars Reconnaissance Orbiter (MRO) with a ~ 25 cm/pixel
238 resolution were used to derive Digital Terrain Models using the Integrated Software for Imagers and
239 Spectrometers (ISIS3) and Socet Set 5.6.0 following the method outlined in Kirk et al., (2008). Five
240 DTMs with nominal spatial resolution and relative vertical accuracy of 1 m and ~ 0.5 m respectively
241 were created. Three further publically available DTMs derived using the same procedure were
242 downloaded from <https://www.uahirise.org/dtm/>. Moreover, six terrestrial analogues have been
243 included in this study: Svalbard, Iceland, Sweden, Greenland, the French Alps and the Atacama
244 Desert, whose digital elevation models were derived from photogrammetry or laser altimetry with
245 spatial and vertical resolutions equivalent to or better than the martian data. Locations and detailed
246 information is given in Fig. 6, Table 3 and in the sections below.

247 3.1. Elevation data processing and lobe measurements

248 For martian DTMs we used sinusoidal projections centred on the longitude of the lobe locations. For
249 the terrestrial DTMs, we used local Universal Transverse Mercator (UTM) projections. The narrow
250 extent (6° of longitude and 8° of latitude wide) of each zone of this projection system ensures minimal
251 scale distortion within each zone. For the DTM in the French Alps we used the official French map
252 projection system: Lambert-93 (EPSG 2154), a conic and conformal projection. Thus, our projections
253 minimise spatial distortion which are negligible compared to the other potential sources of error in
254 our study.

To smooth out metre-scale noise in the stereo-derived martian DTMs we passed a mean moving window filter over the DTM of 3 pixels and 5 pixels, each twice. We applied the same procedure to the terrestrial data for consistency. Measurement of lobe geometries was made using orthophotos and hillshaded relief rendering of the topography in ArcGIS 10.4 (Fig. 8). We report these measurements as 3D rather than 2D distances to make full use DTMs. The width of each lobe is measured at the furthest upslope extent of lobes while their length is measured perpendicular to the latter and represents the maximum downslope distance between the upslope end and the riser (the toe). Because downslope movement should follow the line of maximum gradient, we used contour lines to help guide these measurements. The slope for each lobe was calculated along the downslope-axis by averaging the slope map values that fell under the line. All of the data were then extracted and plotted with Matlab. To better define the nearest upslope ridge and quickly identify the steepest upslope direction, we calculated the compound topographic index for each DTM, which does not imply that the study area is wet. It produces a visualisation of the orientation of the steepest downslope/upslope direction that also highlights local ridges (Fig. 8). On Mars, the nearest upslope ridge is more readily identifiable because it is usually the crater rim. The normalised distance of each lobe from its uppermost point to its nearest associated ridge indicates the distribution of lobes along the slopes (Fig. 9a). The length of the slopes varied on each studied site, it is necessary to normalize the distance of each lobe with the total length of the hillslope in order to make meaningful comparisons. We also used topographic long profiles in order to study the position of the lobes upon the hillslope and to visualise the curvature of profiles where they occur.

We estimated the maximum uncertainty in our digitisation of the width and length of the lobes (and of the ridges) to be on the order of 1-2 pixels in the orthoimages, as the lobes were easily distinguishable from their background. This uncertainty translates to at worst 1 metre for the coarsest terrestrial orthophoto resolution (Sweden: 1 m/pix) and about 15 cm for the finest one (Iceland: 0.15 cm/pixel). For the martian orthophotos, this corresponds to 25 cm. Such uncertainties have a negligible impact on our length and width measurements which are typically on the order of tens if not hundreds of metres.

The relative vertical precision of the martian DTMs used in this study is better than ~0.4 m (Table 1). For the terrestrial DTMs, LIDAR (Light Detection And Ranging) data typically have a maximum vertical precision of ~0.2 m (Hodgson and Bresnahan, 2004) while the Atacama DTM made by stereophotogrammetry and based on previous experience should have a vertical precision of ~0.5 m (Conway et al., 2015). Such uncertainties can lead to significant errors of slope measurements at the pixel-scale, but over length-scales of tens to hundreds of metres become negligible.

4. Results

4.1. Morphometric properties of lobes

We analysed 5148 lobes in total, with 1901 SSL on Mars and 3247 lobes on Earth, of which 2759 are solifluction lobes and 488 are zebra stripe lobes (Table 4). On Mars, we find SSL on slopes ranging from ~10° to ~38°, with a mean and median value of 25° despite all our DTMs containing areas where slopes were below 10°. On Earth, solifluction lobes are found on slopes between ~0° and ~35°, the mean and median values are both equal to 16°. For zebra stripe lobes, the slope where they occur ranges between ~5 and ~30°, the mean and median values are 18.5 and 17°, respectively (Fig. 10). Martian SSL tend to be longer and wider than terrestrial solifluction lobes which in turn tend to be longer and wider than zebra stripe lobes (Fig. 11). Martian SSL overlap with the range of dimensions

expressed by solifluction lobes on Earth, whereas the zebra stripe lobes of the Atacama Desert differ from both as they do not exceed 20 m-wide and 20 m-long.

Fig. 11 shows that, for all three lobe types, lobe length tends to increase with lobe width and for terrestrial solifluction lobes this trend has a gradient slightly lower than the 1:1 line, which was also found for solifluction lobes in Austria (Matsuoka et al., 2005). Martian SSL follow a similar trend to terrestrial solifluction lobes, but can also increase in length faster than they increase in width.

The width to length ratio of martian SSL increases slightly with decreasing slope (Fig. 9b) and the same trend is identifiable for zebra stripe lobes. On Earth, the W:L of solifluction lobes has a maximum value of ~15 for almost flat surfaces. On Mars there is a slight tendency for the length to decrease with increasing slope (Fig. 9c), but this trend is not apparent for the terrestrial analogues. On Earth we note that there is a maximum length of approximately 150 m for solifluction lobes and ~20 m for zebra stripe lobes. Lobes are clearly longer on Mars in particular when the slope decreases towards 20°, where the SSL reach a maximum length of ~700 m.

4.2. Topographic context of lobes

Fig. 12 shows slope profiles illustrating the typical positions of the lobate features studied within the surrounding topographic context. Lobes can span the whole topographic profile or be constrained to a small part of it. All slope profiles are concave except for the ones in the Atacama Desert. For site L_45_9, SSL are located mid-slope, whereas in site L_63_292, SSL are located close to the crater rim and at site L_59_44, SSL are spread along the whole profile. In Sweden, solifluction lobes are spread along the whole profile apart from at the highest slopes close to the ridge. On Svalbard, all of the profile has lobes, even the near-flat surface at the bottom of the profile. In contrast to all other sites, the profiles in the Atacama Desert are convex and shorter. Here, zebra stripes are constrained to the upper and middle part of slopes, which are relatively short (note the differences in scale). These case-study examples are reflected by our observations of the whole population. In Fig. 9a, the normalised distance from each lobe to the nearest ridge is plotted against their width to length ratio. On Mars, SSL occur mostly near to the ridge. Only a few SSL are found downslope, where the slopes are less steep contrary to solifluction lobes on Earth, which are mostly found in the lower part of the slopes. Very few solifluction lobes are found near the ridge of hillslopes. The zebra stripe lobes, however, occur across all values.

5. Discussion

5.1. Martian SSL and terrestrial solifluction lobes

Previous work has concluded that SSL on Mars are likely to be a result of solifluction, because they have similar plan-view morphology, slope-side setting and associated landforms (e.g. ploughing boulders) as solifluction lobes on Earth (Johnsson et al., 2018). Our data reinforce the similarity found in previous work, as we find that martian SSL have similar dimensions, similar topographic position and are found on similar slopes as solifluction lobes. In addition, the fact that SSL on Mars tend to have a lower W:L ratio at higher slope gradients indicates their formation mechanics may be fundamentally similar to solifluction lobes (Fig. 9b), which are predicted by theory to be longer on higher slope gradients (Ballantyne and Harris, 1994).

We find that martian lobes differ from terrestrial ones in three ways: they can have larger dimensions, they tend to occur near the top of the slope as opposed to the bottom and martian SSL are rarely found at slopes < 15° (Fig. 10). The slope difference is discussed further in the section that follows. The

origin of martian SSL near the top of the slope suggests a weak influence of upslope contributing area, unlike solifluction lobes on Earth which are thought to require some upslope contributing area to achieve sufficient saturation (e.g., Temme and Veldkamp, 2009). Martian SSL can be much wider than terrestrial solifluction lobes, but are more often longer than terrestrial solifluction lobes (Fig. 12). Lengths that increase faster than widths is a behaviour more similar to terrestrial rock glaciers than terrestrial solifluction lobes (Matsuoka et al., 2005). It is possible that the longer time over which martian SSL can develop (due to lack of landscape disturbance by tectonics), means that they can attain much larger downslope dimensions.

We observed the length of martian SSL tends to decrease with increasing slope (Fig. 9c) whereas this trend is not apparent for lobes on Earth. We think this is likely due to the different hillslopes types between Earth and Mars. On Mars, high slopes are always located near to the crater rim, the position where most SSL originate. Over time, SSL should extend downslope, leading to an increase in their length and a decrease of the average slope. However, on Earth the hillslopes on which solifluction lobes or zebra stripe lobes develop are more diverse and consequently such a consistent signal might not develop. Moreover, we observed that in a given crater, SSL do not necessarily form on the steepest slope, which means that another factor affects the formation of SSL.

5.2. Martian SSL and terrestrial zebra stripe lobes

Whether formed by seismic shaking or another process, our data show that zebra stripe lobes seem to be a poor analogue for SSL on Mars compared to solifluction lobes. Although they have a similar planform shape to SSL and occur on similar slope gradients, they occur on short convex slope profiles contrary to solifluction lobes and SSL which occur on longer concave slope profiles (Fig. 12). Zebra stripe lobes can be located anywhere on the hillslope profile, whereas SSL occur near the top and solifluction lobes occur near the bottom of the profile (Fig. 9a). The dimensions of zebra stripe lobes are significantly lower than SSL and solifluction lobes (Fig. 11). Finally, zebra stripe lobes are very superficial features with low relief, they are landforms whose expression at the surface is revealed by colour-contrasts derived from clast-sorting, rather than topographic relief, in contrast to solifluction lobes and some SSL (Fig. 13). None of these individual arguments are strong enough individually to completely exclude zebra stripe lobes as a valid terrestrial analogue for SSL, but taken together we think that solifluction lobes remain the best terrestrial analogues.

5.3. Martian SSL apparent slope constraint

Martian SSL occur only on slopes higher than 10° and rarely on slopes from 10-15° (Fig. 10). In theory, the process of creep is a continuous process and should only become weaker at lower slopes, rather than cease entirely. Solifluction on Earth occurs continuously down to a few degrees of slope (Kirkbride and Dugmore, 2005; Matsuoka et al., 2005), as also shown by our data (Fig. 10). Consequently, the lobe-forming movement on Mars requires higher slope gradients than on Earth. This could be because lobes are not formed by solifluction process(es), or that solifluction operates differently on Mars to on Earth. In this section we explore how the martian conditions and environment may affect the solifluction process if it is ongoing. To assess the role of different environmental properties for the occurrence of solifluction movement, a factor of safety approach for solifluction movement can be employed following Harris et al. (2001, Eq. 1):

$$FS = \frac{\text{Resisting forces}}{\text{Driving forces}} = \frac{c + (\rho gh \cos(\beta) - \rho_w gh') \tan(\Phi)}{\rho gh \sin(\beta)}$$

with FS factor of safety, c soil cohesion, g gravity, h depth of the potential slip surface, ρ soil density, ρ_w water density, h' height of the piezometric surface above the slip surface, β slope angle and Φ the

angle of internal friction. Pore water pressures (μ) are included in the equation as the product of water density, gravity and height of the piezometric surface above the slip surface ($\mu = \rho_w g h'$). For solifluction movement to occur, driving forces must exceed resisting forces, thus, the factor of safety must become smaller than unity. Following Eq. 1, environmental properties influencing stability of solifluction slopes include gravity, soil properties (cohesion, soil density, angle of internal friction) and soil water content determining the height of the piezometric surface. Theoretical effects of these and further environmental properties (thermal regime, vegetation) on martian solifluction processes and therefore the occurrence of martian SSLs are discussed below.

5.3.1. Effect of gravity (g)

With a value of 3.71 m/s^2 , the gravitational acceleration on Mars is about three times lower than on Earth (9.81 m/s^2). In the factor of safety, this lowered gravity (g) affects both resisting and driving forces (Eq. 1). Thus, for a hillslope with self-same environmental properties, resisting and driving forces will be lower on Mars because of the lower gravity. However, the ratio between resisting and driving forces as expressed in FS stays the same as gravity affects both. Thus, on Earth and Mars the same slope gradient is required for a hillslope to become unstable and for solifluction movement to occur. Consequently, we believe it is unlikely that the lowered gravity on Mars can explain the observed slope constraint.

5.3.2. Effects of soil properties (c, ρ, Φ), soil water content (h') and thermal regime

Soil properties (c, ρ, Φ) included in the factor of safety depend on soil particle size and fabric (Selby, 1982). Mars' soil has a wide range of properties, reflecting the geological diversity of the surface materials (Perko et al., 2006; McGlynn et al., 2012; Meslin et al., 2013; Weitz et al., 2018), and no soil data is available for the studied solifluction sites. Thus, we can only theoretically assess the effects of soil properties on solifluction movement. All considered soil properties, cohesion, soil density and angle of internal friction, increase slope stability by increasing resisting forces (Eq. 1). Thus, if soil cohesion, density or angle of internal friction of martian soils is systematically higher than on Earth, higher slope gradients would be needed for solifluction movement to occur, which could explain the observed slope constraint. Higher cohesion could result from higher clay content, while angle of internal friction is higher for coarser material. However, it is likely that soil cohesion is generally higher on Earth than on Mars due to the contribution of organic material (e.g., Fattet et al., 2011). Hence, we consider a systematic difference in soil properties on its own unlikely to explain the difference in onset slope.

Soil water content influences the height of the piezometric surface above the slip surface (h') and thereby determines pore water pressures (μ). Meteoric water can increase soil water content and pore water pressures and is thereby an important control on solifluction motion on Earth (Matsuoka, 2001). Melting snow, in particular increases soil water content and promotes high solifluction movement rates by increasing pore water pressures (Jaesche et al., 2003). For Mars we assume a lack of meteoric water contribution, thus, the height of the piezometric surface would depend solely on soil water content and availability during thaw, depending on the thermal regime (see below). Following the factor of safety, lower pore water pressures require e.g. a higher slope angle for hillslopes to become unstable and solifluction movement to occur. Thus, lower soil water content and/or availability, e.g. due to missing meteoric water, could therefore be a potential explanation for the observed slope threshold.

In addition, in conjunction with the thermal regime, soil properties and soil water content determine frost penetration depth and speed, formation of segregation ice and spatial distribution and thereby solifluction movement (Harris et al., 2008). Differing thermal regimes between Mars and Earth, e.g. a lower intensity of freeze-thaw action (Johnsson et al., 2018) could explain a lower intensity of

solifluction processes and thereby the observed slope constraint. However, if this were true we might expect lobes to be less-developed on Mars, which is not the case. Interaction of soil properties, pore water pressures and thermal regime are furthermore reflected in the thaw consolidation ratio (Morgenstern and Nixon, 1971), which relates the rate of thaw and how quickly it proceeds into depth to a “coefficient of consolidation”, depending on the permeability of thawed soil in relation to density of water and coefficient of compressibility. Together with soil water content, the thaw consolidation ratio influences the generation of pore water pressures (μ) during thawing, which then affect slope stability as described in the FS approach ($\mu = \rho_w g h'$). If martian soils, for example, were coarser than Earth soils and thaw more slowly, lower pore water pressures would be generated and higher slope gradients would be required for solifluction movement to occur (Eq. 1). However, in martian soil, silt-sized dust is much more common (Bell III et al., 2000; Soderblom et al., 2004) than in terrestrial soil. As silty material limits permeability and promotes ice lens development and thereby the generation of high pore water pressures, solifluction at low slope angles should be promoted rather than retarded on Mars.

5.3.3. Vegetation and biota

Vegetation and biota in general are clearly a differing environmental property between Mars and Earth. By affecting material and thermal properties, vegetation has numerous effects on solifluction processes (e.g., Eichel et al., 2017) and can either retard or promote solifluction movement (Matsuoka, 2001). Thus, missing vegetation and/or organic material in general could also affect solifluction movement and SSL occurrence on Mars in comparison to Earth.

Given the sparse data and large environmental heterogeneity, e.g. of soil properties, on Mars, we can only hypothesize that differing soil properties and/or thermal regime are a likely cause of the observed slope constraint. A more detailed analysis, e.g. of slope stability, which includes available data on Mars environmental properties as far as available, is needed to better understand potential solifluction processes and their effects on landform development on Mars.

5.4. Formation of lobes by dry processes?

The interpretation of martian SSL as solifluction lobes poses a problem for our understanding of the martian environment, because thaw is inevitably involved in their formation on Earth and thaw in the near surface of Mars is believed to have been very difficult due to the low humidity, atmospheric pressure and mean annual air temperature over the last ~1 Ga (Mellon and Phillips, 2001; Kreslavsky et al., 2008). Ground ice on Mars is generally believed to have been emplaced via sublimation-condensation, rather than thaw as on Earth (e.g., Sizemore et al., 2015). Zebra stripe lobes seem to be a good analogue for martian SSL as they likely form via seismic shaking in a hyper-arid environment and we suspect that Mars is also seismically active (Roberts et al., 2012; Taylor et al., 2013; Kumar et al., 2019). However, as discussed in Section 5.2 zebra stripe lobes are actually a poor match for martian SSL in terms of plan view and 3D morphology. Lobate forms are also observed on the Moon (Fig. 14; Xiao et al., 2013), where water is not involved in slope processes. The angle of repose is the maximum angle/slope at which a material can be stable and does not slide or fall. This angle is independent of the gravitational acceleration g , so whether it is on Earth, Mars, or the Moon this angle is about 35° (Sullivan et al., 2011; Atwood-Stone and McEwen, 2013). Lobate forms on the Moon originate at slopes $>35^\circ$ as shown in Fig. 14. The vast majority of martian SSL occur below this value (Fig. 10, Fig. 14), showing that they cannot be formed by a purely dry granular flow process, unlike the lobes on the Moon. In order to initiate a dry granular flow below the angle of repose lubrication is required – this could be water (as for solifluction lobes), or gas released by CO_2 sublimation.

Recent work has revealed downhill movement of boulders, typically over <10 m on the same hillslopes as martian SSL (Dundas et al., 2019) and in all but one case the movements are correlated to the times of year when CO₂ ice should be present. Experimental work shows that sublimation of CO₂ frost can trigger creep-like motion for initial slopes ranging from 10 to 30°, corresponding to the slopes we measured for martian SSL (Sylvest et al., 2016, 2018). The hemispherical difference in SSL occurrence (>41°S compared to >55°N; Johnsson et al., 2018) could be explained by the present-day asymmetry in the occurrence of seasonal CO₂ frost (Piqueux et al., 2015), which follows that of water frost (Vincendon et al., 2010). However, the exact mechanism that leads to lobe-formation under the CO₂ sublimation hypothesis is unclear and requires further work in order to assess if it is consistent with the data.

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486 **6. Conclusions**

Digital terrain models of Mars and Earth are used to measure and characterise the morphology of lobate features on both planets. We present here the first extensive three dimensional study of solifluction lobes on Earth, and the first ever 3D data for zebra stripe lobes in the Atacama Desert and SSL on Mars. Our terrestrial data show that it is important to consider that there is a diversity of periglacial environments that host solifluction lobes, where within-hillslope changes of temperature distribution, soil properties, and depth of the active layer could influence lobe-shape even at a very local scale. We find that martian SSL share almost all their morphometric characteristics with terrestrial solifluction lobes and are less similar to zebra stripe lobes, which are notably smaller in scale than SSL or solifluction lobes and located on convex hillslopes unlike SSL or solifluction lobes. We find that SSL on Mars tend to be found at steeper slopes than terrestrial analogues (averages of ~16° for solifluction lobes, ~18.5° for zebra stripe lobes and ~25° for SSL on Mars) with a slope gradient of at least 10°. We hypothesise that this constraint does not result from the lowered gravity on Mars, but could instead result from differing soil properties and/or thermal regime between Mars and Earth which affect solifluction movement. We cannot rule out a role of CO₂ sublimation in lobe-formation based on our terrestrial measurements.

502

503 **7. Acknowledgments**

This work was supported by the French Space Agency CNES. The data collection in Termignon, France was made possible by a loan of a Terrestrial Laser Scanner by the UK Natural Environment Research Council Geophysical Equipment Facility loan 1030. The LiDAR and aerial images for Iceland at Tindastóll were made available via the UK NERC Airborne Research Facility and funded by the European Facility for Airborne Research project “EUFAR12_02a” acronym “ICELAND_DEBRISFLOWS”. The Greenland data were obtained by NERC ARF and made available via NERC Centre for Environmental Data Analysis. Access to Pléiades images of the Atacama was supported by public funds received in the framework of GEOSUD, a project (ANR-10-EQPX-20) of the program "Investissements d'Avenir" managed by the French National Research Agency. The images are copyright of CNES and distributed by Airbus Defence and Space, all rights reserved. PMG was funded by the UK Space Agency (ST/R002355/1). Andreas Johnsson was supported by the Swedish National Space Agency (SNSA). We would like to thank Dr. Manuel Abad for his help in the field in the Atacama site. We thank Daniel Draebing for helpful discussions on solifluction processes.

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762 Table 2: Characteristics and location for each martian DTM generated for this study.

Stereo pairs	Latitude	Longitude	Description	Emergence angle	Time between images	Site name	Crater diameter (km)
ESP_025668_2390 ESP_026314_2390	58.66°N	217.24°E	Sorted lobes associated with small gullies, clast stripes and polygons.	21.1°	2 months	L_58_217	1.8
ESP_025888_2365 ESP_025664_2365	56.40°N	327.27°E	Sorted lobes, gullies, polygons	29.3°	15 days	L_56_327	3.5
ESP_026564_2405 ESP_027065_2405	60.20°N	236.27°E	Sorted lobes associated with gullies.	16.2°	1 month	L_60_236	3.1
ESP_026455_2460 ESP_025901_2460	65.77°N	334.80°E	Sorted lobes, small gullies, clast stripes and polygons.	22.8°	1.5 months	L_65_334	4.2
ESP_027768_2525 ESP_027860_2525	72.44°N	126.46°E	Sorted lobes and polygons.	29.4°	7 days	L_72_126	2.0
PSP_008141_2440 PSP_007429_2440	63.78°N	292.32°E	Sorted lobes, gullies, retrogressive thaw slump-like form in gully and polygons.	10.2°	2 months	L_63_292	16.6
ESP_019147_2395 ESP_018712_2395	59.40°N	44.40°E	Sorted lobes, gullies and clast stripes	19.6°	1 month	L_59_44	3.5
ESP_024318_1335 ESP_013624_1335	45.92°S	9.54°E	Clast-banked lobes on S-facing slope in close spatial proximity to gully and polygons.	12°	2.5 years	L_-45_9	3.1 Tivat crater

764 Table 3: Terrestrial datasets used in this study.

Site	Latitude	Longitude	Mean elevation	Resolution [pixel] (DTM/orthophotos)	Source	Geology	Lobe type	Vegetation	MAAT °C	Annual Precipitation (mm)
Svalbard	78.24°N	15.66°E	343m	1 m / 0.2 m	Stereo HSRC-AX (Johnsson et al., 2012)	Sandstone, sedimentary (coal bearing)	Non-sorted	Sparse	-6	190
Greenland	71.35°N	22.42°W	372m	1 m / 0.2 m	LIDAR NERC ARSF	Jurassic & Triassic sediments	Non-sorted	Sparse	-7.5	760
Sweden	68.12°N	18.76°E	950m	2 m / 1 m	LIDAR ©Lantmäteriet, Geodatasamverkan	Crystalline basement (Caledonian mountain range)	Non-sorted	Grasses	-1	850
Iceland	65.82°N	19.73°W	798m	1 m / 0.15 m	LIDAR NERC ARSF	Basalt	Non-sorted	Grasses	3	634
Alps (France)	45.35°N	6.83°E	2300m	1 m to 5 m / 0.5 m	Terrestrial Laser Scanner	Bedrock (eclogite facies)	Non-sorted	Grasses	6	1114
Atacama	24.38°S	69.95°W	1351m	2 m / 0.5 m	Stereo Pléiades images (CNES)	Diorites, monzodiorites, granodiorites and monzogranites	Sorted	None	17	2

765 Table 4: Summary of lobe analysis.

Earth		Mars	
Site	Number of lobes	Site	Number of lobes
Sweden	1374	L_65_334	136 767
Iceland	730	L_63_292	537
Alps	174	L_60_236	237 700
Greenland	140	L_-45_9	62
Svalbard	341	L_72_126	288
Atacama	488	L_59_44	398
		L_56_327	84 771
		L_58_217	159
Subtotal	3247	Subtotal	1901 772
TOTAL		5148

774 Fig. 1: Examples of martian Small Scale Lobes (SSL) and terrestrial lobes. Double-headed arrows
775 indicate downslope direction. a) Sorted martian SSL in the northern hemisphere, in a 1-kilometre-
776 crater. HiRISE image: ESP_027768_2525. 72.44°N, 126.46°E. Inset shows the position of the main
777 image (blue box) within the crater. b) Non-sorted solifluction lobes near Termignon in the French
778 Alps, France. Credit: IGN BD ORTHO. c) Non-sorted SSL in a 4-km-crater on Mars. HiRISE image:
779 ESP_026455_2460. 65.77°N, 334.80°E. Inset shows the position of the main image (blue box) within
780 the crater. d) Non-sorted solifluction lobes located on Tindastóll, Iceland. Credit: NERC ARSF. Note
781 the similarity in scale and shape between lobes on Mars and on Earth.

782 Fig. 2: Martian Small Scale Lobes (SSL), gullies and ploughing boulders. Double-headed arrows
783 indicate downslope direction. (a) HiRISE image PSP_008141_2440 (site L_63_292) showing the
784 spatial proximity of gully alcoves and channels, SSL and polygonally patterned ground. Panels (b)
785 and (c) show ploughing boulders on the exterior slope of a high latitude crater. On Earth, these
786 features are strongly associated with solifluction. White arrows indicate the furrow behind the
787 boulder. HiRISE image: ESP_017626_2825.

Fig. 3: (a) Classification of surface processes according to their velocity and water content (from Pawlik and Šamonil, 2018). (b) Simplified diagram outlining the processes contributing to the solifluction processes.

Fig. 4: Sorted and non-sorted Small Scale Lobes (SSL) on Mars. (a) HiRISE image ESP_027860_2525 showing sorted lobes banked by large clasts. (b) HiRISE image PSP_007832_2410 showing non-sorted lobes where the risers are not demarked by clasts, but are visible because of their relief.

Fig. 5: Locations of HiRISE images with Small Scale Lobes. White squares are HiRISE images and black points are stereo pairs, hosting SSL (based on Johnsson et al., 2018). Red points are DTMs used in this study. The global map of Mars is generated using colourised Mars Orbiter Laser Altimeter (MOLA) elevation data overlain by hillshaded relief.

Fig. 6: World map showing the location of the terrestrial analogues used in this study.

Fig. 7: Pléiades orthophoto showing zebra stripe lobes on hillslopes, in the Atacama Desert. 24°14'S, 69°54'W. Double-headed arrows indicate the downslope directions.

Fig. 8: Images illustrating the method used for lobe measurements and identification of the nearest upslope ridge. Double-headed arrow indicates the downslope direction. Panels (a) and (c): downslope and cross-slope dimensions of lobes (in black) digitised on the orthoimage for martian site L_72_126 and on a hillshaded relief map of the Sweden DTM (Elevation data 2m, raster © Lantmäteriet, Geodatasamverkan), respectively. The nearest upslope ridge is shown in red. Panels (b) and (d): colour-coded map of the “compound topographic index” (a visualisation tool, allowing the identification of the orientation of the steepest downslope/upslope direction and the local ridges in the terrain) and overlain hillshaded relief map were used to identify the nearest upslope ridge and digitise it (red lines). Panel (e): Sketch outlining the main steps undertaken in our GIS analysis.

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Fig. 9: (a) Scatter plot of the normalised distance from each lobe to its nearest upslope ridge versus its width to length ratio (the closer the value is to 0, the closer the lobe is to the crest). (b) Scatter plot of slope versus lobe W:L, medians for each population are plotted for each bin of 0.5. (c) Scatter plot of slope versus lobe length. Red markers indicate martian SSL which are shown on their own on the top row, blue markers represent solifluction lobes, which are superposed on SSL on the second row and green markers represent the zebra stripe lobes of the Atacama Desert and are superposed on SSL and solifluction lobes on the third row.

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Fig. 10: Violin plot of the distribution of slope for the lobes in each site. White dots and horizontal lines represent mean and median values, respectively. The “violin” represents the shape of the distribution. This plot shows that SSL do not occur below 10°, and that all but 3 of the lobate features studied here occur below the angle of repose of dry loose materials. On the right is plotted the Probability Density Function (PDF) of slopes for lobes on Mars and Earth showing this distribution with a 95% confidence intervals.

Fig. 11: Scatter plot of lobe length versus lobe width, where the box indicates the location of the detailed plot shown on the right. Red points are martian SSL, blue points are solifluction lobes and green points are zebra stripe lobes in the Atacama. Terrestrial solifluction lobes are generally restricted to the parameter space indicated by the black lines on the right plot.

Fig. 12: Example topographic profiles in blue illustrating the typical position of lobate forms in the profile for Earth and Mars. Red dots are individual lobes. Note the different vertical and horizontal scales.

Fig. 13: (a) Photo of zebra stripe lobes in the field, in the Atacama Desert - they are low relief landforms. The black line denotes the shape and the contrast between darkly-varnished gravels and the light-coloured, salt-rich soil. Credit: T. Izquierdo. (b) Photo of solifluction lobes from Abisko, Sweden. Credit: A. Johnsson. The height of the riser is about 30 cm. (c) Hillshaded relief representation of L_65_334 showing that these martian SSL have marked relief (risers approx. 4 m in height).

Fig. 14: Lobate forms on Mars and on the Moon. Top: slope (a) and hillshaded relief (b) maps of a crater on the Moon (NAC_DTM_NEARLENTS1_M151169370_70CM), where lobate features are visible. Bottom: slope (c) and hillshade relief (d) maps of a martian crater (site L_65_334) with SSL.