**Response to reviewers**

*We are **grateful and thank** Reviewer#1 and Reviewer#2 for thorough assessment of our manuscript and for providing us constructive comments and suggestions.*

*In the revised version, **all the comments and suggestions have been taken into account** and changes have been made to improve the presentation.*

*We now add point-by-point reply (in italics, in red color fonts) to the comments and suggestions of the reviewers and make clear where and what changes have been made in the revised version of the manuscript.*

*Please note that the (1) comments from referees, (2) author's response, and (3) author's changes in manuscript are all described below. The marked-up manuscript version has been added after the response section.*

**Reviewer #1**

**Comment.** This manuscript reports on the differences between gullies formed on different substrates on Mars. Martian gullies are widespread, relatively young, features in the mid-latitudes, with similarities with some types of gully on Earth. Given the possibility of debris-flow processes being present, these features are important in attempts to understand fluidization processes on Mars. The manuscript is a timely addition to body of work on martian gullies.

Overall the manuscript is excellent, and it is a pleasure to say that I think that it should be accepted without any changes. The justification for this recommendation is that the study is well-designed, has been carried out to an excellent standard, interpretations are sound without speculation, and the conclusions make a solid contribution to our understanding of martian gullies.

***Response:*** *We sincerely thank the reviewer for this assessment and providing a summary of our paper. We acknowledge the reviewer for providing a positive feedback on our manuscript.*

**Reviewer #2**

**Overall comments (see attached supplement for figures)**

**Comment 1:** Overall the manuscript is well-written and with some minor improvements will be a nice contribution to the field. The manuscript could use more discussion about the significance of the results.

As written it is not really clear why it matters that there is a morphologic distinction between gullies carved into bedrock and mantling.

Most of the discussion is about comparing the morphometry of martian gullies with gullies on Earth, and doesn't really involve the bedrock/LDM distinction at all.

***Response 1.*** *Morphological distinction between gullies formed in the bedrock and LDM signifies that Martian gullies may have multiple formative mechanisms. Bedrock gullies would have formed by mechanisms unrelated to LDM. For instance, alcoves of the bedrock gullies have a crenulated shape, suggesting possibility of headwards erosion into the crater rim. The alcoves are composed of multiple sub-alcoves. Whereas, gullies in association with LDM have elongated alcoves that are V-shaped in cross-section, indicating presence of ice-rich unlithified sediments constituting the LDM. The elongated V-shaped cross-section could be related to the fine-grained, loosely packed, unconsolidated materials within LDM. Accordingly, we have found that the estimated length of alcoves formed in LDM/glacial deposits is found to be relative higher than that of alcoves formed in bedrock. This discussion is already there in the section 5.1, lines 274-290 of the revised version.*

*The comparison between combinations of Melton ratio with alcove length and fan gradient of terrestrial and Martian gullies suggest that the Martian gully systems studied in this work were likely dominated by terrestrial debris-flow like processes during their formation.*

*In the revised manuscript, based upon the reviewers' suggestion, we have added the following in the conclusion section 6 (line no. 377-380):*

*The morphological distinction reported between gullies formed in the bedrock and LDM/glacial deposits signifies that Martian gullies may have multiple formative mechanisms. We infer that the presence of mantling material could be one of the key factors in constraining the mechanisms forming Martian gully systems and that presence of LDM would promote formation of elongated alcoves with perimeter and relief relatively higher than that of alcoves formed in coarse-grained bedrock substrate.*

**Comment 2a.** The authors should be clearer about how they distinguish a gully incised into LDM and a gully incised into bedrock that is later mantled. You mention in Section 4.1 (second paragraph) that the gully systems in four craters appear to have incised prior to being mantled. Shouldn't these be in a separate class rather than being included with the LDM craters?

**Comment 2b.** A related question is whether there are any constraints on the depth of mantling material. One would imagine that a gully eroding into one meter of mantle over bedrock would be morphologically different from a gully eroding into hundreds of meters of mantle over bedrock.

***Response 2a.*** *The gully systems formed within LDM are consistent with elongated V-shaped alcoves, polygonized gully banks and adjacent crater wall surfaces, and smoothened gully-fan surfaces. On the other hand, gully systems formed in the bedrock would have alcoves directly cutting into the crater-rim material and may host many boulders, exposing bedrock. The polygonal patterned surface is not evident in these craters. We have used this observational criteria to differentiate between gullies incised into bedrock and LDM.*

*Emplacement of mantling material on the crater walls is a cyclic phenomenon, driven primarily by insolation at the Martian poles during the past epochs of higher spin axis obliquity excursions (i.e. obliquity >35°). Hence, it would be difficult to infer about the presence or absence of LDM for the gullies that currently appear to be mantled. Moreover, potential evidence of elongated V-shaped alcoves, polygonized gully banks and adjacent crater wall surfaces, and smoothened gully-fan surfaces, are all evident in the 4 craters (Raga, Roseau, unnamed crater in Newton basin and unnamed crater-1 in Terra Sirenum) studied in this work. Therefore, we think that we cannot separate the gullies in these 4 craters as a separate class (based on the appearance of the pre-existing mantled gully systems in these craters) and included with the LDM craters.*

*In the second paragraph, we intend to infer that among the 24 gullied craters, 4 gullied craters have only LDM and the remaining 20 craters have both LDM and glacial deposits.*

*We have revised the second paragraph to clearly bring out the aforementioned aspect. Please see below:*

*'4 craters out of 24 craters (i.e. Raga, Roseau, unnamed crater in Newton basin and unnamed crater-1 in Terra Sirenum) have gullies that are only influenced by LDM. In these craters, we have found morphological evidence of LDM in the form of polygonized, smooth textured material on the pole-facing walls of the craters. Morphological evidence of VFF is not evident in these craters. In these craters, the gully-alcoves and gully channels appear to have been incised into the polygonized LDM material, and the gully-fan deposits are mantled. A typical example of this can be found in the unnamed crater formed inside the Newton basin (Fig. 4a). Roseau crater, in particular, contains a large number of gully systems whose alcoves and fans are extensively mantled (Fig. 4b). The remaining 20 out of 24 craters contain evidence for gullies that are influenced by both LDM and glacial deposits (Table 1). The base of the….'*

*Please refer to line no. 177-184 of the revised version.*

***Response 2b.*** *In our study, we have not carried out observations to infer the thickness of mantling material. Our study is focused upon inferring whether the morphology and morphometry of gully systems vary in presence or absence of LDM. Therefore, we think, we cannot comment on this aspect right now.*

**Comment 3.** "Melton ratio" should be capitalized throughout.

**Response 3.** Done. 'Melton ratio' has been capitalized at all the places.

**Comment 4.** "LDA" is never defined.

**Response 4.** Done. We have defined 'LDA' as lobate debris apron at its first occurrence (in Table 1) in the revised manuscript.

## Line comments

**Comment 1.** Line 47: I suggest defining "viscous flow features (VFF)" as an umbrella term for glacial-type formations (https://doi.org/10.1007/978-1-4614-9213-9_596-1). Debris flow deposits could be considered are "viscous flow features" but presumably are not what you are referring to.

***Response 1.*** *Done. As suggested, we have rephrased this sentence as follws:*

*VFFs are defined as an umbrella term for glacial-type formations covering a broad range of landforms that include lobate debris aprons, concentric crater fill, and lineated valley fills.*

*Also, added this reference: Hargitai, H. (2014). Viscous Flow Features (Mars). In: Encyclopedia of Planetary Landforms. Springer, New York, NY. https://doi.org/10.1007/978-1-4614-9213-9_596-1.*

*Please see line no. 48-50 of the revised version.*

*Yes, the debris-flow deposits reported in this work are not 'viscous flow features'.*

**Comment 2.** Line 114: Suggest changing "the features listed in 1" to "LDM or glacial features"

***Response 2.*** *Done. Changed 'the features listed in 1' to 'LDM/glacial deposits'. Please see line no. 115 of the revised version.*

**Comment 3.** Line 152: "which may eventually influence the morphometric measurements" suggest changing to "which may have influenced the morphometry".

***Response 3.*** *Done. Changed 'which may eventually influence the morphometric measurements' to 'which may have influenced the morphometry'. Please see line no. 152 of the revised version.*

**Comment 4.** Line 153: "gully fans" should this be "gully systems"?

***Response 4.*** *Done. Changed 'gully fans' to 'gully systems'. Please see line no. 154 of the revised version.*

**Comment 5.** Line 155: How certain are you that the gullies are incised into LDM material rather than being incised into bedrock and then later mantled by LDM material? You mention some of the latter in Section 4.1.

***Response 5.*** *We request the reviewer to please refer to the response to comment no. 2a. We think we cannot infer about formation of gullies initially into the bedrock and then later it got mantled by the LDM material.*

*We have revised the section 4.1. Request the reviewer to please see the response to comment no. 2a.*

**Comment 6.** Line 156: "At first,"-> "First,"

***Response 6.*** *Done. Changed 'at first' to 'First'. Please see line no. 158 of the revised version.*

**Comment 7.** Line 180: "generation" -> "generations"

***Response 7.*** *This line got deleted during the revision of the manuscript.*

**Comment 8.** Line 185: "Gullies incised into LDM/VFFs are found to have a distinctive V-shaped cross section" As written it is unclear if this applies to just the 20 or the 24 craters (including Raga, Roseau, unnamed crater in Newton basin, and unnamed crater-1 in Terra Sirenum)?

***Response 8.*** *This sentence has been revised as follows:*

*In majority of the gullied craters (except Raga, Roseau and unnamed crater-1 in Terra Sirenum) influenced by LDM and glacial deposits, gully alcoves are found to have a distinctive V-shaped cross section in their mid-section, they do not extend up to the crater rim, and gully systems often show multiple episodes of activity, inferred by the presence of fresh channel incision on the gully-fan surfaces (Fig. 4d-e).*

*Please see line no. 186-190 of the revised version.*

**Comment 9.** Line 185: "distinctive V-shaped cross section" You might add a figure showing the differences in cross sections between a gully incised into LDM/VFF and a gully incised into bedrock.

***Response 9.*** *We request the reviewer to please see Figure 4d-e (for V-shaped cross-section of gully alcoves incising into LDM/VFF) and Figure 4f (for gullies incising into bedrock). As suggested, we have added reference to these figures in the text on line no. 188 and 281 of the revised manuscript.*

**Comment 10.** Line 217: "167 gullies" I suggest adding a column to Table 1 that contains the number of measured gullies in each crater

***Response 10.*** *Done. A column has been added to Table 1 to show the number of gullies analysed in each crater.*

**Comment 11.** Line 264: "viz. grain size" What is "viz"?

***Response 11.*** *'viz.' is used as a synonym for 'namely', 'that is to say', 'to wit', 'which is', or 'as follows'. For clarity, we have replaced 'viz.' with 'namely'. Please see line 268 of the revised version of the manuscript.*

**Comment 12.** Line 289: "V- shape of the incision" this was never really demonstrated in the manuscript

***Response 12.*** *V-shaped incision has been shown on Figures 4d-e and 7a-d. We request the reviewer to please see these figures. V-shaped incision is marked by arrow and/or labeled on the figure panels. As suggested, we have added reference to these figures in the text on line no. 188 and 281 of the revised manuscript.*

**Comment 13.** Line 342: "combinations of Melton ratio" I think that you need to specify the significance of the Melton ratio here. Why not use some other metric like form factor or elongation ratio on the x-axis?

***Response 13.*** *Done. We have added the following on line no. 347-350 of the revised version:*

*We have specifically chosen the combinations of Melton ratio with alcove length and fan gradient to infer the Martian gully formative mechanism because they have been widely used in discriminating terrestrial drainage basins and fans prone to flooding from those subject to debris flows, debris floods and floods (e.g. De Scally and Owens, 2004; Wilford et al., 2004).*

**Comment 14.** Line 356 "debris-flow like process" What was the fluid source? You mention sublimation of $CO_2$ ice in the conclusions but I think you need to elaborate more here.

***Response 14.*** *Done. We have added the following:*

*It is likely that the present-day sublimation of $CO_2$ ice on Mars provided the necessary flow fluidization for the emplacement of deposits similar to terrestrial debris-flow like deposits (De Haas et al., 2019b).*

*Please see line no. 364-366 of the revised version.*

**Figure comments**

**Comment 1.** Figure 2: Are the examples shown in Figure 2 representative of all of the study craters you examined? Were there craters where the distinction between bedrock and LDM/glacial was more ambiguous?

***Response 1.*** *Yes, they are representative of all the craters. As such, there were no issues in differentiating between craters influenced by LDM/glacial deposits and bedrock. Gullied craters with LDM could be identified unambiguously based on the evidence of polygonal cracks on the crater walls and gully banks. Glacial deposits were evident in the form of arcuate ridges (at the base of crater wall) and crater floor deposits such as small-scale LDAs. In case of gullies forming within the crater wall bedrock, we have not encountered evidence of polygonal cracks on the wall and/or gully banks, alcoves were having more boulders and appeared to be directly cutting into the crater rim material, and glacial deposits were not evident in these craters.*

**Comment 2.** Figure 2d: On line 148 you say that you only selected gully systems that were "not superimposed by or interfingering with the fans from the neighboring channels" and had "no evidence of extensive cross-cutting". This does not appear to be the case for the gullies shown in Figure 2d (see portion of HiRISE image ESP_056668_1345_RED attached. North is toward the left). You should replace 2d with an example of a bedrock gully that you collected morphometric measurements for (or if you did collect measurements of the system shown in 2d, revise the text on line 148).

***Response 2.*** *Yes, we have selected only those fans that do not superimpose with the fans from the neighboring channels. Additionally, gully channels that exhibit evidence of cross-cutting were not selected for measurements. If in any case the fans superimpose or channels cross-cut, we have carefully demarcated the alcove-channel-fan boundary, to minimize the inaccuracies in the measurements.*

*In order to improve the clarity in presentation of the ideas, as suggested by the reviewer, we have revised Figure 2d. The revised Figure 2d shows the portion of the gully system that was selected for measurement.*

*Additionally, we have added the following in the section 3.3:*

*If in any case the fans superimpose or channels cross-cut, we have carefully demarcated the alcove-channel-fan boundary, to minimize the inaccuracies in the measurements.*

*Please see line no. 152-154 of the revised version.*

**Comment 3.** Figure 3: Consider changing "Alcove top" to "alcove crest" in left frame for consistency with text on line 133

***Response 3.*** *Done. As suggested, Figure 3 has been revised. 'Alcove top' is replaced with 'Alcove crest'.*

**Comment 4.** Figure 4b: Same commend as 2d. The fans appear to partially overlap.

***Response 4.*** *Please refer to our response to comment no. 2. Please note that 'If in any case the fans superimpose or channels cross-cut, we have carefully demarcated the alcove-channel-fan boundary, to minimize the inaccuracies in the measurements.'*

**Comment 5.** Figure 5: I suggest making this figure smaller by reducing the space between the green and pink boxes in each frame. Also make the order of the figures match the order in Table 2 (e.g., "Melton ratio" should come after "Fan area" instead of "Alcove relief"). "RCI" is never defined in the text - add it to "Relative concavity index (RCI)" in Table 2

***Response 5.*** *Done. As suggested by the reviewer, Figure 5 has been revised. The spacing between boxes has been reduced and the plots are arranged as per their order in Table 2.*

**Comment 6.** Figure 6: This figure does not add much to the paper. The main finding of the paper (that gullies formed in bedrock and LDM are morphologically distinct) is presented in Figure 5. It doesn't really matter for the paper's results which metrics correlate with which other metrics. Furthermore many of these metrics are related making the correlation (or lack thereof) somewhat meaningless (e.g., length and area, or length and form factor).

**Response 6.** *We used the correlation analysis to investigate the relationship between the different attributes of gully systems formed in LDM/glacial deposits and bedrock. This is an important analysis because it tells us about the variations in the selected morphometric attributes of the gully systems with respect to the other. For example, from this analysis we came to know that the perimeter and relief of alcoves formed in bedrock shows very strong positive correlation with alcove length, but the correlation was slightly weaker for alcove relief and alcove length in the case of LDM/glacial deposits. Furthermore, it can be seen that there are relatively less number of morphometric attributes in LDM/glacial deposits than in bedrock, which shows negative correlation.*

**Comment 7.** Figure 6: Same comment as Figure 5 - make the order of the figures match the order in Table 2. I would rotate the labels along the diagonal by 90°. The number of significant figures should be consistent in (a) and (b) (a is all 2, but b varies). There only needs to be one red-blue scale bar.

***Response 7.*** *As suggested by the reviewer, the correlation matrix plot has been revised. The order of parameters appearing in the figure matches with Table 2. The number of significant figures is consistent in both the panels. There is only one scale bar in the revised figure.*

**Comment 8.** Figure 8: The green triangles and blue circles are very difficult to distinguish from each other. Use the same pink and green colors as Figure 5. Also I suggest using filled circles/triangles rather than outlines. What are the dray areas (question mark in second attached figure)?

***Response 8.*** *Done. The colors of the triangles and circles have been changed to green and pink, respectively. This is consistent with the color of boxes in the box plot shown in Figure 5. We have not filled the symbols since those prevent seeing the overlap clearly. The gray area shows the realm of the colluvial, debris-flow, and fluvial fans together. It has been included in the figure caption.*

# Morphologic and Morphometric Differences between Gullies Formed in Different Substrates on Mars: New Insights into the Gully Formation Processes

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**Abstract.** Martian gullies are kilometer-scale geologically young features with a source alcove, transportation channel, and depositional fan. On the walls of impact craters, these gullies typically incise into bedrock or surfaces modified by latitude dependent mantle (LDM; inferred as consisting ice and admixed dust) and glaciation. To better understand the differences in alcoves and fans of gullies formed in different substrates and infer the flow types that led to their formation, we have analyzed the morphology and morphometry of 167 gully systems in 29 craters distributed between 30°S and 75°S. Specifically we measured length, width, gradient, area, relief, and relief ratio of alcove and fan, Melton ratio, relative concavity index, and perimeter, form factor, elongation ratio and circularity ratio of the alcoves. Our study reveals that alcoves formed in LDM/glacial deposits are more elongated than the alcoves formed in bedrock, and possess a distinctive V-shaped cross section. We have found that mean gradient of fans formed by gullies sourced in bedrock is steeper than the mean gradient of fans of gullies sourced in LDM/glacial deposits. These differences between gullies were found to be statistically significant and discriminant analysis has confirmed that alcove perimeter, alcove relief and fan gradient are the most important variables for differentiating gullies according to their source substrates. The comparison between the Melton ratio, alcove length and fan gradient of Martian and terrestrial gullies reveals that Martian gully systems were likely formed by terrestrial debris-flow like processes. It is likely that the present-day sublimation of $CO_2$ ice on Mars provided the adequate flow fluidization for the formation of deposits akin to terrestrial debris-flow like deposits.

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## 1 Introduction

Gullies are found on steep slopes polewards of about 30° latitude in both hemispheres on Mars and manifest as kilometer-scale, geologically young features (formed within the last few million years) comprising an alcove, channel, and depositional fan (Malin and Edgett, 2000; Dickson et al., 2007; Reiss et al., 2004; Schon et al., 2009). Gullies occur in a wide assortment of settings, varying from the walls and central peaks of craters to walls of valleys, and steep faces of dunes, hills and polar pits (e.g. Balme et al., 2006; Dickson et al., 2007; Dickson and Head, 2009; Conway et al., 2011, 2015; Harrison et al., 2015). On the walls of craters, gullies are found to have incised into the (1) surfaces covered by latitude dependent mantle (LDM; e.g. Mustard et al., 2001; Dickson et al., 2012, 2015), (2) surfaces modified by former episodes of glaciation (Hubbard et al., 2011; Souness et al., 2012; Souness and Hubbard, 2012; Sinha and Vijayan, 2017), and (3) bedrock (e.g. Johnsson et al., 2014; de Haas et al., 2019a; Sinha et al., 2020). Detailed investigation of the gullies formed over these different substrates is key to understanding the intricacies of past processes by which these gullies have formed on Mars (Conway et al., 2015; de Haas et al., 2019a).

A variety of models have been proposed to explain the formation of gullies, which include: (1) dry flows triggered by sublimation of $CO_2$ frost (e.g. Cedillo-Flores et al., 2011; Dundas et al., 2012, 2015; Pilorget and Forget, 2016; de Haas et al., 2019b), (2) debris-flows of an aqueous nature (e.g. Costard et al., 2002; Levy et al., 2010; Conway et al., 2011; Johnsson et al., 2014; de Haas et al., 2019a; Sinha et al., 2020), and (3) fluvial flows (e.g. Heldmann and Mellon, 2004; Heldmann et al., 2005; Dickson et al., 2007; Reiss et al., 2011). To better understand the gully formation processes, morphometric investigation of gullies formed over different substrates needs to be undertaken at a level of detail previously not attempted.

The global distribution of gullies shows a spatial correlation with the landforms indicative of glaciation and LDM deposition on Mars (e.g. Levy et al., 2011; Dickson et al., 2015; Harrison et al., 2015; Conway et al., 2018; de Haas et al., 2019a; Sinha et al., 2020). With respect to glacial landforms, many gullies have formed into viscous flow features (VFF) and they are found in the same extent of latitudes (e.g. Arfstrom and Hartmann, 2005; de Haas et al., 2018). VFFs are defined as an umbrella term for glacial-type formations covering a broad range of landforms that include lobate debris aprons, concentric crater fill, and lineated valley fills (e.g. Squyres, 1978; Levy et al., 2009; Baker et al., 2010; Hargitai, 2014). Together, they are inferred to be similar to terrestrial debris-covered glaciers (Conway et al., 2018). With respect to LDM, gullies are mostly found on the pole-facing slopes of crater walls at lower mid-latitudes (30-45°) (e.g. Balme et al. 2006; Kneissl et al. 2010; Harrison et al. 2015; Conway et al. 2017), wherein, LDM is found to be dissected (e.g. Mustard et al., 2001; Milliken et al., 2003; Head et al., 2003). In the higher latitudes (>45°), LDM is found to be continuous (e.g. Kreslavsky and Head, 2000), and gullies are evident at both the pole and equator facing slopes (e.g. Balme et al. 2006; Kneissl et al. 2010; Harrison et al. 2015; Conway et al. 2017). Gullies formed on the formerly glaciated walls of craters are fed from alcoves that do not extend up to the crater rim, and appear elongated to V-shaped, implying gully-channel incision into ice-rich, unlithified sediments (e.g. Aston et al., 2011; de Haas et al., 2019a). The alcoves, channels and fan deposits of gullies formed within craters covered by a smooth drape of LDM, are usually found to have experienced multiple episodes of LDM covering and subsequent reactivation of some of the pre-existing channels or formation of fresh channels within the draped LDM deposits (e.g. Dickson et al., 2015; de Haas et al., 2019a). Additionally, there are gullies that directly emanate from well-defined bedrock alcoves that cut into the crater rim in the absence of LDM and/or glacial deposits (e.g. Johnsson et al., 2014; de Haas et al., 2019a; Sinha et al., 2020). Gullies formed in these craters have alcoves with sharply defined crests and spurs, exposing the underlying bedrock, and meter-sized

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boulders are found throughout the gully system (e.g. Johnsson et al., 2014; de Haas et al., 2019a; Sinha et al., 2020). Further, De Haas et al., 2015a found that the stratigraphy of the fans whose source area was in bedrock were more boulder-rich than those fans fed by catchments in LDM. The findings in these studies suggest that a more detailed investigation of the morphology and morphometry of the gullies formed over contrasting substrates is important for improving our understanding of the formative mechanisms of gullies.

In this work, we focus on addressing the following research questions:

(1) Do the morphology and morphometry of gully systems formed in different substrates differ (i.e. LDM/glacial deposits and bedrock)?

(2) How do the morphometric characteristics of gullies formed on Mars compare to those formed by a range of processes on Earth, and what does that tell us about the formative processes of Martian gullies?

To parameterize the morphometry we will primarily study long profiles. Previously, only a few studies have analyzed the morphometric characteristics of the gullies by studying long profiles of gullies (e.g. Yue et al., 2014; Conway et al., 2015; De Haas et al., 2015a; Hobbs et al., 2015). These studies have focused observations on a part of the gully system and suggested that the differences in the properties of substrate into which the gullies incise play a significant role in promoting the flows that led to gully formation. Hence, for a more detailed differentiation of the gully types and interpretation of the dominant flow type that led to gully formation on Mars, quantification of the morphometric characteristics of the entire gully system is crucial.

## 2 Study sites and datasets

We characterize the morphology and morphometry of gullies in 29 craters distributed over the southern hemisphere between 30° S and 75° S latitude (Fig. 1). These 29 craters are selected based on the availability of publicly released High Resolution Imaging Science Experiment (HiRISE) stereo-pair based digital terrain model (DTM) or the presence of suitable HiRISE stereo-pair images to produce a DTM ourselves. The HiRISE stereo-pair images are usually ~0.25 - 0.5 m/pixel (McEwen et al., 2007), so the DTM post spacing is ~1-2 m with vertical precision in the range of tens of centimeters (Kirk et al., 2008). Among the 29 gullied craters, publicly released DTMs are available for 25 craters (https://www.uahirise.org/hiwish/maps/dtms.jsp - last accessed 18th September 2021) (Table 1). For the remaining 4 craters, DTMs are produced with the software packages USGS ISIS and BAE Systems SocetSet (Table 1) (Kirk et al., 2008). We investigated HiRISE images of these 29 gullied craters for detailed morphological characterization of the substrate into which the crater wall gullies incise (Table 1).

**Table 1.** Summary of the craters included in this study, their locations, number of gullies investigated from the crater, substrate on the crater wall in which gullies have incised, key morphological attributes of the substrate, and IDs of HiRISE imagery and DTM used for morphological and morphometric investigation of gullies in these craters.

| Crater | Latitude | Longitude | No. of gullies | Substrate | Key morphological attributes | HiRISE ID | HiRISE DTM ID |
|---|---|---|---|---|---|---|---|
| Artik | 34.8° S | 131.02° E | 2 | LDM/glacial deposits | Polygons, V-shaped incisions, arcuate ridges, small-scale lobate debris aprons (LDAs) on the floor | ESP_020740_1450 | DTEEC_012459_1450_012314_1450_A01 |
| Asimov | 47.53° S | 4.41° E | 4 | LDM/glacial deposits | Polygons, V-shaped incisions, mantled alcoves/channels/fans, arcuate ridges, small-scale LDAs inside valleys | ESP_012912_1320 | DTEEC_012912_1320_012767_1320_A01 |
| Bunnik | 38.07° S | 142.07° W | 8 | LDM/glacial deposits | Polygons, V-shaped incisions, mantled alcoves/channels/fans, arcuate ridges | ESP_047044_1420 | DTEEC_002659_1420_002514_1420_U01 |
| Corozal | 38.78° S | 159.48° E | 6 | LDM/glacial deposits | Polygons, mantled alcoves/channels/fans, arcuate ridges, small-scale LDAs on the floor | PSP_006261_1410 | DTEEC_006261_1410_014093_1410_A01 |
| Dechu | 42.23° S | 158° W | 8 | LDM/glacial deposits | Polygons, mantled alcoves/channels/fans, arcuate ridges, small-scale LDAs on the floor | PSP_006866_1375 | DTEED_023546_1375_023612_1375_A01 |
| Dunkassa | 37.46° S | 137.06° W | 5 | LDM/glacial deposits | Polygons, V-shaped incisions, mantled alcoves/channels/fans, arcuate ridges, small-scale LDAs on the floor | ESP_032011_1425 | DTEEC_039488_1420_039343_1420_A01 |
| Hale | 35.7° S | 36.4° W | 8 | LDM/glacial deposits | Polygons, V-shaped incisions, mantled alcoves/channels/fans, talus slope deposits | PSP_003209_1445 | DTEEC_002932_1445_003209_1445_A01 |
| Langtang | 38.13° S | 135.95° W | 5 | LDM/glacial deposits | Polygons, V-shaped incisions, mantled alcoves/channels/fans, arcuate ridges, small-scale LDAs on the floor | ESP_030099_1415 | DTEEC_024099_1415_023809_1415_U01 |

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|---|---|---|---|---|---|---|---|
| Moni | 46.97° S | 18.79° E | 5 | LDM/glacial deposits | Partly infilled alcoves, mantled fan surfaces, arcuate ridges | ESP_056862_1325 | DTEEC_007110_1325_006820_1325_A01 |
| Nybyen | 37.03° S | 16.66° W | 8 | LDM/glacial deposits | Polygons, mantled alcoves/channels/fans, arcuate ridges | ESP_059448_1425 | DTEEC_006663_1425_011436_1425_A01 |
| Palikir | 41.56° S | 157.87° W | 5 | LDM/glacial deposits | Polygons, V-shaped incisions, mantled alcoves/channels/fans, arcuate ridges, small-scale LDAs on the floor | ESP_057462_1380 | DTEEC_005943_1380_011428_1380_A01 |
| Penticton | 38.38° S | 96.8° E | 7 | LDM/glacial deposits | Polygons, V-shaped incisions, mantled alcoves/channels/fans, arcuate ridges, small-scale LDAs on the floor | ESP_029062_1415 | DTEEC_001714_1415_001846_1415_U01 |
| Selevac | 37.37° S | 131.07° W | 8 | LDM/glacial deposits | Polygons, mantled alcoves/channels/fans, small-scale flows on the floor | ESP_045158_1425 | DTEEC_003252_1425_003674_1425_A01 |
| Raga | 48.1° S | 117.57° W | 4 | LDM | Polygons, mantled alcoves/channels/fans | ESP_041017_1315 | DTEEC_014011_1315_014288_1315_A01 |
| Roseau | 41.7° S | 150.6° E | 1 | LDM | Polygons, mantled alcoves/channels/fans | ESP_024115_1380 / ESP_011509_1380 | ESP_024115_1380_ESP_011509_1380* |
| Taltal | 39.5° S | 125.8° W | 7 | LDM/glacial deposits | Polygons, V-shaped incisions, mantled alcoves/channels/fans, arcuate ridges, small-scale LDAs on the floor | ESP_037074_1400 / ESP_031259_1400 | ESP_037074_1400_ESP_031259_1400* |
| Talu | 40.34° S | 20.11° E | 7 | LDM/glacial deposits | Polygons, V-shaped incisions, mantled alcoves/channels/fans, arcuate ridges, small-scale LDAs on the floor | ESP_011817_1395 | DTEEC_011817_1395_011672_1395_O01 |
| Triolet | 37.08° S | 168.02° W | 4 | LDM/glacial deposits | Polygons, V-shaped incisions, mantled alcoves/channels/fans, arcuate ridges, small-scale LDAs on the floor | ESP_047190_1425 | DTEEC_023586_1425_024008_1425_A01 |
| Unnamed crater | 32.31° S | 118.55° E | 4 | LDM/glacial deposits | Polygons, mantled alcoves/channels/fan | PSP_006869_1475 | DTEEC_021914_1475_022336_1475_U01 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | s, arcuate ridges, small-scale LDAs on the floor | | |
| Unnamed crater in the Argyre basin | 40.3° S | 40.4° W | 6 | LDM/glacial deposits | Polygons, mantled alcoves/channels/fans, arcuate ridges, small-scale LDAs on the floor | ESP_032047_1395 | DTEEC_012795_1395_013507_1395_A01 |
| Unnamed crater in the Newton basin | 38.8° S | 156.8° W | 5 | LDM | Polygons, V-shaped incisions, mantled alcoves/channels/fans | PSP_002686_1410 | DTEEC_002620_1410_002686_1410_A01 |
| Unnamed crater north of Corozal crater | 38.53° S | 159.44° E | 5 | LDM/glacial deposits | Polygons, mantled alcoves/channels/fans, small-scale LDAs on the floor | ESP_020884_1410 | DTEEC_020884_1410_020950_1410_A01 |
| Unnamed crater-1 in the Terra Sirenum | 32.55° S | 154.11° W | 2 | LDM | Mantled alcoves/channels/fans | PSP_007380_1470 | DTEEC_010597_1470_007380_1470_U01 |
| Unnamed crater-2 in the Terra Sirenum | 38.88° S | 136.36° W | 6 | LDM/glacial deposits | Polygons, V-shaped incisions, mantled alcoves/channels/fans, arcuate ridges, small-scale LDAs on the floor | ESP_020407_1410 | DTEEC_022108_1410_022385_1410_A01 |
| Istok | 45.1° S | 85.82° W | 8 | Bedrock | Alcove cut directly into the original crater-wall material, clasts embedded into fresh deposits on fan | ESP_056668_1345 | DTEEC_040607_1345_040251_1345_A01 |
| Galap | 37.66° S | 167.07° W | 8 | Bedrock | Alcove cut directly into the original crater-wall material, clasts embedded into fresh deposits on fan | ESP_059770_1420 | DTEEC_048983_1420_048693_1420_U01 |
| Gasa | 35.73° S | 129.4° E | 7 | Bedrock | Alcove cut directly into the original crater-wall material, clasts embedded into fresh deposits on fan | ESP_057491_1440 | DTEEC_021584_1440_022217_1440_A01 |
| Los | 35.08° S | 76.23° W | 7 | Bedrock | Alcove cut directly into the original crater-wall material, | ESP_020774_1445 / ESP_050127_1445 | ESP_020774_1445_ESP_050127_1445* |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | clasts embedded into fresh deposits on fan | | |
| Unnamed crater-3 in the Terra Sirenum | 34.27° S | 165.71° E | 7 | Bedrock | Alcove cut directly into the original crater-wall material, clasts embedded into fresh deposits on fan | ESP_049261_1455 / ESP_049828_1455 | ESP_049261_1455_ ESP_049828_1455* |

*(*) DTMs are produced with the software packages USGS ISIS and BAE Systems SocetSet.*

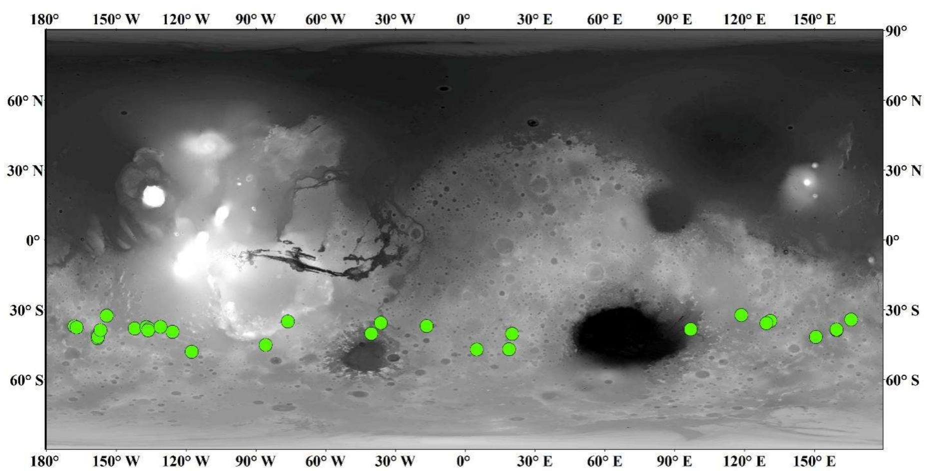


**Figure 1: Locations of craters analyzed in this study (green circles). Background: Mars Orbiter Laser Altimeter gridded data, where white is high elevation and black is low elevation, credit MOLA Science Team/NASA/JPL.**

## 3 Approach

### 3.1 Identification of substrate

The substrate into which the gullies have incised is identified based on the following criteria:

1. LDM/glacial deposits: Any crater whose gullies incise walls that appear to be softened by the drape of smooth mantling material with polygonal cracks is inferred to have LDM as the substrate within which gullies have incised (e.g. Mustard et al.,

2001; Kreslavsky and Head, 2002; Levy et al., 2009a; Conway et al., 2018; de Haas et al., 2019a) (Fig. 2a). The alcoves on the walls of these craters may be partially to completely filled by LDM, and in some cases, polygonized LDM materials may be seen covering the alcove walls (e.g. Christensen, 2003; Conway et al., 2018; de Haas et al., 2019a). These infilled alcoves on the crater walls are not the alcoves of gullies formed within the LDM substrate; instead, they represent the alcoves that were formed prior to the LDM emplacement epoch. Additionally, gullied craters that show evidence in the form of arcuate ridges at the foot of the walls and VFFs that cover part or the entire crater floor are inferred to have been modified by one or multiple episodes of glaciation (e.g. Arfstrom and Hartmann, 2005; Head et al., 2010; Milliken et al., 2003; Hubbard et al., 2011). These craters host gullies that are often partially or fully covered by LDM deposits.

2. Bedrock: Craters where the features listed in LDM/glacial deposits are absent and where rocky material is visible extending downwards from the crater rim. This rocky material usually outcrops as spurs and can be layered or massive. The slopes can be smooth or covered with boulders, with concentrations of boulders at the slope toe.

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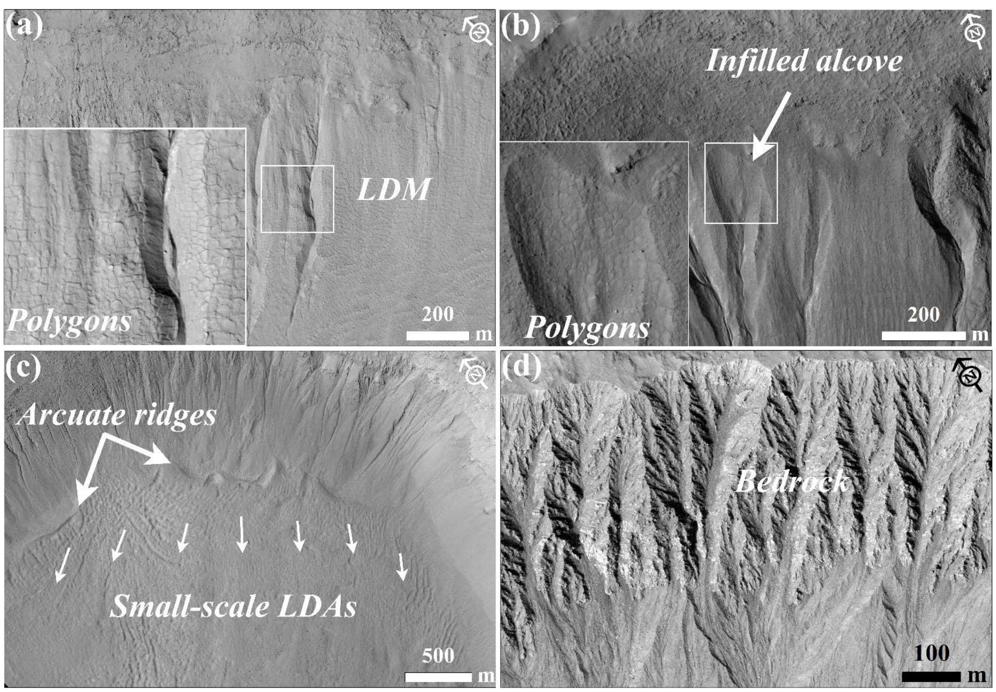

**Figure 2: Examples of morphological evidence used to identify LDM, glacial deposits, and bedrock. (a) Smooth mantling material inferred as LDM draped on the wall of Talu crater on the basis of polygonal cracks formed in the material. The bigger box is an expanded view of the polygons seen over the region outlined by the smaller box. (HiRISE image ESP_011817_1395). (b) An infilled alcove on the wall of an unnamed crater-2 in the Terra Sirenum. Evidence of polygons in the infilled material suggests presence of LDM deposits draped on the wall. The region shown in smaller box is expanded in the bigger box to show evidence of the polygons. (HiRISE image ESP_020407_1410). (c) Glaciation inferred in the Corozal crater on the basis of arcuate ridges formed at the foot of the crater wall and small-scale LDAs on the crater floor. Arrows indicate the downslope flow of LDAs on the floor. (HiRISE image PSP_006261_1410). (d) Exposed fractured bedrock identified on the walls of Istok crater within which alcoves have incised. (HiRISE image ESP_056668_1345). HiRISE image credit: NASA/JPL /University of Arizona.**

## 3.2 Morphometric variables

The measurements we made of each gully system include alcove area, alcove perimeter, alcove length, alcove width, alcove gradient, fan area, fan length, fan width, and fan gradient (Fig. 3). In total, we derived 18 morphometric variables to characterize each gully fan and its alcove. The morphometric variables are classified into geometry, relief, gradient, and dimensionless variables and they are calculated with established mathematical equations shown in Table 2. For the gradient measurement using the DTM, the topographic profile from (1) crest of the alcove to the apex of the fan was extracted for the alcove, and (2) apex to foot of the fan was extracted for the fan.

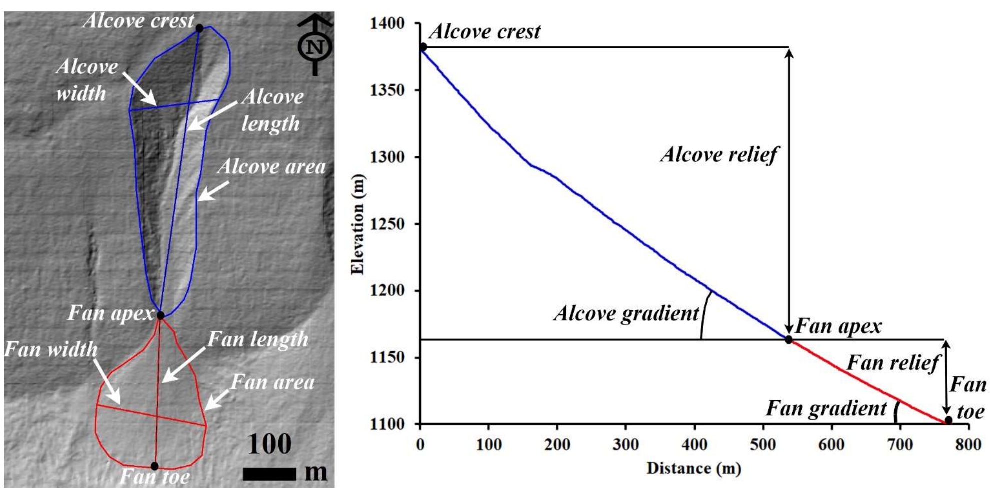


**Figure 3: Examples of morphometric variables estimated in this work. Left panel: HiRISE DTM (Id: DTEEC_002659_1420_002514_1420) based hillshade. HiRISE DTM credit: NASA/JPL /University of Arizona. Right panel:**

**Topographic profile: blue profile represents the topography of gully alcove from alcove top to fan apex and red profile represents the profile of gully fan from fan apex to fan toe.**

**Table 2.** Set of morphometric variables extracted from the studied gully systems and their formulas and/or description of method.

| Morphometric variable | Formula and/or description of method | References |
|---|---|---|
| Alcove length and width | Measured in km | **Tomczyk, 2021** |
| Alcove area | Measured in $km^2$ | **Tomczyk, 2021** |
| Fan length and width | Measured in km | **Tomczyk, 2021** |
| Fan area | Measured in $km^2$ | **Tomczyk, 2021** |
| Melton ratio | (Alcove relief)/(Alcove area$^{-0.5}$) | **Melton, 1957** |
| Relative concavity index (RCI) | Concavity Index/(maximum relief between the uppermost and lowermost points along the gully fan profile/2). Concavity Index is estimated as $\sum (H_i^* - H_i) / N$, where $H_i^*$ is the elevation along the straight line, $H_i$ is the elevation along the gully fan profile, $N$ is the total number of measurement points. | **Langbein, 1964; Phillips and Lutz, 2008** |
| Alcove gradient | Measured in (°) | **Tomczyk, 2021** |
| Fan gradient | Measured in (°) | **Tomczyk, 2021** |
| Alcove relief | Measured in km | **Tomczyk, 2021** |
| Fan relief | Measured in km | **Tomczyk, 2021** |
| Relief ratio (alcove and fan) | Alcove/fan relief divided by the length of the alcove/fan | **Schumm, 1956a, b** |
| Perimeter | Measured in km | **Schumm, 1956a, b** |
| Form factor | Alcove area divided by the square of the length of the alcove | **Horton, 1932** |
| Elongation ratio | Diameter of a circle of the same area as the alcove divided by the maximum alcove length | **Schumm, 1956a, b** |
| Circularity ratio | Alcove area divided by the area of the circle having the same perimeter as the alcove perimeter | **Miller, 1953** |

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### 3.3 Gully system selection for morphometric measurements

We have selected only those gully systems for morphometric measurements in which: (i) the depositional fan from an alcove-channel system is not superimposed by or interfingering with the fans from the neighboring channels, (ii) there is clear association between the primary channel emanating from the alcove that extends downslope and then deposit its respective fan, (iii) no evidence of extensive cross-cutting is seen with the neighboring channels on the walls, (iv) no evidence of extensive mantling by dust/aeolian deposits is apparent, and (v) no evidence of channel/fan superposition on any topographic obstacle on the walls or the floor of the crater is apparent, which may have influenced the morphometry. If in any case the fans

**Deleted:** eventually influence the morphometric measurements superimpose or channels cross-cut, we have carefully demarcated the alcove-channel-fan boundary, to minimize the inaccuracies in the measurements. Note that the selection of the gully systems was also constrained by the coverage of HiRISE DTM that was used for morphometric analysis.

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### 3.4 Statistical analysis of morphometric variables

We have two groups of gullies in our study: (1) gullies whose source area is incised into LDM/glacial deposits and (2) gullies whose source area is incised into the bedrock. First, for both the groups we have calculated descriptive statistics for each of the morphometric variables shown in Table 2. The significance of the difference between the values of each of the morphometric variables calculated for each group was tested using a Student's t-test. To apply t-tests, we have transformed the morphometric variables to remove skewness by taking their natural logarithm. Correlation analysis has been used to investigate the correlation between the selected morphometric attributes of alcoves and fans. We infer strong positive correlations between variables if the correlation coefficient value is more than 0.7 and strong negative correlations if the value is less than -0.7. Very strong positive correlation between variables is inferred if the correlation coefficient is ≥0.9. Further, we used canonical discriminant analysis (CDA) to determine morphometric variables that provide the most discrimination between the groups of gullies. In CDA, functions are generated according to the number of groups, until a number equal to n-1 functions is reached (n is the number of groups) (Conway et al., 2015). For the two groups of gullies in our study, there is going to be a function for which there is a standardised canonical discriminant function coefficient associated with the morphometric variable. The higher the magnitude of this coefficient for a particular morphometric variable, the higher the role of that variable in separating the groups of gullies. Standardisation was done by dividing each value for a given variable by the maximum value.

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## 4 Results

### 4.1 Morphology of gully systems

Out of the 29 gullied craters analysed in this work, we have found that there are 24 craters influenced by LDM and VFFs. The remaining 5 craters have gullies incised into the exposed underlying bedrock on the wall of the crater. Below we describe the substrates identified in the studied craters and then compare the morphology of the gullies formed into those substrates.

4 craters out of 24 craters (i.e. Raga, Roseau, unnamed crater in Newton basin and unnamed crater-1 in Terra Sirenum) have gullies that are only influenced by LDM. In these craters, we have found morphological evidence of LDM in the form of polygonized, smooth textured material on the pole-facing walls of the craters. Morphological evidence of VFF is not evident in these craters. In these craters, the gully-alcoves and gully channels appear to have been incised into the polygonized LDM material, and the gully-fan deposits are mantled. A typical example of this can be found in the unnamed crater formed inside the Newton basin (Fig. 4a). Roseau crater, in particular, contains a large number of gully systems whose alcoves and fans are

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extensively mantled (Fig. 4b). The remaining 20 out of 24 craters contain evidence for gullies that are influenced by both LDM and glacial deposits (Table 1). The base of the pole-facing walls and the floor of the craters within which the gully systems have formed host linear-to-sinuous arcuate ridges and VFFs, respectively. Typical examples of VFFs can be found in Corozal, Talu, unnamed craters in Terra Sirenum and Argyre basin, Langtang, Dechu and Dunkassa craters (Fig. 4c). In majority of the gullied craters (except Raga, Roseau and unnamed crater-1 in Terra Sirenum) influenced by LDM and glacial deposits, gully alcoves are found to have a distinctive V-shaped cross section in their mid-section (Figures 4d and 4e), they do not extend up

**Deleted:** Additionally, younger generation of gullies are visible that have incised within the LDM.

**Deleted:** specifically incised LDM as opposed to LDM that infills pre-existing alcoves and gullies, and

**Deleted:** VFFs

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to the crater rim, and gully systems often show multiple episodes of activity, inferred by the presence of fresh channel incision on the gully-fan surfaces (Fig. 4d-e).

Istok, Galap, Gasa, Los, and an unnamed crater in the Terra Sirenum contain gully systems on the pole-facing walls that are not associated with LDM and VFFs (Table 1). The alcoves inside these craters have a crenulated shape and appear to have formed by headward erosion into the bedrock of the crater rim (Fig. 4f). These craters have formed large gully systems on their pole-facing walls, with brecciated alcoves, comprising of multiple sub-alcoves and hosting many clasts/boulders (Fig. 4f).

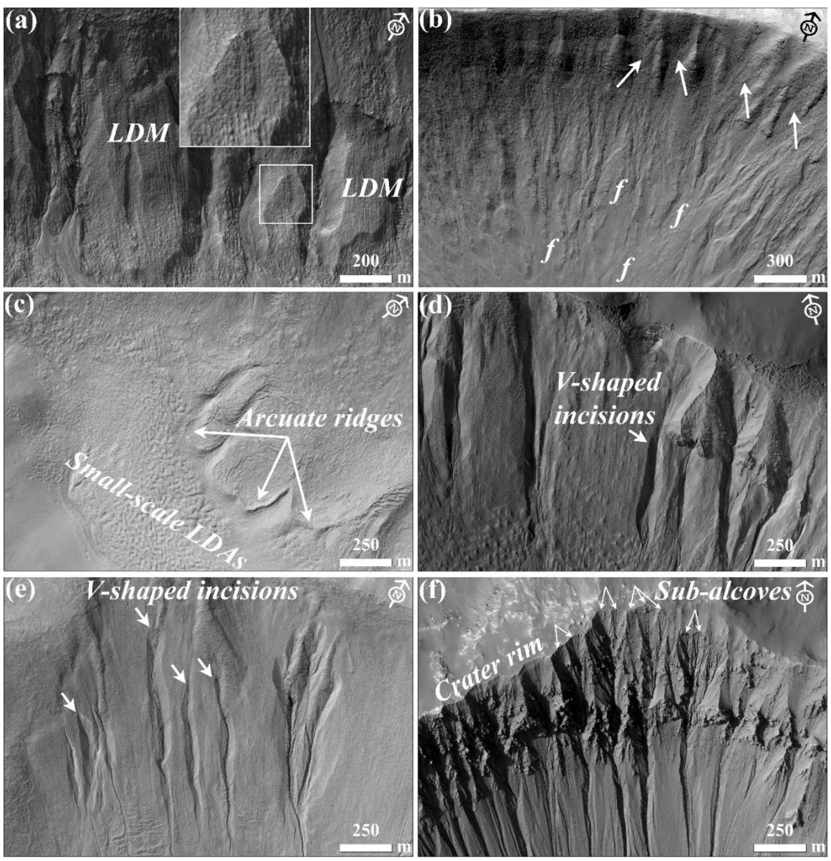

**Figure 4: (a) LDM draped on the wall of an unnamed crater in the Newton basin. The inset shows details of the polygonal texture of the LDM. (HiRISE image PSP_002686_1410). (b) Infilled alcoves (arrows) and mantled fan surfaces (marked by letter 'f') on the wall of Roseau crater. (HiRISE image ESP_024115_1380). (c) Arcuate ridges at the foot of the crater wall and small-scale LDAs on the floor in Langtang crater. (HiRISE image ESP_030099_1415). (d) V-shaped incisions on the LDM draped walls of Taltal (HiRISE image ESP_037074_1400) and (e) Langtang crater (HiRISE image ESP_030099_1415). (f) Alcoves formed in Los crater by headward erosion into the crater rim. Individual alcoves formed in bedrock have multiple sub-alcoves. (HiRISE image ESP_020774_1445).**

## 4.2 Morphometry of gully systems

Based on the criteria summarized in section 3.3, we have studied 167 gullies across 29 craters for calculation of morphometric variables. 130 gullies are formed within LDM/glacial deposits, and 37 gullies are formed within the bedrock. The results of morphometric calculations are summarized for visual comparison as a boxplot (Fig. 5).

The results of the Student's t-test indicates that all of the morphometric variables in Table 2, except fan width, fan area, Melton ratio, form factor, elongation ratio, and circularity ratio, differ significantly between LDM/glacial deposits and bedrock (Fig. 5). Compared to the mean gradient of gully-fans formed in LDM/glacial deposits, bedrock gully-fans are steeper and possess a higher relief ratio. The interquartile range of length, relief, and perimeter of alcoves formed in bedrock are also higher than the interquartile range of similar variables in LDM/glacial deposits, but the alcoves in LDM/glacial deposits possess much higher values of length, relief, and perimeter (Fig. 5).

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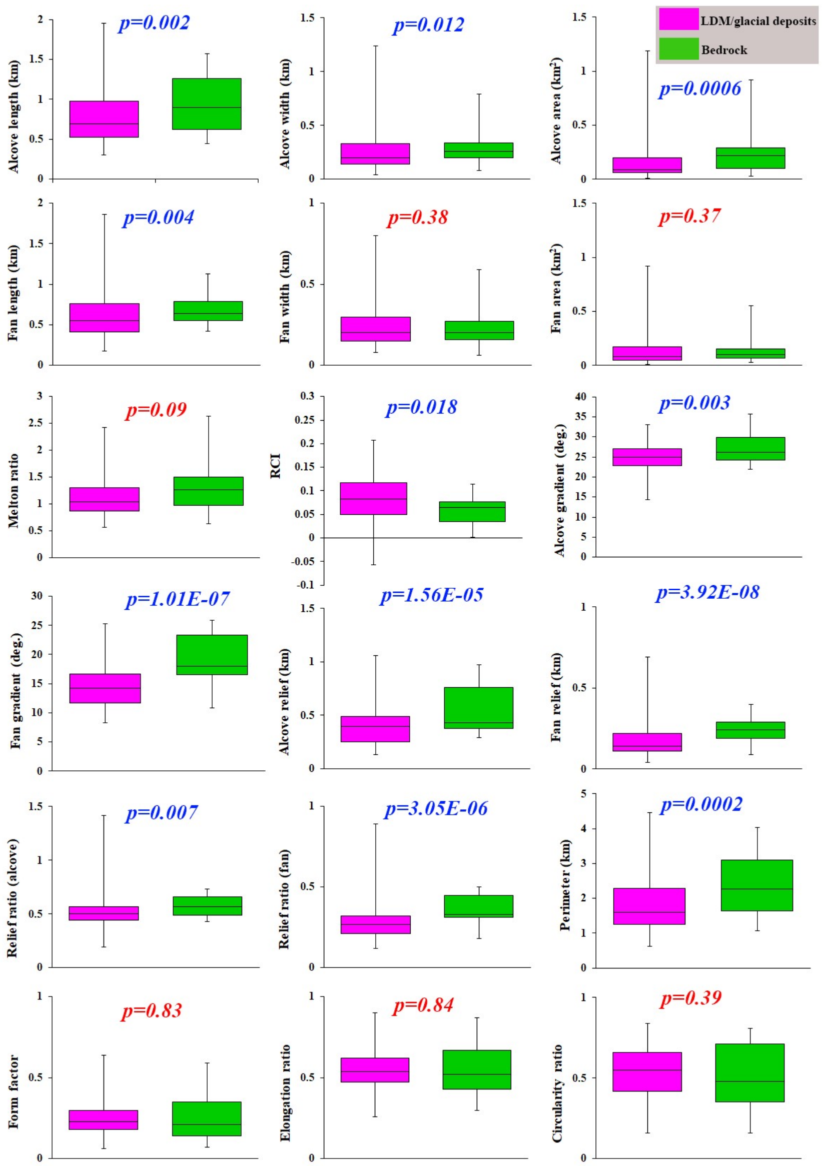
LDM/glacial deposits
Bedrock
p=0.002
Alcove length (km)
p=0.012
Alcove width (km)
p=0.0006
Alcove area (km²)
p=0.004
Fan length (km)
p=0.38
Fan width (km)
p=0.37
Fan area (km²)
p=0.09
Melton ratio
p=0.018
RCI
p=0.003
Alcove gradient (deg.)
p=1.01E-07
Fan gradient (deg.)
p=1.56E-05
Alcove relief (km)
p=3.92E-08
Fan relief (km)
p=0.007
Relief ratio (alcove)
p=3.05E-06
Relief ratio (fan)
p=0.0002
Perimeter (km)
p=0.83
Form factor
p=0.84
Elongation ratio
p=0.39
Circularity ratio

**Figure 5: Boxplots showing the range of values of alcove/fan geometry, relief, gradient, and dimensionless variables of gullies incised into LDM/glacial deposits (pink) and bedrock (green). P-values on the plots represent the results of the student's t-tests for testing the significance of difference in means of the morphometric variables between gully systems formed on LDM/Glacial deposits and bedrock. P-values in blue correspond to significant difference (with respect to a p-value of 0.05) and those in red are non-significant.**

Correlations between morphometric attributes of alcoves and fans formed in bedrock and LDM/glacial deposits are summarized in Fig. 6. For bedrock, there are strong positive correlations between 12 pairs of morphometric variables and strong negative correlations between 3 pairs of morphometric variables. For LDM/glacial deposits, there are strong positive correlations between 18 pairs of morphometric variables and strong negative correlations between 3 pairs of morphometric variables. Very strong positive correlations are found between 9 pairs of morphometric variables for bedrock and between 4 pairs of morphometric variables for LDM/glacial deposits.

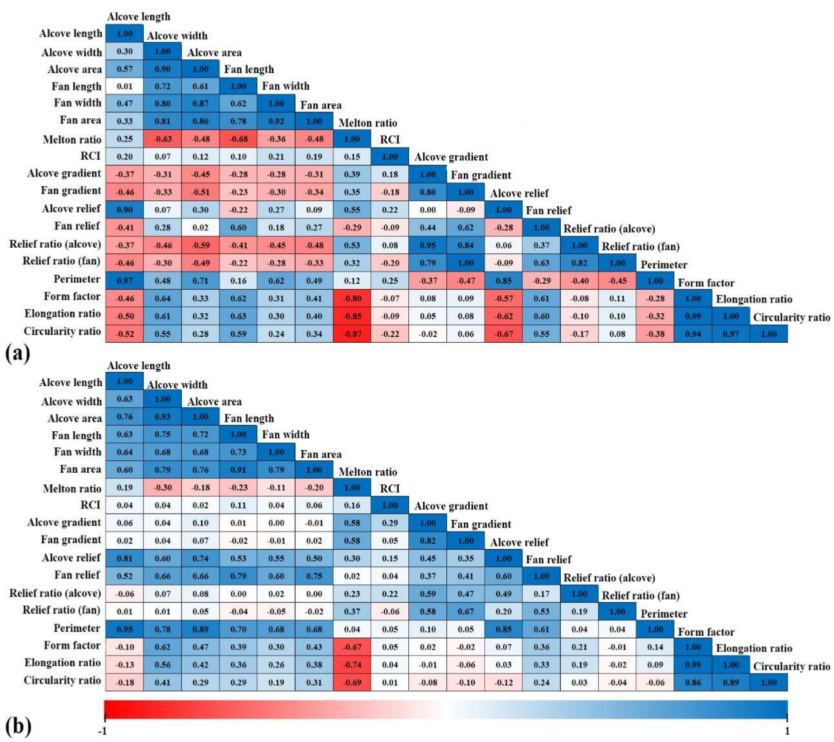

**Figure 6: Correlations between morphometric attributes of alcoves and fans formed in (a) bedrock and (b) LDM/glacial deposits. Higher the value of the correlation coefficient, higher is the strength of the correlation.**

The canonical discriminant analysis reveals that the following morphometric variables best distinguish between the gully systems formed in LDM/glacial deposits and bedrock, in descending order of importance: alcove perimeter, alcove relief, fan gradient, fan relief, fan length, relief ratio (alcove), alcove width, relief ratio (fan), alcove gradient, alcove area, alcove length, and relative concavity index (Table 3). The alcove perimeter is most important in discriminating among the gully systems formed within LDM/glacial deposits and bedrock, and the next two most important variables are alcove relief and fan gradient. Alcove relief and fan gradient have 4/5 and 1/3 the weight of alcove perimeter, respectively. The remaining variables such as fan relief, fan length, relief ratio (alcove), alcove width, and relief ratio (fan) have nearly 1/5 the weight of alcove perimeter or greater (but less than 1/3) discriminatory power in separating between the gullies formed in LDM/glacial deposits and bedrock. The variables with the smallest magnitude, alcove gradient, alcove area, alcove length and relative concavity index, have less than 1/10 the weight of the most important variable in separating the gully systems.

**Table 3.** Standardised canonical discriminant function coefficients (F1) that best separate gully systems formed on LDM/Glacial deposits and bedrock.

| **Variable** | **F1** |
|---|---|
| Perimeter | 3.552 |
| Alcove relief | -2.828 |
| Fan gradient | 1.278 |
| Fan length | -1.06 |
| Fan relief | 1.06 |
| Relief ratio (alcove) | 0.971 |
| Alcove width | -0.692 |
| Relief ratio (fan) | -0.665 |
| Alcove gradient | -0.331 |
| Alcove area | -0.319 |
| Alcove length | 0.23 |
| Relative concavity index | -0.182 |

## 5 Discussions

### 5.1 Unique morphology and morphometry of gully systems in different substrates

We have found that the gully systems formed in LDM/glacial deposits and bedrock can, using discriminatory analysis, be distinguished from one another in terms of perimeter and relief of alcoves (Table 3). Additionally, we have found statistically significant difference between the perimeter and relief of alcoves formed in LDM/glacial deposits and bedrock (Fig. 5). It is likely that these differences in the perimeter and relief of alcoves formed within morphologically distinct substrates could be due to the integral nature of the surface material within which the alcoves have formed. In other words, it is possible that the differences in the physical properties of the sediments (namely grain size, compactness etc.) within which alcoves have formed played a key role in erosion of the substrate leading to differences in their morphometric variables. Below we elaborate on the uniqueness of the substrates within which alcoves have formed, and discuss further the relationships between the morphometric variables of the morphologically distinct gully systems.

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On Mars, VFFs contain high purity glacial ice with a debris cover (Sharp, 1973; Squyres, 1978, 1979; Squyres and Carr, 1986; Holt et al 2008, Plaut et al 2009, Petersen et al. 2018). Their surfaces have been interpreted to be comprised of finer, reworked debris derived from sublimation of the underlying ice (Mangold, 2003; Levy et al., 2009a; Morgan et al., 2009). The smooth, meters thick draping unit on the walls of formerly glaciated craters has been suggested to be derived from the atmosphere as a layer of dust-rich ice primarily constituting of fine-grained materials (Kreslavsky and Head, 2000; Mustard et al., 2001). The fine-grained materials are loosely-packed, unconsolidated materials exhibiting low thermal inertia values (Mellon et al., 2000; Putzig et al., 2005). Typically, gullies formed within this substrate display a smooth surface texture, wherein, evidence of individual clasts or meter-scale boulders is not resolvable in HiRISE images, substantiating the dominant component of fine-grained materials within the LDM (e.g., Levy et al., 2010; de Haas et al., 2015a). Additionally, it has been found that alcoves incised into the LDM always have a distinctive V-shaped cross section in their mid-section (Figures 4d and 4e), which when compared with similar-scaled systems on Earth also corresponds to the presence of loose sediments constituting the LDM (Conway et al., 2018). The alcoves with V-shaped cross sections are found to be elongated, likely indicating incision within ice-rich unlithified sediments (Aston et al., 2011). In the studied craters, we have found that gullies incised into LDM/glacial deposits are having an elongated, V-shaped cross section in their mid-section (Fig. 4). We propose that the presence of fine-grained, loosely packed, unconsolidated materials within LDM/glacial deposits has facilitated formation of elongated alcoves with perimeter and relief relatively higher than that of alcoves formed in coarse-grained bedrock substrate. This is consistent with the previous studies suggesting that gullies eroding into LDM/glacial deposits have elongated catchments, whereas gullies eroding into the bedrock have more amphitheater-shaped catchments (Levy et al., 2009b). For this reason, the estimated length of alcoves formed in LDM/glacial deposits is found to be relative higher than that of alcoves formed in bedrock (Fig. 5). Furthermore, statistical analysis has revealed a significant difference between the length of alcoves formed in LDM/glacial deposits and bedrock (Fig. 5). Additionally, the presence of finer-grained sediments in LDM/glacial deposits is the likely cause of the V-shape of the incision of alcoves investigated in this study (Aston et al., 2011). On Earth, V-shaped incisions through glacial ice-rich moraines have been observed to have occurred during the paraglacial phase of glacial retreat (Bennett et al., 2000; Ewertowski and Tomczyk, 2015) (Fig. 7). The paraglacial phase refers to a terrestrial post-glacial period that represents the response of changing environment to deglaciation (Bennett et al., 2000; Ewertowski and Tomczyk, 2015).

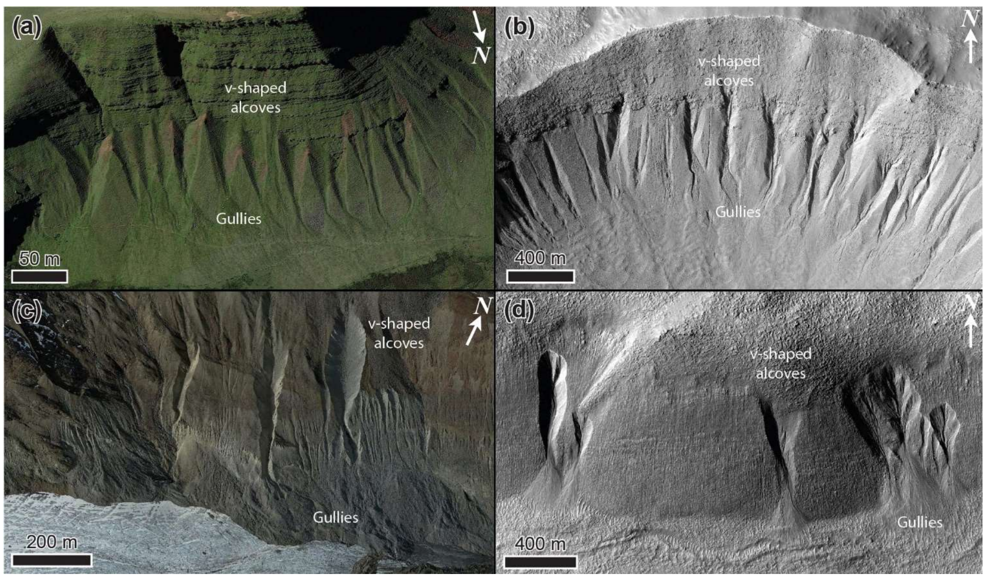


**Figure 7: Gullies forming in glacial sediments in deglaciated terrain in the (a) Brecon Beacons, Wales, UK on Earth (Google Earth coordinates: 51°52'59.11"N, 3°43'33.26"W), (b) Talu crater (https://www.uahirise.org/ESP_011817_1395) on Mars, (c) Hintereisferner, Austria (Google Earth coordinates: 46°48'54.25"N, 10°47'8.18"E), on Earth, and (d) Bunnik crater (https://www.uahirise.org/ESP_047044_1420) on Mars. HiRISE image credit: NASA/JPL-Caltech/University of Arizona.**

The next most important difference between these two types of gullies is the mean gradient of gully fans. At the foot of the fans, mean gradient of the fans influenced by LDM/glacial deposits is <15° for 61% of the studied fans. For bedrock, 84% of the studied fans have a mean gradient >15° at the foot of the fans. Hence, gully-fans formed in bedrock are emplaced at a relatively steeper gradient than the fans formed from gullies in LDM/glacial deposits. We propose that the nature of the material mobilized can explain this difference, with the finer-grained sediments characteristic of the LDM/glacial type gullies being easier to mobilise and being entrained to lower slope angles, than the coarser sediments found within the bedrock type gullies.

### 5.2 Evaluation of the gully formation process

On Earth, alcove-fan systems can roughly be subdivided in flood-dominated, debris-flow dominated, and colluvial systems. Following the terminology of De Haas et al., (2015b) and Tomczyk (2021), we define these systems as follows:

1) Flood-dominated systems: These are systems dominated by fluid-gravity flows, i.e., water floods, hyperconcentrated floods, and debris floods. The fans of such systems are commonly referred to as fluvial or alluvial fans (e.g., Ryder, 1971; Blair and McPherson, 1994; Hartley et al., 2005).

2) Debris-flow dominated systems: These are systems dominated by sediment-gravity flows, i.e., debris flows, mud flows. Irrespective of their radial extent and depositional gradients, the fans aggraded by these systems can be commonly called debris-flow fans or debris fans (Blikra and Nemec, 1998; de Scally et al., 2010).

3) Colluvial systems: These are systems dominated by rock-gravity and sediment-gravity flows, with their dominant activity relating to rockfalls, grain flows, and snow avalanches (in periglacial and alpine settings). Debris flows typically constitute only a relatively minor component of geomorphic processes in such systems. The fans of these systems are also commonly known as colluvial cones or talus cones (Siewert et al., 2012; De Haas et al., 2015b).

Although these systems may be dominated by one type of geomorphic process, it is important to stress that other processes may also occur. For example, on Earth water floods are not uncommon on many debris-flow dominated systems, while debris-flow deposits are commonly recognized on colluvial cones.

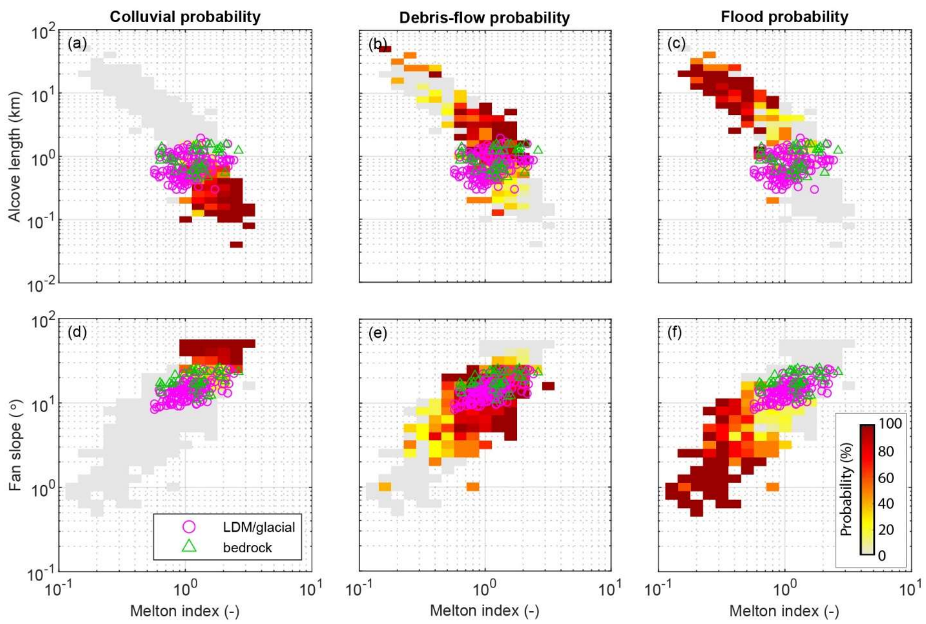


**Figure 8: Comparison of combinations of Melton ratio with Alcove length and Fan gradient. The probability heat maps are based on previously published data – see text for references. The Martian gully systems formed in LDM/glacial deposits and bedrock are found to be in the debris-flow regime on Earth.** <u>**The gray area shows the realm of the colluvial, debris-flow, and fluvial fans together.**</u>

To compare the morphometric characteristics of the Martian gully systems to terrestrial systems, we have compiled morphometric data of alcoves and fans across several continents, mountain ranges, climate zones, and process types on Earth. This dataset includes published data from the Himalayas, Ladakh, India (Stolle et al., 2013), the tropical Andes, Columbia (Arango et al., 2021), Spitsbergen, Svalbard (Tomczyk, 2021), British Columbia, Canada (Kostaschuk, 1986; Jackson et al., 1987; and newly presented data), the southern Carpathians, Romania (Ilinca et al., 2021), the Southern Alps, New Zealand (De Scally and Owens, 2004; De Scally et al., 2010), the North Cascade Foothills, USA, the European Alps (including Switzerland, Italy, France, and Austria), and the Pyrenees (from multiple authors compiled by Bertrand et al., 2013). The dataset comprises information from colluvial, debris-flow, and flood (also including debris flood) dominated systems. In total, it contains 231 colluvial systems, 749 debris-flow dominated systems, and 369 flood-dominated systems. In total, data were compiled for 1349 systems, although not all information was available for all systems, with data availability ranging from 729 sites for alcove length to all 1349 systems for Melton index and process type. Based on this data we have made a heatmap of the probability of flood, debris-flow, or colluvially-dominated conditions for combinations of Melton ratio with alcove length and fan gradient, to which we compare the Martian gullies (Fig. 8). We have specifically chosen the combinations of Melton ratio with alcove length and fan gradient to infer the Martian gully formative mechanism because they have been widely used in discriminating terrestrial drainage basins and fans prone to flooding from those subject to debris flows, debris floods and floods (e.g. De Scally and Owens, 2004; Wilford et al., 2004). We have found that the Martian gullies are indeed in the debris-flow regime on Earth. Moreover, they are closer to the transition to the smaller and steeper colluvial cones than to transition to flood-dominated fans. As expected, bedrock systems in Fig. 8d-e are closer to the colluvial systems than the LDM systems.

According to the previous reports of debris-flow like deposits found in Martian gullies (e.g. Johnsson et al., 2014; Sinha et al., 2019, 2020), the morphological attributes of debris-flow like deposits typically include overlapping tongue-shaped lobes with embedded clasts, channels with medial deposits, and channels with clearly defined lateral levees. Although it is still not clear whether the formation of these deposits in gullies are from sublimation of $CO_2$ ice or due to meltwater generation. De Haas et al., (2019b) showed that $CO_2$ sublimation may lead to flow fluidization on Mars in a manner similar to fluidization by water in terrestrial debris flows; a concept supported by the recent finding of lobate deposits and boulder-rich levee formation during the present-day in Istok crater (Table 1) (Dundas et al., 2019). The formation of these morphologically similar deposits during the present-day is attributed to sublimating $CO_2$ frost, which likely produces the necessary fluidization likely by gas generated from entrained $CO_2$ frost (Dundas et al., 2019). On the basis of these recent reports (De Haas et al., 2019b; Dundas et al., 2019) and based on our own findings in this study, we argue that a debris-flow like process similar to those operated in the terrestrial gully systems has likely dominated the flow types that lead to gully formation on Mars. It is likely that the present-day sublimation of $CO_2$ ice on Mars provided the necessary flow fluidization for the emplacement of deposits similar to terrestrial debris-flow like deposits (De Haas et al., 2019b).

## 6 Conclusions

This paper compares morphological and morphometric characteristics of gully alcoves and associated fans formed in LDM/glacial deposits and bedrock over walls of 29 craters between 30° S and 75° S latitudes. 5 craters out of 29 have alcoves-fans formed within the bedrock and remaining 24 craters have alcoves-fans formed within LDM/glacial deposits. From our analysis of 167 gullies, we posit that gully systems formed in LDM/glacial deposits and bedrock differ from one another using the following lines of evidence:

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• Alcoves formed in LDM/glacial deposits are more elongated than the alcoves formed in bedrock, and possess a distinctive V-shaped cross section.

• The mean gradient of gully-fans formed in bedrock is steeper than the mean gradient of fans formed from gullies in LDM/glacial deposits.

The morphological distinction reported between gullies formed in the bedrock and LDM/glacial deposits signifies that Martian gullies may have multiple formative mechanisms. We infer that the presence of mantling material could be one of the key factors in constraining the mechanisms forming Martian gully systems and that presence of LDM would promote formation of elongated alcoves with perimeter and relief relatively higher than that of alcoves formed in coarse-grained bedrock substrate.

Based on the combinations of Melton ratio with alcove length and fan gradient, we suggest that the gully systems studied in this work were likely dominated by terrestrial debris-flow like processes during their formation. This is consistent with the findings reported in previous studies that showed evidence of formation of deposits morphologically similar to terrestrial debris-flow like deposits, both in the past and during the present-day (e.g., Johnsson et al., 2014; Dundas et al., 2019). The present-day sublimation of $CO_2$ ice on Mars is envisaged to provide the necessary flow fluidization for the emplacement of deposits similar to debris-flow like deposits on Earth (De Haas et al., 2019b).

## 7 Author contribution

RKS, TDH and SJC conceptualized this work. The methodology was developed by RKS, TDH and SJC. Data curation and formal analyses were performed by RKS. TDH and AN also contributed in collection of datasets used in this work. RKS, DR, TDH and SJC contributed to the interpretation of the data and results. RKS wrote the original draft of this paper, which was reviewed and edited by all authors.

## 8 Conflict of interest

SJC is a Guest Editor of this special issue (Planetary landscapes, landforms, and their analogues) of ESurfD and on the editorial board for ESurf. The peer-review process was guided by an independent editor, and the authors have also no other competing interests to declare.

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