Response to reviewers

*We are **grateful and thank** 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 reviewer and make clear where and what changes have been made in the revised version of the 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 CO2 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 CO2 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.*