Review by Susan Conway

The manuscript contains novel results pertaining to alcoves in the glaciated mid-latitudes of Mars that the authors argue are carved by glacial erosion akin to cirques on Earth. The contribution is worthy of publication, but the paper (and most notably, the discussion) needs to be shortened and the methods (and some of the results) expanded to better represent their work. Only the conclusions that are robustly supported by the author's collected data should be presented and the paper shortened via that mechanism. I have included detailed comments on the attached PDF and reproduced below those that require a response and either a change to the manuscript or a reason why the manuscript has not been changed (I note from the previous review that the authors made many replies to the review and yet did not necessarily change the manuscript – the reviewer's question about map projection of Fig 3 is an example, where a response was provided as a reply, but the information should also have been added to the text, so I have had to raise a similar comment in this review).

We thank the reviewer for taking the time to provide very detailed and helpful comments.

In Section 3.1, we added the following sentence about the map projection: "Measurements from all of the imagery and DEMs used a Sinusoidal projection centered on longitude 25.5 degrees East, and were based on the IAU Mars 2000 Sphere datum."

In general, the paper reads as if the authors were arguing strongly that these cirque-like alcoves were formed by the erosion of wet-based glaciers in the first version and after a round of reviews they were forced to acknowledge that their data do not allow them to conclude this (I wrote this text before looking at the previous reviews). So even though the paper does acknowledge that these cirque-like alcoves could be formed by the erosion of cold-based glaciers, it is somewhat begrudging. I encourage them to take a fresh look at the paper and try to "clean it up" by focussing on the conclusions that are best supported by the data collection effort they have undertaken. Briefly these would be in my opinion: that the alcoves they investigate are likely caused by significant glacial erosion, they are bigger than cirques on Earth, their orientation/size/distribution shows climate signal also seen in gullies and GLF globally, the timescales for formation under wet and cold based glaciation are realistic, but different (with different implications). An effort should be made to shorten the text substantially. Hence, I feel that the main concern in the previous round of reviews "My main concern is that from the very start of the manuscript, the wet-based model is accepted as an assumption" has not been fully addressed.

We have removed paragraphs of both the Introduction and Conclusion to address this concern, and deleted what was previously Section "5.5 Discussion of wet-based versus cold-based glacial erosion of cirque-like alcoves." While we have softened our language that the cirque-like alcoves must point to wet-based glaciers, we maintain the position that it remains a possibility alongside cold-based glaciation.

In summary, the main points that need addressing before publication are:
1. The discussion is very speculative and not focussed so the reader gets lost as to how the authors' work even pertains to what is being discussed. I think the authors should focus their paper to present 4-5 solid conclusions which have a direct link to the data they have collected and remove the other conclusions with associated discussion to make the paper easier to understand and read.
Following the reviewer's recommendation, we deleted sections 5.5 "Discussion of wet-based versus cold-based glacial erosion of cirque-like alcoves" and 5.6 "Possible alternative mechanisms for alcove formation using examples from Earth" so that the discussion and relevant conclusions are more straightforward.

2. That cirques on Mars indicate wet-based glaciation is going too far. Even that these alcoves are probably cirques is already enough of a finding without the authors needing to go further. The wet-based glaciation can appear where the authors consider rates of erosion and timescales, but should not form part of the abstract, the introduction and conclusions. The other parts of the discussion dealing with this are speculative and unfounded, so should be reduced/removed. See my detailed comments. This was the main concern of one of the previous reviewers.
Following the reviewer's recommendation, we greatly reduced the discussion on wet-based glaciation and instead focused on glacial erosion generally. This included deleted sections related to wet-based erosion in the introduction, section 5.5, and conclusion.

3. The comparison in the discussion to rock glaciers (and its recurrence in the abstract and conclusions) is speculative and no comparison data from Earth are directly presented to support this point. Personally, I do not see the resemblance, yet I should not need to make a personal judgement if this is a conclusion of the paper, I should have the data presented to me and be convinced by the authors' arguments. This is not the case – please see my detailed comments – so I suggest removing this comparison as it distracts from the more robust conclusions in the paper.

We deleted this section in the discussion, however, we did want to note below that rock glaciers are considered to be analogs for GLFs as well.

In addition to being compared to debris-covered glaciers, GLFs/VFFs are also compared to rock glaciers on Earth (e.g., Hubbard et al., 2011; Hubbard et al., 2014). Hubbard et al. (2014) also notes that the distinction between debris-covered glaciers and rock glaciers isn't always clear on Earth. For example, one complex glacier system can include components that are mapped as both a rock glacier and a debris-covered glacier (e.g., Janke et al., 2015; Tanarro et al. 2021).

While rock glaciers oftentimes have furrows, similar to the glacier-like form studied by Hubbard et al. (2011), the furrows are not a requirement for a rock glacier. For example, Janke et al. (2015) identifies Class 6 rock glaciers as glaciers that have deflated and contain <10% ice content. These Class 6 rock glaciers lose their defined furrows and their sharp transition from their toe to the front slope (Janke et al., 2015).

References:

Hubbard, B., Souness, C., & Brough, S. (2014). Glacier-like forms on Mars. The Cryosphere, 8(6), 2047-2061.

Hubbard, B., Milliken, R. E., Kargel, J. S., Limaye, A., & Souness, C. (2011). Geomorphological characterisation and interpretation of a mid-latitude glacier-like form: Hellas Planitia, Mars. Icarus, 211(1), 330-346.

Janke, J. R., Bellisario, A. C., & Ferrando, F. A. (2015). Classification of debris-covered glaciers and rock glaciers in the Andes of central Chile. Geomorphology, 241, 98-121.

Tanarro, L. M., Palacios, D., Fernández-Fernández, J. M., Andrés, N., Oliva, M., Rodríguez-Mena, M., Schimmelpfennig, I., Brynjólfsson, S., Sæmundsson, Þ., Zamorano, J.J., Úbeda, J. and ASTER Team. (2021). Origins of the divergent evolution of mountain glaciers during deglaciation: Hofsdalur cirques, Northern Iceland. Quaternary Science Reviews, 273, 107248.

4. The methods need some clarification so the reader fully understands the data and methods used. Namely:

a) Demonstrate the difference to other alcove forming processes on Earth up front by integrating Table 6 on page 15 and removing section 5.6. This provides additional justification for the down-selection using the alcove morphometrics and frees up space in the discussion.

Following the reviewer's recommendation, we moved Table 6 to page 15, so that it is now Table 2. In addition, we deleted section 5.6. We added the following text to page 15 as well: "By using morphometrics, we also exclude other types of mechanisms for alcove formation, including active-layer detachments, deep-seated landslides, and theater-headed valleys (Table 2). This is because the H/L ratio of a terrestrial glacial cirque is expected to be deeper than any of the other alcove landforms with known morphometrics on Earth (Table 2)."

b) Clarify the data used to make the initial alcove classification (e.g., simple, joined, staircase, etc). Longitudinal profiles are included in Figure 4 which presents the classification, yet it is not explicitly stated that they have been used to inform the classification and what attributes of them were used. If they were indeed used then section

3.2.3 which speaks to the effect on the long profiles in the uncertainty of the elevation data used, makes more sense. The authors should make sure to update this section to incorporate the effect of the elevation uncertainty on each attribute they list in the methods as being critical for the classification, as well as comment c below. A similar point was raised in the previous review, but the manuscript not changed in response.
Longitudinal profiles were not used to classify the alcoves. Following the reviewer's #5 comment, we moved Figure 4 to the Supplementary Material Section as Figure S1.

c) when considering the uncertainties in the elevation data in section 3.2.3 please address how these may also affect the ACME data collection, specifically consider the noise in the HRSC product (clearly visible as step-artefacts on Figs 4 and 6), and how well the CTX and HRSC data were co-registered. Noise is accentuated in topographic derivatives such as slope, which is amongst the parameters extracted. Presumably the position of the long profile was determined based on the CTX image data (if this or is not the case then it should be described in the methods as mentioned in point b), hence co-registration is critical to have reliable and representative elevation data. Please state what projection system was used for the morphometric analyses and consider whether this introduced any uncertainties/distortion (including the slope calculation from the HRSC DTM).
We added the following text to what is now section 3.2.3 "Uncertainties in elevation and alcove longitudinal profile": We mapped the cirque-like alcove and identified the mid-threshold point using the CTX imagery. As mentioned in Section 3.1, both the CTX imagery and HRSC DEM were aligned to a Sinusoidal projection centered on longitude 25.5 degrees East, and were based on the IAU Mars 2000 Sphere datum. Any misalignment of up to 100 m between the image and the DTM is of little concern when it translates into metrics made by ACME2 since most metrics rely on multiple pixel measurements. This is certainly the case for slope, aspect and average elevation along the cirque length or the entire cirque area. Any misalignment might affect minimum and maximum elevation, but this is not a concern when using a large sample size to evaluate population-scale metrics."

d) How the different ice-related-morphologies were recognised in the HiRISE images should be explained in the methods, with references to support their ice-related-origin. The results of this work should be in the results and then this frees up space in the discussion.
We added Table 3 in the methods section 3.3 to explain ice-related-morphologies and Table S1 in the Supplementary Material Section to demonstrate the associated HiRISE frames with these features. We also provide Table 5 to demonstrate the percentage of HiRISE and CTX imagery with each type of icy geomorphic feature. The tables are included below in response to the specific comments.

5. Further, the inclusion of all the alcoves types in the methods and in the first part of the results makes the paper bulky and are unnecessary as these results are not used to support the main conclusions. I strongly suggest omitting them. In the methods it can simply be

stated that “alcoves that show any of the following morphologies [bulleted list of properties of joined, staircase, channel, etc], were not included in our database”. I understand that work was done by the authors to map these landforms, but this is not a masters’ thesis where one has to demonstrate how much work was done, and so I do not think this is adequate justification to include them in the paper.
An earlier version didn’t include these in the results but they were added back in by request from other reviewers. However, we agree with this reviewer’s suggestion, and what was previously section 4.1 describing all alcoves was deleted, along with the associated figure.

6. The objective distinction between what was previously mapped as GFL and the alcoves mapped by the authors is not clear to me. It seems that many of the alcoves mapped by the authors contain GLF missed in this previous survey and as demonstrated in the HiRISE survey many of the alcoves contain deposits that have one or more ice-related morphologies (these need to be tabulated somewhere, as noted in my detailed comments) which could be the extension of the VFF up into the alcove (I am talking about the visible extension of VFF as can be seen on images and not mapped outlines, which are never totally reliable as they are usually made using low resolution image bases suitable for global studies – not meant to be looked at “in detail”). Global surveys are often incomplete so this statement is not a criticism of the previous work. I think the back and forth discussion when comparing the GLF and cirque-like alcove distribution would become clearer if these landforms were treated as a continuum. This is a similar comment to that raised in previous review point 3 and was not addressed by the authors by a change to the manuscript.
We addressed these comments by splitting the discussion section up into three sections in the methods (3.3), results (4.3), and discussion (5.2.1). The associated text, tables, and figures are included in the response to comments for page 33.

Detailed comments (please refer to PDF for placement as no line numbers were included)

Page2:
***please include references for each of these types of ice, especially because subsurface ice captures debris covered ice, so the distinction that is trying to be made is not clear
We edited the sentence on lines 36-37 to read as follows: “The surface morphology of the mid-latitudes of Mars (especially between 30 and 60°, north and south) is characterized by glacial remnants in the form of subsurface ice (Fig. 1; e.g., Brough et al., 2019; Levy et al., 2014), and icy mantling deposits (Mustard et al., 2001).”

***it is not clear for a general reader why this is "in addition" to the previous sentences that point to evidence of wet-based glaciation, so make it clearer this is also being used to make that case or remove
We removed “in addition” on line 47.

***suggest being more specific and saying "where ground penetrating radar data are exploitable"

We edited the sentence on lines 56-57 to read as follows: “In the cases where subsurface radar sounding data are available, lobate debris aprons consist of up to ~90% of ice…”

***this is vague, be more specific

The sentence now reads as follows on lines 61-62: “All mid-latitude viscous flow features are believed to have been deposited during orbital excursions of ≥45° in the Amazonian (Madeleine et al., 2009) and to have been cold-based (e.g., Head and Marchant, 2003).”

Page3

***not a good citation for the LDM and not in reference list

The Conway et al. 2018 reference was removed from that sentence and added to the reference list since it is mentioned later.

***this is vague, be more specific

More specificity was added on lines 69-70 as follows: “The latitude-dependent mantle consists of different layers rich in water ice and dust (Schon et al., 2009). The ice was deposited during high obliquity excursions and the dust formed during low obliquities when the ice sublimated and left behind a dusty lag (Schon et al., 2009).”

***not in reference list

We added Conway and Balme (2014) to the reference list.

***not good refs for the age, better: Schon et al PSS 10.1016/j.pss.2012.03.015 Willmes et al PSS 10.1016/j.pss.2011.08.006

We changed the references for age to the recommended papers on line 76.

Page 4

***this text should appear after the first sentence as it applies to both panels a and c.

Following the reviewer’s suggestion, we moved the text to after the first sentence on line 80.

***place with text describing legend items, above

Following the reviewer’s suggestion, we moved the text about “Green filled polygons” to follow the third sentence of the caption.

***missing space

We added a space between at and 41.5 on line 86.

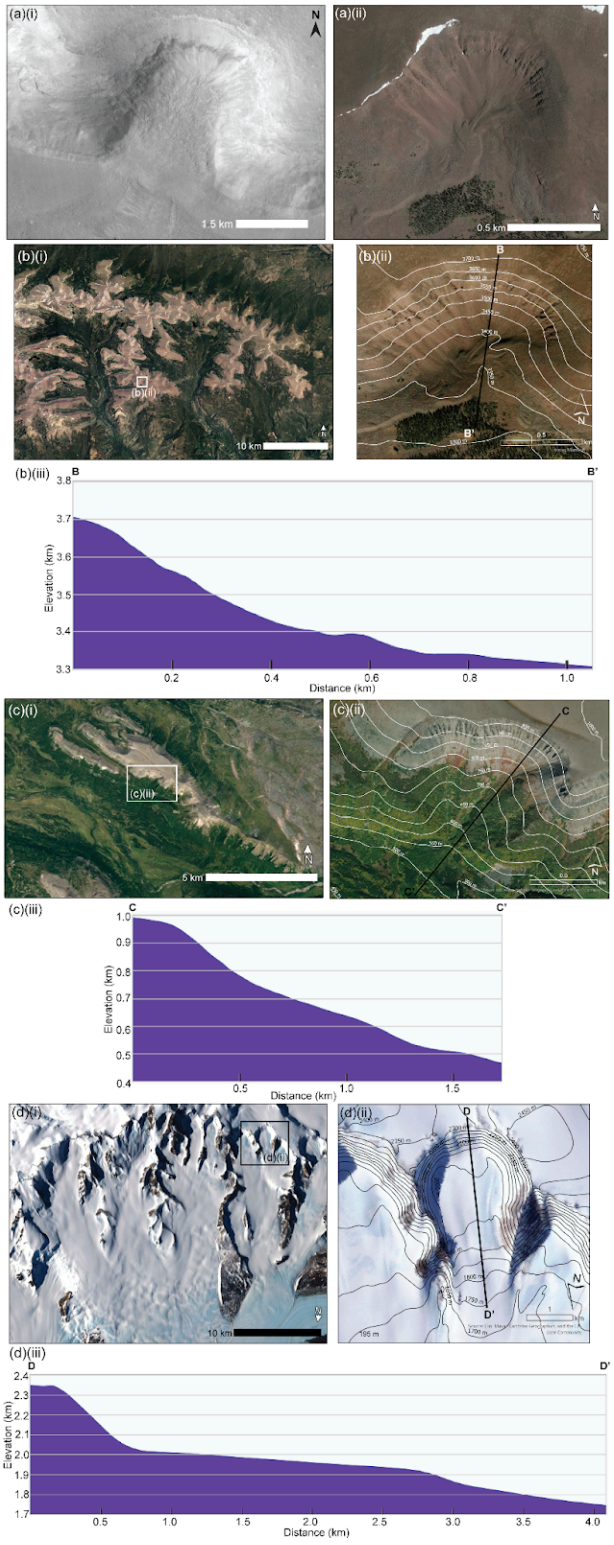
***This section is not convincing. There is no good evidence presented that cold based glaciation cannot create cirques. We do not observe them on Earth because currently cold based glaciers hide them and any currently exposed cirques have experienced warm-based conditions at some point confusing the signal. On Mars there is a lot of time to do geomorphic work because of the lack of plate tectonics and active hydrosphere/biosphere, so "it takes too long" is not a good reason to throw out cold based glaciation. I think simply ignoring the uncertainty is dishonest to the reader. It also sets a precedent for future works to use cirques as "proof" of wet-based glaciation on Mars or other planets.
I don't disagree that terrestrial cirques are generally associated with wet-based glaciation, but this does not prove that cold-based glaciers cannot make them. In order to use these as evidence of wet-based glaciation on Mars or even suggestive of wet-based glaciation on Mars there needs to be solid proof that water is needed to form cirques on Earth, which to my knowledge does not currently exist in the literature.
I think all this paragraph should be in the discussion and not the introduction
We moved this paragraph to discussion section 5.4.

Page 5
***it would be useful to mention briefly what processes contribute to cirque growth/formation, see the nice summary in the intro of this paper:
https://journals.openedition.org/geomorphologie/13057
NB: this paper also highlights that not everyone thinks that cirques are principally glacial, I am not saying the weight of evidence is on their side (e.g. Evans ESurf 2020), I am just saying it is better to acknowledge that cirque origin is not a completely "solved problem"
Following the reviewer's recommendations, we edited the sentence to read as follows: "Cirques develop from incipient depressions in mountain and plateau sides that fill with snow/ice and over time support active, wet-based glaciers that deepen the depressions by glacial erosion (Evans and Cox, 1974; Glasser and Bennett, 2004) via a combination of plucking, abrasion (e.g., White, 1970), and frost weathering (e.g., Sanders et al., 2012), though it is debated whether non-glacial processes such as rock-slope failures may have a substantial contribution to erosion as well (e.g., Turnball and Davies, 2006; Coquin et al., 2019; Evans, 2020)."

***move to discussion
We moved the following sentences to Section 5.4 starting on line 626: "If these martian alcoves are analogous to terrestrial glacial cirques, then they may have formed either during an earlier wet-based phase at the scale of an active glacier-like form, or formed during a prior cold-based glacial cycle separate from the glacier-like forms, such as when lobate debris aprons formed."

Page 6

***the colour-keyed DEM is not very useful to show the form, I suggest using the air image (as this approximates the CTX most closely) with contour lines. Or use the hillshaded+colourised DTM and another panel to show the actual image of the cirque
We edited the figure to use contour lines, following the reviewer's suggestion:



Page 8

***all panels have a north arrow, just delete this text

This text was deleted following the reviewer's suggestion.

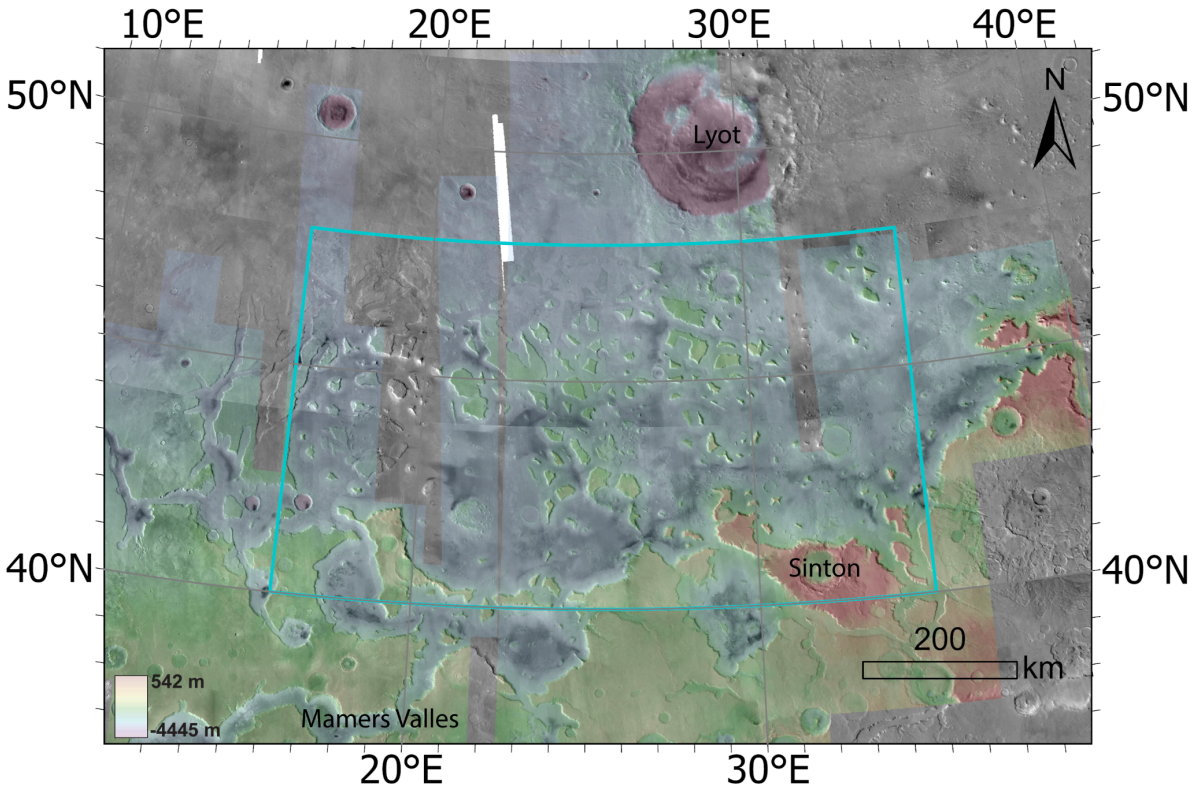
***Russia

We corrected the text to Russia on line 144.

Page 9

***please add longitude labels on bottom axis because the longitude lines do not run straight up-down so the top labels cannot easily be linked to the bottom

We added longitude labels on the bottom axis and latitude labels to the right. We also added gridlines. The figure now looks as follows:



***can be deleted, redundant with legend

The text was deleted.

***white rectangles are extremely hard to see, make more visible

We edited the text to read as follows: “The white sections on the top left show where the CTX beta01 mosaic does not have coverage and grayscale areas of the map show where the mosaicked HRSC DEM does not have coverage.”

***please state the version of the CTX mosaic that was used

We included the version as follows: “We mapped ~2000 alcoves at a 1:30,000 scale using the ~6 m/pixel Context Camera imagery beta01 mosaic (Malin et al., 2007; Dickson et al., 2023a). ”

***please state how this mosaicing was done and how the alignment between HRSC and CTX was managed (or not) and if it was not please say how much the mismatch was and therefore the inaccuracy on the placement of your profiles. to assess the mismatch it is easiest to use the orthorectified ND4 image and the CTX mosaic. Note the CTX mosaic is not controlled, so is unlikely to align properly with the HRSC which is controlled at level 4.
We added the following sentence at the end of Section 3.1 to explain how mosaicking was done in ArcGIS Pro: “The HRSC DEMs were mosaicked together using the Mosaic to New Raster tool in ArcGIS Pro.” We addressed any mismatch between the HRSC and CTX in our response to 4c) above.

Page 10
***please list the images used in your data availability statement
We edited the statement to read as follows: Where available, we used ~25 cm/pixel High Resolution Imaging Science Experiment (HiRISE; McEwen et al., 2007) images to examine glacial geomorphic features within and next to the alcoves, which are listed in the Data Availability section.

In the Data Availability section, we added this sentence: “The HiRISE frames that we examined for icy geomorphic features included the following: ESP_041934_2265, ESP_040853_2275, ESP_036844_2225, ESP_036580_2260, ESP_036514_2210, ESP_026941_2275, ESP_025873_2230, ESP_025781_2220, ESP_025477_2280, ESP_025253_2245, ESP_023618_2270, ESP_023605_2205, ESP_019768_2220, ESP_019214_2270, ESP_016748_2255, ESP_016471_2260, ESP_016247_2270, ESP_016194_2260, ESP_067108_2240, ESP_060013_2250, ESP_057877_2245, ESP_056004_2255, ESP_055872_2270, ESP_055661_2230, ESP_054527_2225, ESP_053762_2280, ESP_052826_2240, ESP_052681_2240, ESP_052417_2220, ESP_050558_2245, ESP_048949_2230, ESP_046853_2200, ESP_046220_2235, ESP_046075_2200, ESP_046022_2265, ESP_043688_2245, ESP_025319_2240, ESP_016959_2240, ESP_027574_2245, ESP_035011_2240, PSP_006147_2250, ESP_068441_2230, ESP_033745_2270, ESP_035156_2220, and ESP_028418_2240.”

***these classes were determined using the image data only? if so explicitly say so. If not say what other data was used and how.
Yes, these classes were determined using the image data only. We edited the sentence to read as follows: “Based on their kilometer-scale physical characteristics including shape,

size, and associated landforms as seen in CTX imagery,, we classified our population of mapped alcoves into seven broad classes: a) simple, b) joined, c) interiorly ridged, d) staircase, e) channel-related, f) branching (Fig. 4).”

***In the figure the longitudinal profiles are included, but in the table the longitudinal profile characteristics are not cited.
The longitudinal profiles are included in the figure for the reader to reference, but are not actually used for distinguishing the different classes in the table. We removed this figure from the Methods and moved it to the Supplementary Material Section following the reviewer’s #5 comment.

Page 12
***please state what the i and ii panels mean before getting into the descriptions
The following sentence was added in the caption on line 201: “For each alcove class, panels (i) on the left correspond to an image example, and panels (ii) on the right correspond to an example of the profile.”

***there is no b-ii in my version
The sentence was deleted.

***ridges not visible in elevation data
The ridges are too narrow (<50 m) for the resolution of the elevation data (resolution ~50-100 m).

Page 13
***colourised elevation
Following the reviewer’s suggestion, the word colorized was added to the sentence.

***elevation values
Following the reviewer’s suggestion, the word elevation was added to the sentence.

***make clear if this is in in addition to the number above it, or subsampled from it (perhaps in the caption as *)
The parenthesis was edited to read as follows: “(and subsampled number that fit in multiple classes).”

Page 15
***this is the first time craters are mentioned as possible origins for these features. However, craters on the lip of the slope are highly unlikely to have the same morphology as craters on the plains, so this comparison is invalid and does not rule out that these are craters. This

perhaps should be something in the discussion, at least should be mentioned whenever this comparison is brought up

We edited the third paragraph of the Section 5.1.2 to include a discussion of impact cratering for alcove initiation as follows: “While it is likely that multiple processes contributed to the incipient form of a cirque-like alcove like those mentioned in Table 2, we suggest that the morphometrics and conditions observed eventually require substantial glacial erosion. For example, for impact cratering, while glacial geomorphic features may override any signature of impact ejecta, it is very unlikely that similarly sized impacts all happened to occur along mesa edges. Instead, it is more likely that cratering would occur in stochastic sizes and locations. Ultimately, we acknowledge that these other processes likely contributed to at least some erosion of cirque-like alcoves, but the prevalent glacial geomorphic features and consistently sized features are what correspond most to glacial erosion.”

***specify you downsampled from (1266 - 81) which were considered similar to cirques based on image analysis only

We followed the reviewer’s recommendation and changed the sentence to read as follows: “By applying these constraints, we were able to identify 456 most cirque-like alcoves after downsampling from our initial mapping and classification based on only image analysis of 1991 alcoves.”

Page 16

***Fig 5 really doesn't show this

We deleted the reference to Fig 5.

***simply state "by using standard circular statistics calculation methods"?

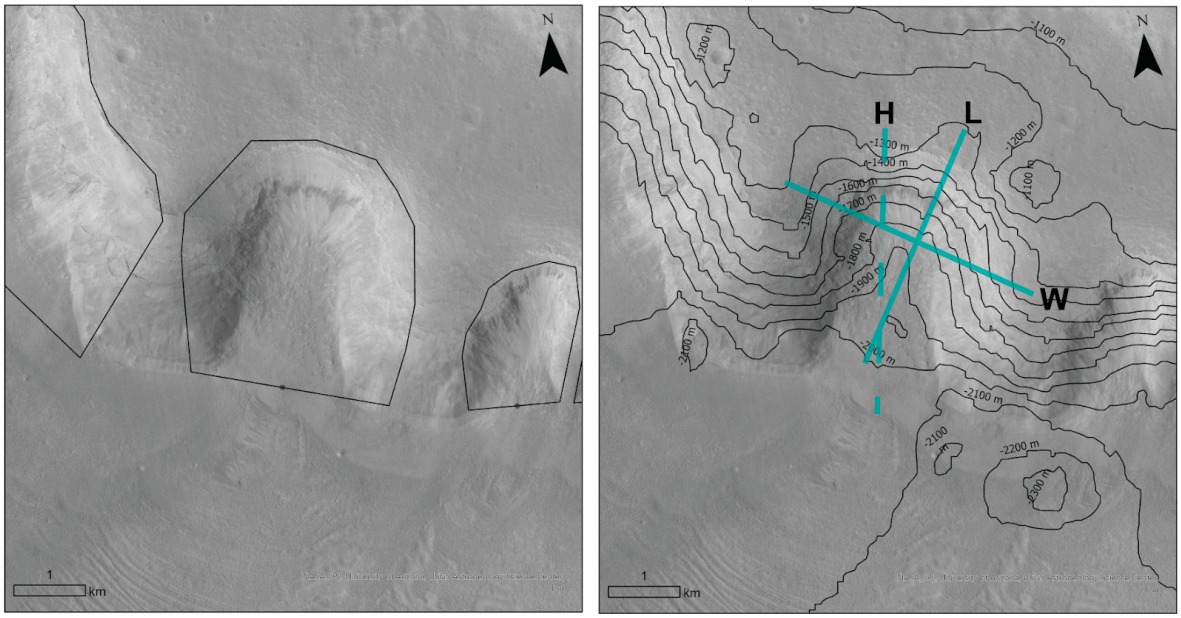
We changed the statement to read as follows: “Mean of all pixel aspects across the entire surface of alcove by using standard statistical calculation methods for circular features.”

***Fig 5 the "H" line is misleading in planview, use a different line colour or use points.

We changed the “H” line so that it is dashed instead of solid.

include the contour lines and labels so it can be seen that "H" is the difference between the max and min height, and the min is not necessarily at the point where L starts, i.e. the midpoint

We added contour lines and labels to the figure:



Page 17

***Figure 6 seems to show a lot more uncertainties than discussed here. Please add discussion on the noise of the HRSC DTM and the resolving power as demonstrated with the comparison with CTX (I note here that you must make sure these two datasets are spatially aligned to make this comparison valid)

We added a paragraph to section 3.2.3, which we provided in our response to the first comment on page 15.

***the longitudinal profile is not used to decide on which alcoves are included in the study, as far as I understand from the text (which if I am mistaken please correct the text), but the elevation data are, so please instead discuss the effects of the elevation data uncertainty on the measurements made by ACME2, which are used to downselect the data further

We added this paragraph to section 3.2.3: “We mapped the cirque-like alcove and identified the mid-threshold point using the CTX imagery. As mentioned in Section 3.1, the CTX imagery and HRSC DEM were aligned to a Sinusoidal projection centered on longitude 25.5 degrees East, and were based on the IAU Mars 2000 Sphere datum. Any misalignment of up to 100 m between the image and the DTM is of little concern when it translates into metrics made by ACME2 since most metrics rely on multiple pixel measurements. This is certainly the case for slope, aspect and average elevation along the cirque length or the entire cirque area. It might affect minimum and maximum elevation, although any effect should be evened out by the large sample size.”

***this should be recorded as an attribute and presented as a result.

We changed the sentence to read as follows: “However, in some cases, we do not see the threshold because of low DEM resolution or because the feature may be covered by other material (Section 4.3).” Section 4.3 now reports the percentage of cirque-like alcoves that were observed to have icy geomorphic features.

Page 18
***save interpretation for after the results are presented
We deleted the text “from glacial erosion.”

***given the steps in this profile that clearly do not exist in the images, it casts doubt on the "overdeepening" being a real signal or an artefact like the steps.
We added the word “potential” in front of overdeepening and added that it is hard to discern with the current resolution: “Example of the longitudinal profile of a mapped alcove using the HRSC DEM that includes the potential overdeepening (difficult to discern at this resolution).”

Page 19
***briefly say what methods were used and how it was controlled to the HRSC data in sect 3.2.3
This sentence was added to the end of Section 3.1: “Measurements from all of the imagery and DEMs used a Sinusoidal projection centered on longitude 25.5 degrees East, and were based on the IAU Mars 2000 Sphere datum.”

In addition, we added the following sentences in Section 3.2.3: “For comparison to the HRSC DEM, we include a CTX DEM generated by the GALE lab at UCLA using the Ames Stereo Pipeline (Beyer et al., 2018; Fig. 6).”

***did you do circular statistics to calculate this? in essence this means the alcoves are in all orientations? Aspect would be better shown as a rose diagram or histogram
Following the reviewer’s suggestion 5), this section was deleted.

***15°
Following the reviewer’s suggestion 5), this section was deleted.

***this would have to be done using circular statistics
Following the reviewer’s suggestion 5), this section was deleted.

Page 21
***explain the symbology, i.e. what is the blue box, the organe line, what are the circles, what are the whiskers…

Following the reviewer's suggestion 5), this section was deleted.

***a first result should really be a map of where they are , i.e. fig 11
We replaced what was previously fig 11 with what is now Fig. 6:

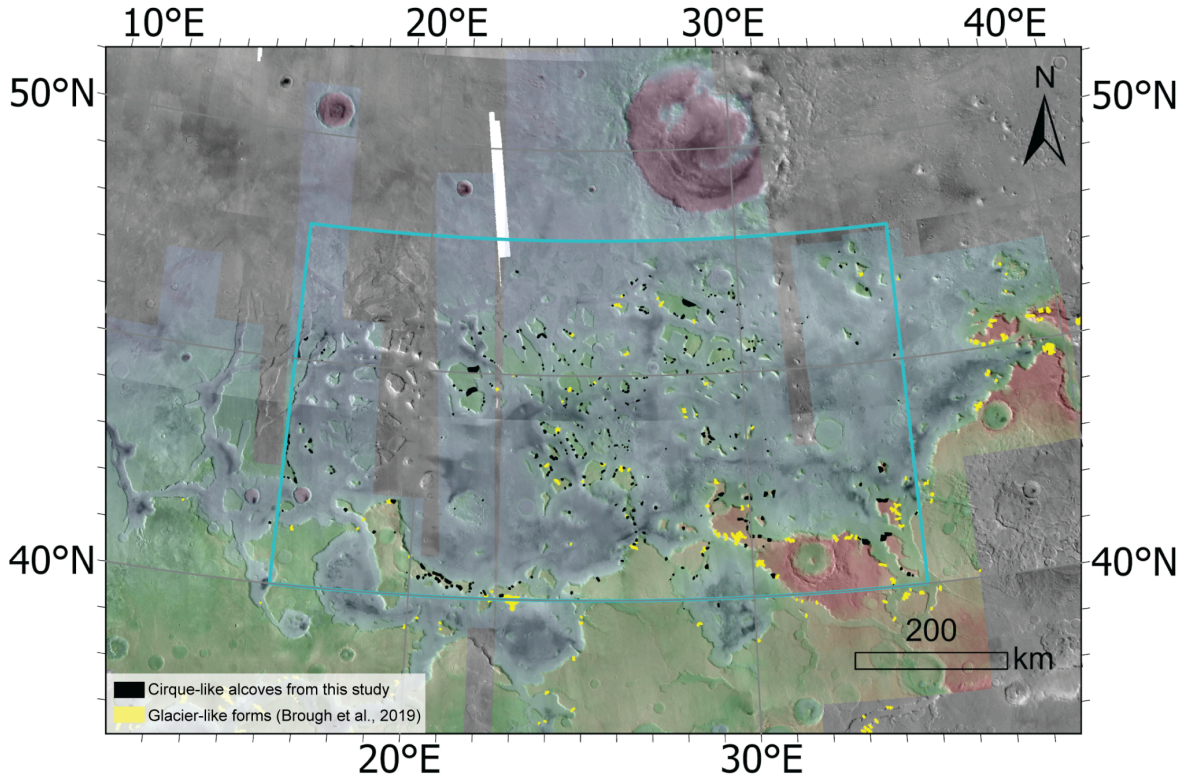


Figure 6. Distribution of 456 cirque-like alcoves and 74 glacier-like forms in the study region Deuteronilus Mensae. Note that while some glacier-like forms (Brough et al., 2019) exist outside of the teal boundary lines, they are not included in the analyses reported in this study.

***are located at
We accepted this change and changed it as suggested.

***throughout the first paragraph of section 4.2 (and in the remaining sections) make sure that the term "alcoves" is not used to mean cirque-like alcoves because otherwise the reader becomes confused as to which group of data is being discussed.
We address this concern by adding "cirque-like" in section 4.2 and other sections to clarify when we are referring to cirque-like alcoves.

***please mention how this was calculated (in methods if it takes more than one sentence to explain, then refer to methods from here)

The following sentences were added in Table 1 of the Methods section: “We also found the relative percentages of cirque-like alcoves in each aspect bin after normalizing by the percent of the total land surface in each aspect bin. We did this by converting the HRSC DEM raster to points, finding the aspect for each point, and calculating the land surface percent that belonged to each aspect bin. We then divided the percent of cirque-like alcoves in each aspect bin by the land surface percent bins and got the normalized percentages.”

In the caption for Figure 6, we edited part (b) to read as follows: “Rose diagram showing the relative percentages of cirque-like alcoves in each aspect bin after normalizing by the percent of the total land surface in each aspect bin (we explain the method in Table 1). After normalizing, we found that the same southeastward trend persisted.”

Page 24

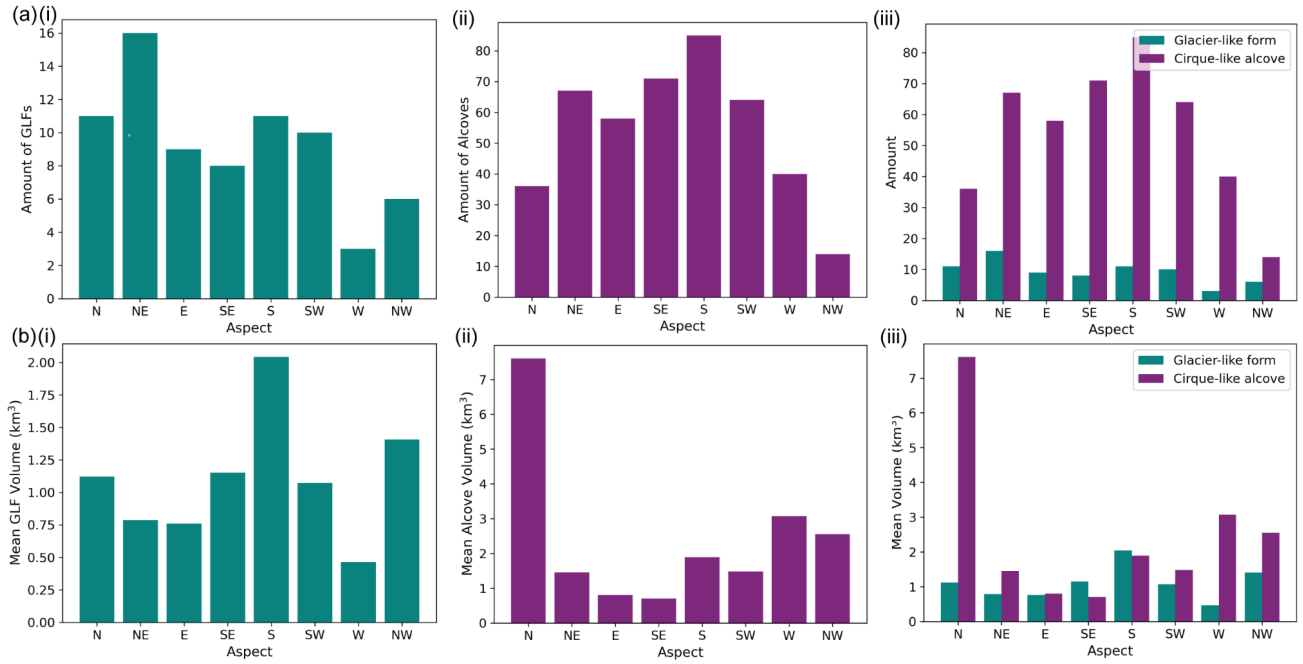
***Fig 11 is not super-easy to understand without the topography/image mosaic for context. It also needs to be a lot bigger (fill page width)

We replaced what was previously Fig 11 with Fig 6, which now includes both the topography and image mosaic for context. The figure is in the response to the second comment on page 21.

Page 25

***stacked bar charts are really hard to interpret, put bars side-by-side?

We edited the bar charts so that they are now side-by-side:



***this section contains a mix of methods, observations, results and interpretation, please add a methods section to describe the morphologies, then results to summarise them, and then this section can be limited to interpretation

We are grouping our response to this comment with the next one below.

***In general, this section is long and hard to follow. There is a lot of speculation and discussion about each landform and it is hard to follow what the authors are arguing for. Each landform has many possible interpretations and discussing every one in turn in detail makes it really hard to understand why the authors are even focussing on these "details". I strongly suggest cutting back this text and organising it differently. If the only point that is trying to be made in this section is that the 9% of cirque-like alcoves with HiRISE coverage a large percentage (how many total is not clear) of the alcoves are filled with some kind of icy materials then this can be a lot shorter (which I interpret is the main message).
A section should be added to methods to describe how the following features were recognised and citing previous literature to say BRIEFLY how they are known to be icy materials:
1. crevasses/washboard, 2. Lineations 3. polygons etc

The Methods now include the following section:

3.3 Criteria for identification of icy geomorphic features

In addition to mapping and calculating the morphometrics of alcoves in Deuteronilus Mensae, we also evaluate the presence of icy geomorphic features in the alcoves where HiRISE imagery is available. While we designed the study so that none of the cirque-like alcoves that we mapped included mapped glacier-like forms, using the available inventory of HiRISE images we observed other features associated with the cirque-like alcoves that appear consistent with the presence of ice or ice loss. The icy geomorphic features that we evaluate for in HiRISE images include flow features, linear terrain, mantle, moraine-like ridges, mound-and-tail terrain, polygonal terrain, moraine-like ridges, rectilinear-ridge terrain, and washboard terrain. We identify these features using the criteria listed in Table 3. Other icy geomorphic features that were observed nearby alcoves but not categorized in this study because they were not directly in or connected to features coming out of alcoves included brain terrain (Levy et al., 2009a) and pitted terrain (Jawin et al., 2018). We note that the icy geomorphic features that we identify may correspond to some of the criteria defined by Souness et al. (2012) for mapping glacier-like forms, which include: 1) surrounded by topography indicative of flow around obstacles, 2) distinct from the surrounding landscape in texture or color, 3) surface foliation indicative of down-slope flow, 4) L/W ratio > 1, 5) discernible head or terminus, 6) appear to contain a volume of ice. However, the icy geomorphic features noted here do not include all of the criteria and were not mapped as glacier-like forms. For example, an icy feature within an alcove might appear to have a terminus, but no convexity from existing ice volume that differentiates it from surrounding topography (Fig. 6).

Table 3: Icy geomorphic features with their descriptions, proposed formation, and references.

Icy Geomorphic Feature	Additional Names	Description	Terrestrial Analog	Proposed Formation Mechanism	Select References

Flow features	N/A	Troughs and ridges	Same	Formed by downslope flow and deformation	Hubbard et al., 2011; Souness et al. 2013
Linear terrain	If supraglacial: longitudinal foliation	Parallel raised ridges, bumpy in appearance	If supraglacial: flow stripes, longitudinal foliation	If supraglacial: Caused by deformation of ice as it flows; can be due to compressed, accelerating flow	Hubbard et al., 2011; Conway et al., 2018
	If subglacial: pasted-on terrain		If subglacial: megalineation,, striations	If subglacial: Ice flow over water-lubricated sediment	
Mantle	Latitude-dependent mantle, thicker version is commonly known as pasted-on terrain	"Raised curvilinear edge for the upslope boundary" (Khuller et al. 2021)	N/A	Airfall of ice on dust; sublimation of lag protects ice deposits	Mustard et al. 2001; Christensen et al., 2003; Conway et al., 2018; Khuller et al. 2021
Moraine-like ridge	Moraine ridge	Ridge of debris	Terminal moraine	Dumping, squeezing, and pushing of debris by a glacier	Arfstrom and Hartmann, 2005
Mound-and-tail terrain	N/A, similar to linear terrain	Steep upglacier-facing core with a shallow elongate tail; typically 30-50 m long, 10-30 m across, and 2-4 m high	Closest to drumlins	Subglacial bedforms formed from subglacial sediment moulding and/or deposition beneath wet-based ice masses	Hubbard et al., 2011
Polygonal terrain	Polygonized terrain and scaly terrain (we group the two together here under the term "polygonal" terrain); mantle polygons	Polygonized terrain: ~10° slope, 5-10 m across, tessellating polygons; Scaly terrain: 12-16° slope, 10-20 m across, tessellating polygons	Periglacial patterned ground	Frost heave and thermal contraction cracking	On Mars: Hubbard et al., 2011; Levy et al., 2009b; Soare et al., 2022 On Earth e.g.,: French, 2018; Marchant and Head, 2007

Rectilinear-ridge terrain	Push moraines	Series of ridges tens of meters across and 2-3 m high, elongated in an arc parallel to former glacier terminus	Thrust-block moraines, push moraines, moraine-moun d complex	Basal debris thrust up from the glacier bed, basal crevasse fills, or ice-contact outwash deposits	On Mars: Hubbard et al., 2011 On Earth e.g.,: Hambrey et al., 1997; Sharp, 1985; Lukas, 2005
Washboard terrain	Crevasse-like features	Transverse scarps, commonly at the base of a steep slope	Crevasses, bergschrunds	Formed from debuttressing and oversteepening of ice on slopes	Hubbard et al., 2011; Jawin et al., 2018; Jawin and Head, 2021

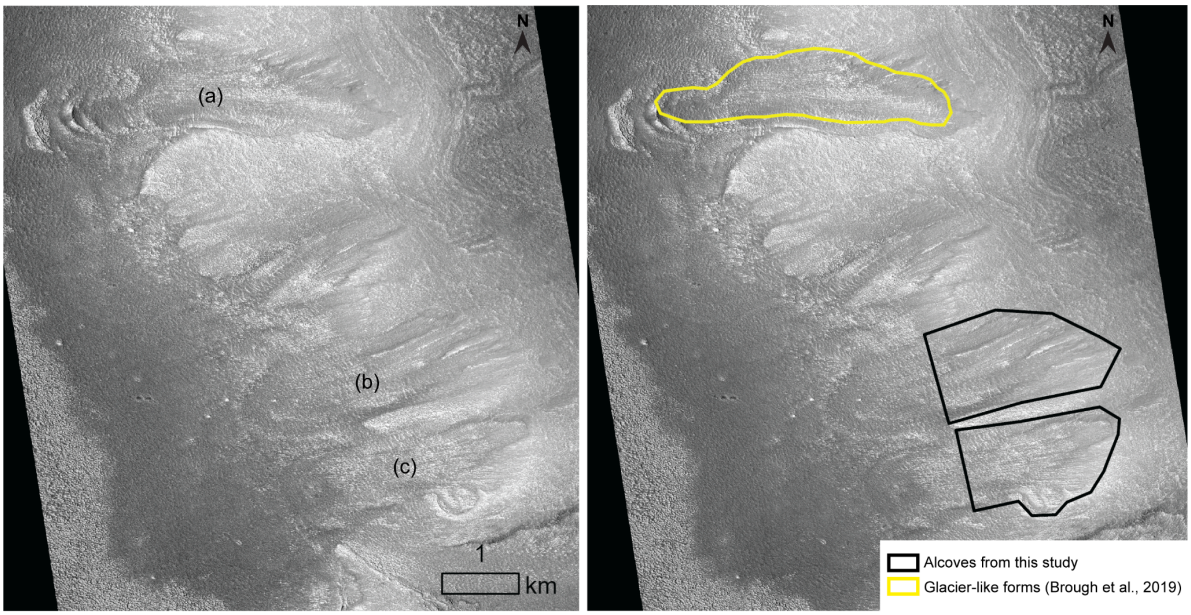


Figure 6: (a) Previously mapped glacier-like form (Brough et al., 2019). (b) and (c) represent previously unmapped cirque-like alcoves no longer appear to contain a volume of ice and raised moraine-like ridge at the terminus. However, they still do contain surface foliations suggesting down-slope flow near the headwall. Cirque-like alcove mapping only extends to where the sidewalls end. This HiRISE image ESP_025873_2230_RED is centered at 42.63°N, 25.02°E. HiRISE data credit: NASA/JPL/University of Arizona.

Then a section in the results saying the percent of the alcoves that have one or more of these and then the separate percentages (with table containing the alcove ID, HiRISE Id, lat/long and features identified).

The new results section now reads as follows:

4.3 Icy geomorphic features identified

In addition to morphometric observations, we identified geomorphic features in association with the cirque-like alcoves as consistent with either remnant or active ice in order to evaluate aspects of the glacial history in the cirque-like alcoves. Using the criteria stated in Table 3, we identified flow features, linear terrain, mantle, moraine-like ridges, mound-and-tail terrain, polygonal terrain, rectilinear-ridge terrain, and washboard terrain in available HiRISE imagery. Out of 435 cirque-like alcoves, there was complete overlap in available HiRISE frames with 26 cirque-like alcoves (8%) and partial overlap with only 10 cirque-like alcoves (1%). In CTX imagery, we were also able to identify flow features, linear terrain, mantle, moraine-like ridges, and washboard terrain. However, at the CTX resolution, it was more difficult to identify features such as mound-and-tail terrain, polygonal terrain, and rectilinear-ridge terrain. For both HiRISE and CTX imagery, the linear terrain and mantle were the two most common features. We provide the percentages of each feature in both HiRISE and CTX imagery in Table 5 and the specific features and HiRISE frames associated with each in Table S1.

Table 5: Percent of HiRISE and CTX imagery with each type of icy geomorphic feature.

Icy Geomorphic Feature	Percent of HiRISE imagery (%)	Percent of CTX imagery (%)
Flow features	8	9
Linear terrain	81	57
Mantle	58	90
Moraine-like ridges	14	5
Mound-and-tail terrain	6	N/A
Polygonal terrain	53	N/A
Rectilinear-ridge terrain	3	N/A
Washboard terrain	42	2

Fig. 12 provides examples of washboard terrain, linear terrain, rectilinear ridges, and polygonal terrain, which all correspond to the presence of ice and/or ice loss, as described in Table 3. In Fig. 12, the linear terrain extends out from the washboard terrain at the base of the cirque-like alcoves (Fig. 12). The rectilinear ridges are downslope of both the washboard terrain and linear terrain. The polygonal terrain is between the two sections of linear terrain (Fig. 12f). In addition, the polygonal terrain is observed farther downslope of the rectilinear ridges (Fig. 12f).

Approximately 14% of cirque-like alcoves with HiRISE imagery coverage have moraine-like ridges. Fig. 13 contains examples of moraine-like ridges. Fig. 13b also shows additional examples of moraine-like ridges downslope of alcoves (that are not all cirque-like), with along-flow linear terrain between the alcove headwall and the moraine-like ridge. As in Fig. 12, washboard terrain, linear terrain, and polygonal terrain are all present.

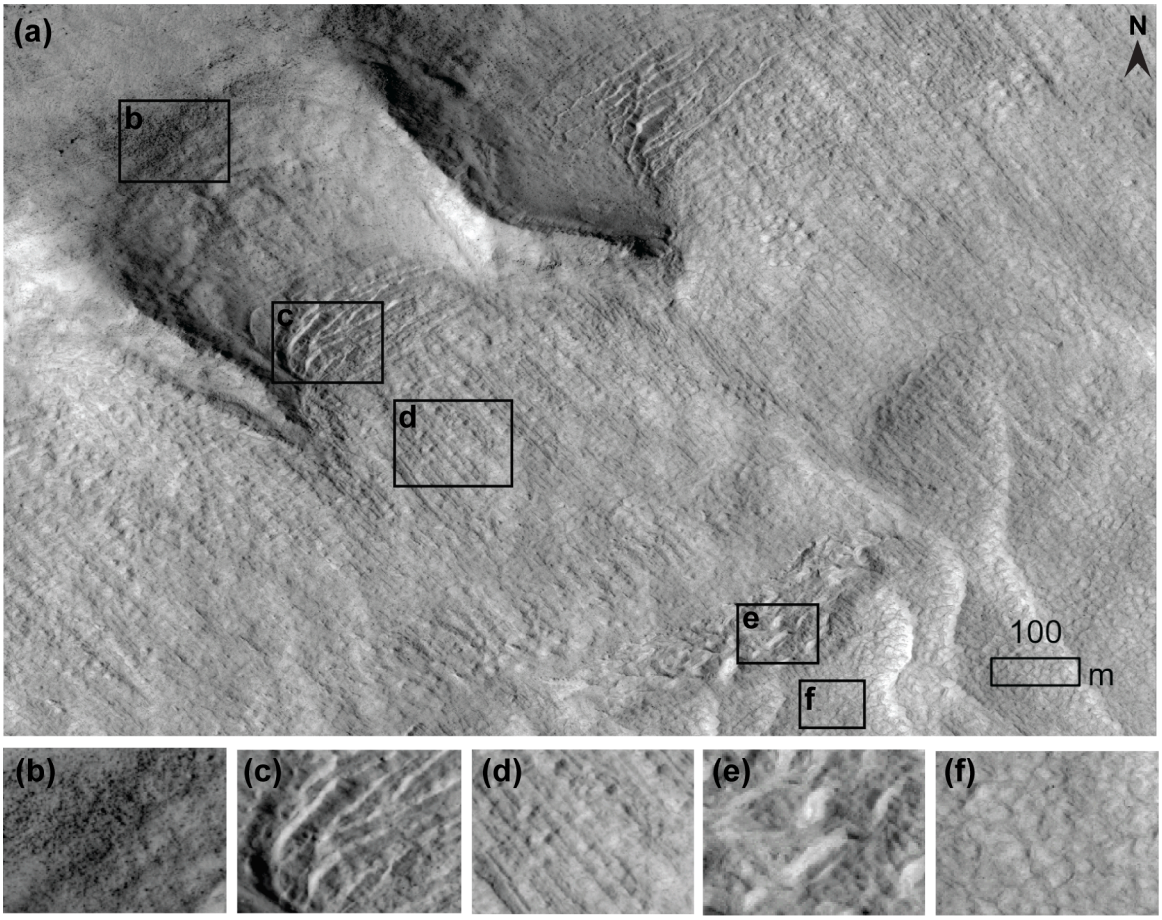


Figure 12: a) Cirque-like alcove with evidence for remnant ice centered at 46.57°N, 22.12°E, 46.57°N in HiRISE image ESP_019214_2270_RED. b) Boulders near the top of the headwall indicating erosion. Features corresponding to ice-loss include the following: c) washboard terrain (Jawin and Head, 2021), d) linear terrain, e) rectilinear ridges (Hubbard et al., 2011), and f) polygonal terrain. (e.g., Levy et al., 2009a; Hubbard et al., 2011).

Table S1: Icy geomorphic features identified in cirque-like alcoves using available HiRISE frames.

Alcove ID	HiRISE ID	Coverage	Latitude, Longitude	Icy geomorphic features identified
50	PSP_007439_2205	Partial	40.18°N, 24.72°E	Linear terrain, mantle, mound-and-tail terrain
56	ESP_072529_2265	Partial	40.29°N, 23.00°E	Mantle
57	ESP_072529_2265	Full	40.26°N, 22.98°E	Mantle
145	PSP_008810_2225	Full	41.85°N, 26.36°E	Polygonal terrain, mantle
572	ESP_067108_2240	Partial	43.70°N, 27.92°E	Mantle
631	ESP_068441_2230	Full	42.63°N, 25.30°E	Linear terrain, mantle, washboard terrain

637	ESP_025873_2230	Partial	42.76°N, 25.06°E	Linear terrain
650	ESP_054527_2225	Partial	41.97°N, 24.63°E	Linear terrain, mantle
704	ESP_046220_2235	Full	42.94°N, 24.06°E	Linear terrain, polygonal terrain, washboard terrain
705	ESP_046220_2235	Full	42.97°N, 24.05°E	Linear terrain, polygonal terrain, washboard terrain
769	ESP_052681_2240	Full	43.64°N, 24.52°E	Flow features, linear terrain, moraine-like ridges, polygonal terrain
783	ESP_052826_2240	Partial	43.43°N, 26.02°E	Linear terrain, mantle
878	ESP_025253_2245	Partial	44.48°N, 29.82°E	Linear terrain, mound-and-tail terrain, polygonal terrain, washboard terrain
911	PSP_007162_2250	Full	44.60°N, 27.66°E	Linear terrain, mantle
1061	ESP_046022_2265	Partial	46.38°N, 29.00°E	Mantle, polygonal terrain, washboard terrain
1088	ESP_033745_2270	Full	46.66°N, 29.85°E	Linear terrain, mantle, moraine-like ridges, polygonal terrain, washboard terrain
1125	ESP_043688_2245	Full	44.16°N, 25.19°E	Linear terrain, polygonal terrain, washboard terrain
1161	ESP_053762_2280	Full	47.40°N, 27.37°E	Polygonal terrain, linear terrain, broad pit
1170	EPS_026941_2275	Full	47.12°N, 26.71°E	Linear terrain, polygonal terrain, moraine-like ridges, washboard terrain
1171	ESP_026941_2275	Full	47.14°N, 26.75°E	Linear terrain, polygonal terrain, washboard terrain
1218	ESP_055872_2270	Full	46.39°N, 27.09°E	Mantle, linear terrain, washboard terrain
1227	ESP_056004_2255	Full	45.25°N, 24.53°E	Linear terrain, polygonal terrain, mantle
1230	ESP_056004_2255	Full	45.25°N, 24.58°E	Mantle, polygonal, linear terrain
1302	ESP_057877_2245	Full	44.13°N, 23.86°E	Linear terrain, mantle, polygonal terrain
1425	PSP_002890_2205	Full	40.09°N, 22.72°E	Linear terrain, polygonal terrain, washboard terrain
1438	ESP_046853_2200	Full	40.25°N, 22.92°E	Mantle
1487	ESP_016471_2260	Full	45.63°N, 33.47°E	Linear terrain, washboard terrain

1594	ESP_019768_2220	Full	41.67°N, 18.43°E	Flow features, linear terrain, rectilinear ridge terrain, washboard terrain
1616	PSP_005857_2225	Partial	42.07°N, 19.52°E	Mantle
1802	ESP_035156_2220	Full	41.90°N, 23.90°E	Linear terrain, mantle, moraine-like ridges
1808	ESP_046075_2200	Full	40.29°N, 24.23°E	Linear terrain, mantle, moraine-like ridges, polygonal terrain
1840	ESP_025781_2220	Full	41.63°N, 16.28°E	Flow features, linear terrain, mantle
1842	ESP_025781_2220	Partial	41.64°N, 16.19°E	Linear terrain, mantle
1965	ESP_019214_2270	Full	46.57°N, 22.14°E	Linear terrain, polygonal terrain, washboard terrain
1967	ESP_019214_2270	Full	46.58°N, 22.14°E	Linear terrain, polygonal terrain, washboard terrain
2026	PSP_006147_2250	Full	44.63°N, 21.05°E	Linear terrain, polygonal terrain

Then perhaps simply a line or two in the discussion about how these observations can be extended to the other filled alcoves in the CTX survey (these filled alcoves need to be identified and reported clearly in the results, which is not currently the case). The details on "possible maybe perhaps" till deposits, glacial dynamics, rock glacier deflation etc etc should be left out and focus maintained on providing evidence pointing to ice as a major component of the fill material.

We edited the discussion so that it now reads as follows:

"**5.2 Geomorphic interpretations of cirque-like alcoves and associated features**

5.2.1 Icy geomorphic features

42% of HiRISE images contained washboard terrain, while only 2% of CTX images did, though this is likely due to a resolution issue since thinner fissures cannot be resolved at CTX scale. Except for two exceptions, cirque-like alcoves that contained washboard terrain did not also have an identifiable mantling unit. Similar to its presence at the bottom of crater walls (Jawin et al., 2018; Jawin and Head, 2021), the presence of washboard terrain here at the bottoms of the mesa sidewalls indicates deglaciation.

In both HiRISE (81%) and CTX imagery (57%), a high percentage of images of cirque-like alcoves contained observable linear terrain. In Fig. 12, since the linear terrain extended out from the washboard terrain, which is due to surficial crevasses, this suggests that the linear terrain there may be most similar to supraglacial longitudinal foliation. However, linear terrain could still result from subglacial erosion despite superposing a mantle unit since a mantle

unit consists of layers of dust and snow that build up in the mantle over multiple obliquity cycles (e.g., Khuller et al., 2021). Applied here, this would imply that the ridges could have been subglacially eroded, but from another layer of ice of the mantle unit (compacted from dust and snow) that formerly existed on top of the rest of what is left of the mantle unit today.

At a potentially earlier stage of evolution of the glacier-like forms, moraine-like ridges may lack elongation outside of the alcove (Fig. 13a), potentially similar to a terrestrial cirque glacier sitting within the cirque basin instead of extending into the valley below. In Fig. 13b, the alcoves are not well-developed and do not have morphometrics corresponding to the criteria we set for cirque-like alcoves. Nevertheless, since the moraine-like ridges correspond to upslope alcoves, similar to Arfstrom and Harmann (2005), we suggest that the moraine-like ridges in Fig. 13b reflect the initiation of cirque-style glaciation before the alcove headwalls and sidewalls develop more as they are increasingly eroded and steepened. This is also referred to as unconstrained piedmont glaciation by Conway et al. (2018)."

*** so the definitions of these should be in the methods and then you can report this part as results
Corresponding to this comment, we moved the definitions to Table 3 in the Methods section 3.3.

*** coverage of what we interpet as remnant or active ice
Here we were actually referring to cirque-like alcoves that had overlap with HiRISE frames. We clarified the text to read as follows: "Out of 456 cirque-like alcoves, 6 cirque-like alcoves (1%) had partial overlap, and 38 cirque-like alcoves (8%) had complete overlap within an available HiRISE frame."

*** replace with "some"
We accepted this change and edited it to "some."

*** unfounded speculation, when you restructure this section such unfounded statements should be deleted and replaced with augmented statements.
We deleted this statement.

*** name them or don't speculate on them here
We deleted this statement and saved the discussion for Section 5.3.

Page 26
*** if this is all the only point that you want to make with this observation, then delete all the following parts, these are unnecessary details

We deleted three sentences but kept the last two remaining sentences: “One interpretation of how these types of downslope surface lineations could still result from subglacial erosion despite superposing a mantle unit is by using the model that layers of dust and snow build up in the mantle over multiple obliquity cycles (e.g., Khuller et al., 2021). Applied here, this would imply that the ridges could have been subglacially eroded, but from another layer of ice of the mantle unit (compacted from dust and snow) that formerly existed on top of the rest of what is left of the mantle unit today.”

*** so instead of doing this, just use ONE of the terms and stick to it please
We edited all instances of “polygonized” terrain to “polygonal” terrain and changed the sentences starting on line 408 to read as follows: “Approximately ~15% of cirque-like alcoves with HiRISE coverage contained “polygonal” or “polygonized” terrain, two terms that are used synonymously (see Fig. 11f). Similar to how it is described in association with the glacier-like forms in Hubbard et al. (2011), we also see this type of polygonal terrain here between the surface lineations (Fig. 113f).”

*** said like the reader already knows what you mean, describe these before you discuss their relation to other features
We deleted the statement.

*** so the interpretation is that these features are related to ground ice? If so say so explicitly
Following the suggestion, we edited the statement to read as follows: “Similarly, on Earth, polygonal terrain results from periglacial processes such as contraction cracking and frost heave (French, 2018), though sublimation-type polygons that arise from thermal contraction and sublimation, indicating the presence of ground ice, have also been observed in the Antarctic Dry Valleys (Marchant and Head, 2007).”

Page 27
*** what is shown in 13e looks like 13ca and doesn't seem to match the description made in this paragraph
While both features in what was previously Figure 13e and 13a are transverse, 13e has thrust-block plates (also seen for Hubbard et al. 2011) that are more curvilinear in appearance. However, we realized that there were inconsistencies in this paragraph for descriptions of 13e and have separated out rectilinear terrain from moraine-like ridges (previously referred to as transverse ridges). We added definitions for the different features in Table 3. We also note that Figure 13 (now Figure 12) does not have good examples of moraine-like ridges, whereas Figures 6 and 13 do.

*** this is going a little too far I think without showing examples of this morphology. in order to not overload this manuscript I suggest just removing this comparison

We followed the reviewer's comment and deleted this sentence.

*** 13e looks nothing like the arcuate ridges described in this paper, so either you are referring to the wrong image or something else is wrong here
We agree with the reviewer and moved the statements about moraine-like ridges to correspond to the paragraph for Figure 12 instead (note that the prior Fig. 13 is now Fig. 12). We also changed all statements of arcuate ridges to moraine-like ridges. For the new Figure 13, we added the following description: "In Fig. 13b, the alcoves are not well-developed and do not have morphometrics corresponding to the criteria we set for cirque-like alcoves. Nevertheless, since the moraine-like ridges correspond to upslope alcoves, similar to Arfstrom and Hartmann (2005), we suggest that the moraine-like ridges in Fig. 13b reflect the initiation of cirque-style glaciation before the alcove headwalls and sidewalls develop more as they are increasingly eroded and steepened. This is also referred to as unconstrained piedmont glaciation by Conway et al. (2018)."

*** this seems to more accurately reflect fig 13e
We agree and changed the Figure 13e description as mentioned in the response to the first comment on Page 27 above.

*** this is too much of a conceptual jump
We deleted the sentence.

*** unfounded speculation
We deleted this sentence.

Page 29
*** missing space between words
We added a space corresponding to the reviewer's suggestion.

Page 30
*** it is impossible to know if what you interpret as "less developed" landforms is how the "more developed ones" looked without a time machine or at least a good knowledge of the process(es) and their rates. I suggest complete removal of this section, it is complete speculation
We find it plausible that in the order of increasing amount of erosion, the mesa edge would go from straight to having shallow depressions then deeper depressions. As such, we kept this section and added the following sentences at the beginning of the second paragraph: "Here, we assume that the side of the mesa evolves from a straight edge to an increasing number and depth of depressions. An alternative interpretation might be that the deeper depressions were subsequently filled up to create a straight edge, however, we do not see

evidence for this amount of infilling." If the reviewer thinks that further analyses might be beneficial, we are open to any suggestions for additional analyses here.

Following the sentence "We suggest that the observed notches are gullies and would be able to act as necessary initiation points for ice accumulation that would later support glaciation and erosion that could form cirque-like alcoves," we also added this reference since this idea of gullying tied to alcove formation has been previously proposed in a paraglacial by Jawin et al. 2018 as well: "This is consistent with the mechanism proposed by Jawin et al. (2018)."

*** missing word?
We added the word "processes" so that the phrase now reads "non-glacial processes" on line 519.

Page 33
*** this section seems like it should be first in the discussion
We agree with the reviewer. Previously, we moved this section in accordance with another reviewer suggestion, but we have moved it back.

*** I did not read any "strong" evidence for glacial erosion in section 5.1, perhaps you meant another section (but I cannot find it)? section 5.1 demonstrates the ice fill of some of the alcoves and speculates based on selected images on the possible development of the alcoves from gullies but doesn't specifically assess the likelihood of glacial erosion processes (simply assumes it must be a given). Rephrase
We deleted that part of the sentence so that it now reads as follows: "We further evaluate whether cirque-like alcoves are candidate cirques by comparing them to cirques on Earth."

*** I think the comparison between alcoves and GLF orientation is somewhat misleading. You show in your HiRISE study that many alcoves are filled with icy materials that are not mapped as GLF, this suggests they are perhaps occupied by glaciers that for some reason did not get classified as a GLF (no good images there when Colin did his survey? too small? don't have a clear divide between the alcove-fill and the VFF below?)... so I suggest rewriting this section with this caveat in mind
We added a section in the Methods "3.3 Criteria for identification of icy geomorphic features" to demonstrate how glacier-like forms are different from the features that we identified here. We included this section in the response to the third comment of page 25. We also added Table 3 and moved Figure 6 to be in this section, as mentioned in the same response.

*** See Kreslavsky PSS 2008 for a nice diagram of this effect
https://doi.org/10.1016/j.pss.2006.02.010
We added Kreslavksky et al. 2008 as a citation as well.

*** are
We accepted this change and changed the word to “are.”

*** pretty sure this should be 2019 - did you mean this one - doi.org/10.1144/SP467.3
We did mean Conway et al. (2018) *Geomorphology* since it included the following sentences: “They [gullies] are found primarily on pole-facing slopes at latitudes between 30° and 40° and then mostly on equator-facing slopes poleward of 40° (but they can also occur on pole-facing slopes in this latitude interval).”

Page 35
*** 2023b
We accepted the change.

*** these two papers do not talk about meltwater
We edited the sentence so that the two papers are referenced earlier in the sentence now: “However, in the case of meltwater, we note that cirque-like alcoves may prefer to reside on equator-facing slopes because this would allow for increased insolation (e.g., Pilorget and Forget; 2016; Dundas et al., 2022) and the chance for meltwater as temperatures increase (Dickson et al., 2023b).”

*** corresponds
We changed “correspond” to “corresponds” as suggested.

*** I can't make this make sense, I have read it three times
We deleted part of the sentence to simplify it so that it now reads as follows: “If cirque-like alcoves do in fact correspond to an earlier phase of glaciation, it is unclear if this glaciation was on the scale of glacier-like forms versus larger scales like the lobate debris apron.”

*** delete? totally unconnected with the rest of the section
We deleted this paragraph following the reviewer’s suggestion.

Page 37
*** section 5.2.2 would be a lot shorter if this is the explanation the authors prefer
Section 5.2.2 (now 5.1.2) was focused on which direction had the most cirque-like alcoves, which was southeastward. Here in section 5.1.4 (previously 5.2.4), the focus is on which aspect has the largest cirque-like alcoves, which is south, in contrast with glacier-like forms, which are largest when facing north in Deuteronilus Mensae. The localized topographic effect was invoked in regards to the largest glacier-like forms facing north.

*** I don't think it was demonstrated that these icy units are more or less remnant than the GLF or indeed the VFF in the area, so either make sure this demonstration takes place or rephrase this statement.
We deleted this section.

*** why? they are morphologically indistinct from the GLF and VFF in the area which are thought to be debris covered glaciers? They do no resemble rock glaciers in my opinion and you do not present any comparisons to defend this interpretation, so I strongly advise not including it, it just distracts from your data
We deleted this section, however, we did want to note that rock glaciers are considered to be analogs for GLFs as well, which we mentioned in our response to #4 above.

*** such hummocky structures occur when there is melting, which is probably not the case on Mars, also why would the upper part of VFF where the alcoves are have dead ice? This seems a nonsensical argument.
This sentence related to dead ice was added in response to another reviewer's comment. We have deleted it. We note for the reviewer that debris-covered glaciers may disconnect or detach (e.g., Pirámide glacier in Janke et al. 2015), though it is true that the part that is most likely to become dead ice would be at the toe of the glacier. Maybe the question is at one point does the deflated glacier become dead ice, but since this example retains glacial geomorphic features, we agree that the term dead ice is likely not representative.

*** the timescale of formation cannot discriminate between cold and wet based because there is no constraint on the age of the alcoves nor on the time taken to form them. delete this sentence
We deleted the highlighted portion of the sentence so that it now only reads as follows: "We estimated erosion rates for both wet- and cold-based ice."

Page 39
*** their initiation would predate, but they would develop during occupation by the LDA? Rephrase?
We rephrased the sentence as follows: "Using the slowest estimated erosion rates corresponding to cold-based glaciers in Antarctica, the initiation of the cirque-like alcoves likely predated the lobate debris aprons. Then they could continue to develop in size during and/or after when the lobate debris aprons formed."

*** I don't see how this argues against the alcoves forming in concert with the LDA - debris from them should superpose the LDA - in cirques on Earth it is rare that the headwall is always completely covered, cirques form in alpine glaciations and not plateau glaciation

We rephrased the sentence to clarify what we meant: “Since debris from the cirque-like alcoves often superposes the lobate debris aprons (e.g., Baker and Carter, 2019), this means that the cirque-like alcoves have been actively eroding after when the lobate debris aprons formed.”

*** or it is the process contributing to the cirque development - hence a short description of the processes leading to cirque development on Earth in the introduction would be useful
Lines around 120 in the introduction now include the following description of cirque development: “Cirques develop from incipient depressions in mountain and plateau sides that fill with snow which eventually evolves into ice, thus supporting active glaciers. The movement of these lead to glacial erosion which deepens the initial depressions modifying the landscape to create the characteristic valley-head cirque shape that is found in all glaciated mountain regions worldwide (Evans and Cox, 1974; Glasser and Bennett, 2004). Glacial erosion occurs via a combination of quarrying, abrasion (e.g., White, 1970), and frost weathering (e.g., Sanders et al., 2012), which all contribute to enlarging the cirque floor and deepening the cirque (Evans, 2020). Non-glacial processes such as rock-slope failures may play a role in cirque-basin erosion as well, especially in terms of headwall retreat (e.g., Turnball and Davies, 2006; Coquin et al., 2019; Evans, 2020).”

*** not sure what you mean by this, but the VFF certainly extend into the alcoves as shown by your HiRISE observations
We deleted this part of the sentence.

*** this doesn't seem unreasonable
Great, we agree!

In general, the part above reads as if the authors want these alcoves to have formed alongside GLF in a wet-based regime, but every argument they make has an equally convincing counter-argument that they were forced to add in previous reviews, but they are still trying to argue for the wet-based.
We deleted the section titled “5.5 Discussion of wet-based versus cold-based glacial erosion of cirque-like alcoves” and have softened the language to not decisively say cirques require wet-based erosion in the Introduction and Conclusion sections.

Page 40
*** this section should be removed, it just goes in circles and does not rely on the data in this paper. mostly it is speculation with no firm conclusion at the end of it all
We deleted this section.

*** this seems to mildly contradict what is said in the previous section, which concludes both wet or cold based glaciation are potential candidates over different, yet realistic timescales
We deleted this section.

*** this seems to lead nowhere, so I suggest remove it
We deleted this section.

Page 41
*** they don't need to keep pace with talus production on Earth, but on Mars, where the rate is likely (a lot) slower as there is not rapid frost-shattering
We deleted this section.

*** strong wording given the noise in the DTM, rephrase or remove
We deleted this section.

*** hard to say require when it totally unknown what processes are going on
We deleted this section.

Page 42
*** I don't think you need a massive discussion about processes that you can reject based on morphology/morphometry without much effort. I suggest reducing the text to an absolute minimum and simply refer to Table 6 to say these features are unlike those formed by other alcove-forming processes on Earth and most like cirques - this compilation should be presented when you present your selection criteria, page 15 and does not belong here
We moved the table to section 3.2.2 in Methods with condensed text:
“By using morphometrics, we also exclude other types of mechanisms for alcove formation, including active-layer detachments, deep-seated landslides, and theater-headed valleys (Table 2). This is because the H/L ratio of a terrestrial glacial cirque is expected to be deeper than any of the other alcove landforms with known morphometrics on Earth (Table 2).”

Table 2: Morphometrics consistent with different alcove-forming erosional mechanisms.

Formation mechanism/Landform	**L/W**	**H/L**	**Aspect**	**Related geology**	**Typical scale (m)**
Glacial cirque on Earth	~1, generally ranges from 0.5-4.25 (Barr and Spagnolo, 2015)	~0.67 (Barr and Spagnolo, 2015)	All directions; poleward is favorable (Barr and Spagnolo, 2015)	Overdeepening, moraines	10^2-10^3 (Barr and Spagnolo, 2015)

Deep-seated landslide on Earth[n.s.]	>2.5 (Fran et al., 2006)	0.1-0.35 (LaHusen et al., 2016; landslide scars from glacial sediment)	Not available*	Hummocky landslide deposits	10^1-10^2 (LaHusen et al., 2016)
Impact crater on Mars	~1	0.1-0.2 (Robbins and Hynek, 2012)	N/A	Ejecta blanket	10^1-10^3 (Palucis et al., 2020)
Amphitheater-headed valley on Mars hypothesized to have formed by either groundwater sapping or outburst flooding	1-10 (Laity, 1988)	Not available*	Not available*	Sandstone, not basalt bedrock (Lapotre and Lamb, 2018)	10^1-10^2 for canyon heads, up to 10^3 for the main channel (Lapotre et al., 2016)

Not available*: As of writing this paper, focused studies on the morphometrics of these landforms on the population scale are not widely available for these other landforms.

n.s.: "n.s." stands for "not scarp" since landslide morphometrics do not usually include measurements of the morphometrics of just the headscarp and sidewalls of where the landslides initiated.

*** these are conditioned on melt and highly unlikely to occur on Mars, also their scale is not big enough and they only affect the active layer and cannot erode into bedrock. I would discourage this kind of hasty comparison based on "looks-like-must-be"

We deleted active layer detachments from the table.

*** if you consider these as "similar" then you have a lot of other features to describe, including rock avalanches, first order fluvial catchments in badlands, debris flow headscarps…

We deleted this section.

*** already this point is debated where there is no ice on Mars, so why open a can of worms? your data don't have anything to contribute here

We deleted this section.

Page 45

*** this cannot be observed as you do not have a time machine, rephrase. I also do not think this conclusion is justified, and should be removed, along with the associated section.

As mentioned for the above comment, we find it plausible that in the order of increasing amount of erosion, the mesa edge would go from straight to having shallow depressions then deeper depressions. As such, we kept this section and added the following sentences at the beginning of the second paragraph: “Here, we assume that the side of the mesa evolves from a straight edge to an increasing number and depth of depressions. An alternative interpretation might be that the deeper depressions were subsequently filled up to create a straight edge, however, we do not see evidence for this amount of infilling.” If the reviewer thinks that further analyses might be beneficial, we are open to any suggestions for additional analyses here.

We also edited the bullet point in the Conclusions to read as follows: “Headwall notches are observed adjacent to increasing sizes of larger alcoves (Fig. 15). Notches and subsequent stages of their development may act as an initiation point for ice accumulation, similar to what happens on Earth for local-slope glaciation. Larger alcoves may have undergone multiple cycles of glaciation and erosion.”

*** also unjustified, suggest remove
We deleted the statement on rock glaciers.

*** remove, not justified
We removed the sentence.

Page 46
*** merge with previous paragraph and shorten both to make a shorter snappier conclusion point
The two paragraphs were merged and now read as follows: “The slight eastward bias in aspect aligns with previous studies is consistent with both glacier-like forms on Mars (e.g., Souness et al., 2012; Brough et al., 2019) and climate models of westerly winds in Deuteronilus Mensae (Madeleine et al., 2009). Terrestrial cirques also show a similar pattern due to westerly winds. Future work could help to better understand the atmospheric controls on cirque-like alcove formation in Deuteronilus Mensae, as well as other locations on Mars. There is a dominant southward bias in the aspect of the cirque-like alcoves (Fig. 6), which becomes more pronounced above 46.5°N. Overall, both cirque-like alcoves and glacier-like forms tend to have greater volumes when facing south, which may suggest an interdependent relationship between glacier-like form size and cirque-like alcove size. The southward aspect bias of cirque-like alcoves may result from poleward-facing slopes receiving more insolation during high obliquity, or an association with gully formation, as gullies also tend to face the equator at high latitudes (Harrison et al., 2015; Conway et al., 2018).”

***remove

Following the reviewer's recommendation, we removed this paragraph.

*** these are extremely tenuous arguments and this paper does not show that this is the case, remove

We edited the sentence to remove "wet-based" so that it now reads as follows on line 888: "The presence of glacial geomorphic features, especially linear terra lineations, moraine-like ridges, mound-and-tail terrain, rectilinear ridges (Fig. 12), and potential overdeepenings (Fig. 5), are all consistent with glacial erosion. In addition, the presence of icy remnants exist in the form of brain terrain, flow features, mantling unit, and polygonal terrain."