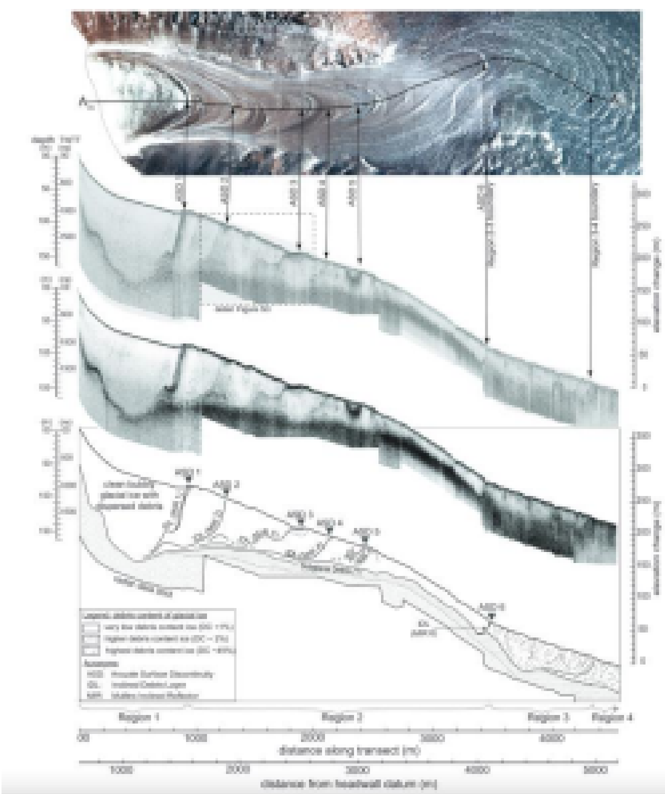
*General Comments.*

*This manuscript presents geomorphic measurements of alcoves associated with martian glacial terrains and interprets the morphometric data and HiRISE observations of the sites to describe a sequence of glacial erosion processes. The alcove measurements are novel, interesting, and exceptionally important for understanding glacial and permafrost processes on Mars.*

*However, the manuscript has several critical weaknesses that need to be addressed.*

We thank the reviewer for their in-depth comments, which we think have helped improve the manuscript, and provide responses in black text below.

*1) One of the foundational assumptions presented in this paper is that glacial cirques require wet based glaciation to form. While this is true for temperate and mid-latitude cirques, particularly for modern alpine glaciers and for older glacial remnants, it is not universally the case. Antarctic, cold based glaciers can produce pronounced alcoves with large reliefs, over-deepened regions where bed shear stress is maximized, and downslope export of eroded or rockfall debris—all without any evidence of wet-based or polythermal conditions. See fig below from (Mackay et al., 2014) and (Mackay and Marchant, 2017):*



*The paper would be greatly strengthened by evaluating the hypothesis that morphometric observations can be used to distinguish wet-based vs. cold-based glacial cirques. If wet-based and cold-based glacial cirques can't be distinguished in the Earth-derived measurements were collected as part of this study and in prior work, then there's no basis for thinking that they can be distinguished on the basis of morphometric observations on Mars. If they can be distinguished in the Earth dataset, then it is a powerful tool applying to the Mars data in order to test the hypothesis* *that the morphology of martian cirques is more similar to the morphology of wet-based cirques than to cold-based. If it's impossible to tell the difference between cold- and wet-based glacial cirques on Earth, or to distinguish "cirque-like" versus non-cirque-like alcoves on the basis of morphometry in the Mars measurements, that's useful to know, too—it means that other tools or measurements need to be applied to figure out the thermal state of martian glacier beds.*

*My main concern is that from the very start of the manuscript, the wet-based model is accepted as an assumption: "Cirques are expected to form from depressions in mountainsides that fill with snow/ice and over time support active glaciers that deepen the depressions by wet based glacial erosion." If that's the only possible model, then there's nothing being tested by the hard-won measurements the team has made. More needs to be done to critically evaluate the many and interesting measurements the team has made.*

While we agree that there are cold-based glaciers in Antarctica that have an overdeepened basin, as shown in Mackay et al. (2014), we disagree that this means the overdeepened basin was eroded by that cold-based glacier rather than by an earlier warm-based phase of glaciation. Previous work has shown that most of the landscape of the Dry Valleys "had largely achieved its form in the middle Miocene" (Sugden and Denton, 2004). This is consistent with the idea that the cold-based glaciation that occurred after the middle Miocene contributed minimally to subsurface erosion (e.g., Sugden et al., 1995; Sugden and Denton, 2004; Lewis et al., 2007).

Mackay et al. (2014) proposed that the rockfall origin for the inclined debris layer (IDL) is the most likely candidate, rather than basal shearing, entrainment, or erosion, which would all likely require a polythermal regime (Mackay et al., 2014). In addition, Mackay et al. (2014) state that where there are smooth basal returns that are interpreted as bedrock, "they appear to lie well below the onset of mapped IDL, suggesting individual IDL are most probably sourced above the bed." This would mean that the entrained IDL could not subsequently erode the bed and act as the source of the overdeepening either. And, while the IDL may correspond to back or sidewall cirque retreat, they do not provide evidence for overdeepening and subglacial erosion. There is evidence from an older study on cirque morphometrics of glaciers in the Dry Valleys that indicates headwall erosion continues after the primary episode(s) of cirque basin erosion (Aniya and Welch, 1981).

In terms of addressing the hypothesis that morphometric observations can be used to distinguish warm-based vs. cold-based glacial cirques, there is currently no strong evidence that glacial cirques can be eroded mainly/only by cold-based glaciers. As mentioned above, while some contribution to erosion is expected, significant subglacial erosion requires at least a polythermal basal condition. Currently, there is no literature on morphometrics of glacial cirques eroded by warm-based vs. cold-based glaciers because glacial cirques are expected to involve some kind of warm-based or polythermal erosion. Glaciers might be eroding cirques over the timescale of over a million years from multiple phases of glaciation. However, cirques most likely experience most erosion and attain much of their present-day size during the first glacial occupation(s) (Barr et al., 2019).

The reviewer's concern is further discussed below and changes to the manuscript have been made to provide additional clarity, as specified below.

*2) The paper would be greatly strengthened by a full assessment of the morphometric data collected for the martian alcoves and the example cirques and alcoves on Earth. Analyses are only shown for the "cirque-like" alcoves, which were determined by a combination of morphometry and image interpretation. This begins to feel like cherry-picking of the data to describe alcoves that look right. It would be great to see summary statistics like those shown in table 4 for all 7 of the morphological groupings. A box and whiskers or violin plot with each group on it for L, W, H, size, area, would be helpful to see if the classes are different. Most statistical software packages could tell if there are significant differences between the groups based on the measured properties. It would be neat if there are—but if there aren't significant differences, it just means that either the morphometric properties being measured don't capture the variation or that the resolution of the dataset wasn't up for the task. Scoping the manuscript's conclusions based on the properties of the whole dataset is very important and without it, the results could be construed to be highly cherry-picked.*

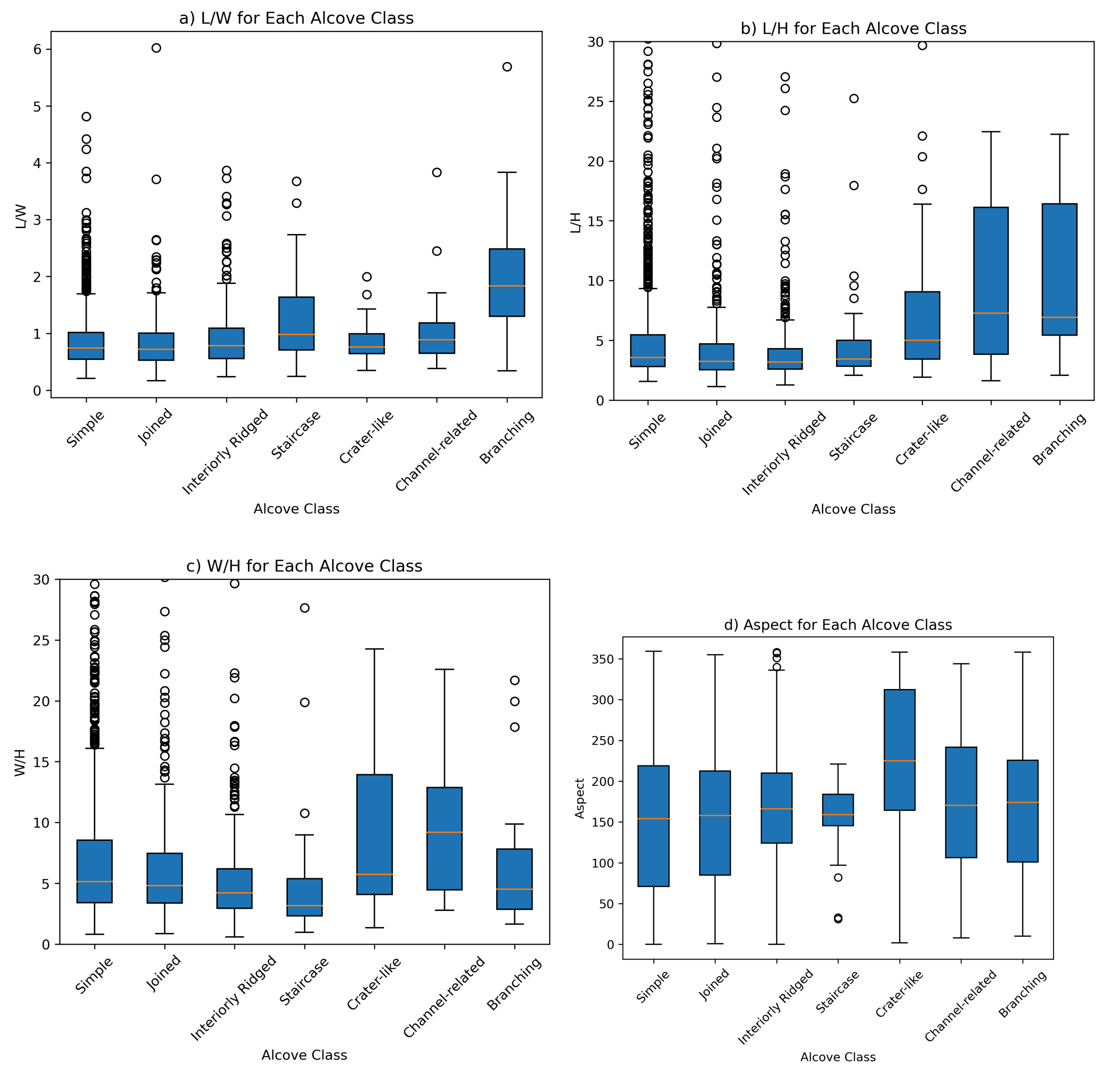
Below we have text for a possible section 4.x.x and possible Figure Y to address this comment, and we appreciate the input and consideration of including all alcoves in the results. Note that the crater-like alcove would be removed due to the reviewer's later comment, but we include it here as a reference point. A similar comment related to the plot style also came up in the editor's comments prior to accepting the paper for Discussion. However, after working up this text and figures we felt that including the section and figure describing all of the alcove classifications did not advance the main goal of our study, which is to evaluate cirque-like alcoves in relation to terrestrial cirques in order to constrain their evolution. We therefore suggest we do not include the text and figure below, unless the reviewer and editor feel that this is important to the paper.

It is interesting that there appear to be different types of alcoves but we do not have a way to evaluate alcove classes against terrestrial counterparts other than the simple alcoves, unless we digitize all of the different classes as individual alcoves. And, the goal of the study is to investigate alcoves that could be candidate cirques, so reducing our initial set of all alcove forms is consistent with our goal in the paper. The classification and calculating morphometrics were designed to be two separate steps that were used together to define a "cirque-like alcove." We have made this more clear in the text as it is an important part of our analysis.

The cirque-like alcoves on Mars are the ones that we can compare to terrestrial cirques on Earth. In addition, the ACME tool that we apply to calculate the morphometrics was designed for a simple terrestrial cirque, which we mention in Section 3.2.2: "However, we note that the ACME tool is designed for classic cirques on Earth and while the tool works with complex shapes, it should not be relied on for curving, elongated features (Spagnolo et al., 2017)." We also added this sentence: "As a result, we only include morphometrics for simple alcoves from the ACME output and not the other alcove classifications." Thus, ACME is not designed for the more complex shapes we see on Mars. In addition, there are no obvious trends in Figure Y that significantly add to the content of this manuscript.

**4.x.x Morphometric observations of all mapped alcoves in Deuteronilus Mensae**

Here we provide morphometric observations of the different alcove classes. However, we note that the ACME tool is designed for classic cirques on Earth and while the tool works with complex shapes, it should not be relied on for curving, elongated features (Spagnolo et al., 2017). For completeness we present key morphometrics for all mapped alcove classes in this section. However, the rest of the paper focuses only on cirque-like alcoves. As seen in Fig. *Ya*, L/W for all alcove classes have medians around 1, except for branching, which is closer to 1.5. The L/H medians approach 5, except channel-related and branching classes both have higher values and ranges (Fig. *y*b). W/H medians approach 5, except for the median for channel-related alcoves is closer to 10. Aspect medians are all close to 150°, though crater-like extends to a median of 210. Median slopes are mostly around 15, except channel-related and branching which are both less than 10.



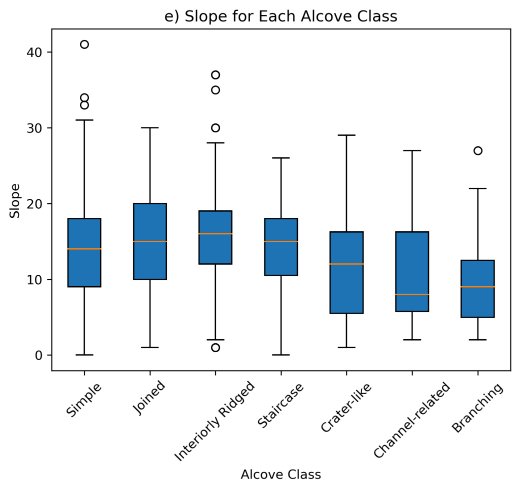



**Figure Y. Box plots for each alcove class based on: a) L/W, b) L/H, c) W/H, d) aspect, and e) slope. Alcoves that belong in multiple classes were included in all corresponding categories.**

*3) One of the challenges in the paper is distinguishing the alcoves from which small, superposing glacier-like forms emerge versus larger alcove which appear to be associated with large LDA/LVF glaciers. Sometimes a small GLF superposes an LDA/LVF, and they may share an alcove. But without distinguishing these two very different sizes and generations of glacial activity, it's difficult to evaluate the estimates of erosion timescales. Small GLF emerging from small alcoves that superpose LDA/LVF may very well have rapidly eroded their alcoves. But LDA are much larger and much older than GLF, and likely had longer timescales to remove material from the large alcoves they occupy. These two classes of alcoves seem to be lumped together in the median and mean height/volume datasets, and might be giving the impression that small, superposing, younger glacier/flow features have done much more geomorphic work much faster than they actually have.*

While it is true that lobate debris aprons/lineated valley fill (LDA/LVF) and glacier-like forms (GLFs) are different scales and these landforms likely relate to different episodes of glaciation, the alcove mapping done here does not connect directly to glacier-like forms. For mapping the alcoves, we excluded alcoves that contained previously mapped glacier-like forms that extended out of the alcoves, and the morphometrics of GLFs have been previously evaluated (Brough et al., 2019). However, alcove mapping did include overlap with some mapped lobate debris aprons from Baker and Head (2015). We did this so that we could evaluate the morphometrics of the alcoves that do not currently contain glacier-like forms.

*Specific comments.*

*Lines 15-17. On Earth, cirques most commonly form due to basal erosion beneath wet-based or polythermal glaciers—but why start this analysis with this assumption? There are many cirque and arete-like landforms in environments where cold-based glaciation dominates, for example, ringing Beacon Valley in the McMurdo Dry Valleys (77.88 S, 160.58 E). Presupposing that cirques form through* ***wet-based glaciation is an unnecessary assumption and sets out the analysis as having something*** *to prove, rather than examining the morphology and seeing what conclusions can be drawn from it.*

To address this concern, we added this sentence after lines 16-17: "Cold-based glaciers may also contribute to headward and sidewall retreat in cirques, though there is limited evidence for their contribution to subglacial erosion." As mentioned above, the example from Mackay et al. (2014) provides evidence for back and sidewall erosion, but not subglacial erosion. This is because the inclined debris layer likely originated from a rockwall rather than basal erosion and is sourced from above the bed (Mackay et al., 2014).

*Line 22-23. Is the proposal that the cirques and the lobes are a late stage of glacier evolution, or that the cirques are? The cirques could pre-date the presently occupying lobes, I'd think.*

The proposal is that the icy remnants or "lobes" residing within the cirque basins represent a late stage of glacier evolution (the cirque basins likely predated this ice). We rephrased the abstract for clarity to the following: "We propose that the icy relicts present in some cirque-like alcoves are similar to debris-covered ice on Earth and represent a late stage of glacier-like form evolution."

*Line 35. "Presumed" is pretty editorial in tone. It has been modeled (Hecht, 2002; Kreslavsky et al., 2008; Schorghofer et al., 2019) to be difficult, but certainly not impossible, that that episodic meltwater occurrences could have happened in the Amazonian, usually during obliquity optima, or on steep slopes, sometimes with the assistance over thermal shielding from overlying CO2 ice. But widespread conditions where ice is present when surface temperatures reach the melting point is not produced in most models, especially on flat surfaces.*

We removed the word "presumed" and rephrased to the following: "Extending from the cold and dry conditions of present-day Mars, the climate of the past 3 Gyr (Amazonian Epoch; Michael, 2013) has limited to no widespread liquid water on the planet's surface (e.g., Kite, 2019)."

*Line 38. (Levy et al., 2016) showed that mean erosion rates during Amazonian glaciation are several orders of magnitude higher than average Amazonian martian erosion rates and bracket erosion rates for cold-based glacial environments (which do erode their beds, just not much!)*

We have a citation of Levy et al., 2016 in Table 1, row 1. We also added this sentence on line 39: "Previous work has estimated cold-based erosion rates of 0.1-10 m/Myr during Amazonian glaciation on Mars (Levy et al., 2016; Table 1)."

*Line 42. There's definitely evidence supporting englacial debris bands in LDA, e.g., (Butcher et al., 2023; Levy et al., 2021), but* ***the jury is still out whether this debris is alcove-derived from rock fall or somehow entrained at the bed.***

We added the following references in the last sentence of the first paragraph on line 43: "In addition, englacial debris bands have been found in viscous flow features, though it is not yet known if the debris is predominantly from rockfall at the headwall or entrained from the subglacial bed (e.g., Butcher et al., 2023; Levy et al., 2021)."

*Line 57. I think the strongest evidence for the age of CCF is 300-800 Ma from (Fassett et al., 2014). The reason I think those dates are less likely to be off from others is because they didn't count craters on the surface of glacial* *deposits themselves, which have been heavily reworked, instead counting on large ejecta blankets from craters.*

We rephrased the manuscript to address this comment: "Lobate debris aprons, lineated valley fills, and concentric crater fills are estimated to range from ~10 Myr to 1.2 Gyr in age (Morgan et al., 2009; Berman et al., 2015) or when excluding potentially reworked craters between 300 and 800 Myr (Fassett et al., 2014). Glacier-like forms can superpose lobate debris aprons or lineated valley fills, suggesting polyphase glaciation (Levy et al., 2007; Brough et al., 2015), with age clusters estimated to be around 2-20 Myr and 45-65 Myr (Hepburn et al., 2020)."

*Line 79. Coordinates are usually reported as lat/long—is there a reason to report location as long/lat here?*

We changed the coordinates to lat/long.

*Line 83. What does it mean to be analogous here? Formed by wet-based glaciation? Formed by subglacial erosion? Formed by evacuation of rockfall from over-steepen cliffs? There's lots of ways these alcoves and cirques could be similar—in what ways are they being compared?*

We rephrased this sentence since Hubbard et al. (2014) did not specify if they were referring to cirques in the context of wet-based glaciation, subglacial erosion, or evacuation of rockfall from over-steepened cliffs. The context in which Hubbard et al. (2014) mention cirques is as follows: "GLFs thereby generally form in small cirque-like alcoves or valleys, appear to flow downslope between bounding side-walls, and terminate in a distinctive tongue which may or may not feed into a higher-order ice-rich terrain type."

However, for the GLFs, they do comment that the "the thermal regime of former GLFs is unknown, and the possibility of partial wet-based conditions remains unproven and their extent unevaluated." They refer to their previous work in Hubbard et al. (2011), which classified bedforms associated with a GLF as 'mound and tail' terrain and 'linear' terrain and were likened to terrestrial drumlins and MSGL, respectively. Since both of these landforms are predominantly associated with wet-based glacial conditions on Earth, these authors proposed that such conditions may have prevailed beneath GLF #948 at a time in the past when it had expanded and thickened to fill its moraine-bounded basin. This interpretation, however, was considered side by side with an alternative – not involving wet-based glaciation – based on the mound and tail and linear terrains representing degraded supra-GLF forms, in this case wind-blown dune deposits and exposed longitudinal foliation, respectively." In the Summary at the end of Hubbard et al. (2014), they state "More extensive former GLFs, and/or their predecessor ice masses, may have been partially wet-based."

Since it is an open question whether former GLFs and/or their predecessor ice masses were warm-based, we edited the line so that it now reads: "Previous work suggested that glacier-like forms are initiated in and extend out of 'cirque-like alcoves' and that it is unknown whether the glacier-like forms and/or any ice masses that came before them were wet-based (Hubbard et al., 2014)."

*Lines 85-86. See comment for line 15-17. Strong analog studies require open-mindedness to the idea that physical conditions may be different between alpine, polar, and planetary settings. I think the best planetary science emerges from framing our Earth-bound heuristics as a question: on Earth, many (though not all) cirques form through wet-based erosion at the point of maximum basal shear stress; how does the morphology of martian alcoves from which glaciers emanate compare to the morphology of terrestrial cirques in cold-based and wet-based environments?*

Thank you for the comment and we agree the environmental setting is an important part of evaluating processes responsible for landform generation. However, on Earth there is no strong evidence that cold-based glacial erosion alone is responsible for cirque erosion. While there are cirques that contain cold-based glaciers in present-day Antarctica, it is unclear how much of the cirque erosion resulted from these cold-based glaciers. Since inclined debris layers (IDL) likely originate from rockfall and not the glacier bed, the IDLs show that cold-based glaciers contribute to cirque headwall and sidewall erosion, but there is no direct evidence of their contribution to subglacial erosion. Specifically, cirques in Antarctica might have primarily developed during earlier (warm-based) phases of glaciation, as suggested for cirques in general (Barr et al., 2019). As a result, there is no clear morphological/morphometrical evidence in the literature for cirques eroded mostly/only by cold-based ice.

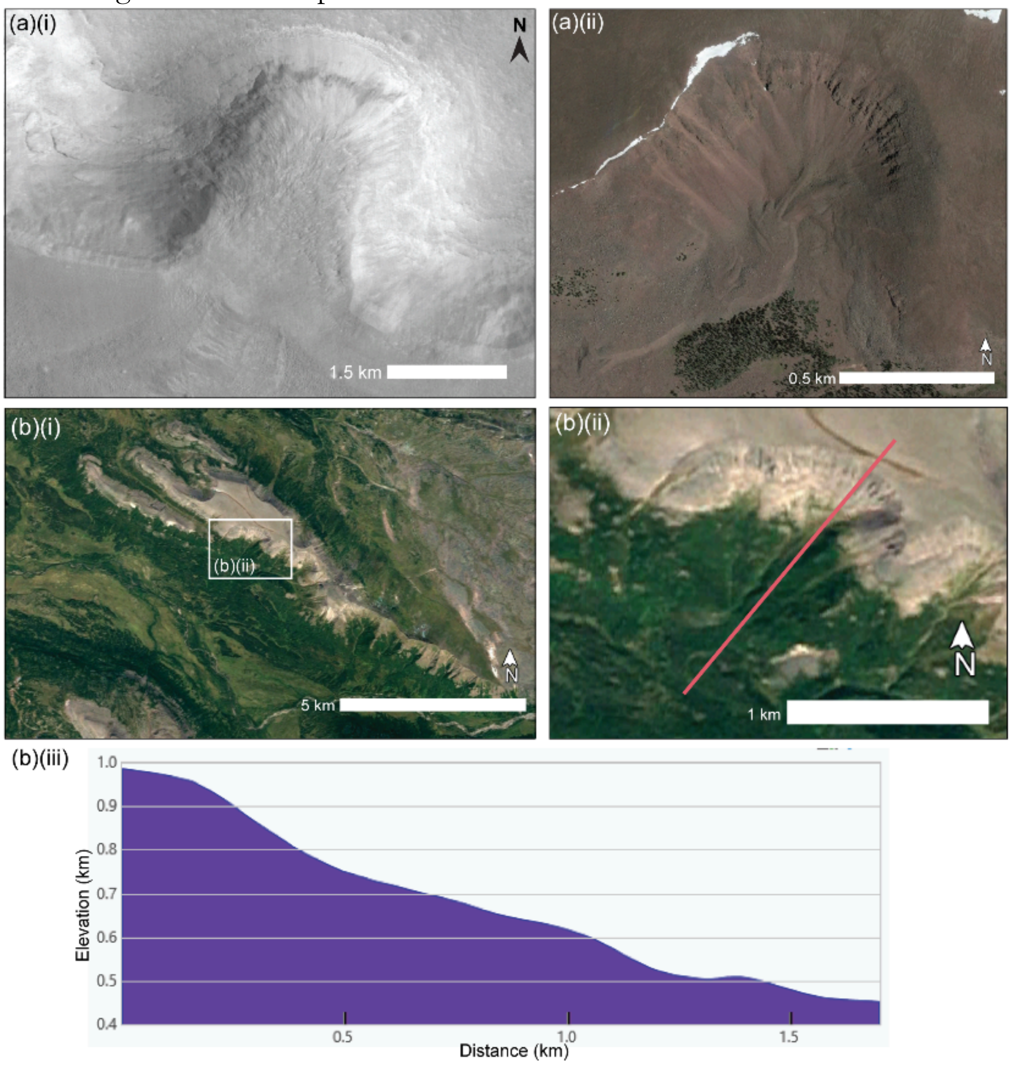
*Line 87. I think the cirques/alcoves you show in Fig 2, and the many glacial valleys/cirques in the Antarctic argue against the idea that cold based glaciers don't carve alcoves/cirques. It's true that most alpine glaciers are wet-based or polythermal and that the erosion rates produced by these glaciers are higher, but the slower rate does not necessarily mean cold-based glaciers don't carve cirques. Put another way, can you show based on your terrestrial analog examples that there's a substantiative difference between the alcoves that cold-based glaciers flow from versus the cirques that are carved by wet-based glaciers? That would make for a really interesting basis for comparison for understanding what attributes of the martian alcoves are more like wet-based cirques or more like cold-based non-cirque alcoves.*

We added the following text to address this comment: "In locations such as Antarctica where cold-based glaciers currently reside within cirques, it is possible that much of the cirque was eroded during earlier, warmer, phases of glaciation, i.e., in the Miocene (e.g., Sugden and Denton, 2004) or even Tertiary (Selby and Wilson, 1971). One way in which an otherwise cold-based glacier might be erosive at its base is when meltwater from the surface of the glacier refreezes at the glacier's base and incorporates loose debris into the ice (e.g., Andrews and LeMasurier, 1973). This might mean there are localized areas of basal water, so that the glacier is not completely frozen to its bed, though how much of a cirque can be eroded downwards through this process is an open question."

*Fig. 2. The DEM served by Google Earth is coarse spatial resolution and is also smoothed in places to improve image draping. It's not the most reliable dataset for geomorphic measurements. For many of your global sites, SRTM (Shuttle Radar Topography Mission) data are available and are certainly not coarser in spatial resolution, but have the advantage of being traceable to a particular dataset with known positioning uncertainties. For alcoves in the US, the National Elevation Dataset (NED) would be a more traceable and higher resolution dataset for measuring cirques. It is served up for easy access by the USDA Geospatial Gateway (https://datagateway.nrcs.usda.gov/). For the Antarctic examples, the REMA reference elevation model for Antarctica might be a good bet for higher spatial resolution topography (served up by the Polar*

*Geospatial Center at [http://pgc.umn.edu](http://pgc.umn.edu)). The best way to measure cirque properties in places like Beacon Valley or the high Asgards/Olympus range in the Antarctica would be to use the lidar data for those sites, distributed in DEM format by OpenTopography.*

We updated Fig. 2 to use non-Google Earth DEMs based on the references recommended by the reviewer. Figure 2 and its caption are now as follows:



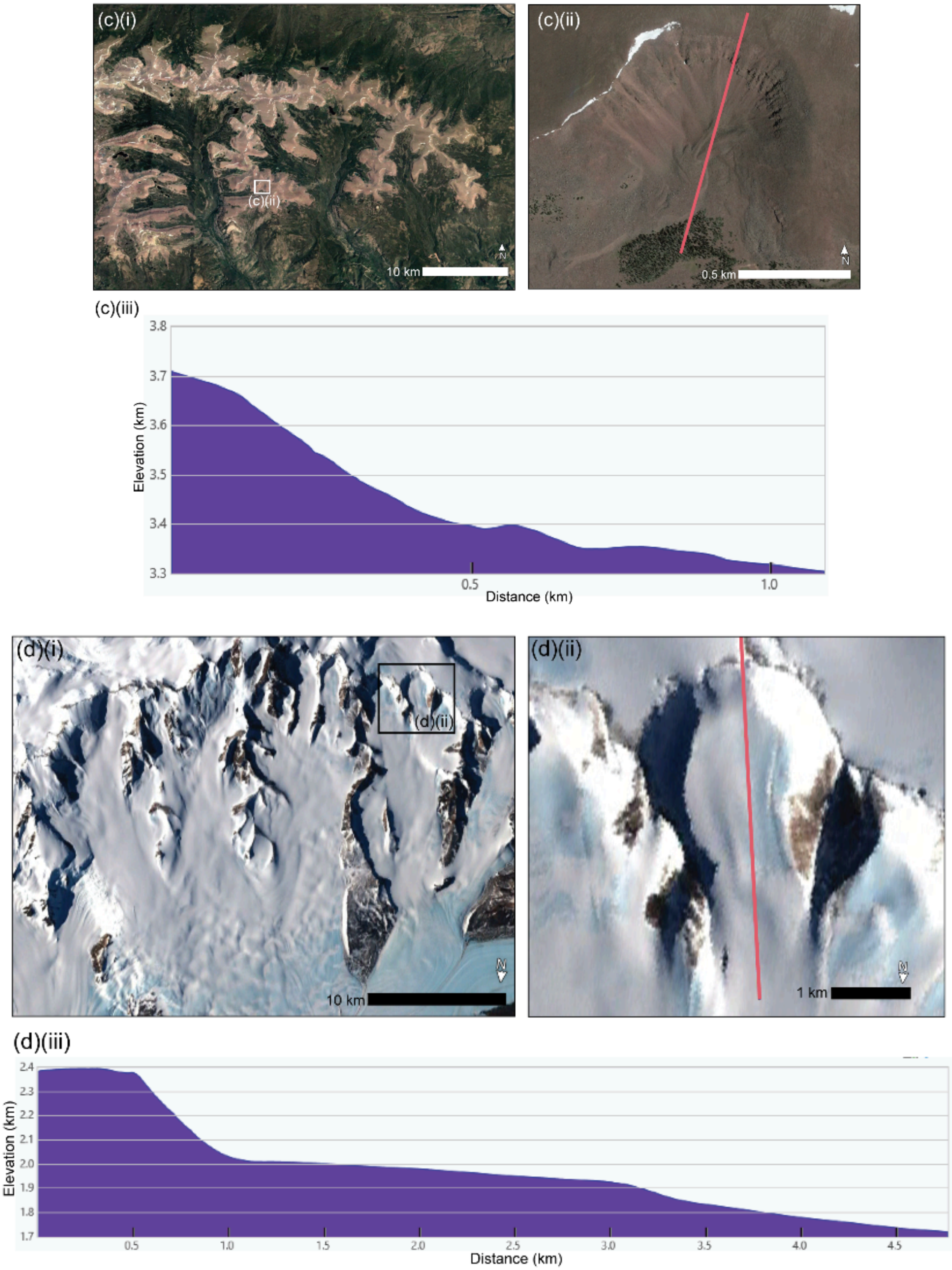



**Figure 2: (a)(i) Example of a cirque-like alcove on Mars (40.24°N, 34.48°E) (CTX mosaic; Dickson et al., 2023a) (a)(ii) a cirque on Earth in the Uinta Mountains (40.712°N, 110.114°W). CTX data credit: Caltech/NASA/JPL/MSSS. Earth imagery is from Google Earth including Landsat/Copernicus/U.S. Geological Survey coverage. North is toward the top of the page, unless otherwise indicated. (b)-(d) Examples of cirques on Earth incised into mesa topography, along with an example of a cirque profile in each. Part (i) of (b)-(d) provides an overview of the cirques in that location with an inset of**

**the location of part (ii). Part (ii) of (b)-(d) offers a zoomed-in view of an individual cirque. Part (iii) of (b)-(d) shows the profile of the individual cirques in part (ii). (b) Kamchatka Peninsula, Russa (58.48°N, 160.70°E). DEM data: Shuttle Radar Topography Mission (NASA SRTM, 2013), access via EarthExplorer. (c) Uinta Mountains, Utah, USA (40.74°N, 110.05°W). DEM data: National Elevation Dataset (Howat et al., 2022), access via The National Map.; (d) Transantarctic Mountains, Antarctica (80.01°S, 156.35°E). DEM data: Reference Elevation Model of Antarctica, access via the Polar Geospatial Center.**

*Lines 91-94. Given that cirques are most commonly recognized when they are empty of ice or nearly empty of ice, what measurement challenges exist for mapping martian alcoves that still have ice and/or debris in them? Are there ice-free cirques on Mars in which an over-deepened depression (a Mars tarn?) could be identified?*

We added the following text to address the concern of ice and/or debris: "For both cirques on Earth (e.g., Barr and Spagnolo, 2015) and alcoves on Mars, infilling ice and debris may affect their topographic profiles and obscure any overdeepening resulting from subglacial erosion." There is a small lip in the example of the profile from Fig. 4aii) of about ~50 m at a distance of about 3 km. However, we recommend future work to obtain and apply higher resolution DEMs than HRSC to have more confidence in the results.

*Lines 100-101. Is it also possible that the alcoves formed slowly during the ~500 My of large-scale (LDA and CCF-producing glaciation) described by (Fassett et al., 2014)? We don't usually have multi-million-year glacial erosion events on Earth—so the timescales on Mars may be different from our terrestrial expectations.*

While it is possible that the alcoves could have formed slowly during large-scale glaciation at the spatial extent of LDAs, it is not known whether erosion rates on Mars would have been consistent throughout the last ~500 Myr. On Earth, Barr et al. (2019) proposed that cirques reach most of their size during the first glacial occupations and while the cirques may be occupied for over a million years on Earth, cirque growth is expected to slow during subsequent occupations. To address this comment, we edited the sentence to read as follows: "If these martian alcoves are analogous to terrestrial glacial cirques, then they may have formed either during an earlier wet-based phase of glacier-like form activity, or formed during a prior glacial cycle separate from the episodes that developed what we observe today as glacier-like forms, for example during episodes when lobate debris aprons formed." We leave further discussion of this point in Section 5.4 Estimating the timescales for cirque-like alcove erosion on Mars.

*Fig. 3. What projection was used for data analysis in the Deuteronilus Mensae region? The craters in Fig. 3 look foreshortened, like they are being plotted in a geographic coordinate system. For length measurements, locally projected coordinates will produce less projection error, which can be large at middle to high latitudes.*

The projection used for the HRSC DEM and mapping the shapefiles was Sinusoidal_Mars and the projection from the CTX mosaic was GCS_Mars_2000_Sphere.

*Fig 1 and Fig 3. I'm a little confused by the selection criteria for branching cirques. There's several features that look like they could be mapped as branching cirques in Fig. 1, but they are not tagged as cirques because they have GLF in them. But many of the features marked as candidate cirques in Fig. 1 have LDA or remnant LDA or debris* *aprons of some kind in them, too. So none of these candidate cirques are empty in the sense that deglaciated cirques in places like the Uintas or the English Lake District are empty. Is it that the GLF-filled alcoves are too small/narrow to map with HRSC DTMs? That's a different issue from what's reported, which is that GLF-filled cirques were not mapped.*

For the most part, Levy et al. (2014) mapping of LDA didn't include the alcoves. While Baker and Head (2015) did include more of the debris entering the alcoves, they did not consistently map the debris in all alcoves. As a result, since it's not always clear why some alcoves were included and some weren't in the overall LDA mapping, we mapped alcoves individually even if previous work included LDA mapping within some of the alcoves. We excluded any cirque basins with GLFs to focus our study on alcoves without constrained valley glaciers. It is not the case that the GLF-filled alcoves were excluded because they were too small/narrow for HRSC DTMs.

*Line 149. The classification of the cirques seems very subjective—especially distinguishing crater like cirques from other rounded alcoves. Do crater-like cirques show ejecta? Is it possible that all the cirques initiated a craters where impact damage broke up rock, allowing for easier down-slope export by the glacier? Craters commonly have internal landslides—could that explain some of the stepped cirques or the features interpreted later to be active layer detachments?*

We agree that the crater-like category might seem subjective. While all crater-like alcoves had height to width ratios of 0.1-0.3, which is consistent with typical depth-to-diameter ratios on Mars (e.g., Robbins et al., 2017), this is something we can exclude in our morphometrics step. As a result, we removed the category of crater-like alcoves in the revised manuscript and put those alcoves under the simple alcove category before it is filtered for morphometrics corresponding to cirques on Earth. Most of the crater-like cirques did not show ejecta and were very degraded. While it is possible that some cirques were initiated by craters, we do not expect that all of them were, since the distribution of cirques adjacent to each other on the edges of the mesas would signify a disproportionately large number of cirques crowded together compared to the typical crater distribution on the mesas.

*Line 149. Having the classification scheme in the Methods feels a little bit misplaced. Classification is interpretation, so it really could be in the Discussion section. Are there natural breaks in the measured morphometry of the cirques that leads to their classification in certain ways? Are the morphological classes of the cirques that are based on inspection distinguishable from one another in the morphometric measurements?*

Thank you for the feedback, though having a classification scheme in the Methods section is a common practice that has been incorporated in other papers as well (e.g., Fig. 3 in Cesar et al., 2022; Table 1 in Orgel et al., 2018). We are happy to take editorial guidance if this is against the journal style.

We think there are not obvious natural breaks in the morphometrics of the cirques (see above in the response to point 2 at the beginning of the comments). We included the morphometrics as a separate step from the classification system. Since the morphometrics are derived from simple cirques on Earth and not from complex cirque shapes, we did not include the morphometrics of other classes (though we do include the example plots in the response to comment 2 above). As an example, since the branching alcove includes alcoves offshooting from one main trunk, it becomes difficult to acquire accurate morphometrics that represent the entire shape rather than the individual parts.

*Line 163. If the description in Table 2 is what is used to define simple alcoves on Mars based on simple cirques on Earth, those are not morphometrics (i.e., things with lengths, volumes, slopes, etc. that are measured)—"having an armchair shape with a defined headwall, two sidewalls, and are open downslope" is a qualitative description of the landform. I think it is not accurate then to say "simple alcoves have morphometrics consistent with simple cirques on Earth." It would be more accurate to say, "Like simple cirques on Earth, simple alcoves on Mars have an armchair shape with an identifiable headwall, two sidewalls, and an opening downslope."*

We edited the sentence to read as follows: "Like simple cirques on Earth, simple alcoves on Mars have an armchair shape with an identifiable headwall, two sidewalls, and an opening downslope."

*Line 163-164. This is the methods section—no data have been presented or analyzed—but a conclusion is being reported: "Herein, we use the term "cirque like alcove" for these martian alcoves that are the most likely candidate cirques." That's a clear indication that this should be in the discussion section, after measurements and results have been presented. This is especially concerning because the introduction implies that "cirque-like" in the context used in this paper has a genetic meaning, i.e., carved by wet-based glaciation. At this point in the manuscript, there is not enough evidence to support that claim. If "cirque-like" just means "an eroded alcove that hosts the accumulation zone of a glacier," it's less problematic to use it here, since these are alcoves, many of which host landforms interpreted by debris-covered glaciers. But if an origin is implied by "cirque like," more evidence needs to be marshalled to show that these shapes are exclusively consistent with wet-based glaciation.*

On Earth, subglacial erosion of cirques is expected to be associated with either warm-based or polythermal glaciation (see comments responding to point 1 above). When we say that the cirque-like alcoves are the most likely candidate cirques, what we mean is that after narrowing down our dataset, we focus on this subset as the most likely to be cirques and focus the rest of the study on evaluating whether the cirque-like alcoves are indeed cirques based on the distribution of their morphometrics. We rephrased our sentence to address this comment: "Herein, we use the term 'cirque-like alcove' for the martian alcoves that we will evaluate in this study as candidate cirques." We also moved this sentence to the end of section 3.2.2. We are open to changing the term "cirque-like alcove" to "armchair alcoves" throughout the manuscript if this is recommended by both the reviewer and editor.

*Fig. 4. It looks like the spatial resolution of the DEM profiles is very different between these alcoves. Is it a different dataset for each of them?*

All of the profiles should have been using the HRSC DEM. However, we redid them and found that the profile for (a) does look smoother than the earlier version.

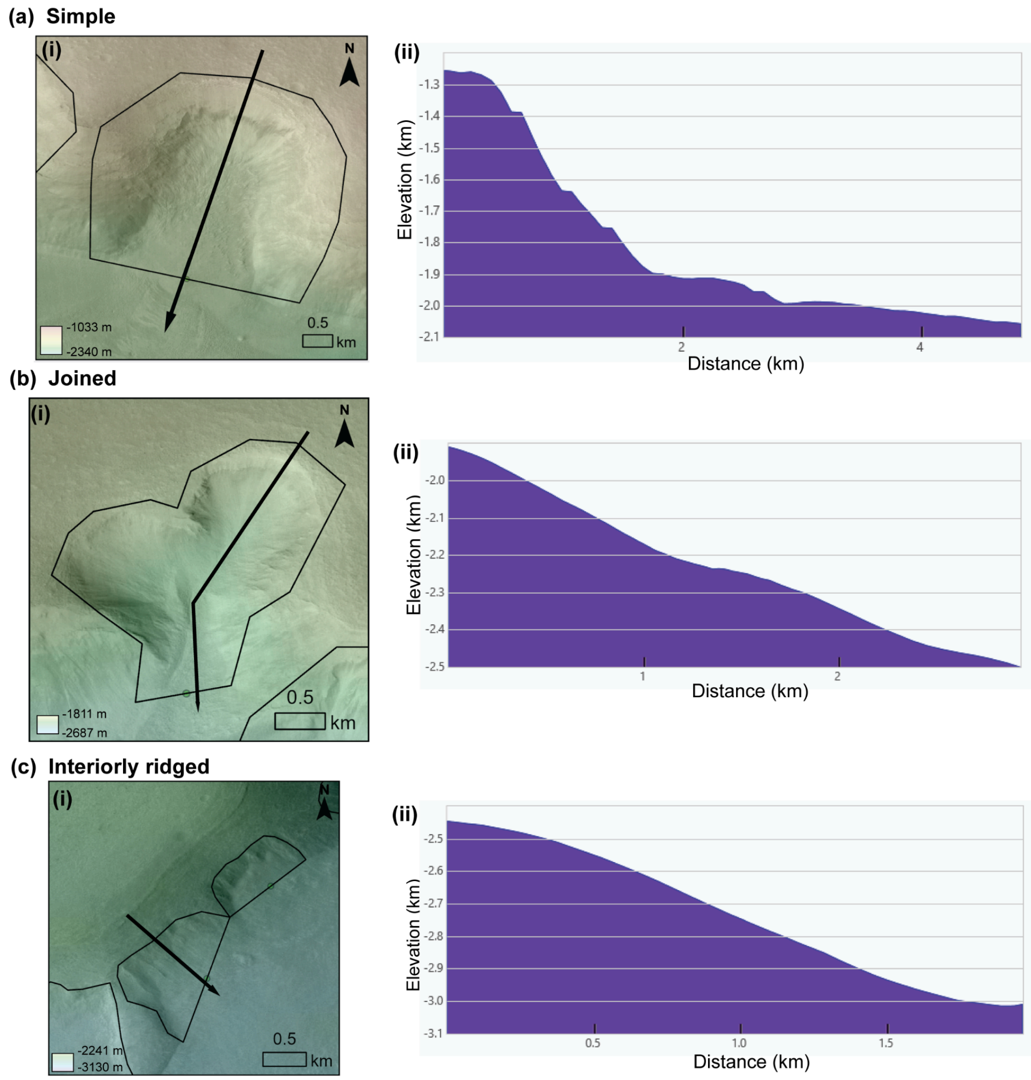



*Fig. 4. What is the purpose of plotting the alcove profiles? To show that they open downslope? Put another way, if someone presented you with a profile of a random alcove in the collection, would you be able to use just the elevation profile to figure out its classification?*

The purpose of plotting the alcove profiles is to provide them as comparison points with the profiles of cirques on Earth in Figure 2. Unfortunately, at the HRSC resolution, it is not possible to use just the elevation profile to inform their classification based on the categories we have put forward from this study of alcoves in Deuteronilus Mensae. While Fig. 4aii) does have a small lip of ~50 m at about a distance of 3 km, this is close to the resolution of the HRSC DEM so we suggest that future work create and analyze higher resolution DEMs for more overdeepenings. Other slight examples of overdeepenings are also present in Fig. 4d and 4f, but at this resolution, it is also difficult to ascertain how much is a result from icy debris such as the LDA.

*Lines 192-193. The use of the morphological classifications suggests that the morphometry does not discriminate well between the observational morphological classes. How many simple alcoves wouldn't have been classified as cirque-like* *if you just used the morphometrics? How many other types of alcoves would have been classified as "cirque-like" if you hadn't excluded them based on the classification?*

We're not sure what the reviewer's first question is referring to since simple alcoves were a morphological class and not a morphometric class. For the second question, using only the morphometrics, 229 more alcoves would have been classified as "cirque-like" for a total of 615 alcoves instead of 386.

*Line 192. How many cirques from cold-based glacier sites are in the Barr & Spagnolo (2015) database? Put another way, could these morphometric means and ranges distinguish alcoves formed in cold-based sites from warm-based sites? Are they diagnostic of one process or another?*

While the database in Barr and Spagnolo (2015) includes 56 cirques in Antarctica, which likely contain present-day cold-based glaciers, this does not mean that these cirques were formed by cold-based glaciers; it means that erosion of these cirque basins predominantly occurred during earlier phases of warm-based glaciation (see responses above). In a different case, for Northern Sweden in the Rassepautasjtjåkka massif, cirques were underneath a cold-based ice sheet and show little evidence of being modified (Barr and Spagnolo, 2015; Jansson et al., 1999). In addition, cirque size and length of glacier occupation do not seem to increase proportionally to each other (e.g., Barr et al., 2024), and currently, for terrestrial cirques, to our knowledge, there isn't work comparing the morphometrics of cirques eroded by warm-based versus cirques that may have potentially been eroded by cold-based glaciers (especially because it is difficult to measure the erosion rates of past glaciations). And, it is an open question on Earth how much of a cirque basin can be eroded by a cold-based glacier, especially since substantial subglacial erosion by a cold-based glacier has not been observed.

*Lines 193-195. This seems like it's a result, not a method section sentence.*

We edited the sentence to read as follows: "Herein, we use the term 'cirque-like alcove' for the martian alcoves that we will evaluate in this study as candidate cirques. By applying these constraints, we narrow down our dataset to 386 cirque-like alcoves from our initial mapping and classification of 2018 alcoves."

*Line 223. It shows a tremendous eagerness to find similarities between the martian alcoves and the terrestrial cirques by grouping results of the measurements in with comparison to their counterparts on Earth. It might be more clear to report the novel measurements for Mars in the results and then compare them to the properties of cirques on Earth in the Discussion section.*

To follow the reviewer's comment, we moved what was previously Section "4.1 Comparison of length, width, height of cirque-like alcoves on Mars with cirques on Earth" to the Discussion section 5.1.

*Line 224. Again, no results shown yet, and more conclusions: "Focusing on cirque-like alcoves only because they are the most likely candidate cirques." Inferences, interpretations, and classifications belong in the discussion section, and should be framed as inferences based on the data analysis, not based on assumptions made going into the* *measurements.*

We moved this sentence to the Discussion section 5.1.

*Line 229. It would be best to show all the DEM-based measurements, not just the measurements for the alcoves that were assumed to be most Earth-like. It would be great to see summary statistics like these for all 7 of your morphological groupings. A box and whiskers or violin plot with each group on it for L, W, H, size, area, would be helpful to see if the classes are different. Most statistical software packages could tell you if there are significant differences between the groups based on the measured properties. It would be neat if there are—but if there aren't significant differences, it just means that either the morphometric properties being measured don't capture the variation or that the resolution of the dataset wasn't up for the task. Scoping your conclusions based on the properties of the whole dataset is very important and without it, the results could be construed to be highly cherry-picked.*

We included examples of box plots for the morphological groupings in response to point 2 at the beginning of this review. There are no significant differences, likely because the resolution of the dataset wasn't up to the task as mentioned by the reviewer. As mentioned in Spagnolo et al. (2017):

> "The tool is designed to work with features that agree with the classic definition of cirques, i.e., features with a sub-circular or semi-circular plan shape, that encompasses an arcuate headwall and an open down-valley extent (Evans and Cox, 1974). The tool will work with more complex shapes, but should not be relied upon for curving, elongated features, though given the definition above, such features are unlikely to be cirques."

We chose not to include this in the manuscript because the ACME tool is designed for simple alcoves and complications arise for applying it to more complex shapes, such as the "joined" and "branching" classes. For example, both of these classes have more than one alcove, but ACME would require that the alcoves are drawn individually. As a result, this would lead to an inaccurate portrayal of the morphometrics of these classes. This is also an issue on Earth, where simple terrestrial cirques are more appropriate for this automated style of analysis. We are open to further discussion on this topic in case the Editor and/or Reviewer have additional concerns.

*Line 236. "Size" is confusing here—it only gets defined later in the paper. Please define it in the main text and not just in the caption.*

We modified the main text to read as follows: "The largest mean size, defined as $(LWH)^{1/3}$, and area for cirque-like alcoves correspond to lower latitudes (Fig. 8a)." We also added this sentence in Methods section 3.2.2: "We also calculate the alcove size by multiplying the length, width, and height as follows: $\sqrt[3]{LWH}$."

*Lines 235-236. Is this trend in all alcoves or just the narrowed down subset?*

The trend of an average of 156.33° is for the narrowed down subset of 386 cirque-like alcoves. However, the trend for all alcoves is very similar with a mean aspect of 157.97°. In the paper, we apply the term "cirque-like alcoves" only to the narrowed down subset: "By examining the aspect of the population of 386 cirque-like alcoves, we observe a south to southeast bias with an average of 156.33° (Fig. 7)."

*Line 243. When doing orientation analyses, it's important to normalize to the availability of host slopes. Are S and SE-facing alcoves abundant because they really form preferentially in that direction, or are there just a lot of E-W slopes in the study area and alcoves will form normal to the slope they are seeded on. Can the rose diagram be normalized based on a sampling of slopes in the study area?*

Using the HRSC DEM, we found the aspect for each point and calculated 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. After normalizing, we found that the same southeastward trend persisted.

Below is the table of the numbers.

| **Aspect Bin** | **Land Surface Percent** | **Cirque-Like Alcove Aspect Percent** | **Normalized Percent** |
|---|---|---|---|
| Northwest | 12.01 | 3.37 | 3.41 |
| North | 15.95 | 6.48 | 4.94 |
| Northeast | 12.92 | 15.03 | 14.15 |
| East | 12.43 | 13.47 | 13.18 |
| Southeast | 10.95 | 16.06 | 17.85 |
| South | 12.21 | 25.65 | 25.56 |
| Southwest | 11.29 | 12.95 | 13.96 |
| West | 12.24 | 6.99 | 6.95 |

We also added part b) to Figure 7 and edited the caption to read as follows:

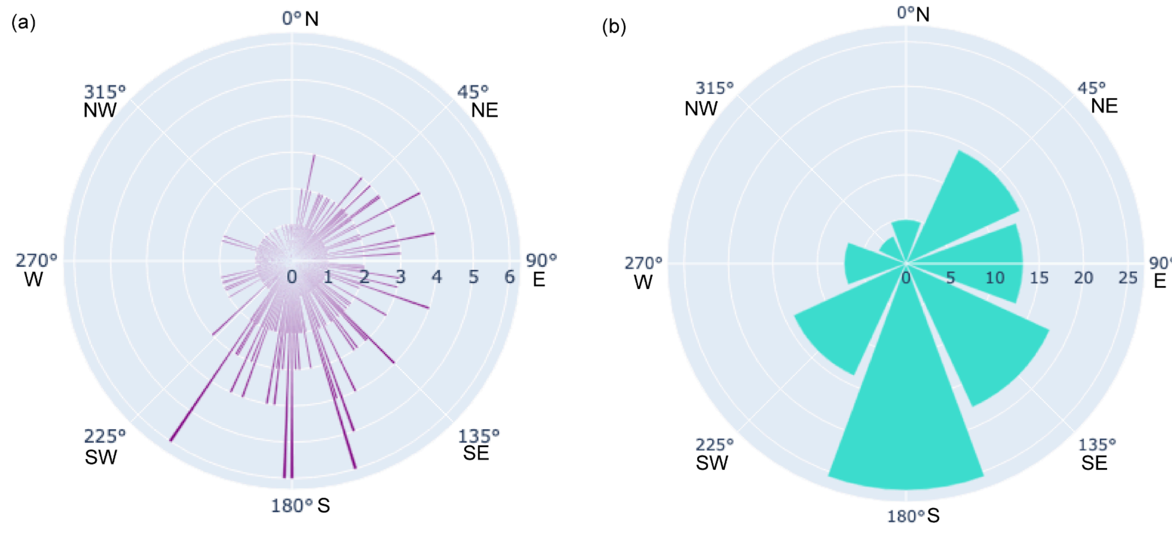


**Figure 7: (a) Rose diagram showing the aspect of cirque-like alcoves. Cirque-like alcove aspect averages 156.33° between the south and southeast directions. (b) Rose diagram showing the relative percentages of cirque-like alcoves in each aspect bin after normalizing by the percent of the total land surface in each aspect bin. Aspect bins are as follows: N, 337.5–22.5°; NE, 22.5–67.5°; E, 67.5–112.5°; SE, 112.5–157.5°; S, 157.5–202.5°; SW, 202.5–247.5°; W, 247.5–292.5°; NW, 292.5–337.5.**

*Fig. 8. Binning the data seems like losing resolution. Could these plots be rendered as scatterplots to show the trend more clearly? If the inference is that there's a correlation between these geographic attributes like latitude and elevation, it would be possible to compute a correlation coefficient using the unbinned data.*

We did include the plots as scatterplots in an early draft of the manuscript. We decided these were less easily interpretable and therefore did not include in the submitted (and now revised) manuscript. Below we include examples of the scatterplots.

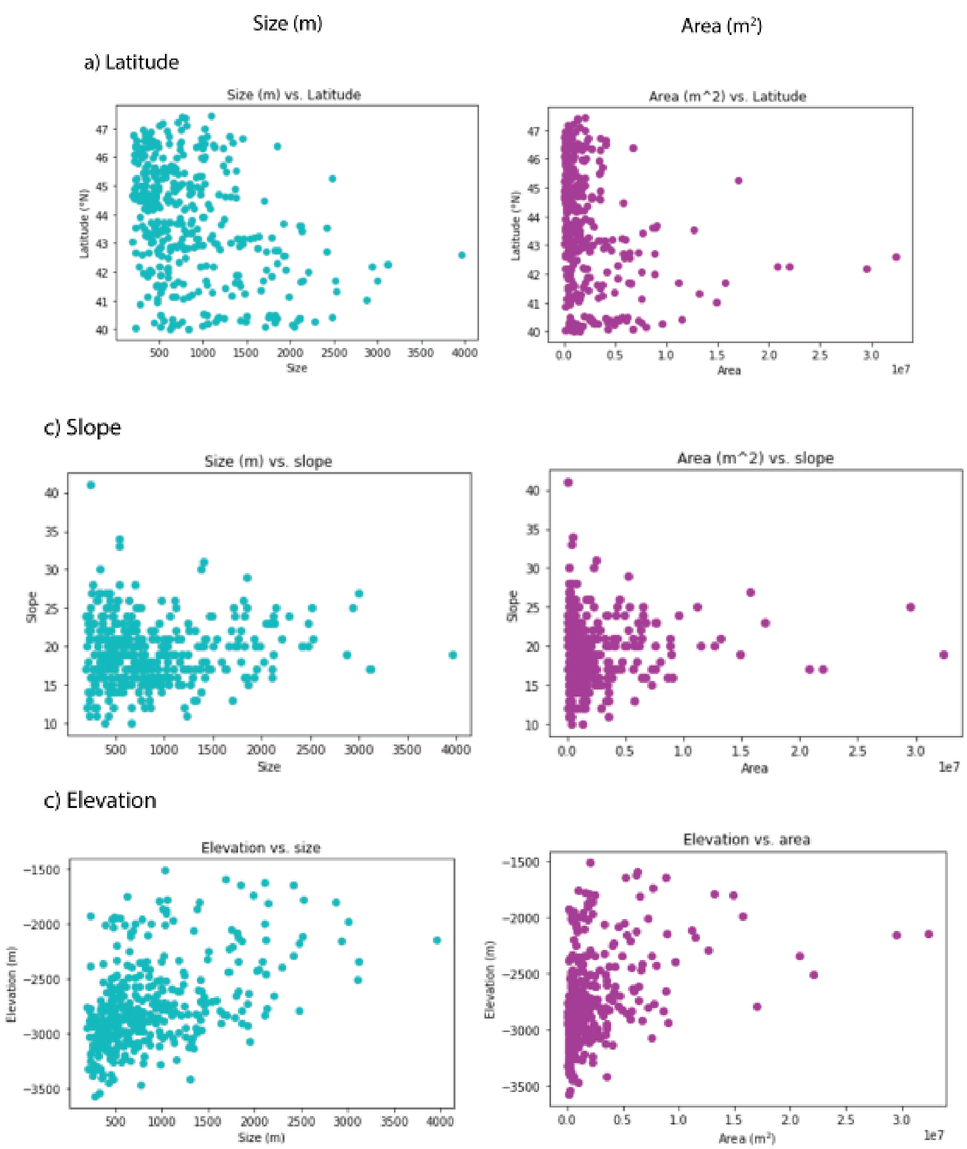


*Fig. 9b. This seems like another case where it's important to check whether the study site increases in elevation towards the north. A random sampling of elevation points in the study area should help normalize to the available elevations for alcoves to see if the alcoves are over- or under-represented at high or low elevations.*

Previously, in Section 5.1.3, we mention that this is due to the topography: "At lower latitudes, the mesas are at a higher elevation relative to the basin at lower latitude, and the overall elevation decreases toward the north" (Fig. 12). We added Fig. 12 (the plots below) to the manuscript. We used the raster to point tool in ArcGIS Pro to get 41,618,659 points from the HRSC DEM. Then we found the average at each half latitude in our study region, and found the below plot Fig. 12a , which demonstrates this same trend.

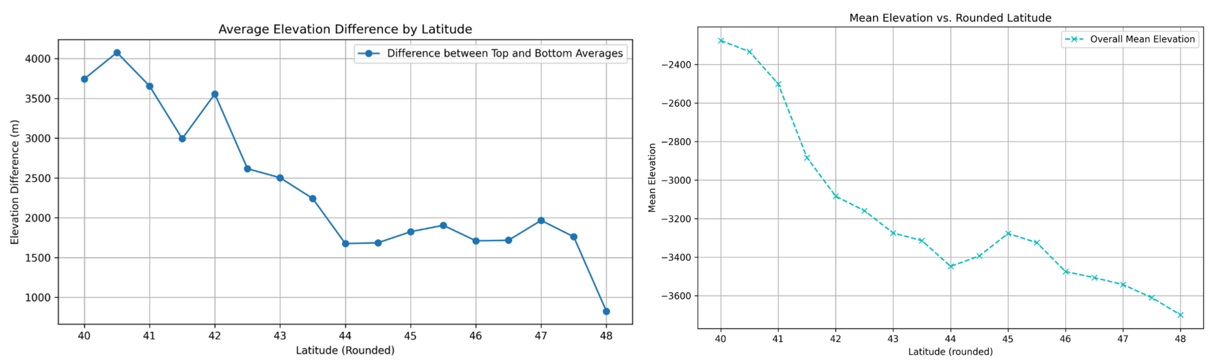



Figure 12: Using the raster to point tool in ArcGIS Pro led to 41,618,659 points from the HRSC DEM. (a) Each point on the plot represents the mean elevation value of all the points at each half latitude in the study region. (b) The elevation difference was calculated based on the mean of the highest 10,000 points and the mean of the lowest 10,000 points at each latitude.

*9c. Likewise, is the mesa heigh limiting cirque height in the study area? All those fretted terrain blocks are about the same elevation above the surrounding plains. Do alcoves cut all the way down through them to plains level? Is there something else that's limiting incision of the alcove into the mesas like internal layering? The change in alcove height with latitude is neat, but it's important to know if the mesas get shorter/ taller with latitude, or if it really is something to do with the alcoves.*

As mentioned above: "At lower latitudes, the mesas are at a higher elevation relative to the basin at lower latitude." We used the raster to point tool in ArcGIS Pro to get 41,618,659 points from the HRSC DEM. Then we rounded the points by half latitude values. The representative height of the mesas at each latitude value was calculated as the difference between the average of the highest 10,000 points and the average of the lowest 10,000 points. This led to the plot in Fig. 12b below, which shows that the mesa height does in fact limit cirque height because mesa height decreases as latitude increases.

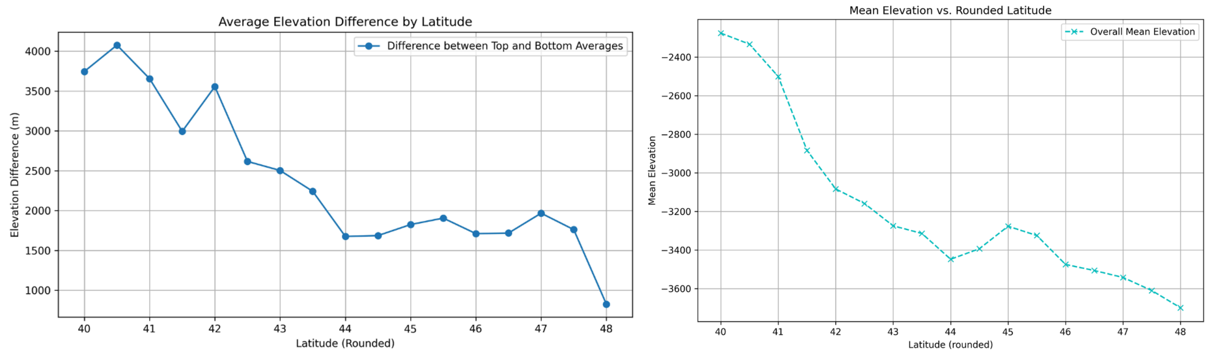



Figure 12: Using the raster to point tool in ArcGIS Pro led to 41,618,659 points from the HRSC DEM. (a) Each point on the plot represents the mean elevation value of all the points at each half latitude in the study region. (b) The elevation difference was calculated based on the mean of the highest 10,000 points and the mean of the lowest 10,000 points at each latitude.

*Line 269. If preserved GLF are pointed north, but alcoves are pointed south, doesn't that argue that whatever produced alcoves is driven by being equator-facing (warm at low obliquity or cooler at high) and whatever drives GLF formation is driven by being pole-facing (cold at low obliquity and warmer at high)? So, maybe thermal cycling matters more for alcoves and ice accumulation matters more for GLF? It just seems like so many of the alcoves mapped in this study are associated with much larger, much older LDA and LVF, that the connection to GLF seems very tenuous. It's like looking at the McMurdo Dry Valleys and inferring a causal link between the Miocene fjords cut by ice sheet draining outlet glaciers and the small alpine glaciers that occupy the valleys today—except the time scale may be more directly comparable to linking LGM glaciation to Proterozoic snowball Earth glaciation (which is what the age difference between the alcoves and the GLF may be).*

We agree that it seems like the alcoves are driven by being equator-facing. On the other hand, GLFs are mostly pole-facing, which correspond to present-day conditions that are favorable for ice accumulation. This is a good point for why it is likely that the cirque-like alcoves were generated during an earlier phase of glaciation rather than by the current GLFs. Whether this earlier phase of glaciation was on the scale of valley glaciers like GLFs (a GLF predecessor) versus larger scales like the LDA is unclear. It is also possible that valley glaciers in the alcoves eventually connected with larger ice bodies like the LDA and LVF.

*Line 307. In most places where gullies and glacier-related alcoves are present and have been mapped (Dickson et al., 2023; Dickson and Head, 2009), they postdate the LDM which postdates the alcoves (based on superposition relationships). The hypothesis that gullying could provide seed points for alcove formation is intriguing and implies cyclicity to ice accumulation and melt, but there's not evidence to support that interpretation that has been presented here.*

Later in the paper in Figure 15, we further evaluate potential geomorphic links between gully and cirque-like alcove generation, though we agree that future work is necessary to establish whether there is an actual link between gullies as seed points for alcove formation and how that connects to cyclicity in ice accumulation and melt. Here, we merely mention it as a possibility based on the similar aspects of gullies and cirque-like alcoves. We added the following sentence to address this concern: "Future work is necessary to elucidate the potential relationship between gullying as initiation points for alcove formation and how that is tied to cyclicity in ice accumulation and melt."

*Line 322. One interesting thing we saw in (Levy et al., 2021) was that the number of boulder bands on LDA (inferred to be internal debris bands) increases with latitude—so further north sites seem to meet threshold conditions to both start and stop glaciation more often than low-latitude sites. So it's interesting that the alcoves get smaller closer to the pole. That suggests that glaciation on Mars is very inefficient at moving rock, especially at higher latitudes, where even though glaciation spins up more over the course of the Amazonian, it doesn't move more rock than low latitude sites.*

That is an interesting point. We wonder though if this may also be due to less availability of material to move in the northern latitudes. At least in Deuteronilus Mensae, the mesas in the north are smaller than the mesas in the south. Again, this would be an interesting avenue for future work.

*Line 332-333. This does not follow. Not all alcoves have GLF emanating from them, and not all GLF emerge from mapped alcoves. So how can a correlation be drawn between them?*

We edited this paragraph to address the comment: "Since both the largest cirque-like alcoves and glacier-like forms are located in southeast Deuteronilus Mensae, this may indicate that there is a local factor impacting both glacier-like form size and cirque-like alcove size, or that the two are connected in how they form. For the first case where local factors have influence, this may be because of local topography that enhances the conditions for precipitation and snow accumulation. If we assume that the cirque-like alcoves were eroded by the same phase of glaciation as the glacier-like forms, then the cirque-like alcoves may not contain glacier-like forms today because their preservation became unfavorable in current obliquity conditions. In that case, conditions in the southeast of this region resulted in both the largest glacier-like forms and cirque-like alcoves. In the second case, if we instead assume that all alcoves had reached most of their current size before the glaciation cycle that brought the glacier-like forms, then the size of glacier-like forms may be limited to the initial size of the alcove that it occupies. However, the paucity of craters in the cirque-like alcoves suggests that the cirque-like alcoves have recently been eroded, which makes it less likely that the cirque-like alcoves had already existed in their present form before glacier-like forms. While we do not distinguish between these two cases in this study, we recommend future work to investigate reasons for finding the larger glacier-like forms and the larger cirque-like alcoves in the southeast part of Deuteronilus Mensae."

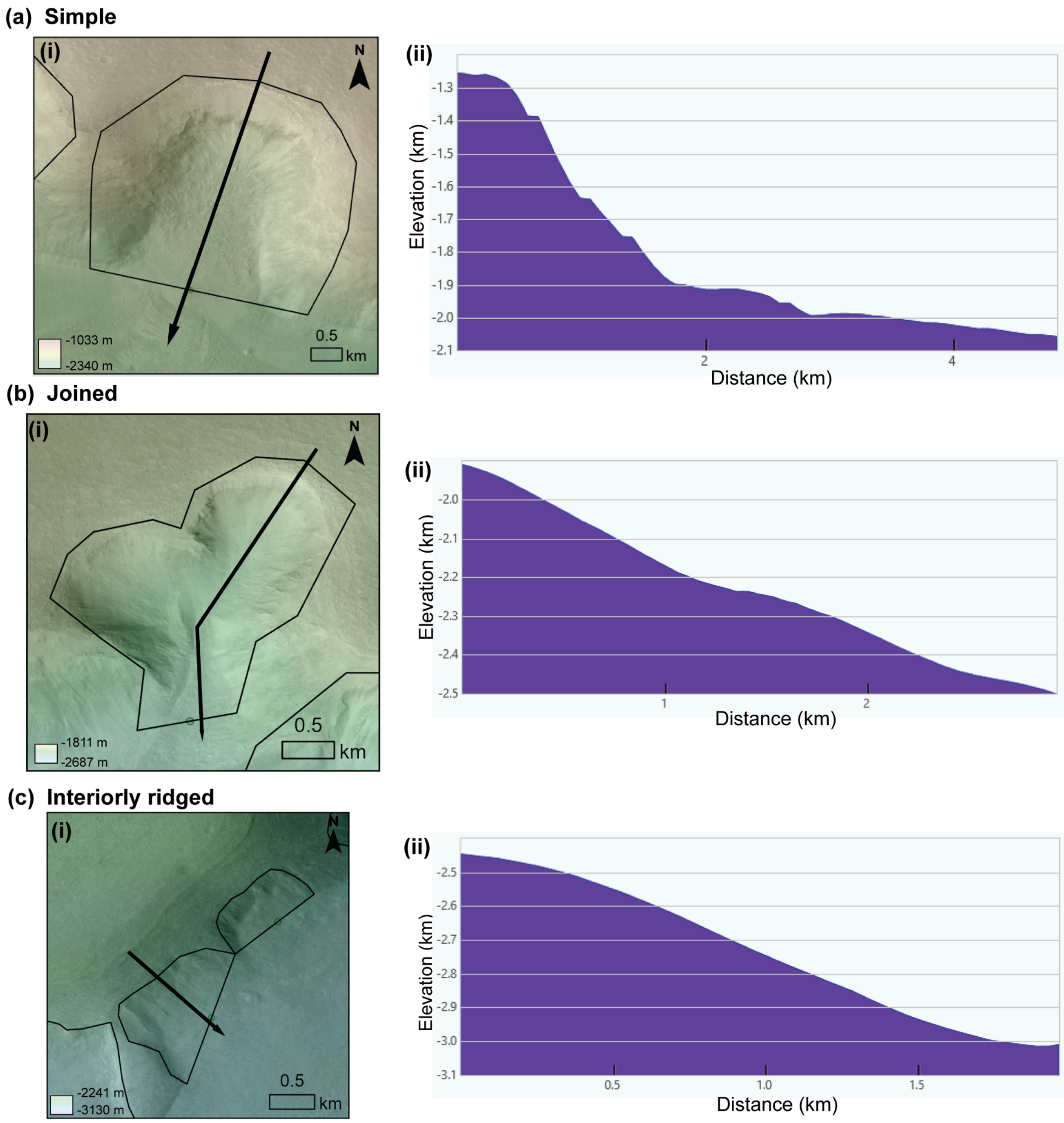
*Line 342. Again, this assumes that GLF and alcoves are contemporary processes, which is an assumption not supported by the measurements here. All these alcoves fall within the zone over which large debris-covered glaciers (LDA, LVF) are found, so there's not a need to expand the area over which glacial activity occurred. There is not a causal or time link shown between alcoves and GLF, so I don't understand the basis for inferring that there is a much larger area over which GLF were active but are somehow vanished now.*

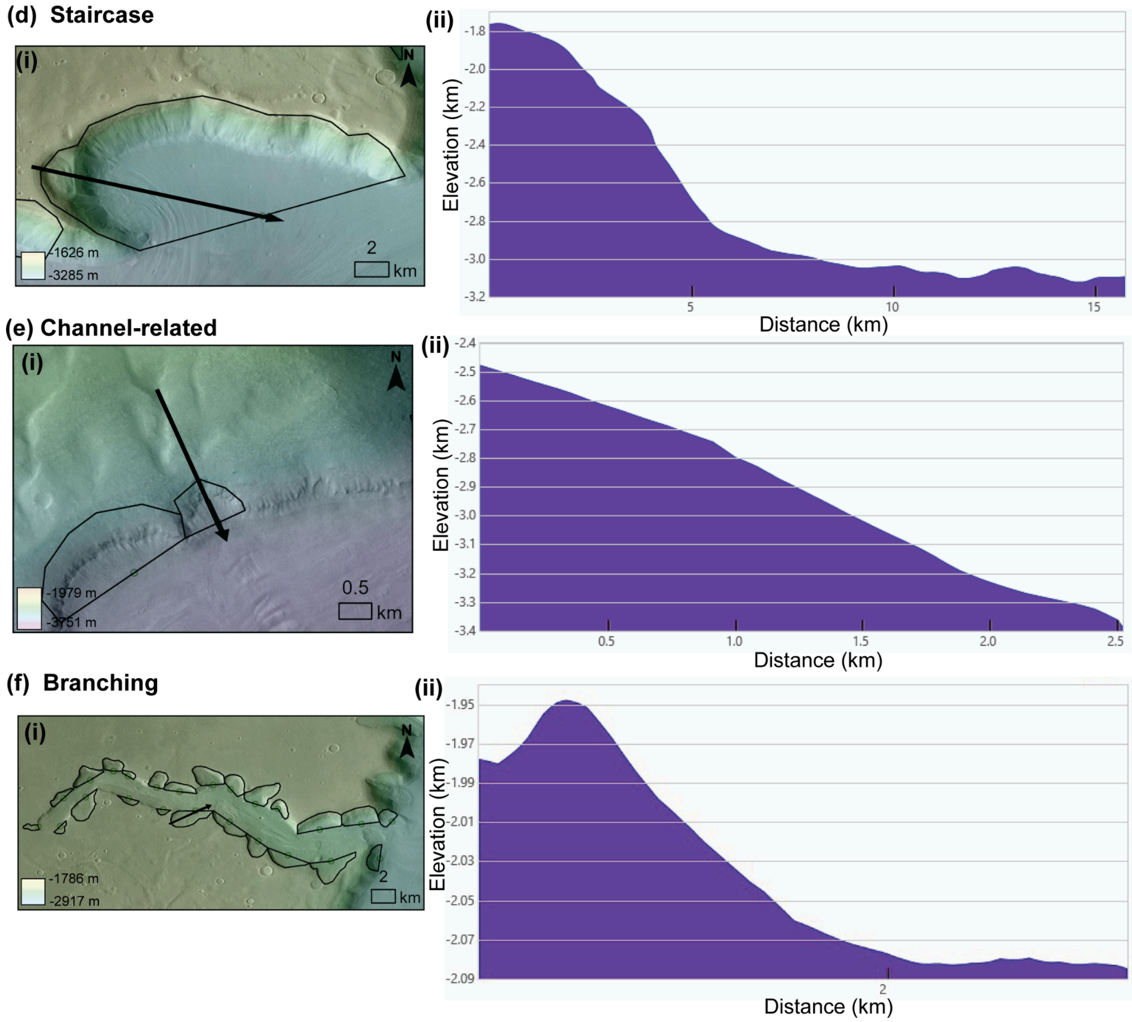
We added the following text to Section 3.1: "~10% of the cirque-like alcoves included some partial coverage from lobate debris apron and lineated valley fill mapping using Baker and Head (2015) and much less with Levy et al. (2014). It wasn't always clear how the cutoffs for the lobate debris aprons and lineated valley fills were decided on relative to where the alcoves and mesa sidewalls were, which is why alcoves were mapped regardless of where the boundaries for the lobate debris aprons and lineated valley fills were drawn."

The alcove also has lobe deposits extending out of it that superpose the LDA (e.g., Fig. 12), which means glaciation periods of alcove formation and LDA formation are not necessarily contemporaneous. We are not requiring that cirque-like alcoves were formed by GLFs, however, we are instead suggesting that they were eroded by a similar size of glaciation as the GLFs, rather than something at the scale of LDA. On Earth, most of the glacial erosion is expected to occur during small scale cirque glaciation (e.g., Barr and Spagnolo, 2015). Once the glacier extends beyond the cirque, then more subglacial erosion occurs further downvalley and and the cirque may be occupied by a cold-based, minimally erosive glacier (Barr and Spagnolo, 2015).

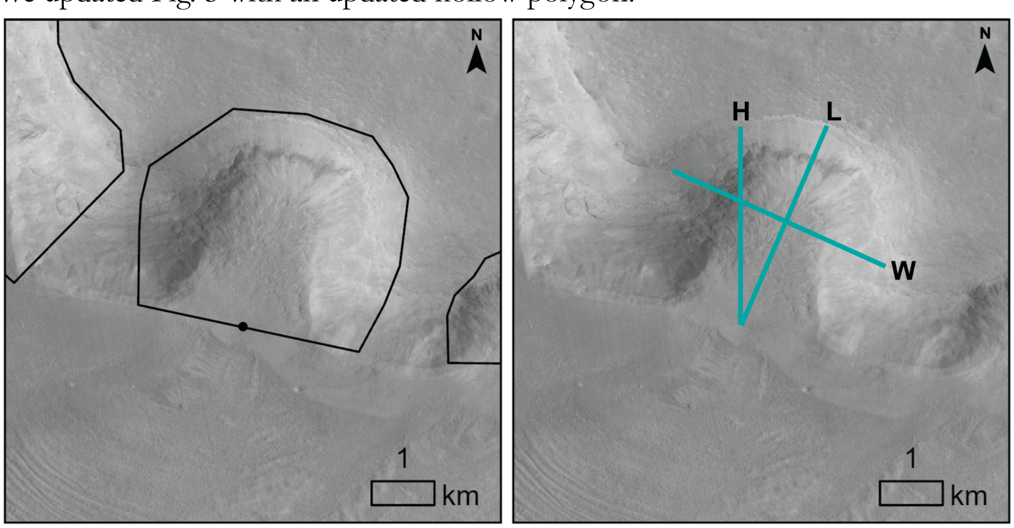
*All Figures. It would be helpful to show the alcoves that were digitized using hollow polygons and/or dashed lines. In Fig. 5, the opaque polygons cover up details that would help a reader understand the extent and morphological features in the alcove zone. In Fig. 4 the mapped alcoves are absent from the figures. It would be very helpful to see what was being considered.*

Fig. 4 has been updated to include the mapped alcoves:


(a) Simple
(i)
N
-1033 m
-2340 m
0.5
km
(ii)
Elevation (km)
-1.3
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
-2.0
-2.1
2
4
Distance (km)
(b) Joined
(i)
N
-1811 m
-2687 m
0.5
km
(ii)
Elevation (km)
-2.0
-2.1
-2.2
-2.3
-2.4
-2.5
1
2
Distance (km)
(c) Interiorly ridged
(i)
N
-2241 m
-3130 m
0.5
km
(ii)
Elevation (km)
-2.5
-2.6
-2.7
-2.8
-2.9
-3.0
-3.1
0.5
1.0
1.5
Distance (km)




We updated Fig. 5 with an updated hollow polygon:



*Line 348. Presenting new geomorphic observations seems like results. Can this be moved from the discussion section to the results section?*

The geomorphic observations were previously in the results section, however, upon the editor's comments, we moved the observations into the Discussion section. While we agree with the reviewer's comments, at this point, we will leave the geomorphic observations in the Discussion section for now since there are interpretations that are interwoven with the results.

*Line 382. Frost heave (needle ice formation via cryosuction) is a mechanism to produce sorted patterned ground on Earth, but it is not a mechanism that is needed to create thermal contraction crack polygons of any type.*

We modified the statement and removed "frost heave."

*Lines 367-375 and Line 428. It seems unlikely that the downslope surface lineations shown here atop the mantling terrain that superposes the bedrock of the cirque resulted from subglacial erosion beneath the glacier that carved the alcove. The ridges superpose a younger mantle unit that in turn superposes the alcove. Neither the stratigraphic relationships, nor the relative ages of the deposits support the interpretation that the ridges formed subglacially.*

We added the following text to address this comment: "Conway et al. (2018) interpret the surface lineations as glacial till deposits (possibly icy sediments) sourced from glacial erosion of the headwall. 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 mean that the ridges were subglacially eroded but from another layer of ice (compacted from dust and snow) that formally sat on top of the rest of what is left of the mantle unit now."

*Line 402 and Fig 14. These ridges are really interesting, but also very mysterious. I think we don't know what those ridges, which appear within LDA, near the toes of LDA, and sometimes along the edges really are. They could be drop moraines or medial moraines (Baker and Carter, 2019). They could also be some kind of internal thrusting feature (Stuurman, 2017). They could be eskers (Butcher et al., 2021), or internal debris bands outcropping (Levy et al., 2021). So it's best practice to not give them a genetic name when a descriptive one will do. Unless there's new evidence here suggesting they are moraines, it would be best to call them transverse or flow-parallel ridges and then to use the observations to help evaluate their origin. What seems most important here is that these ridges are on or in the top-most mantling unit that superposes the bedrock alcoves. So it's stratigraphically some of the most recent material present. Inferring moraine deposition based primarily on ridge sinuosity seems like insufficient evidence. Is there a different in lithology, color, grain size—any other evidence that might help shape the interpretation?*

We edited the terminology from "moraine-like ridges" to "transverse" and "flow-parallel" ridges throughout the manuscript, except in cases where we are referencing another paper that specifically used the terminology "moraine-like ridges." Unfortunately, we did not find THEMIS imagery with fine enough resolution to capture a difference in lithology or grain size for comparing the ridges to the mesa bedrock.

*Lines 417-419. Is the area/ridge size relationship something seen in this study? The alcove measurements made in this paper seem very well suited to evaluate this previously reported trend.*

This study did not examine the area/ridge size relationship. However, this would be an interesting component for a future study. The main issue is having DEMs that are high enough resolution to resolve the height of the ridges across all of the alcoves in question, which is not possible with the HRSC DEM and the HiRISE and CTX DEMs do not have coverage of all the cirque-like alcoves.

*Line 483. What does it mean for these blobs to be glacial remnants? Does that imply shrinking of a previously expansive glacier that accumulated and flowed? Or is it possible they are dead ice fields that never grew large enough to deform and flow? How could the two be distinguished?*

We are not sure what the reviewer means regarding the difference between the shrinking of a previously expansive glacier versus dead ice fields. Typically, dead ice fields in literature refer to "stagnant glacial ice where movement by glacier flow have ceased" (Schomacker 2008). There are also "glacierets" that result from disconnections of existing glaciers, which usually occurs at icefalls or steeply crevassed regions of ice (Davies et al. 2022), though the term has also been applied to perennial snowfields (e.g., Ødegård et al. 2017). "Ice patches" is a term that has been applied to both (e.g., Ødegård et al. 2017) glacierets and perennial snowfields, though these wouldn't be expected to have lobate shapes (e.g., Tussetschläger et al., 2020) like in Figure 12 and what rock glaciers typically have (e.g., Janke et al. 2013). There are also protalus lobes and ramparts, though these are not usually found in front of cirque headwalls (e.g., Harrison et al., 2007). We apply the idea that the glacial remnants are similar to rock glaciers. While there may be different pathways for rock glaciers to form, one hypothesis is that they did evolve from a clean-ice glacier that accumulated and flowed and then progressively degraded with rock/debris cover and reduced flow (Anderson et al., 2018). We added the following sentence to include the consideration of dead ice fields: "The lobes of the glacial remnants resemble a rock glacier more than the hummocky structures of dead-ice, which typically form from stagnant debris-covered glaciers (Schomacker 2008)."

*Lines 492-493. Many assumptions go into using Earth-based erosion rates to estimate the duration of processes on Mars, many of which could be orders of magnitude off in scale. Is it possible to use evidence from Mars to constrain the timescales through crater counting, or published age estimates for mantles, LDA, etc.?*

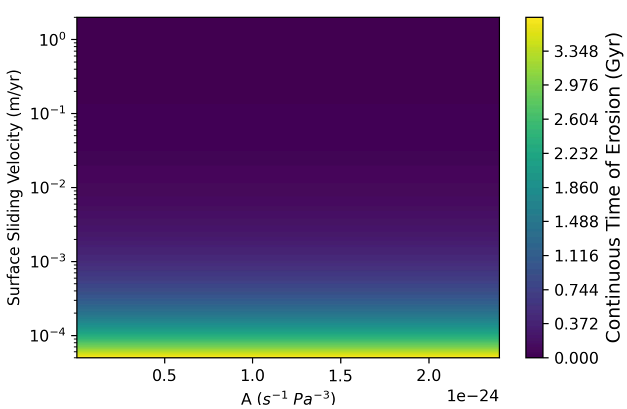
Unfortunately, likely due to both latitude dependent mantling and the slopes of the alcoves, there is a limited number of craters available. Out of the 386 cirque-like alcoves, with an area of 856 $km,^2$ there were ~100 craters, many of which are on the latitude dependent mantle. Using crater counting, we would have gotten a more accurate age for latitude dependent mantle, which has been dated before, than the alcoves. Since both the mantles superpose the cirque-like alcoves, and the LDA are seen to at least partially superpose ~10% of the cirque-like alcoves, it is possible that the more developed cirque-like alcoves attained much of their size prior to both the mantles and the LDA. However, as noted in Section 5.2.2, while the cirque-like alcoves focused on more fully eroded landforms similar to cirques on Earth, we also propose an incipient form for the depression that could host a glacier that would then go on to erode the cirque-like alcove, and that this depression may be connected to gully formation. In addition, debris currently residing within the cirque-like alcoves and superposing the LDA (e.g., Fig. 12) and previous work showing debris sourced from the alcove headwalls (e.g., Baker and Carter, 2019) indicates that the alcoves are likely still actively eroding. As a result, we propose that the more fully developed cirque-like alcoves versus other types of alcoves reached much of their size before LDA and mantles, but now they are covered by young mantles and continue to erode, thus making it difficult to estimate their exact formation age.

*Line 504. At Mars temperatures and ice grain sizes and dust contents, ice can be quite brittle and resistant to flow, see (Milliken et al., 2003). How important is the A parameter in this Earth-derived model?*

To address this comment, we added the following text in the manuscript: "For the A parameter, since it is unknown how much the temperature of ice on Mars has fluctuated throughout the Amazonian, we use both a warm and cold ice scenario. For cold ice, while values for *A* exist down to -50 ℃ (Cuffey and Paterson, 2010), compared to -20 ℃, we found approximately the same results for erosion rate when keeping the other factors the same. Here, we use the *A* parameter corresponding to -20 ℃ to match the temperature near the surface of the rock glacier in Beacon Valley (Rignot et al., 2002), which is the glacier that the surface velocity we use is based on. We also do not know how the Mars temperatures have fluctuated throughout the Amazonian epoch."

In addition, to match the slowest rock glaciers on Earth, we edited the surface velocity from 8 mm/yr to 1 mm/yr: "for the cold-based case we use a surface velocity of $18 \times 10^{-3}$ m/yr, which was measured for a rock glacier in the Beacon Valley sector of the McMurdo Dry Valleys of Antarctica, (Rignot et al., 2002) which represents a low glacier flow speed on Earth."

The A parameter has a negligible effect on the ultimate value of time required for erosion, as seen in the plot below. The color represents the continuous time of erosion, which assumes constant glaciation. It is more likely that due to obliquity changes, only around 20% of the total time would include glaciation. As a result, the surface sliding velocities slower than 1e-3 m/yr become unrealistic relative to the age of Mars. The plot includes surface sliding velocities as low as 5e-5 m/yr, however, measured values on Earth have only reached as low as 1e-3 m/yr. Currently, this plot is not included in the manuscript, but we are open to including it if the reviewer suggests so.



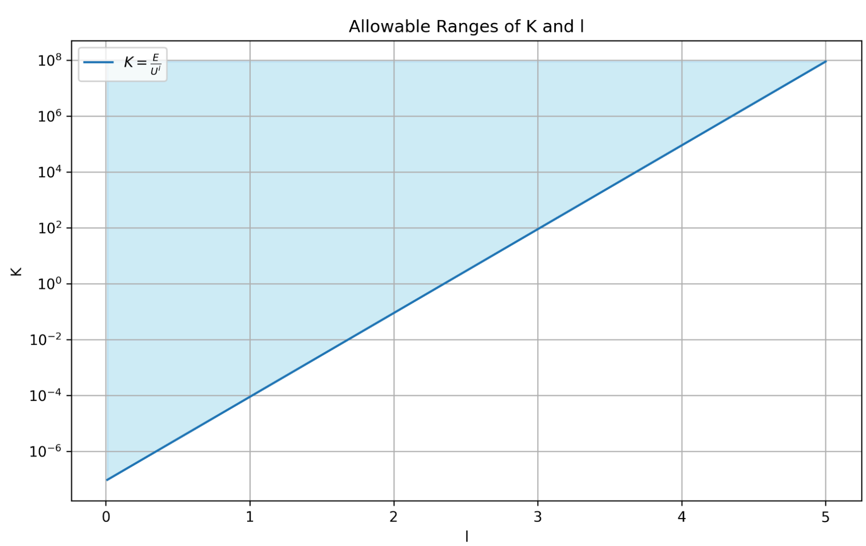
*Line 508. In the mapping, h represents the relief of the alcove—it's maximum minus its minimum elevation. Why is it used here to stand in for ice thickness? In many modern alcoves or cirques, ice thickness is quite a bit thinner than the relief of the headwall. See radar cross sections from (Mackay and Marchant, 2017; Petersen et al., 2020). h is a kind of "bank full" flow, but it's not the maximum possible ice thickness, nor the minimum.*

In the mapping, we used uppercase "H" for the height of the alcove. Here, lower case "h" is for ice thickness, which is what the equation calls for (Cook et al., 2020). The equation uses ice or glacier thickness because the equation is to calculate the surface velocity of the glacier.

*Line 513. $K_g$ seems like an important parameter, too. Are there reported $K_g$ values for basalt? How much do Kg and l values vary? Could the erosion amounts be framed in terms of that range of possible inputs?*

To our knowledge, there is not a $K_G$ for basalt. $K_G$ and l are empirically derived and a range of values of the two together can produce accurate erosion rates. We used an l value of 0.69, which is lower than previous estimates that have used l = 1 or greater (Cook et al., 2020). The value of l = 0.69 or < 1, calculated based on a global dataset, implies that the erosion rate is slower than the rate of increase in sliding (Cook et al., 2020). Meserve Glacier, a cold-based glacier in the Antarctic Dry Valleys, fits within these global values. As such, we believe that the lower l value used by Cook et al., 2020 fits for the type of cold-based glacier we might expect on Mars.

The plot below demonstrates the effect of $K_G$, which is bedrock erodibility constant, and l, which is the erosion exponent, on the continuous time needed for erosion of a median cirque-like alcove. These calculations were done using the lowest A parameter for -50 ℃ and lowest observed surface velocity of 1 mm/yr for rock glaciers on Earth. Values in the shaded region are all possible given a 4.5 Gyr time restraint on erosion. The blue line represents the minimum K and maximum l required. However, they are not all likely given the typical values for K and l found in previous work mentioned above. Currently, this plot is not included in the manuscript, but we are open to including it if the reviewer suggests so.



*Line 538. This ~500 My timescale is pretty consistent with the duration of LDA and CCF-forming glaciation based on the (Fassett et al., 2014) crater counts. That's very neat!*

This will be an interesting point to continue considering, especially if we had better constraints on the climate within the last 500 Myr. To represent an even lower cold-based erosion rate estimate, we used a different surface velocity of 1 mm/yr (previously 8 mm/yr), which led to a timescale closer to 2.3 Gyr. We added the paragraph to read as follows: "On the other hand, if we assume cold-based conditions for glaciers that occupied the cirque-like alcoves, then the erosion rate estimated from the median values for cirque-like alcoves is ~0.85 m/Myr, which is consistent with the wide-ranging estimate of 0.1-10 m/Myr for cold-based viscous flow features on Mars (Levy et al., 2016) but is lower than the Conway et al. (2018) estimates for glaciated crater walls. Thus, for a cold-based glacier, a total glacier occupation time of ~470 Myr would be required for the cirque-like alcoves to form, which is consistent with the ~500 Myr timescale of LDA- and CCF-forming glaciation based on crater counts (Fassett et al., 2014). However, accounting for obliquity variations, a median height cirque-like alcove would require ~2.3 Gyr to erode with only cold-based glaciation. If the glaciers were cold-based during their entire evolution, the erosion timescale is longer and therefore the alcoves must be much older than if they evolved during warm-based glaciation. A timescale of hundreds of millions to a billion years is in the range of when lobate debris aprons were thought to have formed, such as in Deuteronilus Mensae, the lobate debris aprons are estimated to be as old as 1.1 Gyr (Berman et al., 2015). Thus, using the slowest estimated erosion rates corresponding to cold-based glaciers in Antarctica, the alcoves would predate the lobate debris aprons. While ~ % of the cirque-like alcoves do have partially overlapping LDA, there are also cases where the debris on the LDAs are clearly sourced from the alcoves (e.g., Baker and Carter, 2019)."

*Lines 546-547. Is it possible that erosion of the supra-glacial debris is what carved or evacuated the alcove?*

It is possible that erosion of the supra-glacial debris contributed to what carved the alcove, though the amount of the contribution remains unclear. For example, Baker and Carter (2019) used THEMIS images to find trails of debris going from the mesas onto the lobate debris aprons, indicating that there is a contribution from rockfall for the debris on the lobate debris aprons. However, it remains an open question how much of the alcove erosion was created by this process versus an earlier, separate process due to glacial erosion. On Earth, Barr et al. (2019) propose that cirques attain most of their size during the initial onset of glaciation of a previously non-glacially sculpted landscape. Similarly, Bickerdicke et al. (2017) conclude that cirques exist where the land system is at the threshold of glaciation and the volume of debris in the cirques can indicate cirque modification associated with a glaciation period rather than their creation. As such, it remains ambiguous in Deuteronilus Mensae whether the cirque-like alcoves attained much of their size from earlier glaciations prior to any erosion that might be associated with lobate debris apron or later glaciations.

*Lines 573-577. Taking a look at the steep, concave shape, and over-deepened basin and threshold in the (Mackay et al., 2014) radargrams, there is not evidence that those formed through wet-based glaciation. I think the heuristic that steepness, over-deepening, and concave shape only form in wet based glaciers is incorrect and inappropriate to apply* *here.*

Radargrams in Mackay et al. (2014) demonstrate overdeepening in the basin, however, as mentioned at the beginning of the response to reviewer, this does not necessarily mean cold-based glaciation was responsible for this overdeepening and subglacial erosion. Previous work has stated that most of the landscape of the Dry Valleys "had largely achieved its form in the middle Miocene" (Sugden and Denton, 2004). This is consistent with the survival of 8 Ma ashes on buried glacier ice in Beacon Valley (Sugden et al., 1995) and cold-based glaciation for millions of years after the middle Miocene that relatively contributed to much less erosion. In addition, Mackay et al. (2014) propose that the rockfall origin for the inclined debris layer (IDL) is the most likely candidate, rather than basal shearing, entrainment, or erosion, which would all require a polythermal regime (Mackay et al., 2014). In addition, Mackay et al. (2014) state that where there are smooth basal returns that are interpreted as bedrock, "they appear to lie well below the onset of mapped IDL, suggesting individual IDL are most probably sourced above the bed." This would mean that the entrained IDL could not subsequently erode the bed and act as the source of the overdeepening either.

We added the following sentence so that this point now reads as follows: "In addition, the type of overdeepening observed in the profiles (Fig. 6) is consistent with wet-based glacial erosion on Earth. While cold-based glaciation has been observed to contribute to headward and sidewall erosion, such as through rockfall at the headwall, a polythermal regime rather than a pure cold-based regime is likely necessary for any substantial basal erosion (e.g., Mackay et al., 2014)."

*Line 600. Active layers are difficult to produce on Mars during the past 10 Ma. While not impossible, especially in steep settings (Kreslavsky et al., 2008), generating saturated conditions at the base of a detachment surface might be expected to produce downslope spring features, channelized erosion, etc. Are these accessory features observed as well?*

A subset of the alcoves did have channels nearby or feeding into the alcove. However, these constituted a small percentage of the total alcoves mapped (0.3%) and weren't included in the cirque-like alcove analyses.

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