GLACIATION IN MID-LATITUDE TERRA SIRENUM CRATERS OF MARS

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I. INTRODUCTION

The evolution of the Martian surface, especially as pertaining to the presence of water, is a fundamental consideration for understanding the history and current state of the red planet. Modern efforts have helped to develop a tentative past of hydrologic activity and possibly even habitability on Mars. In the present era of increasing interest in the deeper exploration and potential colonization of the planet, knowledge of the varied surface proves vital. Based on existing observations of Mars, it is known that the presence of water on the surface has been influential in the past as both liquid and ice through a variety of geologic processes. This has yielded regions of considerable complexity displaying diverse features such as channeling and carving intermingled with ejecta and impact cratering, such as within the southern mid-latitudes. In deeper context, evidence of glacial activity has been recognized as especially prominent in the mid-latitude bands where it may be recognized as a significant contributor to crater degradation (Berman et al., 2008). In general, a survey of craters within a given latitude band, featuring examination of lobate flow fronts, gullies, and carving features, may provide insight into the latitudinal and regional distribution of particular glacial features as well as their extent.

II. BACKGROUND

According to global circulation models, large scale transportation of glacial ice has occurred from polar regions equatorially as driven by oscillatory behavior in the obliquity of Mars (Mischna et al., 2003). This relationship is exists such that periods of high obliquity correspond to extensions of ice-rich mantle from the poles, representing a Martian ice age, whereas periods of low obliquity align with a recession of this ice to the poles (Head et al., 2003). The orbital trends of Mars beyond ~20 Myr into the past are relatively uncertain. However, recent estimates place the present obliquity of Mars at ~25.2°, which is considered low in relation to the trends of the last 20 Myr (Laskar et al., 2004). It is then reasonable to assume that the current state of the Martian surface is interglacial with smaller scale flow features and remnants.

Of these features, a considerable variety have been observed at the mid-latitude bands as features of the craters present there. Lobate debris aprons (LDA) are described as protruding flows displaying patterns of down-gradient flow, bending around topographic obstacles, and broadening when unrestricted by the present topography (Baker et al., 2009). The formation of these flows is not certain, leading to an array of proposals regarding the methods of development, such as frost creep, rock glacier flow, and debris-covered glacier flow. While many of these features are analogous to terrestrial glacial features, there is disagreement over classifications for such terrestrial counterparts, providing a further obstacle to identifying Martian flows (Baker et al., 2009).

Often associated with lobate flows is evidence of sublimation, primarily texturing. Sublimation, in general, is the phase transformation from solid directly to vapor without transitioning to the liquid state. Especially in regard to glacial ice, the sublimation is generally rate-controlled by vapor transport from the outer surface (Douglas and Mellon, 2019). This process can result in heavily textured glacial surfaces with patterns of varying complexity. Larger scale trends in the pattern of sublimation texturing may also provide insight into the direction of an associated lobate flow. Alternatively, dissected mantle terrains may be the result of subsurface sublimation. Regardless, the combination of these processes, ice flow, and differential sublimation can be responsible for more complex and potentially curvilinear valley terrains (Douglas and Mellon, 2019). It is therefore reasonable that such texturing can serve as evidence supporting a presence or history of glacial ice on the Martian surface.

Gullies are features that tend to be common in the mid and upper latitudes of Mars characterized as small, narrow incisions resembling terrestrial features of the same name. These Martian features are typically found on steeper slopes, such as the inner gradients of sharp crater rims, stemming from an alcoved head and ending with a fanned apron at the base of the slope. A related classification of flow feature is the moraine-like ridge (MLR), which are accumulations of glacial debris of up to 100 m in height. Systems of these ridges are sometimes seen near the fan-like outflow of the gulley bottoms. The majority of these ridges are found within craters of the southern mid-latitudes. Beyond this, the most prominent, developed of these MLR features are considered to exist at the base of pole-facing crater walls (Arfstrom and Hartmann, 2004).

There exist a variety of other features of interest when examining Martian craters, although not necessarily tied to glacial activity. Channeling can be found in many regions of the Martian surface but likewise can have a presence within a crater or on its rim, generally indicating a previous or current fluid flow. Similarly, craters may contain evidence of alluvial fanning as a result of the presence of such fluid, namely liquid water. Beyond hydrological and glacial activity remains the possibility of dunes and dune-like features along a crater floor. It is suspected that such dunes would be more prevalent in larger craters where wind flow may be less obstructed.

III. METHODOLOGY

In attempting to examine and potentially classify craters exhibiting glacial activity or history, a region of study was first selected for use with ArcGIS, ArcMap. Given the significance of preserved glacial evidence at the Martian mid-latitudes, the band of interest was chosen to be the range from -40.000° to -50.000°, corresponding to a portion of the southern mid-latitudes. Starting from the -180.000° longitudinal line, the intent was to examine the selected latitude band from the starting point to as far east as possible. Given circumstantial constraints, the range of examination extended only to approximately -126.700° longitude. This corresponds to the Terra Sirenum region of Mars.

The data taken was organized into three primary categories and further broken into several subcategories. Regarding the selection of craters for examination, it was determined to consider craters with a minimum diameter of 10.00 km, thus incorporating the larger, more prominent craters of the region. Under this criterion, for every crater examined, identifying information was first recorded. This consisted of the name, corresponding geographic coordinates, and diameter as provided by the Robbins Crater Database, making up the 'identification' primary category of the project data.

The actual structural and characteristic examination of the craters was conducted by first identifying a small group of craters at the 1:1,250,000 scale and examining each crater within the group through primarily Context (CTX) imaging. Once all craters in a group had been examined, focus was shifted either north or south until a limit of the latitude band was reached. Once this occurred, the process was repeated for the Martian surface to the east. Essentially, the immediate area of examination passed eastward using something of a boxed serpentine course, constrained by the northern -40.000° and southern -50.000° boundaries.

Beyond identifying information, the characteristics observed in the craters were broken into two additional primary categories, titled 'floor' and 'rim' in reference to the corresponding component of each crater. The first recorded characteristic of the 'floor' data was the type, classified as either flat or complex. Although rather intuitive, a flat rating corresponded to a relatively smooth inner surface of the crater, disregarding the presence of a central peak. In contrast, the complex classification was used to indicate significant complexity, such as a concentric crater or substantial ridging and peak remnants. Following this, the presence of a defined central peak was recorded along with an alternative distinction to indicate whether only remnants were visible.

The next floor subcategory, titled 'Glacial Carving / Flow Front,' was the first directly related to glacial flow. The data under this column was meant to indicate the presence and relative location of a lobate flow (LDA), linear flow front, significant glacial carving, or a related feature. Figure 1 provides examples of each of these feature classifications as observed in the respective craters. Each entry provided a direction with respect to the crater center of where such a feature was found, if applicable. The following subcategory was then used similarly to recognize the presence and locations of apparent sublimation texturing. Although this often corresponded to the data entries for glacial carving and flow fronts, there were many cases where texturing was visible without a defined flow

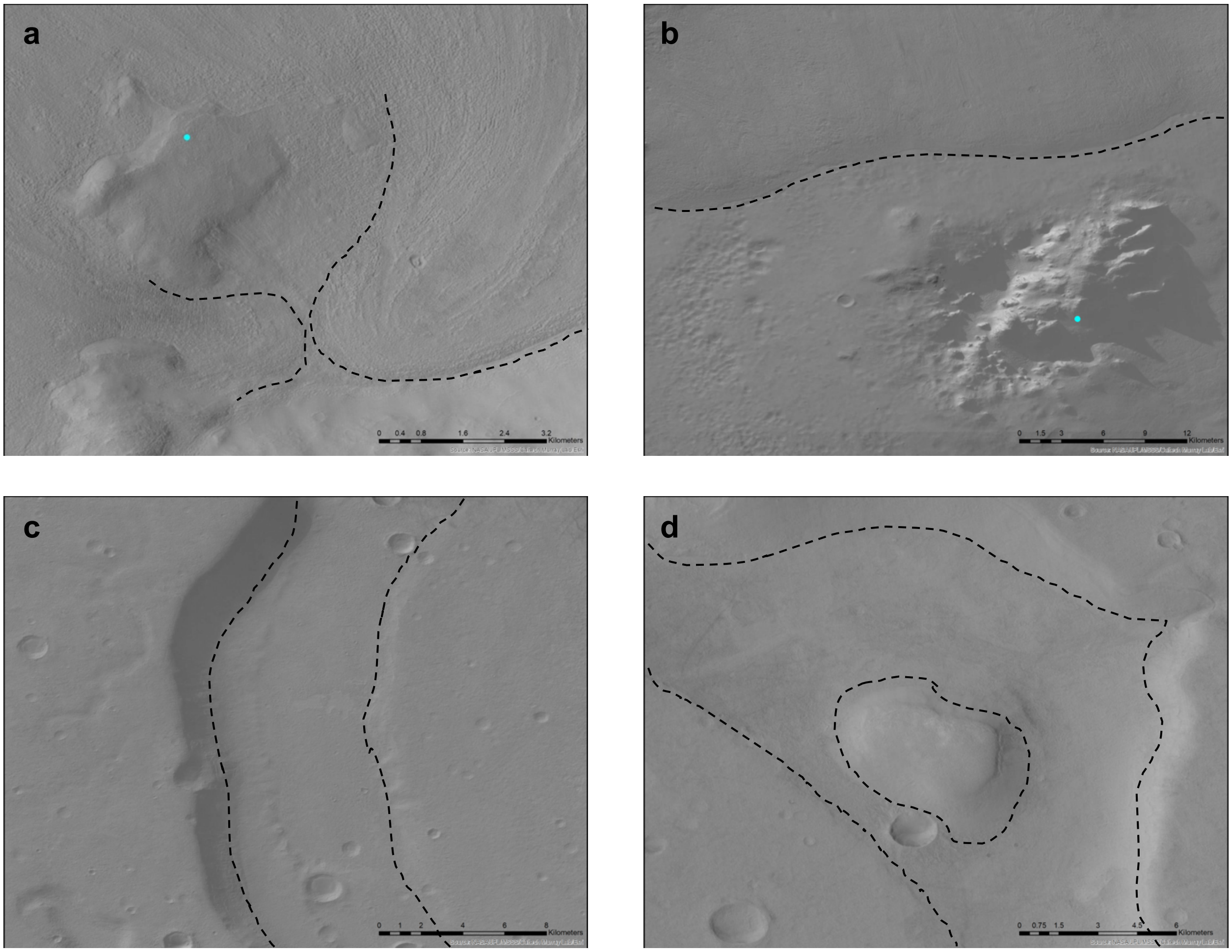

Figure 1: (a) Annotated map displaying converging lobate flows (LDA) within crater 24-001016. (b) Annotated map displaying a more linear flow front to the north and northwest of the central peak in crater 24-000159. (c) and (d) Annotated maps exhibiting areas of glacial carving at different points (southwest and northeast, respectively) on the rim of crater 24-000413.

front or carving was apparent without accompanying sublimation. Figure 2 provides a reasonable example of the former. Furthermore, attempts were made to disregard texturing that was clearly the result of ejecta from a nearby, younger crater. In cases where it was difficult to make this distinction or there was the possibility of various different texturing sources present, a note was made suggesting the texturing was possibly or likely ejecta, depending on the approximate level of observational confidence. For both of these subcategories regarding glacial flow and sublimation texturing, in cases where the feature was present over nearly all of the crater floor, the term ‘areal’ was used. One such case is provided in Figure 3. In contrast, if the feature was absent, the label ‘none’ was assigned. Lastly, ‘circumferential’ was used to describe cases in which the feature was present across the crater floor, excluding the center.

This directional recording scheme was likewise used for the remaining floor subcategories. The first of these was dedicat-

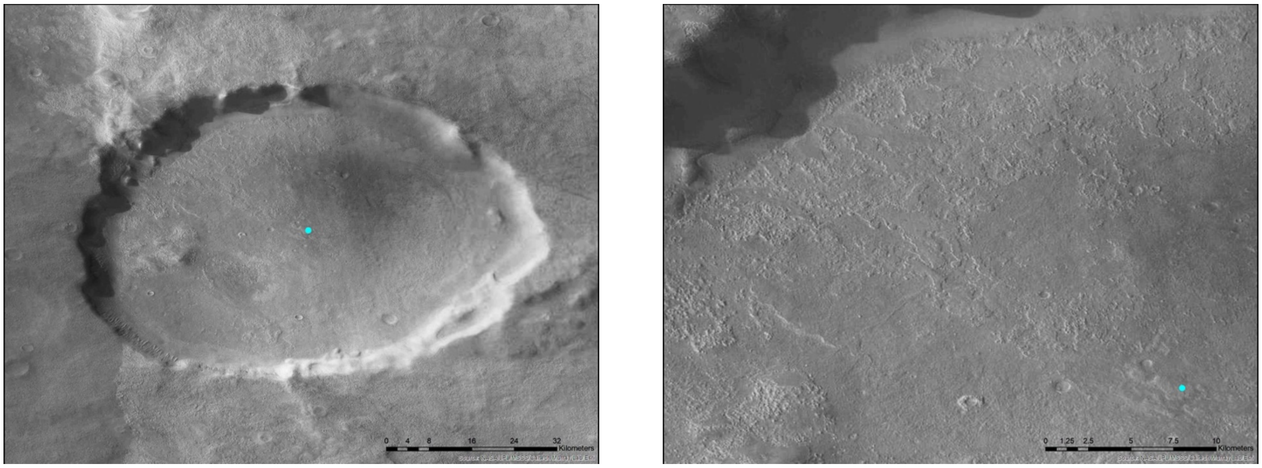

Figure 2: Alternatively scaled, contrast-enhanced images of crater 24-000405 displaying apparent sublimation texturing without a defined flow front verifying glacial activity or nearby cratering to indicate ejecta.

ed to the presence of channeling on the crater floor. Subsequent was a column for the identification of any sort of alluvial fanning features, if present. Additionally, if dunes were located on the crater floor, this was recorded in a separate subcategory using relative directions. Figure 4 shows an example of dunes observed. The last component of the 'floor' primary category was a section for noting any abnormal or interesting features of the floor or further explaining prior classifications.

Following the 'identification' and 'floor' primary categories was a similar grouping for features defining the crater rim. The first 'rim' subcategory was a general classification of the rim erosion, based on observation. The rim was given a 'rounded' rating to describe substantial weathering of its structure. Alternatively, a 'sharp' classification was used to represent craters with stronger, more defined rims suggesting a younger age. This data was recorded in conjunction with a 'relative uniformity' entry which was meant to communicate the approximate consistency of the crater rim. Factors contributing to a 'varied' classification rather than 'uniform' are noticeably asymmetric weathering, disruption of the rim by another crater, or drastically varying rim width.

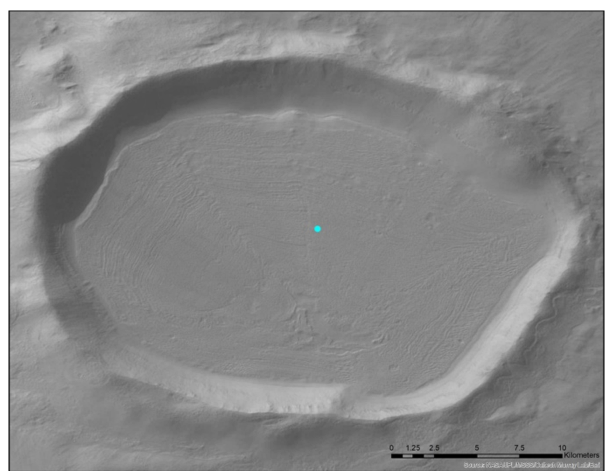

Figure 3: Example of areal glacial flow on the floor of crater 24-001333.

Further 'rim' subcategories were organized similarly to those of the crater floor. The only difference was that rather than considering the presence of dunes, an

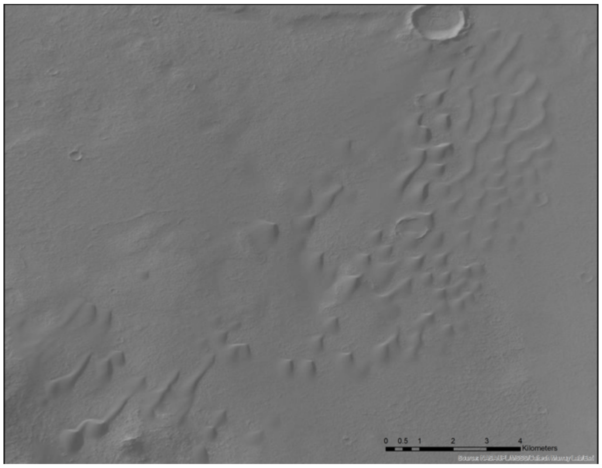

Figure 4: Dunes located on the eastern floor of crater 24-000182.

examination into the presence of gullies was included. An exhibit of these gullies is shown in Figure 5a along with a defined set of MLR in Figure 5b.

In order to attempt to discern which features were being observed in a crater, the scale was adjusted as necessary. In general, the CTX imaging provided the degree of detail needed to discern surface features for the purposes of this examination. However, in some cases, regions of a crater were obscured by surface shadows or the Context (CTX) mosaic was incomplete. In these scenarios, the identification of surface features relied on the lower resolution THEMIS IR imaging. In these scenarios, a note was made with the corresponding data indicating presumed entries based on the THEMIS displays. In some cases, as with the images given in this paper, the crater maps were examined with an altered contrast in order to try and given surface features more definition relative to the rest of the image.

IV. RESULTS

The observed data, although originally recorded in the Excel spreadsheet format, was reformatted to CSV for use in a Python environment. Using Python, a simple code was written in order to interpret the CSV data, primarily by counting the number of craters exhibiting a particular trait.

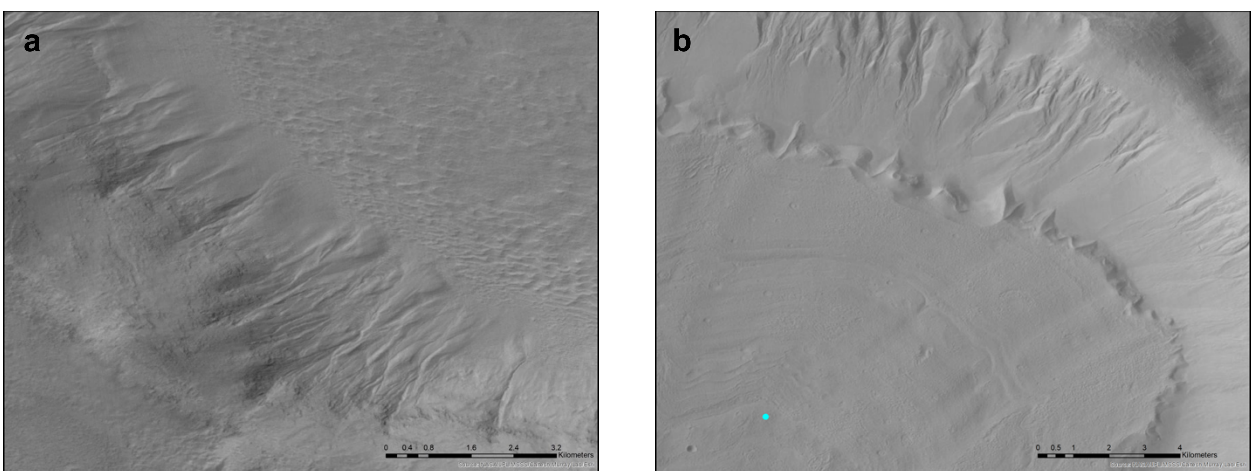

Figure 5: (a) Series of gullies on the southwestern rim of crater 24-001138, complete with fanned aprons at the base. (b) Set of MLR (moraine-like ridges) along the northeastern rim of crater 24-001053.

In total, 400 craters were examined. Of these, 333 craters possessed rounded or generally worn rims whereas the other 67 were considered to have generally sharp rims. Only 21 of the craters studied exhibited a defined central peak or remnants of one.

Of the 400 craters examined in the scope of this survey, 324 exhibited evidence of glacial flows in some form, specifically lobate flows, glacial carving, and flow fronts. The relative directional distribution of these flows is given in Table 1 and alternatively in Figure 6a.

Relative Location	Number of Craters
Areal	88
Center	37
North	123
South	92
East	135
West	146
Northeast	156
Northwest	154
Southeast	133
Southwest	130

Table 1: Table where the first column provides the directional location of observed lobate flows, glacial carving, or flow fronts whereas the second column gives the number of craters exhibiting such features in the corresponding location.

Beyond evidence of explicit lobate flows, glacial carving, or other flow fronts, the presence of potential sublimation texturing was also examined. Of the 400 craters studied, 313 exhibited texturing that was interpreted to be a result of sublimation. The relative directional distribution of this texturing is given in Table 2 and displayed alternatively in Figure 6b. In general, the presence of observed sublimation texturing corresponded to the presence of a defined flow front, lobe, or carving. The maximum difference between the two sets of values is 20 craters whereas the mean difference in count is only 6.22 craters.

Relative Location	Number of Craters
Areal	108
Center	35
North	124
South	93
East	127
West	135
Northeast	148
Northwest	150
Southeast	131
Southwest	123

Table 2: Table where the first column provides the directional location of observed texturing, assumed to be due to sublimation, whereas the second column gives the number of craters exhibiting the feature in the corresponding location.

Regarding other recorded features of the craters, 50 possessed a significant channel or channeling on the crater floor. However, 107 craters displayed similar features at some point on the rim. Interestingly, alluvial fans were not found in any of the 400 craters, whether on the floor or along the rim. It is possible that this is the result of an oversight. Otherwise, this indicates a relative rarity of this feature. Dunes were found on the floor of a mere 9 craters.

Gullies were distributed somewhat more extensively, however. Of the 400 craters examined, 96 craters, approximately one fourth, held gullies at some point on the crater rim. The directional distribution of these gullies is given in Table 3 and alternatively in Figure 7.

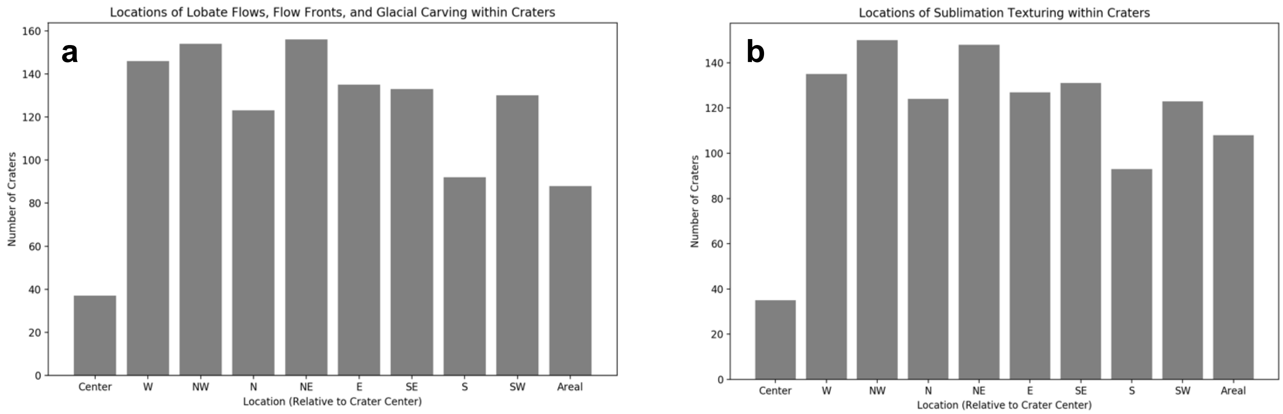

Figure 6: (a) Bar representation of the number of craters exhibiting a lobate flow, flow front, or glacial carving in each location with respect to the crater center. (b) Bar representation of the number of craters exhibiting sublimation texturing in each location with respect to the crater center.

Relative Location	Number of Craters
North	5
South	19
East	14
West	26
Northeast	20
Northwest	12
Southeast	9
Southwest	59

Table 3: Table where the first column provides the directional location of observed gullies whereas the second column gives the number of craters exhibiting the feature in the corresponding location.

An additional relationship considered how the frequency of glacial activity changed with latitude as correlated to the observations made. In order to do this, the latitudinal distribution of craters exhibiting lobate flows, flow fronts, or glacial carving was examined as well as that of craters exhibiting these features in the northern half of the crater and those exhibiting the behavior in the southern half. These distributions are shown in Figure 8a. A similar production of distributions was done for sublimation texturing and is shown in Figure 8b.

Figure 7: Bar representation of the number of craters with observed gullies in each location with respect to the crater center.

Interestingly, the latitudinal distribution of craters with the respective feature in the northern half of the crater appears to exist more northward whereas the distribution of craters exhibiting the feature in the southern half exists more southward. In order to verify that the differences displayed in Figure 8 are statistically significant, a

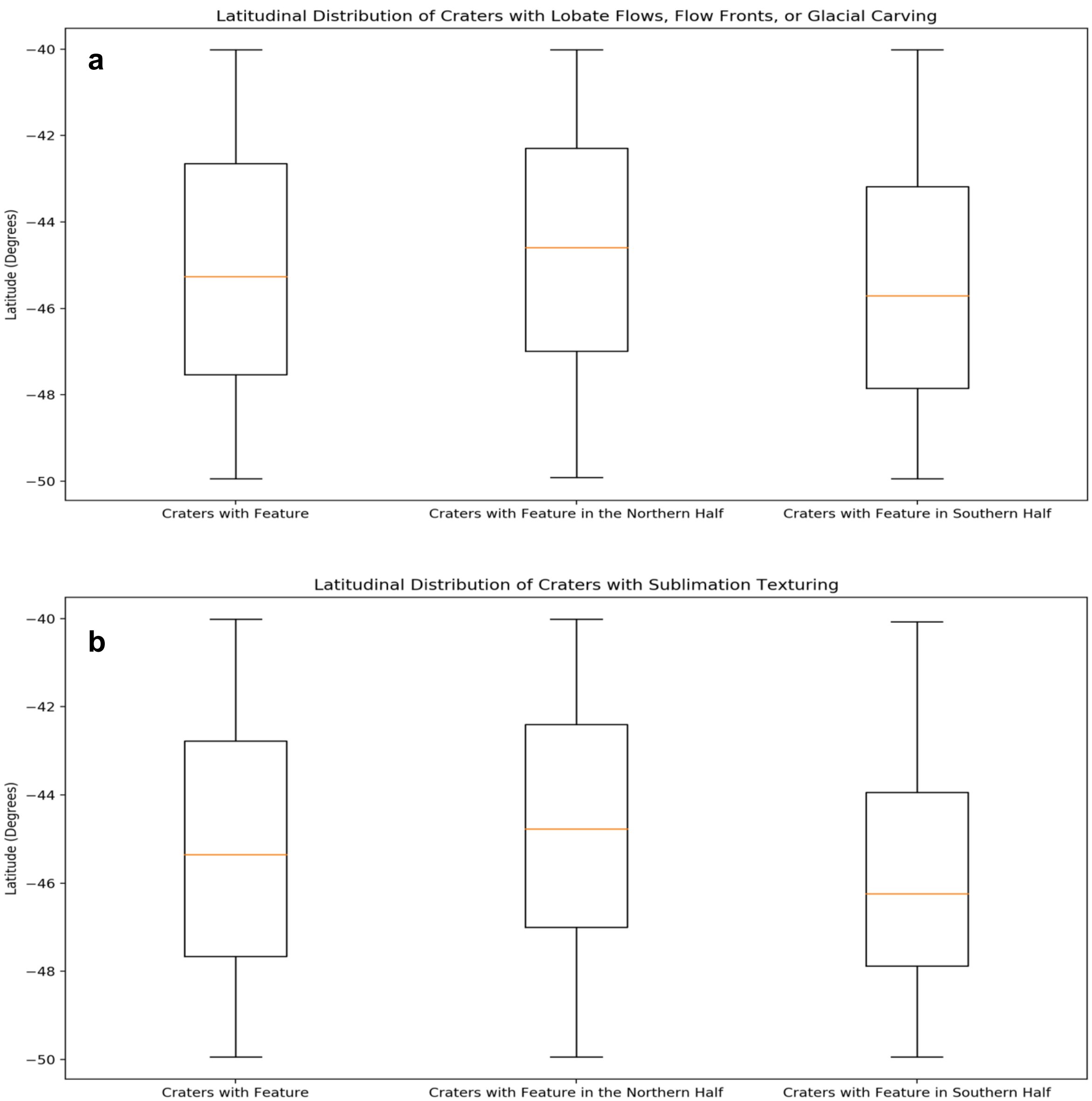

Figure 8: (a) Box plot describing the latitude-based distribution of craters with glacial activity and again when broken into northern activity and southern activity. (b) Box plot describing the latitude-based distribution of craters with sublimation texturing and again when broken into northern activity and southern activity.

two-sample t-test was conducted for both glacial activity and sublimation texturing. The former yielded a p-value of approximately 4.942×10^{-5} and the latter a p-value of approximately 6.456×10^{-7}.

V. DISCUSSION

To follow the previously introduced statistical analysis, both resulting p-values were well below the commonly accepted critical value of 0.05, it can be concluded that the difference found in the distribution of craters with glacial and texturing features in the northern half from those with the same features in the southern hemisphere is statistically significant. This suggests that there is indeed a relationship between the orientation of glacial flows and sublimation texturing and latitude. With this possibility considered, it is important to recognize liabilities to this finding. One potential source of error involves the differentiation of the relative direction. For example, what orientation constitutes an eastern data entry versus a northeastern data entry may vary between observers. This is significant given that a northeastern data entry would be considered in the analysis of Figure 8 whereas an eastern indication would not.

According to the work done by Berman et al. (2008), craters were examined in two mid-latitude study regions, one of which was located in the southern hemisphere of Mars. Lobate flows, channels, and additional glacial features were found to be common in craters greater than 20 km in size. The validity of this finding can be considered in terms of the examination conducted in this paper. Of the 400 craters examined, 174 possessed diameters greater than 20.00 km. Of these, 145 displayed evidence of glacial activity in the form of a lobate flow, flow front, or carving, representing a frequency of 83.33%. Based on this value, there is reason to believe that the finding of Berman et al. (2008) is supported.

An additional finding by the aforementioned authors suggests that within the latitude band ranging from ~45° to 60°, lobate flows and gullies tend to have equator-facing orientations rather than pole-facing. While recognizing a slightly different range of examined latitudes, the study conducted in this paper yielded data that supports the findings of Berman et al. (2008). To specify, of the 400 craters examined, a combined total of 281 displayed lobate flows, flow fronts, or carving in the east-west direction as opposed to 215 with a north-south orientation. This likewise holds true for sublimation texturing and gully distribution. A combined 262 craters displayed the texturing in equatorial directions versus a combined 217 in the polar. A combined 40 craters had gullies on the eastern or western rim in contrast to a combined 24 craters displaying gullies on the northern or southern rim.

As described in Pearce et al. (2010), lobate flows examined in Utopia Planitia possess core characteristic similarities to terrestrial flows. These similarities are summarized as a common, lobate form, curvilinear ridges on the surface, and frontal ridges resembling terminal and recessionary moraines seen on Earth. As these features can be recognized in the craters displayed in Figures 1a and 3, the study conducted in this paper generally agrees with this similarity.

VI. CONCLUSION

The conclusions reached from this study can be summarized as follows. It is found that the distribution of craters with northern glacial activity and the distribution of craters with southern glacial activity have some latitudinal dependence. The characteristic high frequency of lobate flows and additional glacial features in craters larger than 20 km in diameter is supported. In addition, the relative orientation of lobate flows, sublimation texturing, and gullies in the eastern and western directions is more common than in the northern and southern directions, agreeing with other studies. Lastly, the observations made agree with a structural similarity between Martian and terrestrial lobate flows.

Moving forward, the methodology driving this study could be advanced by first and foremost examining an overall larger sample of craters falling within the aforementioned -40.000° to -50.000° latitude band. This would most notably improve the representation of craters in the southern mid-latitudes of Mars. Likewise, there is the supplemental possibility that relationships with latitude would become more defined or more significant with a larger sample. As previously mentioned, a larger sample was aligned with the original intent of this study, but circumstantial constraints resulted in the limitation to 400 craters of the Terra Sirenum region.

Additionally, a more systematic approach to defining the relative orientations with respect to the crater center could be implemented to provide a more definite distribution of glacial features. One possibility involves dividing the circumference of a crater in order to establish angular ranges that would properly categorize features by direction. This range would then act as a degree of tolerance to the 45° counterclockwise from the equator corresponding to northeast, for example. In this manner, the definition of the directions would be certain and consistent across craters, and there would be no dispute regarding whether a feature should be listed as a cardinal direction or intercardinal.

One other evolution of this study could involve introducing greater distinction to the features examined in each crater. For example, rather than recognizing lobate flows, more linear flow fronts, and glacial carving as a single subcategory of the floor and rim, individual data entries could be made for each feature. Furthermore, additional subcategories could be included for moraine-like ridges, lineated valley fill, and several other distinct characteristics. This would allow a more in-depth consideration of the craters and add the potential for the discovery of further relationships.

VII. ACKNOWLEDGEMENTS

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