AN INVESTIGATION OF ALCOVES AND OTHER UNCLASSIFIED LANDFORMS IN THE NORTHERN MID-LATITUDES OF MARS AS POTENTIAL EVIDENCE OF PAST GLACIATION. A. Y. Li[1], E. Johnson[1], M. R. Koutnik[1], S. Brough[2], and A. Manoj[1]. [1]Department of Earth and Space Sciences, University of Washington, Seattle, WA (anli7@uw.edu), [2]School of Environmental Sciences, University of Liverpool.

Introduction: Glacial environments develop and preserve characteristic landforms due to the interplay of ice, climate, soil, and rock. These landforms are used as indicators of past and present climate conditions, as well as past ice dynamics, and the base of knowledge established by studying glacial morphologies on Earth has been applied to aid interpretation of ice-rich or ice-remnant landforms on Mars. Glacial forms on Mars, including lobate debris aprons [LDAs; 1], glacier-like forms [GLFs; 2, 3; Fig. 1a], recessional GLFs that exhibit more than one terminal moraine-like assemblage [4], superposed GLFs [SGLFs; 5], that extend across (and therefore postdate) other viscous flow features are pervasive between ~30-50° N and S. GLFs extend from alcoves, so some alcoves are expected to be source regions for ice that fed these systems in the past when they were active [e.g., 6].

Motivation: To extend our understanding of mid-latitude glacial activity, we have mapped previously unclassified landforms that may retain ice and may be related to GLFs (Fig. 1c), but many others are mostly empty alcoves that do not contain GLFs (Fig. 1b). It is unknown if these alcoves and the unclassified landforms were formed due to glacial activity.

While most ice deposits on Mars are typically considered to be cold-based (where the base of the glacier is frozen to the bedrock), cold-based glaciers are minimally erosive. Furthermore, the erosion of terrestrial cirques requires liquid water at the base of the glacier [7]. Recent work has presented evidence for regionally more widespread wet-based glaciation (where a thin layer of liquid water exists between the base of the glacier and the bedrock), such as with landforms interpreted as eskers and glacial grooves [8, 9], or wet-based glacial erosion on crater walls [10, 11], indicating warmer subglacial conditions due to endogenic and exogenic heating. To further constrain past glacial extent and basal thermal conditions, we evaluate if observed alcoves on Mars are comparable to glacially eroded cirques on Earth.

We focus our mapping and interpretations in the northern Martian mid-latitudes. Specifically, we discuss the distribution and characteristics of our mapped landforms and the role of terrestrial analogues in these interpretations.

Mapping alcoves that do not retain mapped GLFs: While select alcoves have been interpreted as cirques in multiple locations on Mars [9, 12], we assess a large-scale population of alcoves as potential cirques across Deuteronilus Mensae (16-35ºE, 40-48ºN), a region in the mid-latitudes of Mars characterized by mesas encompassed by glacial relicts from previous glaciations. Excluding filled alcoves with mapped GLFs, we map a total of 1952 alcoves using Context Camera images and High Resolution Stereo Camera digital elevation models (Fig. 1b). We apply the Automated Cirque Metric Extraction tool [13] in ArcMap to calculate 16 metrics such as length (L), width (W), elongation (L/W), depth (H), area, elevation, and aspect. To evaluate alcoves shaped by glacial versus nonglacial processes, we define seven classes of alcoves but for this abstract focus on one: a simple alcove, defined as one standalone alcove with most clearly defined sidewalls and a headwall.

We use subcategories to define any type of debris within the alcoves, ranging from boulders to lineations for a likely glacial origin, in contrast with layers and mass-slumping debris that are more likely dominated by nonglacial erosion (Fig. 2). We refine our dataset using empirically derived morphometrics for cirques mostly eroded by ice action on Earth, including: L/W between 0.5-4.25, L/H ratio between 1.5-4, and W/H ratio between 1.5-4 [14]. After accounting for morphometrics and classes, 373 simple alcoves remain.

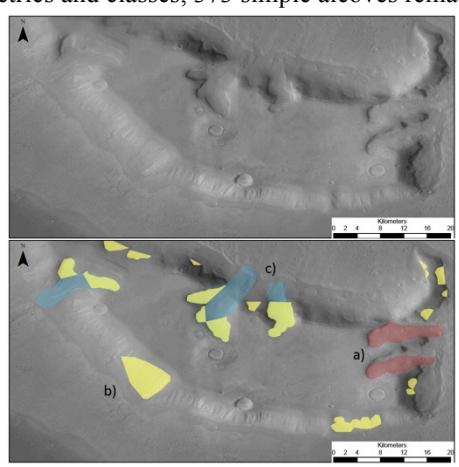

Fig. 1: *a) Red polygons correspond to previously mapped GLFs [2, 3]. b) Yellow polygons correspond to alcoves mapped in this study. c) Blue polygons indicate flow features like GLFs, which are not included in the inventory of [1]; these may or may not retain ice.*

Comparison between alcoves and GLFs: We find that for alcove aspect, the simple alcoves on average have a southeastward bias (Fig. 3a). The eastward bias is similar to the trend of cirques in the mid-latitudes on

Earth, where cirque aspect commonly faces eastward because glaciers are more likely to grow on the lee side of westerly winds present at these latitudes [14]. In contrast, however, cirques in the northern hemisphere of Earth are expected to be oriented northerly (poleward), where total solar radiation is lowest and lower air temperatures allow for glaciers to persist for longer [14]. This is seen in previous work with GLFs as [2] found GLFs to have a poleward (north in this case) and slightly eastward aspect. This contrasting trend between aspect for alcoves and GLFs may suggest that the empty alcoves without GLFs have a southeastern bias because when it was more climatically favorable for ice (i.e. at higher obliquity), GLFs were less discriminate in aspect. However, once conditions became less climatically favorable for ice to remain in the alcoves, south-facing alcoves were depleted in ice first.

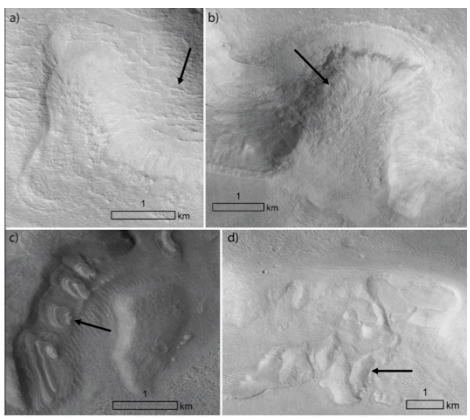

Fig. 2: *Arrows point to the following features within CTX images of alcoves: a) organized boulders; which may be glacially deposited moraines [6]; b) lineations that are likely glacially eroded according to [11], (though aeolian erosion is possible too); c) layers that likely indicate aeolian erosion as seen with nearby dunes [15]; d) mass-slumping features suggestive of nonglacially dominated erosion.*

The mapped distribution of areas of alcoves and GLFs (Fig. 3b) demonstrates that the largest alcoves and GLFs within Deuteronilus are in the southeastern part of the region. Similarly, both alcove and GLF elevation range is largest toward the southeast, which also corresponds to larger ranges in topography in the southern versus the northern parts of the region. We also find all alcoves are within 146 km of GLFs in this region, and ~18% of alcoves are within 10 km of a GLF. Distances are greatest in the northwest and northeast of the study region due to fewer GLFs there.

Mapping landforms that may retain ice: Using the CTX mosaic we also mapped previously unclassified landforms across Deuteronilus and Protonilus Mensae (15-60ºE, 30-60ºN) that exhibited at least one characteristic of a GLF, but would not be defined as GLFs [2, 3; Fig. 1]. The initial inventory in this region has ~250 landforms. A few landforms may be candidate GLFs, some landforms may not retain ice, but many exhibit surficial features that appear related to ice flow and may indicate the presence of remaining buried ice. We mapped these landforms as well as notable characteristics like terminal moraine-like assemblage(s), layering, and/or if originating from an alcove.

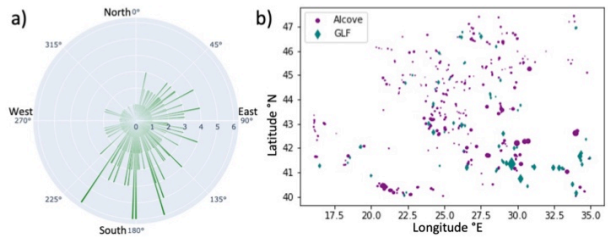

Fig. 3: *(a) Rose diagram of alcove aspect direction. Alcoves demonstrate a southeastward bias. (b) Purple circles represent alcoves and teal diamonds represent GLFs. Both are plotted by relative area. Both the largest alcoves and GLFs are toward the southeast.*

Conclusions and future work: While both simple alcoves and GLFs have an eastern bias in aspect, we find alcoves to also face the south while GLFs mostly face north (poleward). We predict this is consistent with a glacial interpretation of the alcoves in which they were filled with ice when it was more favorable for ice deposition. Within Deuteronilus, the largest alcoves and GLFs are in the southeast. We will also present whether similar alcove trends hold for Protonilus Mensae. In this regional evaluation we will include unclassified landforms that may retain ice, in particular to look for any systematic differences in landform appearance or degradation. The distribution and characteristics of landforms that may relate to the activity of past glaciers will be discussed.

Acknowledgments: This work was funded in part by the grant NASA SSW 80NSSC20KO747.

References: [1] Levy et al. (2014), *JGR: Planets* 119, 2188-2196. [2] Souness et al. (2012), *Icarus* 225, 495-505. [3] Brough S. et al. (2019) *EPSL*, *506*, 10-20. [4] Brough et al. (2016), *Icarus* 274, 37-49. [5] Hepburn et al. (2020), *JGR:Planets* 125(2). [6] Morgan et al. (2009) *Icarus*, *202(1)*, 22-38. [7] Glasser & Bennett (2004) *Prog Phys Geogr.*, *28(1)*, 43-75. [8] Butcher et al. (2017) *JGR: Planets*, *122*(12) , 2445-2468. [9] Gallagher et al. (2021) *Icarus*, *355*, 114173. [10] Hubbard et al. (2011), *Icarus* 211, 330-346. [11] Conway et al., (2018), *Geomorph.*, 318, 26-57. [12] Bouquety (2019) *Geomorph.*, *334*, 91-111. [13] Spagnolo et al. (2017) *Geomorph.*, *278*, 280-286. [14] Barr & Spagnolo (2015) *Earth Sci Rev*, *151*, 48-78. [15] Baker & Head (2015), *Icarus* 260, 269-288.