BOULDER BANDS ON LOBATE DEBRIS APRONS: DEBRIS-COVERED GLACIER GROWTH AT MARTIAN MID-LATITUDES SPANS MULTIPLE GLACIATIONS.

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Introduction: Significant debate exists whether the global population of martian debris-covered glacier deposits formed continuously over the past 300-800 million years (Ma) [1], whether they formed during punctuated episodes of ice accumulation during obliquity maxima (tens to hundreds of thousands of years) [2], or whether they are remnants of a larger glaciation [3]. We show that, like ancient Antarctic debris-covered glaciers on Earth [4,5], boulder banding on martian glacial deposits indicates multiple episodes of ice accumulation and advance. In our analysis, glacial periods are followed by ice removal from the glacier accumulation zone, forming debris bands. We report a median of 5-6 glacial/interglacial transitions recorded on martian debris-covered glaciers, suggesting the cadence of glaciation on Mars is set by orbital forcing over tens to hundreds of Ma, not individual ~120 ka obliquity cycles.

Methods: Boulders were mapped on full-resolution, 25 cm/pixel HiRISE images that overlapped lobate debris aprons (LDA) identified in the [6] catalog. Boulders were mapped along a 100 m-wide transect down LDA centerlines. Boulders were identified on the basis of image features with clearly visible edges, bright, sun-facing sides, and elongate shadows extending in the down-sun direction, after [7]. Boulder location was then transformed from Mars geographic coordinates to centerline path coordinates to produce measures of boulder location relative to the LDA headwall scarp and distance along the centerline.

Spatial clusters of boulders were identified using a K-means clustering approach [8]. The nominal number of bands at each site was determined by maximizing the Bayesian Information Criterion (BIC). Because K-means clustering analysis is sensitive to boulder clustering at all spatial scales, a second banding parameter, “preferred number of clusters” was determined by examining each LDA for natural breaks in boulder density revealed through kernel density analysis and inspection of the K-means clustering report in order to highlight long-range clustering.

Results & Discussion: Boulder clusters interpreted as bands are present on all mapped LDA (Figs. 1 and 2). Across Mars, 2/3 of mapped sites have a boulder cluster within the first 10% of the centerline, in the vicinity of the bedrock headwall immediately upslope of the LDA. In addition to headwall-vicinity concentrations, 32 of 45 martian sites also have clusters of boulders in the final 10% of the centerline profile, suggesting the presence of drop-moraine-like clusters, e.g., [9] at many sites.

The presence of boulder clusters on LDA that are associated with arcuate surface discontinuities and other surface lineations (Fig. 1), suggests that rocky debris is incorporated into LDA at accumulation zone headwall scarps, and is advected down-glacier as fine-scale internal debris layers. These debris layers outcrop at the surface in response to sublimation, producing boulder clusters. If, as on Earth, debris layer accumulation occurs predominantly during periods of negative mass balance in the glacier’s headwall region, it suggests that multiple ice deposition events are recorded in each lobate debris apron.

Accordingly, these findings provide a geomorphic climate proxy that extends the record of orbitally paced climate change on Mars over hundreds of millions of years.

Particular support for this model comes from the widespread presence of headwall boulder clusters currently found on LDA. Mid-latitude ice accumulation is not presently occurring at LDA sites, however, boulders are accumulating through rockfall near LDA apices. This observation suggests that the clasts that will form internal debris layers during the next period of positive mass balance are presently accumulating in the headwall regions of LDA. Debris layers currently growing in the absence of ice deposition in LDA headwalls is a prediction of the internal debris layer formation process models suggested by terrestrial debris covered glaciers.

Intriguingly, the increase in debris band number at higher latitudes suggests that near-polar sites have experienced more cycles of ice deposition and ablation than low-latitude sites. This suggests that near-surface ice stability is a key factor in controlling LDA accumulation and ice flow, and that polar sites reach the threshold at which ice can flow more regularly than lower latitude sites where surface ice deposition occurs only at the highest of obliquities [10].

The positive correlation between latitude, flow orientation, and boulder bands suggests that energy balance and ice mass-balance work across global length scales on Mars to drive glaciation at LDA sites. Boulder clustering on short length scales (e.g., high numbers of nominal bands) may reflect site-specific idiosyncrasies of rockfall frequency (e.g., [13]) related to local geology, or ice mass balance.

Conclusions: Boulder banding provides independent evidence of episodic accumulation and flow of LDA over long timescales. If boulder band accumulation occurred evenly over the past ~800 Ma period of LDA emplacement the number of boulder bands observed on LDA suggests accumulation zone deposition hiatuses occur on timescales ranging from ~10-100 Ma. Along with variable resurfacing, this process helps explain the multiple surface ages recorded by crater size-frequency measurements on LDA [11,12]; some portions of LDA may be tens to hundreds of Ma older than other segments, as indicated by crater counts.

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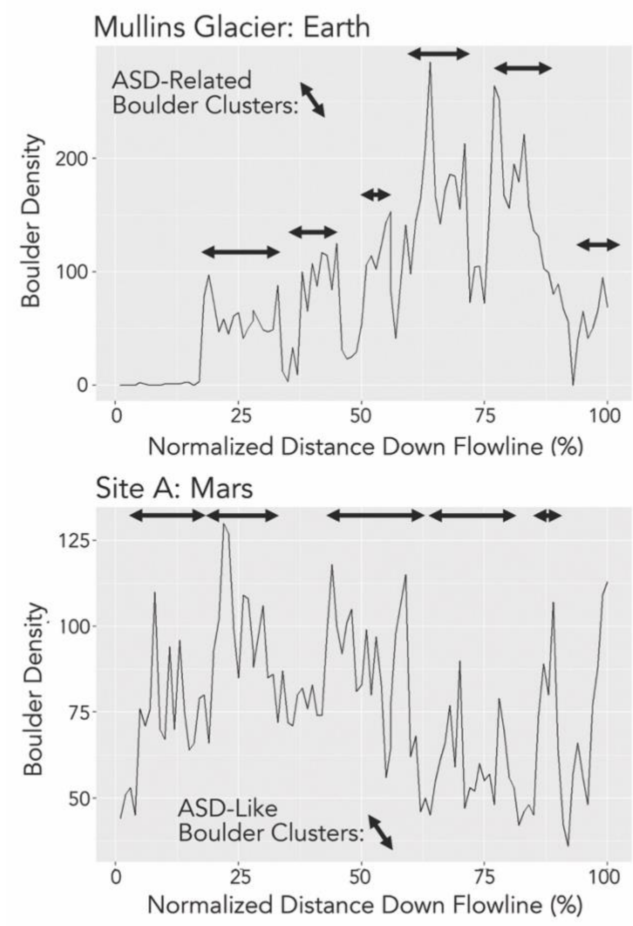

Fig. 2. (Above) Comparison of surface boulder densities in boulders down-slope. Boulders cluster into ASD-like bands on both terrestrial and martian debris-covered glaciers.

Fig. 1. (Below) Comparison of surface boulder densities in boulders per hectare for Mullins and Friedman glaciers (Earth) and three sites on Mars. All martian lobate debris aprons are oriented with downslope to image bottom. Color coding shows kernel densities of boulders. Boulders are clustered at all sites, and on Earth, boulder bands align with arcuate surface discontinuities (labelled as ASDs) mapped by (4).