BOULDER BANDS ON LOBATE DEBRIS APRONS: DOES SPATIAL CLUSTERING REVEAL ACCUMULATION HISTORY FOR MARTIAN GLACIATIONS?

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Introduction: Glacial landforms such as lobate debris aprons (LDA) and Concentric Crater Fill (CCF) are the dominant debris-covered glacial landforms on Mars. These landforms represent a volumetrically significant component of the Amazonian water ice budget [1], however, because small craters (diameter D≤ 0.5-1 km) are poorly retained glacial "brain terrain" surfaces [2], and, since the glacial landforms are geologically young [1], it is challenging to reliably constrain either individual glacial deposit ages or formational sequences in order to determine how quickly the glaciers accumulated. A fundamental question remaining is whether ice deposition and flow that formed LDA occurred episodically during a few, short instances, or whether glacial flow was quasi-continuous over a long period (~10^8 yr [1]). Because glaciation is thought to be controlled largely by obliquity excursions [3-4], a larger question is whether glacial deposits on Mars exhibit regional to global characteristics that can be used to infer synchronicity of flow or degradation.

Methods: We mapped boulder size and spatial distribution over 14 LDA and CCF landform groups, totaling 23 boulder-counting transects including replicates on the same glacial landform and sites with multiple LDA deposits. Boulders were mapped manually on 25 cm/px HiRISE images, down a convex-out flow-line determined through observations of CTX and HiRISE stereo DEMs generated for each site using ASP [5]. Flow direction was determined by calculating the orientation of the flow-line transect. Boulder measurement sites are widely distributed over the martian surface, and include examples in Protonilus/Deuteronilus, eastern Hellas, and Mareotis Fossae.

Results & Discussion: Across all sites, boulder size is highly variable, and typically does not increase or decrease with distance down-glacier. Most notably, at all sites, boulders are present in spatially clustered groups or "bands." Boulder bands are apparent to visual inspection, but were quantified using a Bayesian Information Criterion (BIC) approach [9]. The number of bands at each site was determined by minimizing the penalty associated with adding an additional cluster during model selection (Fig. 1). Sites range between 1 and 21 bands, with a median of 6 bands.

The presence of zones of dense boulder banding in lobate debris aprons separated by thousands of km suggests the possibility that these LDA are growing in similar ways—perhaps responding to a large-scale climate signal associated with either ice deposition and flow and/or erosion rate. Such bands of dense clast cover could emerge from periods of slow ice flow (little accumulation), or periods of rapid erosion [6].

What determines the number of boulder bands on each glacial landform? Band number is moderately correlated with feature length; longer LDA transects generally have more bands on them ($R = 0.4$, $P < 0.05$). With regards to a possible climate signal in band number, it is notable that number of bands is poorly correlated with latitude ($R = 0.22$, $P > 0.6$).

Instead, we are investigating the possibility that band number is associated with glacier flow direction. Orientation has a strong effect on ice net accumulation and also on flow rates via controls on ice temperature [7]. As a group, our data suggests that glaciers with pole-facing down-slope directions (inferred flow direction) have larger numbers of bands on them than deposits with equator-facing orientations ($P = 0.05$ in one-way ANOVA) (Fig. 2). The number of boulder bands was fit with a cosine model in R [8] to test for orientation control on band-forming episodes: bands = M+(A·cos(orientation + k) (Fig. 2). Best fit parameters are $M = 6.7$ ($P < 0.001$), $A = 3.2$ ($P = 0.05$), and $k = 0.2$ ($P = 0.8$). This best-fit model can be interpreted to indicate that widely spaced glacial features on Mars show evidence for 6-7 boulder band forming events, with marginally significant evidence for orientation control on perturbations from this average number of band-forming events: slightly more bands on pole-facing slopes; slightly fewer on equator facing slopes.

Conclusions & Future Work: One possibility is that boulder bands represent cessation and resumption of net ice accumulation that is paced by obliquity excursions in a similar manner to that observed in Antarctica [6]. If so, it suggests that LDA may be responding to changes in orbital forcing by changing accumulation and flow rates. Pole-facing LDA may experience more accumulation events than equator-facing LDA, resulting in more pulses of flow, marked by propagation of boulder bands down-slope. This suggests LDA that surround massifs with both pole- and equator-facing components may experience inhomogeneous accumulation, growth, and flow histories.

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References: [1] Fassett, C. I., et al. (2014) Geology. doi:10.1130/G35798.1 [2] Levy, J. S. et al. (2009) Icarus 202, 462–476. [3] Forget, F., (2006) Science 311, 368–371. [4] Head, J. W. et al. (2006) EPSL 241, 663–

671. [5] Beyer, R. A., et al. (2018) Earth & Space Science, 5(9), 537–548. [6]. Mackay, S. L. & Marchant, D. R. (2017) Nature Communications 8, 1–12. [7] Parsons, R. A., et al. (2011) Icarus 214, 246–257. [8] R Core Team (2019). R: A language and environment for statistical computing. [9] Wang, H. and Song, M. (2011) The R Journal 3(2), 29-33. [10] H. Wickham (2016) ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York.

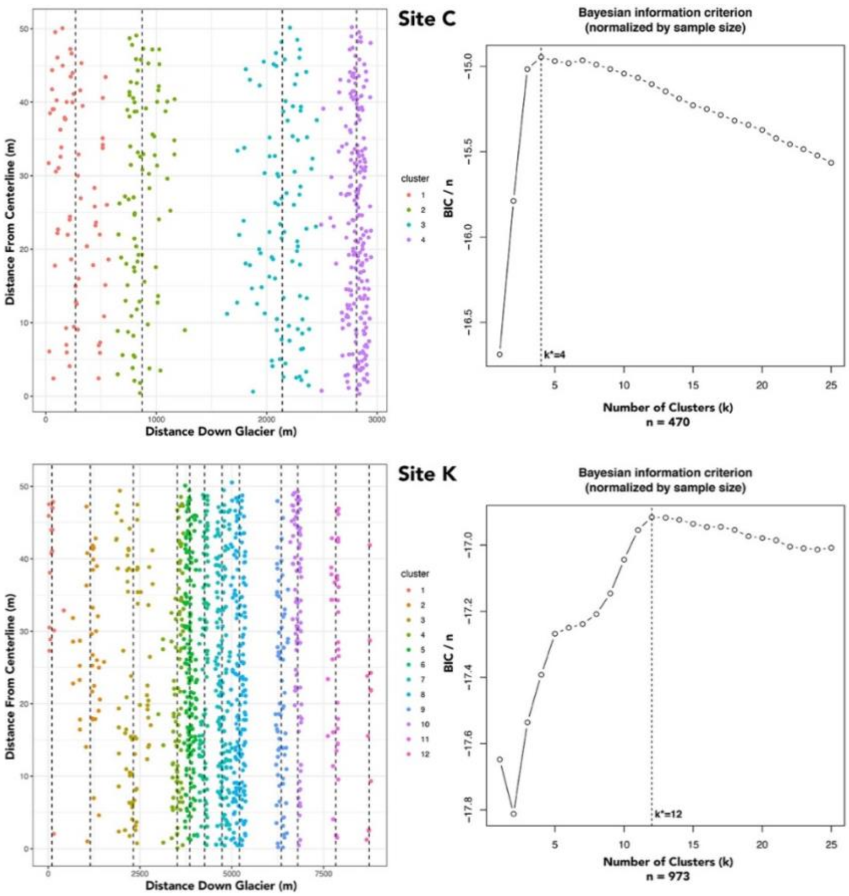

Fig. 1. (Above and below) Examples of BIC-derived clustering models for glacial boulder count transects. Left plots show boulder locations (distance down-glacier and distance from centerline)—each dot indicates one boulder. Color-coding indicates which cluster each boulder is assigned to. Right plots show BIC score used to minimize the number of clusters needed to fit each data

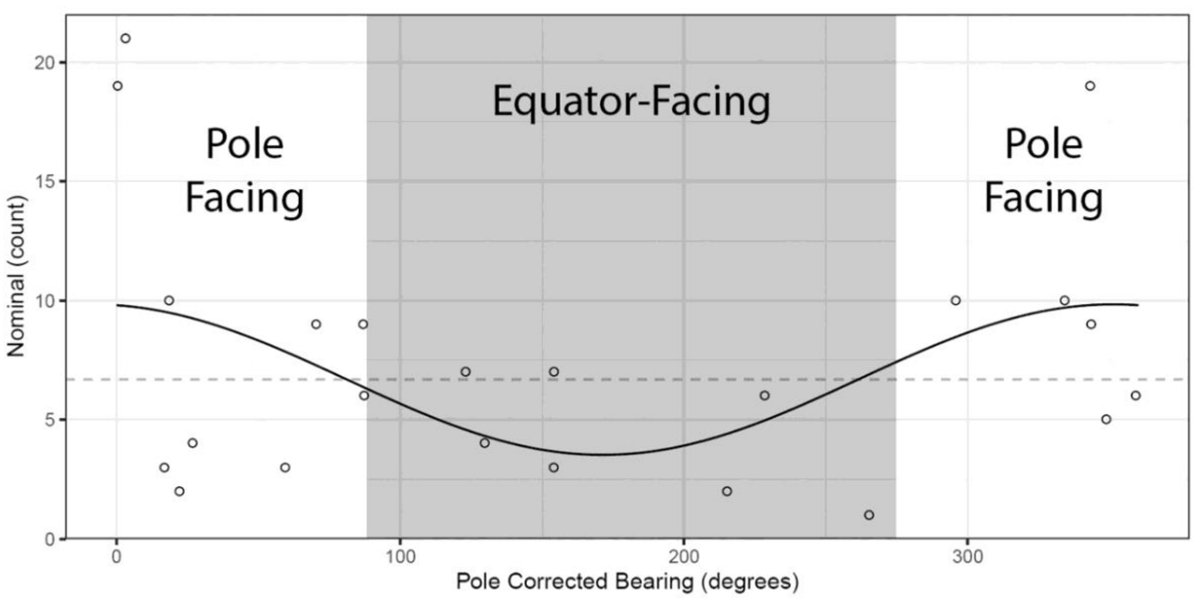

Fig. 2. Number of bands (boulder clusters) as a function for flow direction. 0˚ indicates pole-facing, 180˚ indicates equator-facing. For glacial deposits in the southern hemisphere, orientations were corrected by adding 180˚. An cosine model fit to the data is shown that optimizes fit by adjusting amplitude, period, and x-offset. Pole-facing is defined as azimuths from 270˚ to 0˚ to 90˚. Equator-facing is defined as azimuths from 90˚ to 270˚ via 180˚. Made with [10].