STRATIGRAPHY OF THE NORTH POLAR LAYERED DEPOSITS OF MARS FROM HIGH-RESOLUTION TOPOGRAPHY.

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Introduction: One of the longest-standing questions in Mars polar science remains open today: "What chronology, compositional variability, and record of climatic change is expressed in the stratigraphy of the Polar Layered Deposits (PLD)?" [1]. In order to answer this question, our first step must be to accurately describe the stratigraphic record present in these deposits. The spiraling troughs that expose PLD layers allow stratigraphic study from orbit (fig. 1). However, past efforts have been limited by the lack of layer-scale topographic data, which forced the use of quantities such as brightness to describe a layer.

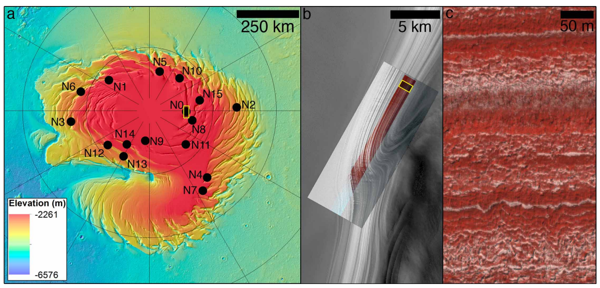

Fig. 1. (a) Topographic map of the NPLD. Black dots indicate study sites. (b) Area around site N0. Background is a CTX image overlain by a HiRISE image. (c) Full resolution view of the section highlighted in (b), featuring the sublimation-lag that affects the brightness of exposed layers.

The Shallow Radar instrument (SHARAD) detected reflectors within the North PLD (NPLD) that are interpreted to be depositional layers [2], implying that the layers are laterally continuous and form a coherent record of depositional conditions. Past studies have attempted to identify periodic signals from stratigraphic sequences of the layer brightness observed in images of PLD scarps [3-7]. These studies reconstructed virtual ice cores of layer brightness as a function of depth from Mars Orbiter Camera (MOC) images and Mars Orbiter Laser Altimeter (MOLA) topography. A problem with past efforts is that brightness is a complicated product of slope, frost retention, albedo, surface texture, and most importantly a sublimation lag deposit that mantles the exposures (fig. 1c) [8]. Thus, it is not clear how brightness relates to intrinsic properties of the layers, if at all.

High-resolution images and Digital Terrain Models (DTMs) from the High Resolution Imaging Science Experiment (HiRISE) now allow for significant advances in the accurate description of PLD stratigraphy. Fishbaugh et al. [6] created the first high-resolution stratigraphic column of the NPLD based on morphology of discrete layers. Limaye et al. [7] made similar columns based on bed thickness. The disadvantage of such discrete layer mapping is the lack of continuous depth-varying quantities that can be spectrally analyzed.

In this work, we use HiRISE DTMs to create continuous stratigraphic columns based on a layer property that has previously not been quantitatively studied: the relative protrusion of NPLD layers from the scarp face, which we take as a proxy for the layers' resistance to erosion. We seek to answer three key questions: (1) Is layer protrusion representative of the internal properties of the strata? (2) Is this property continuous throughout the NPLD? (3) Does the use of protrusion represent a significant improvement over using apparent brightness to describe the stratigraphy?

We have greatly increased the number of HiRISE DTMs of exposed NPLD layers (fig. 1a) and coupled them with Context Camera (CTX) images to build protrusion-based columns at different sites throughout the NPLD. We correlate stratigraphic sequences across hundreds of kilometers and estimate relative accumulation rates between these areas based on changes in the separation of the layers. We use signal-matching algorithms and traces of visual layers in CTX images to correlate layers between DTM sites. The continuous nature of our signals allows spectral analysis to compare dominant stratigraphic periodicities with temporal changes in Mars' insolation history.

Data and Methods: The 1 m/pixel DTMs are made from 30 cm/pixel HiRISE stereo pairs using the procedure described in [9]. Figure 1a shows the sites we have selected for study.

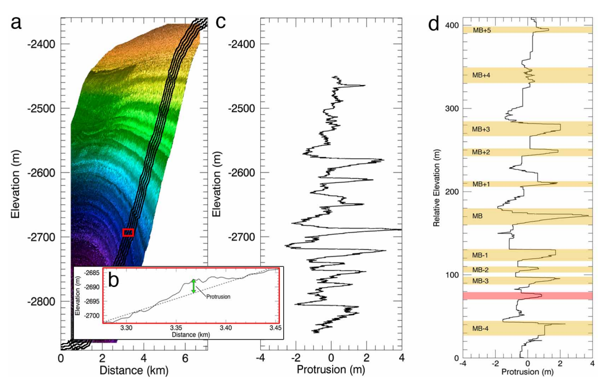

Fig. 2. (a) DTM at site N0 with elevation profiles to calculate protrusion. (b) A linear fit in a window is moved down the profile and protrusion is evaluated as the vertical difference between each point in the profile (solid) and the fit (dashed). (c) Mean protrusion profile for site N0. (d) Protrusion-based

stratigraphic column of the Main Sequence valid for all locations correlated with the N0 profile.

Protrusion Measurement

For each DTM, we perform a best linear fit to topographic profiles within a local "window" (~350 m) along the scarp, and compute the vertical difference between the actual topography and the fit at each point [10,11] (fig. 2a,b,c). To reduce noise in the protrusion signal, we extract sets of 5 parallel protrusion profiles offset 10 m from each other along strike and take the average of each set to create a representative profile for that location.

Correlation Techniques

We identify prominent layers in the protrusion profiles at each site, and then correlate the signals from selected sites to each other using image-based correlations and a signal-matching technique known as Dynamic Time Warping (DTW). This algorithm maximizes the covariance between two depth-varying signals by adjusting their depth dimension, tuning one signal to the other (fig. 3a). The statistical value of the match is then tested using a Monte Carlo procedure that evaluates the percentage of similar random signals that achieved a worse match than the real data (fig. 3b). Percentages >90% indicate a good match To correlate sites that lie along the same scarp (e.g. N0 and N10) we use Arc GIS to trace the most prominent layers in CTX images and then apply DTW. For pairs of signals that do not share a scarp, we use the DTW first, and then compare our results to a previous study done by Fishbaugh et al. [13].

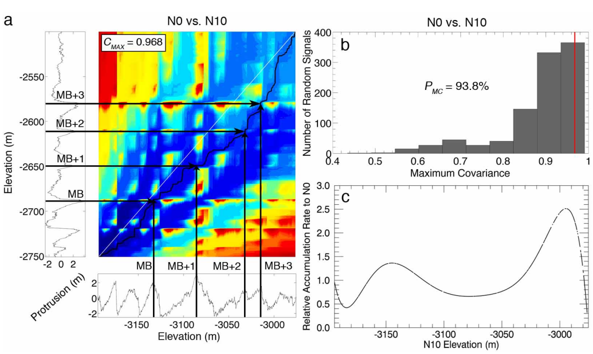

Fig 3. (a) DTW output from comparing N0 to N10. The color-coded region is the cost matrix of squared differences between each point in N10 and every point in N0 (warmer colors = higher cost). The black line through the matrix is the lowest cost path, and shows the nature of the match. (b) Histogram of the distribution of C_{MAX} for the correlation of random signals to the N0 profile. The C_{MAX} with the N10 data is 0.968 (vertical red line), greater than 93.8% of that with random signals. We consider this a reliable correlation. (c) Accumulation rate of site N10 relative to N0 at every point in the N10 profile, calculated as the derivative of a polynomial fit to the least cost path of (a).

Results: We built protrusion profiles and identified high-protrusion layers in 16 sites across the NPLD. Of these sites, we correlated 6 sites (N0, N1, N6, N8, N10, N15) to each other, identifying a stratigraphic sequence that we call the Main Sequence (fig. 2d). This sequence is present in all six sites, and is valid for at least 9% of the total area of the NPLD. The continuous column we have built can be analyzed with spectral techniques in order to compare its periodicities to those of Mars' insolation history.

We tested the relative merit of protrusion vs. brightness for stratigraphic mapping. We extracted brightness profiles from all sites and attempted to correlate the same sites with brightness that we did protrusion. Out of 9 pairs of sites that we compared, only 4 achieved a reliable correlation when using brightness. In comparison, 8 cases showed a reliable correlation when using protrusion. This implies that protrusion is continuous throughout the NPLD in more cases than is brightness, and is therefore better suited to describe the stratigraphy.

We selected study sites without known unconformities, so that differences in the relative elevation of matched layers between two sites are assumed to be due only to differences in accumulation rate. We estimated relative accumulation rates between the 9 pairs of sites we correlated and found that the largest difference in accumulation rate between one site and another is a factor of four. These relative rates are valid over elevation scales of ~ 100 m. An example is shown in fig. 3c.

Conclusions:

1. The topographic expression of the layers reveals a property (relative resistance to erosion) likely related to layer composition throughout the entirety of a particular layer at depth, and not just the part exposed in troughs.
2. A description of the stratigraphy based on layer protrusion, as seen by HiRISE, represents a substantial improvement over one based on brightness. Protrusion is more consistently continuous than brightness over long distances, implying that brightness is affected by extrinsic factors that change across the NPLD.
3. Relative accumulation rates at any given epoch vary geographically by less than a factor of four. This has important implications, as the lateral variation of accumulation rates complicates the modeling of processes that drive formation of the NPLD.

References: [1] Clifford et al., Icarus 225 (2013) [2] Phillips et al., Science 320 (2008) [3] Laskar et al., Nature 419 (2002) [4] Milkovich and Head, JGR 110 (2005) [5] Perron and Huybers, Geology 37 (2009) [6] Fishbaugh et al., GRL 37 (2010) [7] Limaye et al., JGR 117 (2012) [8] Herkenhoff et al. Science, 317 (2007) [9] Kirk et al., JGR (2008) [10] Byrne et al., V Mars Polar Sci. Conf. (2011) [11] Becerra et al., submitted to JGR [12] Sori et al., Icarus 235 (2014) [13] Fishbaugh et al., JGR 111 (2006).