SIGNALS OF ASTRONOMICAL CLIMATE FORCING IN THE EXPOSURE TOPOGRAPHY OF THE NORTH POLAR LAYERED DEPOSITS OF MARS. P. Becerra[1,2], M. M. Sori[1], S. Byrne[1]; [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA, [2]Physikalisches Institut, Universität Bern, Bern, Switzerland. becerra@lpl.arizona.edu.

Introduction: The stratigraphy of the icy layered deposits at Mars' poles has long been hypothesized to record recent climatic changes due to temporal variations in the planet's astronomical parameters [e.g. 1,2]. We explore the possible climatic record of the North Polar Layered Deposits (NPLD) by analyzing the dominant periodicities of stratigraphic columns based on the topographic expression of the layers.

The NPLD layers are viewable in a series of spiraling troughs that dissect the NPLD (Fig. 1a-c). Past studies have relied on the observed brightness of exposed layers to build stratigraphic profiles and analyze their periodicities [3–7]. Most of these agree that there is a dominant stratigraphic wavelength of 25–30 m in the upper 500 m of the NPLD [3,4], although wavelet analysis of similar data [5] showed little evidence for any signal in that range. However, brightness-based descriptions of the layering may be unreliable, as brightness is heavily influenced by a sublimation lag that slumps over the deposits, and thus may not be directly related to the composition of a layer [8–10]. Here, we apply wavelet analysis to stratigraphic profiles based on the topography and brightness of layers exposed at 16 study sites across the NPLD in order to identify periodicities that could be related to insolation forcing throughout the last 5 Myr [11]. To confidently relate the geologic record to the climatic driving function, we identify overlapping dominant stratigraphic wavelengths and compare their ratios to that of the dominant modes of oscillation of north polar insolation. We apply the same analysis to synthetic stratigraphies from a climate-driven model of ice and dust accumulation to investigate the nature of astronomical forcing in the NPLD stratigraphy.

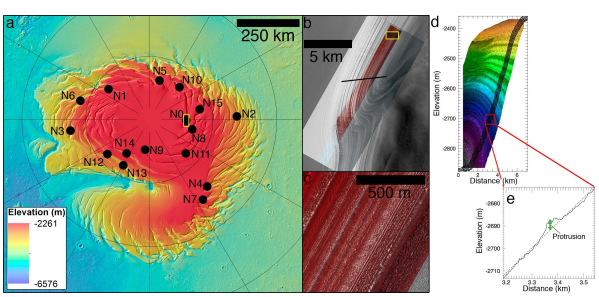

Fig. 1. (a) MOLA map of Mars' NPLD. Black dots = study sites. (b) HiRISE and CTX images of site N0. Black line = track of the profiles. (c) Zoom view of yellow rectangle in 1b. (d) Perspective view of HiRISE DTM with 1D topographic profiles. (e) Schematic of the protrusion calculation.

Data and Methods: We used Digital Terrain Models (DTMs) made from HiRISE stereo images to extract profiles of layer protrusion and local slope vs. depth at our NPLD study sites (Fig. 1a). Protrusion is measured as the vertical difference between each point in a 1D topographic profile of the scarp taken from the DTM, and a local linear fit to the scarp wall (Fig. 1e). Local slope is the first derivative of the topographic profiles. The profiles of layer brightness are constructed by extracting I/F values from orthorectified ("map-view") images, which are by-products of the DTM production and match the DTMs pixel for pixel. For all three datasets we averaged five adjacent 1D profiles to reduce noise. Using these data along with CTX images, we correlated a stratigraphic sequence through six study sites, and showed that combining protrusion with brightness leads to a more reliable description of the stratigraphy than using brightness alone [10].

We use wavelet transforms [12] to create 2D images of spectral power, or Wavelet Power Spectra (WPS, colored plots in Fig. 2), to identify dominant wavelengths in the stratigraphy at each depth [12].

To be confident that periodicities seen in the WPS are real, we assess the probability that similar periodicities could arise at random. We assume that a random 1st-order autoregressive (red noise) signal modulates the real profile. We test for significance using a Monte Carlo procedure in which we assume significance for features in the real WPS that have higher power than 95% of 10,000 simulated red noise signals. The black curves in Fig. 2a (right) show the 95% confidence contours for the protrusion profile in the left panel. If stratigraphic profiles have two significant periodicities, we can test for orbital forcing and constrain accumulation rates by comparing the ratio of those periodicities to the ratio of insolation periodicities [13].

Results: At each site, we measure the most dominant overlapping wavelengths that exceed 95% confidence in the WPS. We restrict this to peaks that extend over at least three full wavelengths in depth. Eight sites have protrusion profiles with two overlapping significant wavelengths that meet these criteria. This is true for only one site in the slope dataset, and only two in brightness. Fig. 2a (right) shows the WPS of the protrusion profile of site N0, and notes the ratio of the two most dominant wavelengths (results for all sites and datasets are in the presentation and paper [14]).

The eight protrusion profiles with valid results have a mean ratio of periodicities of 1.87 ± 0.17. The valid slope profile has a ratio of 1.89 ± 1.17, and for brightness this value is 2.21 ± 0.64. When including all valid profiles of any type the mean ratio of dominant

periodicities is 1.93 ± 0.2. A number of short sections with wavelengths between 1–5 m also exceed the 95% confidence level in the slope and brightness profiles. However, these appear to be significant only in small pockets comparable in depth-range to the wavelengths, consistent with [5]. A similar analysis of the insolation signal (Fig. 2b, left) shows two modes of oscillation (Fig. 2b, right) that correspond to the obliquity (~120 kyr) and precession of the argument of perihelion (~51 kyr). The ratio of these periods is 2.3 ± 0.44.

The periodicity ratio in the stratigraphic record is systematically lower than that of the dominant frequencies in the insolation record, implying either (a) that the proposed cycles of 51 and 120 kyr are not the main control of NPLD formation or (b) that a non-linear time-depth relationship in the NPLD leads to a lower ratio in the stratigraphy.

Discussion: To test whether such a non-linear relationship could lead to lower stratigraphic periodicity ratios relative to that in the insolation, we apply wavelet analysis to synthetic stratigraphic profiles created with a climate-forced model of NPLD formation developed by [15]. The annual net deposition rate of ice is controlled by the north polar surface temperature, and the annual net deposition rate of dust depends on the temperature difference between the pole and the equator. Using the best fit parameters of [15], we evaluate three scenarios: one in which the ice deposition rate is constant but the dust deposition rate varies with time, one in which the reverse is true, and one where both vary with time.

The WPS of the constant ice deposition rate profile differs very little from that of the insolation, with a ratio of 2.19 ± 0.53. Scenarios with varying ice deposition rate have similar spectral signatures to the stratigraphic data, with ratios of 1.91 ± 0.39 (constant dust rate) and 1.97 ± 0.45 (variable dust rate, Fig. 2c). This implies that a variation of ice deposition rate is necessary to produce the observed stratigraphy through climate forcing, while changes in the dust deposition appear to have only a minor effect on the spectral signature of the stratigraphy.

The history of accumulation that the model suggests correctly predicts the spectral characteristics we measured in the stratigraphy. Here, we use this model to show that the observed difference between the periodicity ratios of the insolation and the stratigraphy can be reasonably attributed to a non-linear time-depth relationship. However, future research is needed to know if other historical solutions would also correctly predict the same spectral characteristics.

If the NPLD are formed primarily as a result of orbital forcing, then our results show that the time-depth relationship must be non-linear. In addition, the geographic variation in stratigraphic wavelengths and lack of variation in their ratios indicates that deposition rates can be spatially variable while still being driven by the same climatic forcing. While a link between climate and stratigraphy requires a variable ice deposition rate, observations are consistent with either a constant or variable dust deposition rate.

References: [1] Cutts *JGR* 78 (1973) [2] Tanaka, et al. *Icarus* 196 (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] Byrne et al. V *Mars Pol. Sci. Conf.* (2011) [10] Becerra et al. *JGR* 121 (2016). [11] Laskar et al. (2004), Icarus 170. [12] Torrence and Compo, *Bull. Am. Met. Soc*. 79 (1998) [13] Lewis et al *Science*, 322(5) (2008) [14] Becerra et al., *GRL,* 10.1002/2016GL071197 (2016) [15] Hvidberg et al. *Icarus* 221 (2012).

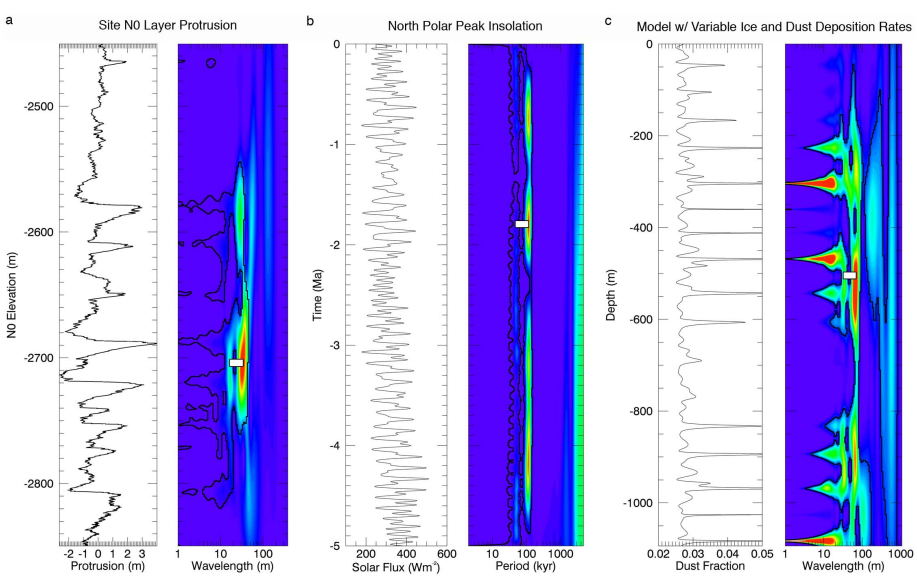

Fig. 2. (a) Stratigraphic protrusion profile of site N0 (left) and its WPS (right). White bar on WPS = ratio between dominant wavelengths of 1.94. (b) Peak insolation at 85ºN over 5 Ma (left), and its WPS (right). White bar = ratio of 2.3 (c) Synthetic stratigraphic profile of dust to ice ratio from best fit model parameters with variable deposition rates (left) and its WPS (right). White bar = ratio of 1.97. In all WPS plots: Warmer colors = higher power. Black lines = 95% confidence contours for red noise.