TIMESCALES OF THE CLIMATE RECORD IN THE MARTIAN SOUTH POLAR LAYERED DEPOSITS

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Introduction: The South Polar Layered Deposits (SPLD) of Mars are kms-thick stratified deposits of ice and dust, whose internal structure can be observed remotely through troughs that dissect their volume. Oscillations in Mars' astronomical parameters, which directly affect insolation and thus climate, are believed to be responsible for the layered accumulation of the PLD [1]. One of the main objectives of Mars polar science is to attempt to connect patterns in the bed structure to patterns in these oscillations, in order to "read" the Martian climate record [2]. Many observations and models of the North PLD support this theory of orbital forcing [2–7]. However, the SPLD (Fig. 1) appear to be orders of magnitude older than the NPLD [8,9], and the southern strata are thicker, darker, and more eroded than in the north [10–12]. In addition, Mars' orbital solutions become chaotic before 20 Ma [13], near the SPLD surface age, hindering the prospect for age dating the SPLD. Here, we measure periodicities in SPLD bedding exposures and compare them to the characteristic frequencies of Mars' insolation to test for astronomical forcing. We use Digital Terrain Models (DTMs) of SPLD outcrops made from stereo images taken by the HiRISE [14], along with the first DTM of the SPLD produced by TGO's CaSSIS [15]. We investigate discrepancies in the signals that may discriminate between different epochs of accumulation, and estimate accumulation rates. In addition, we compare the detected signals and stratigraphic profiles of the SPLD to those of the NPLD, to investigate the relationship between orbitally forced accumulation in Mars' polar caps.

Data and Methods: Our dataset (Fig. 1a) is 15 HiRISE DTMs (e.g. Fig. 1b,c, [16]) and 1 CaSSIS DTM (Fig. 1d) of exposed SPLD beds. The CaSSIS stereo image pair was taken within the same orbit of TGO [15], and the DTM was produced using the 3DPD pipeline [17]. The stratigraphic analysis was performed on linear profiles of depth-varying bed properties, or "virtual ice cores" of the SPLD. We extracted profiles of bed protrusion within a 350m window, a proxy for resistance to erosion [18]. For both, five profiles ~10 m apart along-strike are averaged to minimize noise. An example profile is shown in Fig. 2a.

We searched for periodicities in the profiles using wavelet analysis [19]. The depth-varying wavelet power spectrum (WPS, Fig. 2a) reveals dominant forcing wavelengths in the profile, and their depth-dependence. To ensure statistical significance, we required the detected wavelengths have higher power than 95% of 10000 red noise background simulations (Fig. 2a; [6,19]). We also required they be valid for at least 5 times the wavelength value, and for at least 20% of the depth of the total extracted profile. This ensures true periodicity in sections of stratigraphy of at least 50 m in the smallest profile. We could test for orbital forcing by comparing the ratio of pairs of wavelengths measured in the stratigraphic profile with the ratio of forcing frequencies in Mars' insolation function [6,13].

To search for correlations between different geographic and stratigraphic locations, we used Dynamic Time Warping (DTW), a signal-matching algorithm previously used to compare profiles of real and simulated stratigraphy in the NPLD [18,20]. DTW tunes a stratigraphic profile to search for the optimal match between it and another profile that is kept fixed. We also used DTW to compare our SPLD profiles to the NPLD profiles of [6] and [18].

Results: We grouped the study sites based on their stratigraphic and geographic location (Fig. 1a): Promethei Lingula (PL), Ultima Lingula (UL), Australe Scopuli (AS), and Australe Mensa (AM). In addition to searching for signals of orbital forcing, we tested whether each of these groups represented a separate climate record.

Thirteen out of the sixteen sites (81%) display dominant wavelengths in their protrusion profiles that meet our significance criteria, and nine (56%) have overlapping wavelength pairs, and thus an identifiable climate signal. In the AM group, S11 is the only site that qualifies, with wavelengths of 37m and 20 m for a ratio of R_M = 1.85±0.48. The AS group has two "valid" profiles, with an average long wavelength of 16m and a short of 9m, for a ratio of R_S = 1.78±0.35.

The sites in PL and UL sample similar elevations in the SPLD and have similar average wavelengths and ratios, both Lingulae are stratigraphically and morphologically similar regions of the SPLD, and past work has implied that they constitute one stratigraphic unit [11,22]. We thus combined PL and UL into one group (PUL), with average dominant wavelengths of 35±3 m and 16±2 m, and a ratio R_{PU} = 2.19±0.33.

DTW analysis showed that UL profiles match well with each other and with PL profiles. Other groups do not display strong correlations with each other. Using DTW to compare the 16 SPLD profiles with previously extracted NPLD profiles [6], UL profiles again achieved better matches than do other groups. This suggests that the most consistent and ordered record is in UL, in agreement with radar results that find more neatly stacked beds in UL and PL compared to other locations

[22], and supports the PUL representing one separate epoch of accumulation [11,21,22].

Discussion: A positive detection of pairs of stratigraphic periodicities allows a comparison between their ratio and that of the insolation periods, which permits an estimate of limits on the accumulation time of the different SPLD units. These are presented in Fig. 2b, where the long wavelength is tied to the 120 kyr period, and the short to the 51 kyr period. For the PUL, the accumulation rate derived from the 35 m and 16 m wavelengths is 0.29–0.31 mm/yr. The wavelengths of 16 m and 9 m observed in the AS profiles imply a decrease in accumulation rate to 0.13–0.18 mm/yr, and the AM wavelengths of 20 and 37 m signify an increase back to 0.31–0.39 mm/yr.

Assuming a constant, geographically uniform accumulation rate, and no long periods of net ablation, order-of-magnitude estimates on the accumulation time for the SPLD can be made. If we assume the fastest accumulation rate of 0.39 mm/yr – that of AM – to be valid for the whole SPLD stack, it would have taken ~9.7 Myrs to accumulate the 3.8 km [23] of SPLD material. If we consider the slowest accumulation rate of 0.13 mm/yr – that of AS – then the time would have been ~28.5 Myrs. A more detailed estimation of accumulation times for each unit can be calculated by using prior thickness estimates [11,22,23] and the absolute elevations in the DTMs. The PUL group exposures are located in a region of the SPLD between 0.5 and 2 km thick [11]. In AS, this thickness is 2.5–3.0 km. Based on the elevation ranges of our profiles compared with the radar-based thickness measurements of [23], we infer that the AS unit must span at least ~500 m, and if up to 2 km of material corresponds to the PUL, then 0.5–1 km must correspond to AS. The profiles in AM are located in the thickest part of the SPLD, with a maximum thickness of 3.8 km. Therefore, 0.8–1.3 km of material could correspond to the AM record and overlie the PUL and AS groups. In Fig. 2b, we show the minimum estimated accumulation time case in which AS is 0.5 km thick and AM is 1.3 km thick. With these numbers, the 2km stack of the PUL would have accumulated in 6.4–6.9 Myr; the 0.5 km of AS would have been deposited in 2.8–3.9 Myrs, and the 1.3 km in AM in 3.4–4.2 Myrs. These times combine to give a total accumulation time for the entire SPLD between 12.6 Myrs and 15 Myrs.

Conclusions: Statistically significant signals of climate forcing are present in the SPLD, from which accumulation times independent of crater ages can be calculated. These indicate at least three periods of accumulation separated by increases in deposition rate, but probably forced by the same oscillations. UL contains the most consistent record and is thus probably the best place to continue paleoclimate analysis. This happens to be ideal for CaSSIS, given that the 74º inclination of the orbit of TGO provides abundant observation opportunities of bedding outcrops here [24].

References: [1] Murray et al. *Science*, 1973. [2] Smith et al. *Icarus*, 2017. [3] Laskar et al. *Nature*, 2002. [4] Milkovich & Head, *JGR*, 2005. [5] Levrard et al. JGR, 2007. [6] Becerra et al. *GRL* 2017. [7] Hvidberg et al. *Icarus,* 2012. [8] Herkenhoff et al. *Icarus,* 2000. [9] Koutnik et al. *JGR*, 2002. [10] Byrne & Ivanov, *JGR*, 2004. [11] Milkovich & Plaut, *JGR*, 2008. [12] Limaye et al. *JGR*, 2012. [13] Laskar et al. *Icarus*, 2004. [14] McEwen et al. *JGR*, 2007. [15] Thomas et al. *Space Sci. Rev.,* 2017. [16] Kirk et al. *JGR*, 2008. [17] Simioni et al. *ISPRS*, 2017 [18] Becerra et al. *JGR*, 2016. [19] Torrence & Compo, *Bull. Am. Met. Soc.*, 1998. [20] Sori et al. *Icarus*, 2016. [21] Whitten et al. *GRL*, 2017. [22] Whitten et al. *JGR*, 2018. [23] Plaut et al. *Science*, 2007. [24] Becerra et al. *EPSC,* 2019. [25] Smith et al. *Science*, 2016.

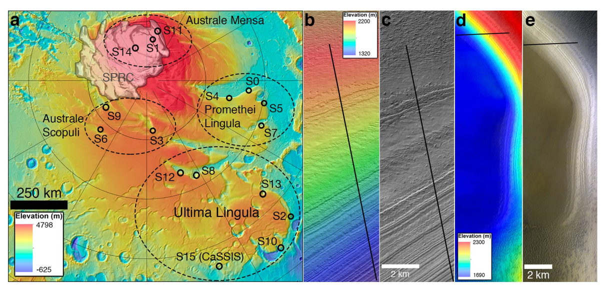

Fig. 1. (a) Map of the SPLD with the study site locations and their grouping. Basemap is a coloured elevation map from Mars Orbiter Laser Altimeter (MOLA) data. (b) HiRISE coloured relief view of DTM of site S5. In (b), (c), (d), and (e) black lines trace the ground track of the extracted profiles. (c) HiRISE orthoimage of site S5 displaying the exposed bedding. (d) Coloured relief view of CaSSIS DTM. (e) CaSSIS full colour image composed of the RED, PAN and BLU filters.

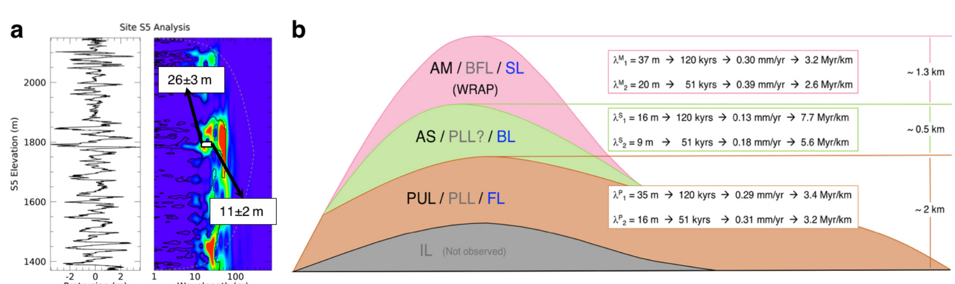

Fig. 2. (a) Protrusion profile (left), WPS (right) of site S5. Warmer colours = higher power, black curves = 95% confidence over red noise. (b) Schematic of SPLD stratigraphic units and accum. times. Unit names on left. Black = units defined here. Grey = units of [11]. Blue = units of [22]. IL [11] and WRAP [25] not observed here.