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Recent progress in studying orbital forcing of late Amazonian climate changes on Mars from Polar Layered Deposits

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Key Points:

- This brief review of recent progress in the study of orbital forcing of late Amazonian climate changes on Mars, based on polar layered deposits (PLD), is relevant to broader questions of planetary climate stability and habitability.
- The main method to study PLD is to establish stratigraphic signals as a function of depth based on its brightness and topography and compare these signals with time series of Martian orbital parameters.
- Future PLD study should focus on integrated research based on multi-profiles throughout the Martian polar regions.

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Abstract: The polar layered deposits (PLD) of Mars can provide deep insight into paleoclimate changes over the planet's last several million years. Since the 1960s, researchers have studied almost all aspects of Martian PLD properties, searching for patterns that might reveal periodic characteristics of the planet's climate history. Although much progress has been made in our understanding of orbital periodicities reflected in the PLD, questions remain regarding how Martian orbital changes have affected the formation of the PLD and regarding the extent of climate information that is recorded in the PLD. Future studies of PLD should be carried out via integrated research that targets multi-profiles throughout the entire Martian polar regions that would clarify their general features at the hemisphere scale. Numerical modeling, coupled with modern observations of dust and water vapor transportation, should greatly advance our understanding of planetary climate evolution. Furthermore, future landing missions may help to clarify the paleoclimatic characteristics reflected in the PLD by drilling into these layered deposits and measuring mineralogical and geochemical compositions of the drilled samples.

Keywords: Mars; Polar Layered Deposits (PLD); climate change; orbital forcing

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1. Introduction

Mars, a neighbor of Earth, is often considered not only our closest planetary analog but also even a 'future Earth', from the perspective of evolutionary habitability. Thus, the paleoclimatic and paleoenvironmental history of Mars is obviously of keen interest to scientists investigating the evolution of planetary habitability. Aquatic sedimentary strata traceable to early Mars have provided an ideal archive for its paleoclimatic and paleoenvironmental study before the Amazonian (~3.0 Ga) (e.g., Horvath and Andrews-Hanna, 2017; Stein et al., 2018; Rapin et al., 2019). The early Martian atmosphere disappeared after the Amazonian (~3.0 Ga); thereafter, glacier and wind became the main geological forces on Mars (Carr and Head, 2010). Therefore, research on recent Martian paleoclimate is scarce due to lack of aquatic sedimentary records. In their absence, researchers have had to focus on wind-blown deposits, i.e., sand dunes, to study paleoclimatic and/or paleoenvironmental changes (Fenton et al., 2003; Hayward et al., 2007; Gardin et al., 2012). This type of deposit is discrete in time and can be used to infer only climate changes that occurred during certain periods (e.g., Liu JJ et al., 2023). In contrast, Martian layered deposits on polar regions may be useful archives in which paleoclimatic changes over the last few million years have been documented, perhaps continuously (e.g., Howard, 2002). To date, many studies have been carried out on these Martian polar layered deposits (PLD); they have revealed periodicity that has been correlated to orbital forcing. These findings provide deep insight into paleoclimatic changes during the late Amazonian period (i.e., the past several million years). In this review we summarize recent progress in PLD research and then pinpoint some unresolved problems. Potential directions for future study are also discussed.

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2. Martian Polar Layered Deposits (PLD)

2.1 Discovery and Definition of the PLD

In August 1969, the Mariner 7 orbiter of Mars first observed the Martian south polar region at close range. In November 1971, the

Mariner 9 orbiter of Mars discovered complex sequences of layered deposits in south polar regions and later around the Martian north pole, too. Later spacecraft provided more detailed views of these deposits. The Martian PLD are stratified sequences of ice and dust, kilometers thick, representing a geologically recent climate record (Figure 1). The north polar layered deposits are referred to as NPLD, south polar layered deposits as SPLD. Cross-sections of the PLD consist of alternating light and dark layers with a kind of structure dissecting a series of spiraling troughs (Figure 1); these structural details were first observed by the Mariner and Viking orbiters (Murray et al., 1972; Cutts, 1973; Cutts et al., 1976). According to ice penetrating radar, these spiral troughs are caused by roughly perpendicular katabatic winds that are spiral due to the Coriolis Effect (Smith and Holt, 2010). One of the main objectives of Mars polar science is to study changing patterns of the alternating light and dark layers in the PLD (i.e., radiance changes of the PLD) and link them to oscillations of Mars astronomical parameters, to effectively retrieve the Martian climate record (Smith et al., 2018).

2.2 Nature, Age Control and Distribution of the PLD

Since the exploration of Mars in the 1960s, researchers have begun to study the composition, density, mass, scale and other physical characteristics of the PLD on Mars. The PLD are likely to have formed via net depositions of atmospherically transported water and dust, given that the polar latitudes are conducive to seasonal ice and dust accumulation (e.g. Cutts, 1973). Both the NPLD and SPLD are composed primarily of water ice (Plaut et al., 2007; Grima et al., 2009), with other materials accounting for no more than a few percent of their total mass. These darkening agents include dust and low-albedo sands, which contain volcanic ash and impact ejecta that are likely to have originated in specific geologic events. It is generally assumed that the layers are formed of frozen volatiles (mainly water) and materials initially suspended in, and then deposited from, the Martian atmosphere (Howard et al., 1982). The SPLD has an additional ~1% of carbon dioxide (CO_2) ice (<5 m thick) that resides permanently in a stratified section above the H_2O layers (Phillips et al., 2011); at the NPLD, a thin (i.e., 1–2 m thick) layer of CO_2 ice is formed and removed from year to year (Smith et al., 2001a).

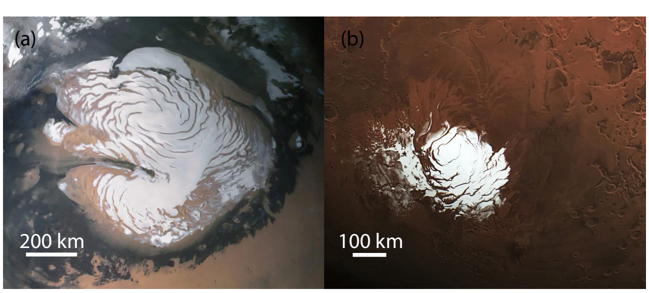

Figure 1. Images of the North and South Polar Layered Deposits from the High Resolution Stereo Camera (HRSC) on Mars Express. (a) NPLD, composed of water and dust; image taken during ESA Mars Express's 14,125th orbit on May 2, 2014 in late spring without seasonal frost cover. The diameter of the NPLD is ~1000 km. The NPLD layers rise about 2.5 km above the surrounding plains. (b) SPLD in late summer, image captured on February 25, 2015. Their diameter is ~350 km. White CO_2 is the south polar residual cap (SPRC). These photos were modified from Smith et al. (2020).

The North polar cap covers an area about ~1100 km in diameter; the South polar cap is smaller (~400 km in diameter) (Oberst et al., 2022). The total volume of the NPLD is estimated to be ~1.14 × 10^6 km^3; that of the SPLD, ~1.2 × 10^6 km^3 (Smith et al., 2001b). The PLD extend to the equator over 80° in the north and 70° in the south (Emmett et al., 2020). High resolution images obtained by the Mars Orbital Camera (MOC) on board Mars Global Surveyor (MGS) (Malin and Edgett, 2001; Kolb and Tanaka, 2001) and the High Resolution Imaging Science Experiment (HiRISE) onboard Mars Reconnaissance Orbiter (MRO) (McEwen et al., 2007) revealed that individual layers varied in thickness from decimeters to tens of meters and also appeared to vary in texture and resistance to erosion (Milkovich and Head, 2005; Fishbaugh and Hvidberg, 2006; Fishbaugh et al., 2010a, b; Limaye et al., 2012; Becerra et al., 2017, 2019). Radar cross-sections obtained by MRO's SHallow RADar sounder (SHARAD; Seu et al., 2007) and Mars Express's Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS; Picardi et al., 2005) suggest that stratified sequences within the deposits extend to ~2 km in depth in the north polar region (Phillips et al., 2008) and up to 3 km thick in the south polar region (Plaut et al., 2007); their horizontal continuous scales are tens to hundreds of kilometers, with some unconformities (Putzig and Mellon, 2007; Milkovich and Plaut, 2008). The NPLD is estimated to be ~5 Myrs in age (Montmessin, 2006; Levrard et al., 2007; Hvidberg et al., 2012); the SPLD is perhaps 10–100 Myrs in age (Plaut et al., 1988; Herkenhoff and Plaut, 2000; Koutnik et al., 2002).

3. Orbital Forcing and Periodicity of PLD Radiance; Implications for Study of Paleoclimate Changes

Earth's ice caps have provided a detailed record of the climatic history of Earth's most recent several hundred thousand years; the Martian PLD presumably could yield similar information on paleoclimate changes on Mars. The earliest images of Martian polar regions revealed alternating bright and dark layers in the PLD; from the start there was speculation that the formation of the PLD might be a consequence of, and constitute a record of, Mars's orbital forcing (Murray et al., 1972; Toon et al., 1980; Howard et al., 1982; Cutts and Lewis, 1982), in analogy to the Milankovitch cycles recorded in Earth's geologic record (Hays et al., 1976). The insolation received at the Martian surface regulates the planet's climate, which in turn modulates both the rate of accumulation and the composition of PLD layers, and probably their removal or thinning by ablation and wind erosion. The global water cycle of Mars involves transportation of water vapor down its gradient between the two hemispheres. Over millions of years, changes in insolation and differences in the rate of accumulation and erosion have affected the quantities of water, ice, and other PLD constituents now at the poles. The bright and dark PLD layers represent different water-ice-dust ratios, presumably indicating specific atmospheric conditions at the time the layers were deposited.

In the 21st century, researchers have begun to use brightness data in remote sensing images of the PLD to construct depth-radiance signal relationships and analyze their periodicity. Laskar et al.

(2002) combined high-resolution images of the PLD with calculated values for the orbit of Mars to explore possible correlations between PLD irradiance, as a function of depth, and variations in summer insolation at the Mars north pole (Figure 2), similar to studies done to determine the Earth's paleoclimate. The techniques employed are similar to those used in correlating quasiperiodic astronomical effects with climate 'proxies' on Earth, such as tree-ring thickness, grain sizes of loess-paleosol, and stable isotopes in ice cores. As has been noted on Earth, changes in insolation of Martian surface are determined by the planet's orbital eccentricity, precession, and obliquity variations of its spin axis. Orbital eccentricity modifies the total insolation received at the Martian surface as the distance between the Sun and Mars changes. Obliquity and precession modify the orientation of the planet relative to the Sun, thus altering the latitudinal distribution of insolation. Various permutations of the three parameters produce widely changing insolation at polar regions and elsewhere.

The orbital parameters are obtained by astronomical calculation through a new numerical integration of the whole Solar System, including all nine main planets, the Moon as a separate object, Earth and solar oblateness, tidal dissipation in the Earth–Moon system, and the effect of general relativity (Laskar et al., 2002). The climatic precession of Mars has a period of about 51,000 yr, which is the shortest periodicity of all known insolation curves for Mars. In contrast, the primary period of eccentricity is from 95,000 to 99,000 yr, and the obliquity has a dominant period of about 120,000 yr (Figure 3), with a strong modulation of period 2.4 Myr on account of the near resonance of the secular proper modes g3 and g4 (Laskar, 1990, 1999). Mars undergoes such dramatic orbital variations because it lacks a large moon and is closer to the massive outer planets. Average annual insolation on Mars at a given latitude is modulated mainly by the planet's obliquity (Laskar et al., 2002), which has oscillated between 15° and 45° during the past ten million years (Figure 3d). In addition, its orbital eccentricity has oscillated between 0 and 0.12 over ~1000 kyr cycles. These variations occur in a complicated 'beat' pattern involving several frequencies. High values of obliquity (>30°) mean that polar regions receive more insolation on average than the mid-latitudes, leading to the ablation of polar ice and transport to lower latitudes. On the contrary, low obliquity facilitates accumulation of polar ice (Figure 4). The present obliquity is around 25°, which is low enough that the average insolation at the poles is lower than at the mid-latitudes, but high enough that the net mass balance is difficult to distinguish from zero (Bapst et al., 2018).

Precise knowledge of periods earlier than ~10^7 years are impossible due to the mathematically chaotic nature of the solutions, but statistical analyses of a series of solutions indicate that the maximum obliquity of the Mars orbit can reach 82°, with an average of ~38°, and with a 63% probability of its having been >60° in the past billion years. Large variations in obliquity lead to significant changes in regional surface temperature, in the concentration of water vapor in the atmosphere, and in the stability of polar ice, but the extent of these changes on a global scale is hard to predict. For instance, warming might result in an increase in surface pressure, permitting more dust entrainment and decreasing albedo, thus leading to cooling; initial cooling may lead to an increased ice stability and albedo, hence more cooling (Fanale et al., 1982; Jakosky et al., 1993). However, we can make some generalizations. At very low obliquity (~10–15°), the atmosphere collapses and condenses onto the surface, with distribution controlled by topography (Kreslavsky and Head, 2005). At low obliquity (such as that of today), seasonal temperature fluctuations and mean annual polar temperatures are at a minimum, while equatorial temperatures are at their maximum. Under these conditions, ground ice is stable only at latitudes above ~60–70°

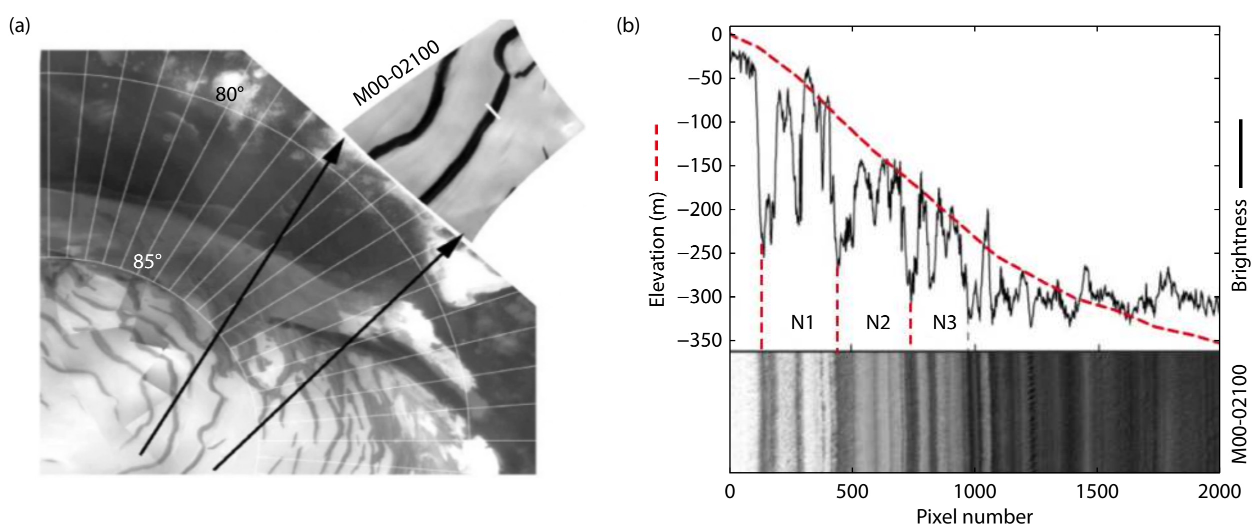

Figure 2. North polar layered terrains. (a) A regional mosaic of Mars Orbiter camera (MOC) wide-angle image of the Martian north pole showing the location of MOC narrow-angle image M00-02100. Circles at latitude 80° and 85° are plotted. (b) The relationship between the brightness profile (solid curve) and pixel number for a section of the MOC narrow-angle image M00-02100 (bottom) is obtained by averaging the pixel value along vertical lines. This picture was taken by the MOC on 13 April 1999 (solar longitude $L_s \approx 123°$), at 86.48°N. The original image was processed in order to straighten it. The dashed line is the elevation resulting from Mars Orbiter laser altimeter (MOLA) experiment measurements. Three similar cycles (N1, N2, N3) between pixels 100 and 1000 are observed. The plots are cited from Laskar et al. (2002).

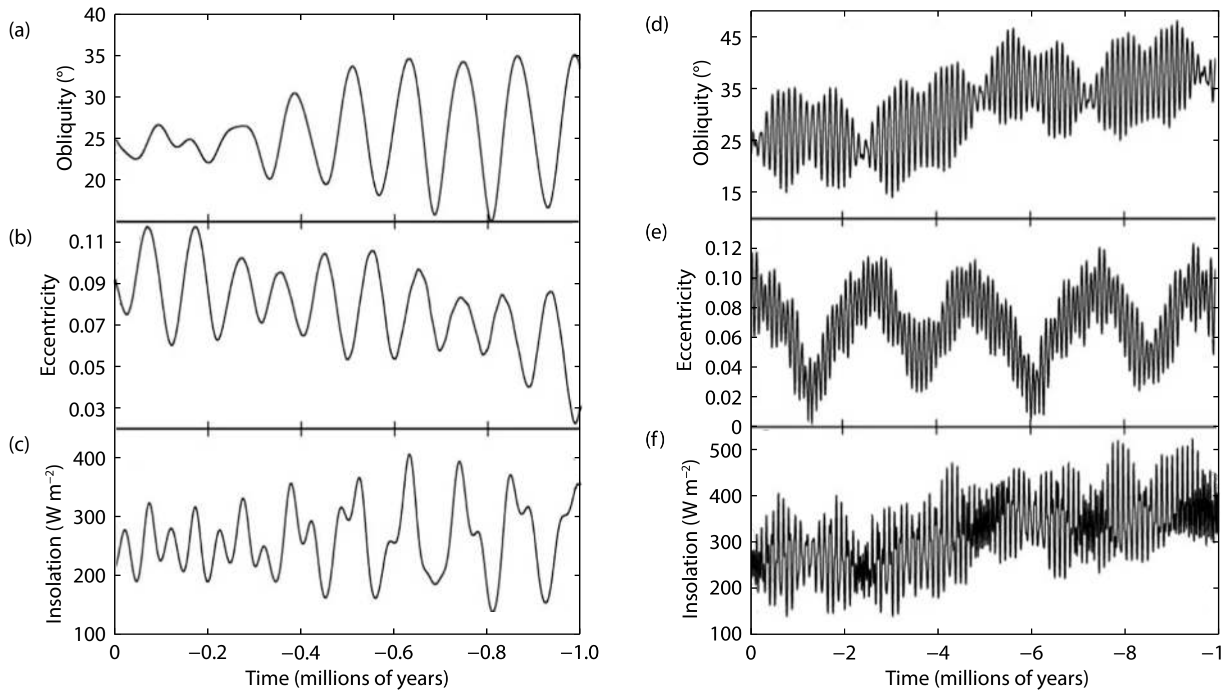

Figure 3. Orbital (a) obliquity, (b) eccentricity and (c) insolation at the Martian north pole surface at the summer equinox over the last 1 Myr; (d)–(f), over the last 10 Myr. In the first 0.5 Myr of (c), as the obliquity variations are small, the insolation is dominated by precession; since then obliquity has dominated the insolation variations. Plots are from Laskar et al. (2002).

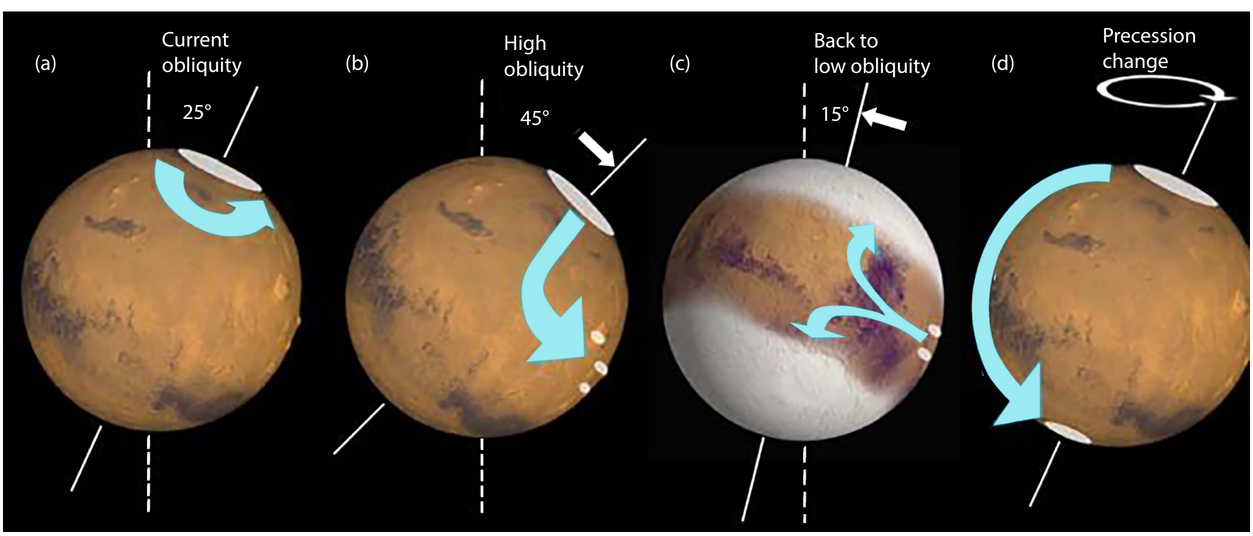

Figure 4. Changes of Martian orbital parameters and their consequences for the transfer of water across the whole Martian surface over recent millions of years. Blue arrows indicate the direction of water transport. The figure was modified from Montmessin (2006).

(Mellon and Jakosky, 1995).

Previous modeling reveals that changes of atmospheric water and dust abundances, atmospheric transport, and the stability of surface water ice in the polar regions of Mars are sensitive to insolation variations resulting from periodic cycles of the planet's orbit (Mischna et al., 2003; Newman et al., 2005; Forget et al., 2006; Levrard et al., 2007; Madeleine et al., 2009, 2014). It has also been suggested that insolation variations could periodically transform the net flux of aerosols in and out of the polar regions, consequently driving formation of the PLD (e.g. Laskar et al., 2002). Observational evidence from remote sensing has since supported this kind of interpretation. For example, the onboard Mars Orbiter Laser Altimeter (MOLA) has detected seasonal variations of 1.5 to 2 m (maximum) in snow deposits at the polar caps during Martian winters (Zuber et al., 2007) at an effective resolution of just 10 cm. Repeated imaging from the HIRSE camera, distributed over the entire Martian year at selected areas, provides a better understanding of the surface processes in the highly dynamic environment (Oberst et al., 2022).

To what extent changes in Earth's orbit affect glacial variabilities is an open question (Hays et al., 1976; Raymo and Huybers, 2008; Perron and Huybers, 2009). Because of the thinner atmosphere on Mars and the planet's lack of oceans and life forms, the current Martian climate system is much simpler than Earth's. In addition, Martian obliquity and eccentricity oscillate in larger amplitudes, resulting in stronger orbitally-driven climate signals (Laskar et al., 2004). Therefore, although frequent dust storms and other accidental events complicate relationships between climate and the stratigraphy of the Martian PLD (Pollack, 1979; Toon et al., 1980; Haberle, 1986; Zurek and Martin, 1993), a correlation should be possible if climate signals over a sufficiently long time are recorded in PLD stratigraphy and have not been removed by ablation (Sori et al., 2014).

To obtain climate signals of sufficient accuracy to test this correlation, it is essential, first, that the stratigraphic record be accurately determined. Then its periodicity must be analyzed in detail. Most of the research thus far has been focused on the NPLD (i.e., see study sites from Figure 5a) due to their younger age and simpler stratigraphic constitution compared to the SPLD.

Previous studies have relied on the observed brightness of exposed PLD layers to establish stratigraphic signals as a function of depth; then these signals have been analyzed to uncover their periodicities (Laskar et al., 2002; Milkovich and Head, 2005; Perron and Huybers, 2009; Fishbaugh et al., 2010a, 2010b; Limaye et al., 2012). Milkovich and Head (2005) studied the vertical stratigraphic sequence at the Martian north pole using a Fourier method and found a wavelength of ~30 m repeated in the upper 300 m part, which was interpreted as a climate signal corresponding to a 51 kyr insolation cycle. Perron and Huybers (2009) found that stratigraphic profiles of the PLD reconstructed from spacecraft images did not produce clear evidence of orbital control but were largely consistent with autoregressive random formation processes. However, a broad rise in spectral power, centered around a wavelength of about 1.6 m, appears in many stratigraphic profiles. This rhythm of sub-layers may record timescales of events related to processes within the Martian climate system, perhaps related to dust storms.

Fishbaugh et al. (2010a) first measured a stratigraphic column of the NPLD at high spatial resolution (i.e., layer scale) using a 1 m digital elevation to classify the strata. However, the absence of clear rhythm in the upper NPLD implies that the relationship between the PLD and periodic climate forcing is more complex; they were unable to link specific layers to specific peaks in the climate forcing, as Laskar (2002) had done. They also created a stratigraphy map of the NPLD and argued that a topographic/morphologic description of the exposed layers may be a more appropriate approach than using layer brightness alone to characterize the NPLD. Fishbaugh et al. (2010b) then reevaluated the method delineating thin NPLD layers and concluded that digital number values, layer thickness, or layer spacing are unlikely to be directly related to any one period of the orbital parameters (including obliquity). However, Limaye et al. (2012) showed that the power spectrum of brightness and slope obtained along the measured stratigraphic profile confirmed the regularity of the thickness of NPLD fine layers. Although this observation is consistent with the quasi-periodic strata, the time relationship is not yet known.

Some investigators have suggested that the brightness of apparent PLD layers has intricate relation to underlying physical properties and is affected by factors that are not directly related to layer composition, e.g., sublimation lags that cover the exposures (Herkenhoff et al., 2007; Becerra et al., 2016). Becerra et al. (2017) argued further that it may be too difficult to extract orbital signals from brightness-based stratigraphy. Instead, Becerra et al. (2016) extracted 16 stratigraphic profiles based on protrusions from the average slope of a trough wall, using High-Resolution Imaging Science Experiment (HiRISE) Digital Terrain Models (DTMs), and correlated them with 6 profiles across a large region of the NPLD.

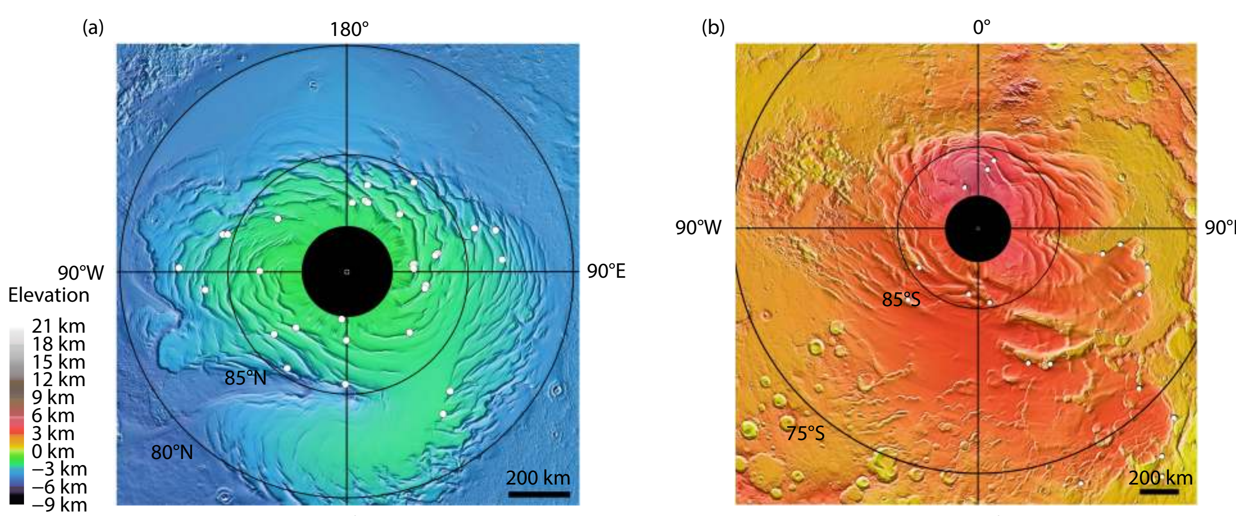

Figure 5. (a) MOLA topographic map of the north polar region of Mars. The white dots in the figure represent PLD study sites from Laskar et al. (2002), Milkovich and Head (2005), Perron and Huybers (2009), Fishbaugh et al. (2010a, b), Limaye et al. (2012), Becerra et al. (2016, 2017). (b) MOLA topographic map of the south polar region of Mars. The white dots in the figure represent PLD study sites from Limaye et al. (2012), Becerra et al. (2019).

They suggested that layer protrusion data can represent the layer's corrosion resistance and has a more obvious relationship to inherent layer attributes than does brightness. Their results show that combining topography with brightness makes it easier to correlate layer sequences over the region, thus improving the description of the exposed stratigraphic records.

However, the regularity observed in the NPLD is not observed in the SPLD. Becerra et al. (2019), using wavelet and series-matching analyses on various SPLD profiles, reported that the periodicity of gray levels in SPLD strata could be correlated to Mars orbital oscillations, with a long wavelength correlating to the 120 kyr obliquity period and a short wavelength to the 51 kyr precession period. Whitten et al. (2017) used SHAllow RADar (SHARAD) sounder date to reveal interior structure of the SPLD, which overall is a subsurface elongate dome probably formed during a period of enhanced local deposition. This SPLD depositional center provides an important sign of south polar climate patterns. According to Whitten and Campbell (2018), the radar results indicate that SPLD materials are superpositions of regional deposition and materials deposited in previous stages, rather than later mergers of local deposition centers.

According to Becerra et al. (2019), the conclusion that the formation of NPLD stratigraphic layers has been forced by orbital oscillations is generally supported by observations on the NPLD by orbital imagers (Laskar et al., 2002; Milkovich and Head, 2005; Fishbaugh and Hvidberg, 2006; Fishbaugh et al., 2010a; Limaye et al., 2012; Becerra et al., 2017), by data from subsurface sounding radar (Phillips et al., 2008; Putzig et al., 2009; Smith et al., 2016; Lalich and Holt, 2017), and by NPLD accumulation models (Levrard et al., 2007; Hvidberg et al., 2012). However, no such conclusion has been reached for the SPLD although it, too, has been studied in multiple widely-separated locations (Figure 5b). There are at least two reasons for this difference. One reason is that the upper surface of the SPLD is not the same layer, especially due to recent erosion, and thus has a complex range of exposure ages that have been difficult to interpret (Milkovich and Plaut, 2008). Another reason is that the lower limits on the accumulation time of the SPLD are between ~10 and ~30 Ma (Becerra et al., 2019). As Mars' chaotic obliquity evolution limits inference of insolation prior to 10–20 Ma (Laskar et al., 2004), there is no reliable climate function to compare to the SPLD stratigraphic columns, which has discouraged prospects of associating the SPLD with astronomical forcing.

Nevertheless, wavelet analysis of SPLD bed exposures has revealed the presence of a statistically significant climate forcing signal in the stratigraphic record. Although the complex internal structure of the SPLD (Figure 6) and its stratigraphic records are more complicated than in the NPLD case, researchers have concluded that a potentially decipherable record of astronomical climate forcing is present and seems to have been influenced by the same oscillations as has their northern counterparts, implying that there is a climatic connection between both polar ice sheets that spans tens of millions of years.

4. Unsolved Problems in PLD Studies

From the 1960s to 2000, researchers focused primarily on the physical characteristics and material composition of the PLD.

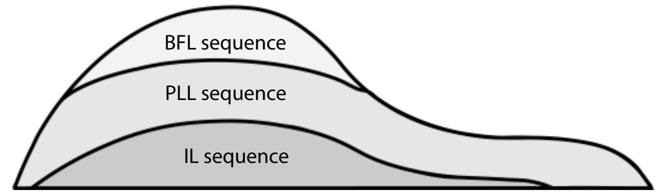

Figure 6. The internal structure of the SPLD. The uppermost sequence is the Bench Forming Layer (BFL) sequence, which is characterized by multiple layers forming pitted topographic benches separated by multiple thin layers. Below this sequence is the Promethei Lingula Layer (PLL) sequence, made up of a series of thin layers on top of many erosion-resistant marker beds or marker packets. Finally, an Inferred Layer (IL) sequence is, as its name indicates, inferred to exist. The internal orientation of individual SPLD layers is not horizontal, but neither does it exactly mirror the topographic profile of the current polar surface deposit. Layers have been widespreadedly deposited, but not always deposited over the same areas, or they may have been deposited but later removed. Moreover, some recent layers have properties different from those of older and lower layers, indicating changes in the processes or components forming the SPLD over time. The figure was modified from Milkovich and Plaut (2008).

Despite recognition that the structures of the PLD may be related to the orbital forcing of Mars, limited techniques for gathering relevant data have made it difficult to test that hypothesis. Since Laskar et al. (2002), most PLD studies have relied on brightness variations observed in profiles of exposed strata, from which brightness–depth curves have been calculated and their periodicities analyzed. The Martian orbital parameters calculated by Laskar et al. (2002) are generally accepted, providing an astronomical data reference against which PLD data can be compared. Becerra et al. (2017) considers the relationship between PLD layer protrusions and the intrinsic properties of the layers to be a meaningful variable, and then uses combined topography and brightness data to reveal a close correlation between the ratio of two major strata wavelengths and the ratio of two major periods of polar insolation variation. However, some researchers (e.g., Fishbaugh et al., 2010a, b) believe that layered deposits cannot be used to reflect the orbital periods. In addition, existing studies have isolated a periodic wavelength in PLD layers that correlates to only a single orbital parameter.

At the 7th international conference on Mars Polar Science and Exploration, scientists highlighted the most important advances and presented the most salient open questions in this field (e.g., Becerra et al., 2021). Questions about whether the PLD can yield a record of past Martian climate include: How has the Martian climate evolved over time? What are the absolute ages of the observable climate records? How should we interpret these records to know what climatic states they represent? These questions have been open for decades and are not completely answered, though some progress has been made. At the conference, the authors Becerra et al. (2021) proposed several lines of investigation that would contribute to answering the above questions:

(a) Clarify and describe plausible and testable connections between astronomically orbital parameters and resultant layer nature of the PLD and off-polar deposits.

(b) Determine unconformities in the PLD to determine missing time records and estimate the volume/mass of the lacking material.

(c) Further verify the present hypothesis that NPLD formation began at ~4 Ma.

(d) Estimate when the SPLD layers formed and under what climatic conditions they were preserved; constrain the SPLD surface age; identify major SPLD water–ice units to determine whether they were deposited in one period or in multiple periods of favorable climate.

(e) Characterize the processes of formation and evolution of the buried CO_2 ice reservoirs at the south pole and determine when these processes took place.

(f) Determine how the much larger southern polar deposits are related to the SPLD expanse in terms of age and climate epochs that are recorded.

5. Potential Directions of Future PLD Study

From previous studies, we have concluded that the uneven distribution of insolation received by Mars' global surface can cause differences in atmospheric pressure between different latitudes, resulting in zonal transport of atmospheric water and dust. Therefore, it is necessary to systematically and deeply study whether evidence of orbital periodicities exist in the PLD and what kind of climatic periodic characteristics can be found in studies of these layered deposits. Like Earth's polar ice cores that document the recent history of atmospheric dust transport and environmental changes on our planet, the alternating bright and dark layers within the Martian PLD may record the history of water and dust transport in the Martian atmosphere, which are likely to reflect changes in the insolation, including its latitudinal distribution, on Mars. Since there is some unconformity in the PLD at local scale, and the stratigraphy of the PLD is apt to have been influenced by episodic events, further studies are needed. More locations need to be examined to elucidate the consistency of depositional processes among the scarps and provide a more complete record of climatic changes over a much longer time. Future PLD study should focus on integrated research based on multi-profiles of PLD locations separated as widely as possible throughout the Martian polar regions. Smith et al. (2020) once proposed a promising work plan to continue studying the PLD using both orbital instruments and platforms onboard surface rovers. For example, the orbital instruments can investigate volatile and dust fluxes into and out of the polar regions and at the surface-atmosphere to bring us a new understanding of the present-day climate. Such monitoring work of modern processes can also explore the influence of dust storm events on the dark layer of the PLD. Meanwhile, the lander followed by a mobile platform or deep drill would then complete the task of extracting climate record data from the PLD. Therefore, as the field and technology progress, future missions that land on the planet and drill into the layered deposits and measure mineralogical and geochemical composition of the drill layers may be able definitively to reveal the past climate cycles on Mars. In addition, comparative studies between the NPLD and the SPLD are also necessary to understand how climate and atmosphere–dust processes on the globe have evolved, especially in combination with numerical modeling that incorporates modern observations of seasonal transport of dust and water vapor.

6. Conclusion

Since the 1960s, researchers have been studying the layered deposits at the Martian poles, and how they may be linked to astronomically forced climate change. In recent decades, much has been determined regarding the ages and properties of Martian polar layers and the Martian climate record, but many questions remain. For instance, different wavelengths correlated with Mars orbital parameters have been found in different regions of the Martian PLD, but how to interpret them is still not completely clear. Future PLD study should concentrate on integrated research via multi-profiles throughout the entire Martian polar regions. Future missions that land on Mars and drill into the PLD may yield data that will be of considerable help in clarifying our knowledge of climate cycles on Mars.

The broader significance of these studies for the scientific community is that comparative studies of orbital forcing of climate changes on different planets can broaden our understanding of the evolution of planetary habitability. The polar layered deposits of Mars are the only known places in the universe, other than the ice at Earth's polar regions, that are likely yield a detailed record of recent climate variations on a planet capable of supporting life forms. Research comparing data extracted from ice-cores on the Earth and the PLD on Mars will be significant in helping us decipher processes associated with water and dust cycles under far different atmospheric conditions. The combined research of Earth systems and planetary evolution is a completely new academic field that is still in its infancy. As such, study of the Martian paleoclimate is significant — even, perhaps, indispensable.

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