Unlocking the Climate Record Stored within Mars' Polar Layered Deposits

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Executive Summary

In the icy beds of its polar layered deposits (PLD), Mars likely possesses a record of its recent climate history, analogous to terrestrial ice sheets that contain records of Earth's past climate. Both northern and southern PLDs store information on the climatic and atmospheric state during the deposition of each layer (WPs: Becerra et al.; Smith et al). Reading the climate record stored in these layers requires detailed measurements of layer composition, thickness, isotope variability, and near-surface atmospheric measurements. We identify four fundamental questions that must be answered in order to interpret this climate record and decipher the recent climatic history of Mars:

1. **Fluxes:** *What are the present and past fluxes of volatiles, dust, and other materials into and out of the polar regions?*
2. **Forcings:** *How do orbital/axial forcing and exchange with other reservoirs affect those fluxes?*
3. **Layer Processes:** *What chemical and physical processes form and modify layers?*
4. **Record:** *What is the timespan, completeness, and temporal resolution of the climate history recorded in the PLD?*

In a peer reviewed report (1), we detailed a sequence of missions, instruments, and architecture needed to answer these questions. Here, we present the science drivers and a mission concept for a polar lander that would enable a future reading of the past few million years of the Martian climate record. The mission addresses as-yet-unachieved science goals of the current Decadal Survey and of MEPAG for obtaining a record of Mars climate and has parallel goals to the NEX-SAG and ICE-SAG reports.

Overview of the Martian Polar Layered Deposits

The layered structure of the PLD can be seen through visible imaging of bed exposures in troughs and scarps (Figures 1, 2) and radar sounding data (Figure 3). Variations in the orbital and axial configuration of Mars likely led to climatic changes that formed the layers we see (2) including multiple angular unconformities in the stratigraphic record that show periods of net ablation and accumulation (3). Extremely dusty layers may be sublimation lag deposits that represent disconformities in the record (4). In addition, the PLDs are partly covered with bright residual ice caps that strongly affect the current climate (Figure 1). The north polar residual cap interacts with the atmosphere and records present day processes - to become a future layer in the climate archive.

The gross and net annual exchange of H_2O onto either polar cap is unknown, but the net flux is thought to average $0.5 \text{ kg m}^{-2} \text{ y}^{-1}$ over the last few Myr onto the North PLD (NPLD). This unknown mass balance value is a key parameter to understand the current climate, so knowledge of this value will help tune and validate global climate models

Figure 1: The NPLD imaged by ESA's High Resolution Stereo Camera in late spring without seasonal frost cover. The NPLD has a surficial dust lag, but much of the bright north polar residual cap is uncovered. The residual cap provides the majority of the atmospheric water vapor of Mars each year.

Figure 2: Layers in the South PLD. Exposed layers imply recent erosion; however, a dust lag may slow sublimation on annual time scales.

(GCMs) of modern climate, supporting their application to understanding past climatic states. In this white paper, we focus on the NPLD, for which hypotheses are much more robust.

Layer Composition: During orbital/axial variations, the transfer of ice, aerosols, and dust from lower latitudes to the poles forms beds with variable ice content. The bulk composition of the NPLD is ~95% water ice (5). Besides ice, PLD composition likely includes dust, salts, other lithic materials, gas bubbles, HDO (deuterated water), and daughter products of radioactive decay, in decreasing order by volume. As on Earth, these components can be used to infer sintering rate, dust/ice ratio, and concentrations of different isotopes in ice, dust, and trapped gases.

Individual beds may be up to 50% dust (6). These dust-rich beds may have formed during periods of high dust accumulation or during periods of ice loss and lag formation (7). Dust-poor beds must have formed during times when ice deposition was high relative to dust accumulation. The stratified variability of each material represents the climate archive.

In order to detect climate signals, we need to be able to observe and describe intrinsic properties of the beds that make up the record, i.e., properties that relate most closely to the environmental conditions at the time of accumulation.

Forcings: Three astronomical cycles drive most of Mars' climate variations: obliquity, argument of perihelion, and eccentricity. These cycles affect the average solar flux at the Martian surface and drive the stability of ice at various locations on the planet. Other external forcings of Mars' climate include solar wind, Jeans escape, cosmic rays, impactors, etc., that act to strip volatiles away from the upper atmosphere or, on smaller scales, implant new volatiles. Secular mass loss driven by the solar wind put Mars into its current, low-pressure state billions of years ago (8). On timescales relevant to the polar ice, atmospheric stripping may have affected fractionation rates for isotopes in parallel with solar cycles (9). The major intrinsic climate driver is the poorly understood dust cycle, an important topic for future investigation (WP: Newman et al.).

Isotope Variability in Layers: PLD layers likely retain a combination of ices (H_2O , CO_2), dust, and trapped gasses. Each may vary in isotopic composition due to fractionation processes. The ratio of deuterium to hydrogen (D/H) in PLD water ice is an invaluable data point. This composition can tell us about variations in obliquity, which in turn provides information on what reservoirs are accessed at different axial states (e.g., (9, 10)).

Layer Formation: Investigating layer formation is critical to reading the stratigraphic climate record that is made up of these layers. Thus, we need to measure the processes forming the current

Figure 3: Comparison of model from (11) (left) to radar stratigraphic mapping of the NPLD (right). Model calculates solar insolation in W m^{-2} starting at ~ 4 Ma and predicts four distinct periods of NPLD accumulation. Blue line in left panel is total accumulation of NPLD ice. Approximately 30 lag deposits are expected to derive from obliquity changes, similar in number to the total number of reflectors that SHARAD detects (right). The Widespread Recent Accumulation Package (WRAP) is associated with the current interglacial period (12).

layer that is expected to eventually be included in the climate archive. Many processes occur at the surface, including ice crystallization, dust deposition, isotope fractionation, and heat loss or gain. Processes continue even after burial, such as sintering, phase partitioning, and impurity exclusion. Observing these processes in today's well-characterized climate would allow us to connect deeper layer properties to past climates...

Major Questions and Observables

Fluxes: Measurements of the modern-day fluxes of volatiles, dust, and other materials from lower latitudes to the polar regions and then onto the polar caps are key steps to interpreting the climate record in the PLDs. These would link observable modern climatic processes to material deposition at the PLD surface, and thereby layer formation. We must measure fluxes at global and regional scales and the exchange between the surface and atmosphere. Several observations are necessary from the surface: 1) wind speed profile near the surface boundary layer to provide input for calculating regional flux; 2) horizontal and vertical wind speeds within the planetary boundary layer; 3) dust and condensate concentrations in the planetary boundary layer; 4) vertical *in situ* surface mass flux of H_2O , refractory material, and CO_2 .

Meteorologic measurements at the surface should be compared to global and regional measurements in order to determine the availability of transportable material through the present epoch. Similar to layer formation, measuring meteorological processes requires *in situ* observation over an entire martian year (ICE-SAG). Measurements should include the ablation and/or accumulation of dust and ice (H_2O and CO_2), saltation and surface transport of materials, wind speed, insolation, albedo, and temperature, pressure, and humidity (TPH).

Layer-Formation Processes: Determining all of the processes that affect layers is a critical knowledge gap. To characterize modern bed-formation processes, we need access to the surface and the upper 50 cm of the subsurface. This is expected to represent the last 1000 years of Mars history (which are expected to have experienced similar climatic and surface processes to the present day) and should capture all of the processes actively affecting layer formation. Impurity

composition, abundance, and distribution are the top priority measurements. Additional items to measure are phase partitioning of salt and other impurities from ice grains; density and grain size distribution of dust, along with isotope fraction.

Age Dating the NPLD: Measuring ages hinges on finding datable lithic material in the form of dust, volcanic ash, or impact ejecta that are accessible to robotic explorers. This can be done by measuring decay products of radioactive elements (e.g. He, Ne, Be, Ar) and the concentrations of cosmogenic radionuclides. Extremely high precision measurements are required in order to achieve useful ages because of the youthfulness and low lithic content of the NPLD, with age resolution on the order of 10^4 - 10^5 years. A highly selective and sensitive mass spectrometer similar in size, mass, and power to the SAM instrument on MSL can compete the task. Additionally, resonance ionization mass spectrometry (RIMS) is a promising technology for this purpose.

Key Properties and Measurement Types:

Flux measurements at the surface will quantify deposition and ablation processes. High frequency sampling of wind speed and direction in combination with TPH is necessary. Heat and momentum fluxes can be derived from these measurements. Airborne dust and ice particles should be counted in aggregate to distinguish particle type (e.g., dust, CO₂ ice, and water ice). With hourly wind measurements, particulate measurements would enable the determination of dust and water ice particle transport through turbulent eddies. Depositional mass and dust-to-ices ratios are also required with microgram sensitivity. Measurement requirements and potential technologies are summarized in Table 1.

Layer formation: At the surface, determining the ratio of present-day accumulation of dust to H₂O to CO₂ is exceptionally important. A thermogravimeter with microgram accuracy can accumulate materials from snowfall and direct condensation, and then measure their mass before heating the volatiles to the appropriate temperature for sublimation. These measurements will have to be made throughout a full year, especially during polar winter. This is a key measurement to ground truth orbital measurements of grain size using emissivity (ICE-SAG).

Measurements of surface albedo, texture, grain size (up to 100 microns), grain density, and grain orientation should be made by reflectance infrared spectroscopy, a high-resolution imager, and nephelometry. Surface temperature, for calculating the thermal balance at the surface-atmosphere interface, can be measured with a thermal imager.

Understanding layer formation also requires access to the near subsurface via drilling. Once a borehole is drilled, an optical imager could be lowered into the borehole in order to identify and count distinguishable layers and measure layer thickness. We expect that a resolution finer than 1 mm will be required to discern annual layers within the ice. A pixel scale of ~ 30 μ m would suffice.

To characterize impurity distribution, miniaturized computerized tomography (microCT) is an excellent option. MicroCT collects axial X-ray scans and achieves a spatial resolution down to several microns, determining particle size and shape; volume concentration; pore size, shape, and distribution, discrimination of salts from Fe-rich sediment; and potentially relative atomic weight. MicroCT has been used recently in terrestrial ice analyses (13, 14). Measurements should require

Table 1: Measurement requirements and potential technologies for in-situ measurements. Possible locations of each instrument on the spacecraft are: Lander Deck Atmospheric Instruments (LDA), Lander Deck Surface Measurements (LDS), Borehole Measurements (BH), Lander Deck Cuttings Measurements (LDC)

Measurement	Sensitivity	Frequency	Location	Potential technology
Wind (near surface)	10 cm/s	20 Hz	LDA	Sonic anemometer
Temperature	0.5 K	0.1 Hz	LDA	Infrared Radiometer (e.g. MEDA)
Pressure	1 Pa	1 Hz	LDA	Barometer (e.g. MEDA)
Absolute humidity	few ppm	20 Hz	LDA	Atmospheric TLS (15)
Dust/water ice flux	μm radius	< 1 Hz	LDA	Nephelometer
Aerosols	μm radius	< 1 Hz	LDA	Nephelometer
Dust/water ice accumulation	< 1 μg	daily	LDS	Micro-balance or thermogravimeter (evaporation capabilities)
Albedo, texture, grains	1 mm	Daily	LDS	IR Spectroscopy, High Resolution Imager, Nephelometer
Ice Strength	1 Pa	1 mm	BH	Drill Telemetry
Layer Properties	30 μm	1 mm	BH	Optical Imager in Borehole
Organics	ppm to ppb	1 mm	BH	XRF/APXS/LIBS/MOMA
Salts	0.1 wt%	1 mm	BH	XRF/APXS/LIBS
Trapped Gasses	3, 5, 100/mil	1 mm	LDC	MOMA
Impurity Distribution	1 wt%, $\sim 1 \mu\text{m}$	1 mm	LDC	micro CT

determining the mineralogy of refractory minerals such as dust and primary mafic sediments to a precision of 1 wt%, distribution to 10 μm , and grain size for 1 μm particles and larger.

Composition: Trapped gases, such as CO_2 , N_2 , Ar, O_2 , and CO are in sufficient abundance to measure at a precision of 0.1% or better, and minor constituents such as NO, Ne, HDO, Kr, and Xe require measurement precision of 10-100 ppb. Other important volatile species like S, Cl, and CH_4 also require ppb precision. Bubble size and density should be measured to 10 μm .

Isotopic measurements should include D/H to a precision of 100/mil over the range of 100-9000/mil, $^{18}\text{O}/^{16}\text{O}$ at a precision of 3/mil, and $^{13}\text{C}/^{12}\text{C}$ at a precision of 5/mil. Concentrations of ^{10}Be are unknown, so determining if it is present in trace quantities will be valuable. Mass Spectroscopy is appropriate for those measurements. Composition and abundance of organics with a sensitivity of ppm to ppb is required. Similarly, determining the mineralogy and elemental composition of soluble impurities such as S/Cl-rich, perchlorate, and sulfate salts to a precision of 0.1 wt% is desired.

Figure 4: Concept of a lander asset using EDL architecture from MER. Left: A drill arm extends past the landing hardware and mechanically drills ~50 cm into the subsurface using several small steps. Right: Pneumatic hardware moves the drill cuttings to the lander deck where they can be analyzed by onboard instruments.

Mission Concept and Approaches to Measurements

Static Lander: A mission to the NPLD surface should include instrumentation that is capable of addressing strategic knowledge gaps within the lower atmosphere, at the surface-atmosphere boundary, and within the top 50 cm of ice (Figure 4, Table 1). Many of the desired measurements require surviving or operating in the polar night, as discussed in the ICE-SAG report.

A meteorologic suite that accesses the bottom 4-5 km of the atmosphere would measure fluxes and boundary layer composition near the pole. TPH, and wind speed, including eddies, should be measured within 2 m of the surface. Imagers, a nephelometer, and a micro-balance would characterize the downward flux of material to the NPLD surface.

Borehole analysis. There are a few options for addressing the measurement requirements of the material within the borehole. The first option is to use the drill itself as an instrument to measure material strength and density from drilling telemetry, density from ultrasonic velocity, a temperature sensor, and bulk electrical resistivity (to detect “slush” formation). The second option is to modify the drill string to include instruments. Finally, a third technique is to lower instruments into the borehole after the drill string is removed.

Instruments that could be built into the drill string or lowered separately include an optical camera system and/or a LED-driven VNIR spectrometer system, a microscope, a spectrometer (such as Ma_MISS on ExoMars (16)), a fine-scale electrical resistivity probe, a temperature sensor, and a laser. The optical camera system should provide a wide field of view. The microscope should have a short working distance and be able to reach micron resolutions. An optical camera,

spectrometer, and the microscope will require some illumination. In addition, we foresee the inclusion of a laser in the borehole as a source for performing Laser Induced Breakdown Spectroscopy (LIBS) and deep UV/Raman (17). The spectrometer would reside on the deck of the lander and be fed via fiber optic cable, while the laser would be integrated in the borehole logger. These instruments may measure D/H or $^{18}\text{O}/^{16}\text{O}$.

Ice composition and ice grain size as well as the mineralogy of impurities could all be assessed rapidly via short-wave infrared reflectance spectroscopy (SWIR; 1.0-4.0 microns), which has been shown via orbital remote sensing to be highly sensitive to key phases in the NPLD and has been successfully miniaturized for small applications.

Bulk chemistry of borehole walls or other solid samples could be assessed via X-ray fluorescence (XRF), as implemented in the Planetary Instrument for X-ray Lithochemistry (PIXL) instrument on Mars 2020; via alpha particle X-ray spectroscopy (APXS), as implemented on multiple Mars rovers; or via laser-induced breakdown spectroscopy (LIBS) – as implemented in the MSL ChemCam and Mars 2020 SuperCam instruments. LIBS has been implemented with long fiber optic cables and may be better suited to small diameter boreholes.

Sample analysis on the lander deck: This may be done using a single core, drill cuttings, melting the sample and transporting it as a liquid, or volatilizing the sample. Instruments that we propose would remain on the lander deck to perform analysis include the high-TRL laser desorption mass spectrometry (cf. the Mars Organic Molecule Analyser (MOMA) onboard the upcoming ExoMars Rover (18)). MOMA could provide information on the bulk and isotopic composition of major gases. A microCT should be employed to study the internal structure of the ice.

Planetary Protection: The PLD are not considered special regions under planetary protection definitions; however, a radioisotope thermoelectric generator (RTG) could induce a special region by warming the ice to the melting point, making the landing site Category IV. One method to mitigate this potential without adding significant mass for batteries is to use wind to power the electronics and instruments that are to be operated during the polar night. Solar power is sufficiently abundant in the martian summer to meet the power demands of instruments and a drill.

Conclusions

In this paper we outline the overarching questions regarding the climate record of Mars and present a landed polar mission concept that is a necessary step for achieving this goal. It is feasible in the upcoming decade with current technology and would lay the groundwork for a mission, in the following decade, that examines ~500 m of stratigraphy, recording ~1 Myr of Martian climate history. A New Frontiers-class static lander (e.g. ICE-SAG) would assess all important qualities of the materials at the PLD surface and near subsurface (50 cm) in order to determine the most appropriate techniques for extracting the great climate record in the future.

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