Co-Evolution of the Martian Atmosphere and South Polar Massive CO_2 Ice Deposit.
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Introduction: A Massive CO_2 Ice Deposit (MCID) that rivals the mass of Mars' current, 96% CO_2 atmosphere was recently discovered to overlie part of Mars' southern H_2O cap [1]. The MCID is layered: a top layer of 1-10 m of CO_2, the Residual South Polar Cap (RSPC) [2], is underlain by ~10-20 m of H_2O ice, followed by up to three 100s-meter-thick layers of CO_2 ice, separated by two layers of ~20-40 m of H_2O ice [3] (Fig. 1). Previous studies invoked orbital cycles to explain the layering, assuming the H_2O ice insulates and seals in the CO_2, allowing it to survive recent high obliquity periods [3,4]. We present a model, also driven by orbital cycles [5], but in which the near surface of the MCID exchanges with the atmosphere rather than being sealed. Pervasive meter-scale polygonal patterning and km-scale collapse pits observed on the sub-RSPC H_2O layer [1,3,6] are consistent with it being fractured and permeable to CO_2 mass flux. Using currently observed optical properties of martian polar CO_2 ice deposits [7], our model demonstrates that the present MCID is a remnant of larger CO_2 ice deposits laid down during epochs of decreasing obliquity that are ablated, liberating a residual lag layer of H_2O ice, when obliquity increases. With these assumptions, our energy balance model explains why only the south polar cap hosts an MCID, the observed MCID stratigraphy, and why the enigmatic [8] RSPC exists. We use our model to calculate Mars' pressure history and the age of the MCID.

Methods: We use a 1D energy balance model to find the equilibrium frost temperature T_{eq} for which thermal emission flux equals mean annual absorbed insolation flux for various orbital configurations. T_{eq} sets the equilibrium pressure P_{eq} at the MCID top through vapor pressure equilibrium. We account for changes in altitude of the MCID top due to mass exchange and simultaneously solve for MCID mass, atmospheric mass, and zero-elevation reference pressure $P_{eq,0}$ normalized to the current pressure $P_{present,0}$. We calculate Mars' $P_{eq,0}$ history from a lookup table of polar insolation as a function of orbital elements.

Model Results: *H_2O Layer Formation*. Our model predicts that the MCID loses mass during epochs of rising polar insolation (Mars' present state), and gains mass when insolation falls. H_2O ice impurities (~1%) also accumulate onto the MCID along with the CO_2 ice in both epochs of rising and falling insolation (Fig. 2). During epochs of rising insolation, the MCID loses ~10^{-3} m yr^{-1} CO_2, leaving behind impurities (~10^{-4} m yr^{-1} H_2O) that consolidate into a lag layer.

RPSC existence. H_2O lag is darker and less volatile than CO_2 ice, so annual absorbed solar flux exceeds emitted thermal flux if H_2O is exposed at any time. Excess energy (heat) is conducted to the CO_2 below, causing CO_2 to sublime beneath the H_2O layer. Thus, H_2O exposure self regulates. If CO_2 sublimation in a given year overshoots equilibrium atmospheric pressure because the extent and/or duration of exposed H_2O is too large then the excess pressure leads to increased persistence of surface CO_2 (covering the H_2O) during the next year, and vice versa. Consequently, the CO_2 layer covering the H_2O layer (i.e., the RSPC) has near net-neutral mass balance (consistent with observation [2]) while the MCID beneath the H_2O layer is presently losing net mass as insolation increases.

Pressure history. Mars' $P_{eq,0}$ has been increasing for the past 40 kyr from a $0.7 \times P_{0,present}$ low (Fig. 2A). The current 0.01 Pa yr^{-1} increase implies ~0.4 Pa gain from Viking 1 to Mars Science Laboratory, not inconsistent with no mean annual pressure change detected between these missions, given the ~10 Pa measurement error [9]. Using the statistical distribution of Mars' chaotic orbital states over the past 3 Gyr [5], we find median $P_{eq,0}$ throughout the Amazonian is $1.3 \times P_{present,0}$ with an interquartile range of 0.7 to $1.7 \times P_{present,0}$ (not including any secular change to Mars' CO_2 inventory).

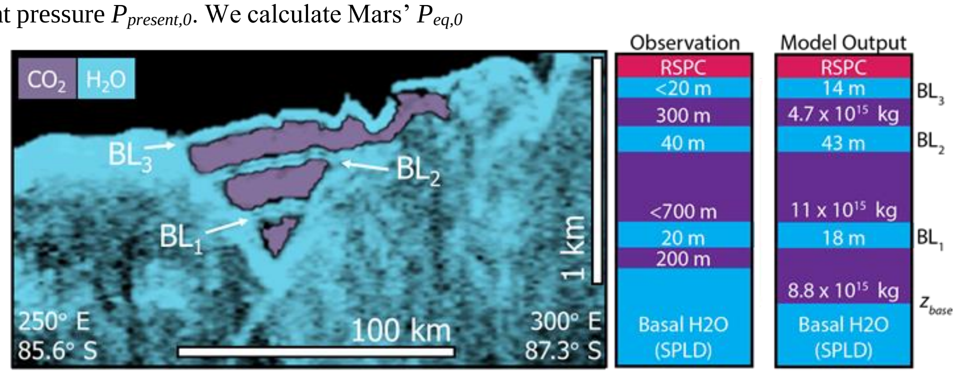

Figure 1: Radar cross-section across a portion of the MCID with H_2O ice "Bounding Layers" (BL) and latitude-longitude end points. Observed mean layer thicknesses [3] compared to our model-predicted H_2O layer thicknesses and CO_2 mass in each layer. CO_2 layer thicknesses are depicted to scale.

MCID Stratigraphy. The MCID stratigraphy co-evolves with $P_{eq,0}$ (Fig. 2). As insolation increases, H_2O lag consolidates as CO_2 sublimes until an insolation maximum. Lag layers formed at relative insolation maxima that are followed by greater insolation maxima are subsumed into the lag that forms at the greater maxima. If insolation is intense enough (e.g., at 510 kyr; Fig. 2B), the entire MCID ablates and all H_2O lag merges with the underlying South Polar Layered Deposit (SPLD), resetting the MCID stratigraphy. Condensing CO_2 buries lag layers when insolation decreases. Fractions of prior CO_2 deposits remain because the amplitudes of the obliquity maxima have been mostly decreasing during the past ~510 kyr (Fig. 2). Our model produces a stratigraphy comparable to observation (Fig. 1).

Discussion: Our model highlights the importance of regional factors (e.g., dustiness, snowfall, etc.) to explain the north-south differences in the polar caps [7]. Our model yields a southern (not northern) MCID for all orbital configurations so long as currently observed martian CO_2 optical properties hold, a result robust for up to a 50% increase in northern emissivity or albedo.

Finally, our model predicts that the interface between the MCID and underlying SPLD should be at altitude +4 km, similar to observation [3], suggesting that the top of the H_2O-rich SPLD may have adjusted over many orbital cycles such that the MCID just barely disappears at especially high peaks in absorbed mean annual polar insolation (e.g., at 510 kyr). In this scenario, the SPLD below the MCID may record a climate history not preserved elsewhere in Mars' polar deposits.

Conclusions: Our model in which the martian atmosphere and MCID co-evolve through vapor contact at all times [6] offers a self-consistent interpretation of the MCID's stratigraphic development and age that also provides a prediction of the RSPC and its equilibration with present atmospheric pressure. The process of CO_2 and H_2O co-evolution and pressure history we describe here is important for deciphering Mars' Amazonian climate and its record preserved in polar cap stratigraphy.

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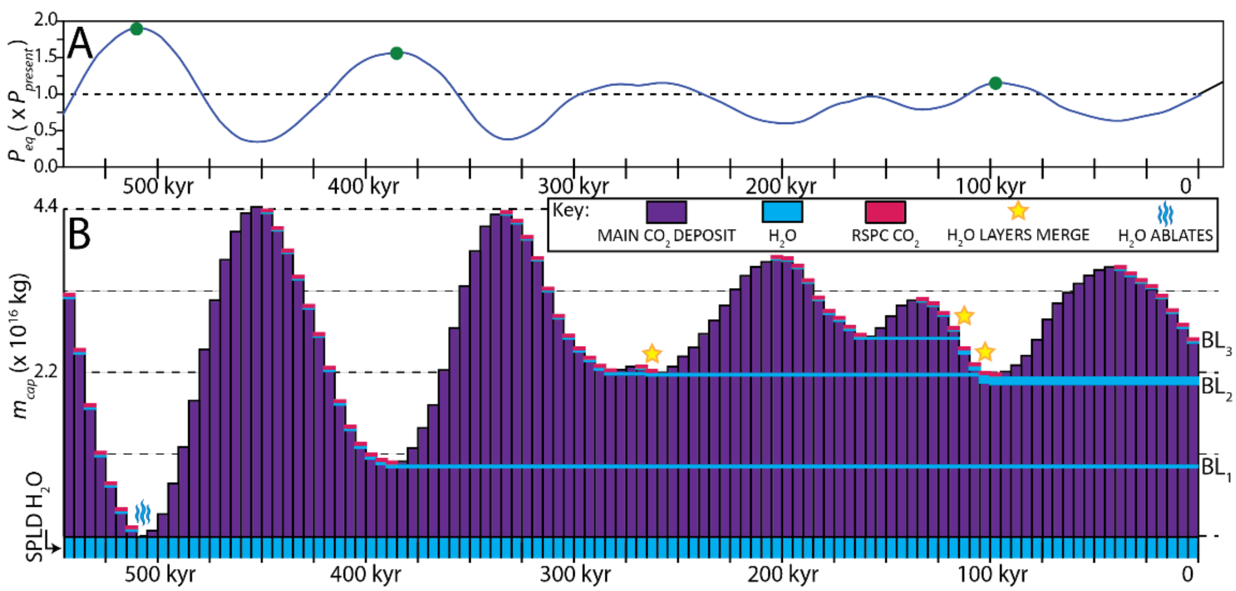

Figure 2: A. Model-predicted pressure history over the past 550 kyr, with monotonically decreasing $P_{eq,0}$ maxima (green dots) since the last total ablation of the MCID. **B.** Model-predicted evolution of MCID stratigraphy in 5-kyr steps. MCID mass shown to scale. H_2O layer thicknesses are depicted proportionally to each other, but at a different scale than the CO_2 for clarity. During epochs of rising polar insolation, CO_2 ablates and H_2O lag covered by a thin layer of CO_2 forms at the top of the deposit. At ~510 kyr, the entire MCID ablates, H_2O lag liberated from the MCID merges with the SPLD and the top of the SPLD ablates to the model-predicted z_{base}. During epochs of decreasing insolation, CO_2 accumulates, burying prior stratigraphy. Stars indicate times when all the CO_2 between two H_2O layers ablates so the H_2O layers merge.