

The Co-Evolution of Mars' Atmosphere and Massive South Polar CO₂ Ice Deposit. P. B. Buhler¹, S. Piqueux¹, A. P. Ingersoll², B. L. Ehlmann^{1,2}, and P. O. Hayne³, ¹Jet Propulsion Laboratory, California Institute of Technology (peter.b.buhler@jpl.caltech.edu), ²California Institute of Technology, ³University of Colorado Boulder

Introduction: A Massive CO₂ Ice Deposit (MCID) that rivals the mass of Mars' current, 96% CO₂ atmosphere was recently discovered to overlie part of Mars' southern H₂O cap [1]. The MCID is layered: a top layer of 1-10 m of CO₂, the Residual South Polar Cap (RSPC) [2], is underlain by ~10-20 m of H₂O ice, followed by up to three 100s-meter-thick layers of CO₂ ice, separated by two layers of ~20-40 m of H₂O ice [3] (Fig. 1). Previous studies invoked orbital cycles to explain the layering, assuming the H₂O ice insulates and seals in the CO₂, allowing it to survive periods of high obliquity [3,4]. We also model that orbital cycles [5] drive the MCID's development, but instead assume the MCID is in continuous vapor contact with the atmosphere rather than sealed. Pervasive meter-scale polygonal patterning and km-scale collapse pits observed on the sub-RSPC H₂O layer [1,3] are consistent with it being fractured and permeable to CO₂ mass flux. Using currently observed optical properties of martian polar CO₂ ice deposits [6], our model demonstrates that the present MCID is a remnant of larger CO₂ ice deposits laid down during epochs of decreasing obliquity that are eroded, liberating a residual lag layer of H₂O ice, when obliquity increases. With these assumptions, our energy balance model explains why only the south polar cap hosts an MCID, why the RSPC exists, and the observed MCID stratigraphy. 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: H₂O 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. H₂O ice impurities (~1%) also accumulate onto the MCID along with the CO₂ ice in both epochs of rising and falling insolation (Fig. 2). During epochs of rising insolation, the MCID loses $\sim 10^{-3}$ m yr⁻¹ CO₂, leaving behind impurities ($\sim 10^{-4}$ m yr⁻¹ H₂O) that consolidate into a lag layer.

RSPC existence. H₂O lag is darker and less volatile than CO₂ ice, so annual absorbed solar flux exceeds emitted thermal flux if H₂O is exposed at any time. Excess energy (heat) is conducted to the CO₂ below, causing CO₂ to sublime beneath the H₂O layer. Thus, H₂O exposure self regulates. If CO₂ sublimation in a given year overshoots equilibrium atmospheric pressure because the extent and/or duration of exposed H₂O is too large then the excess pressure leads to increased persistence of surface CO₂ (covering the H₂O) during the next year, and vice versa. Consequently, the CO₂ layer covering the H₂O layer (i.e., the RSPC) has near net-neutral mass balance (consistent with observation [2]) while the MCID beneath the H₂O 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, consistent with no mean annual pressure change detected between these missions, given the ~ 10 Pa measurement error [7]. 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' CO₂ inventory).

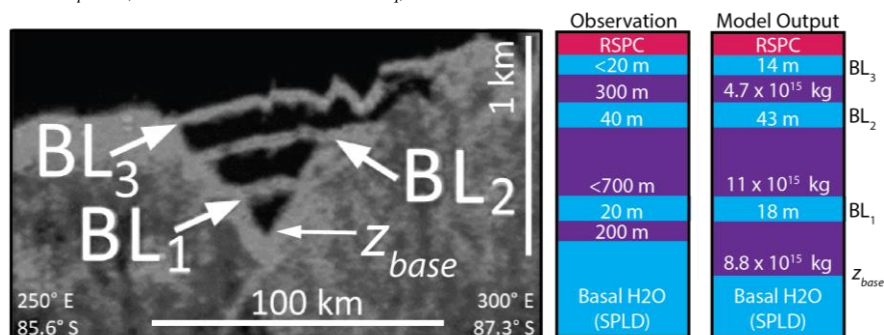


Figure 1: Radar cross-section from [3] with H₂O ice "Bounding Layers" (BL) and latitude-longitude end points. Observed mean layer thicknesses [3] compared to our model-predicted H₂O layer thicknesses and CO₂ mass in each layer. CO₂ layer thicknesses are depicted to scale.

MCID Stratigraphy. The $P_{eq,0}$ history sets MCID stratigraphy (Fig. 2). When insolation increases, H₂O lag consolidates as CO₂ sublimates 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 H₂O lag merges with the underlying South Polar Layered Deposit (SPLD), resetting the MCID stratigraphy. Condensing CO₂ buries lag layers when insolation decreases. Fractions of prior CO₂ 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 [6]. Our model yields a southern (not northern) MCID for all orbital configurations so long as currently observed martian CO₂ 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 H₂O-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 [8] 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 CO₂ and H₂O co-evolution and pressure history we describe here is important for deciphering Mars' Amazonian climate, and connection to polar cap stratigraphy.

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References: [1] Phillips, R. et al. (2011) Science 332, 838-841 [2] Thomas, P.C. et al. (2016) Icarus 268, 118-130 [3] Bierson, C. et al. (2016) GRL 43, 4172-4179 [4] Manning, C.V., et al. (2019) Icarus 317, 509-517 [5] Laskar, J. et al. (2004) Icarus 170, 343-364 [6] Paige, D.A. & Ingersoll, A.P. (1985) Science 228, 1160-8 [7] Haberle, R.M. et al. (2014) JGR Plan. 119, 440-453. [8] Buhler, P.B. et al., in review, *Nat. Aston.*

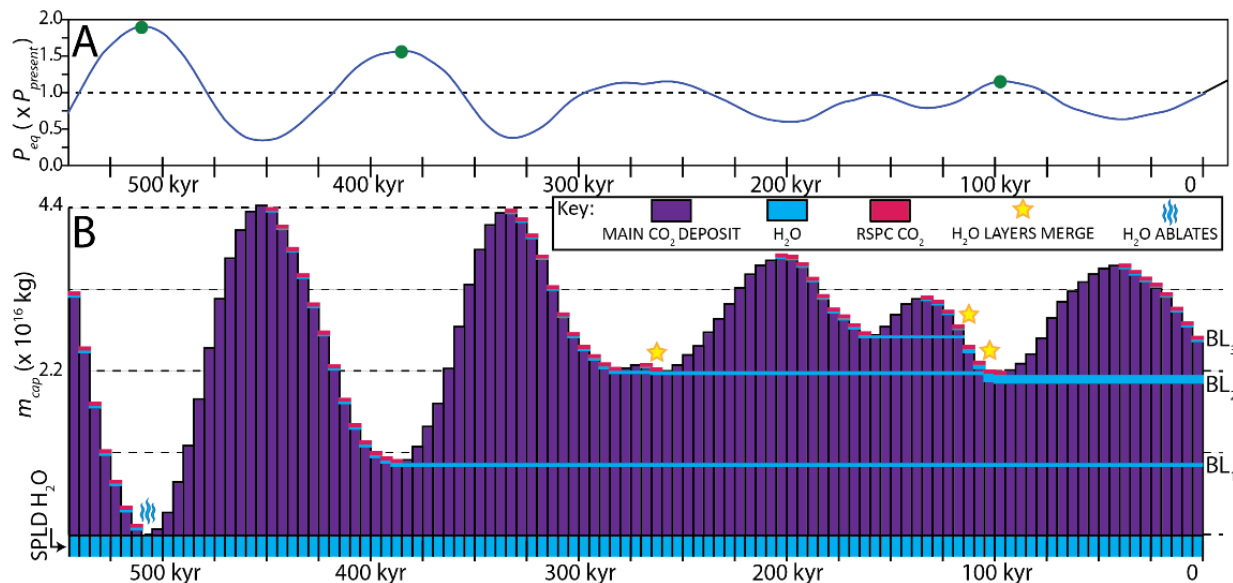


Figure 2: A. Model-predicted pressure history over the past 550 kyr, with monotonically decreasing $P_{eq,0}$ maxima (green dots) since the last total ablation of the MCID. B. Model-predicted evolution of MCID stratigraphy in 5-kyr steps. MCID mass shown to scale. H₂O layer thicknesses are depicted proportionally to each other, but at a different scale than the CO₂ for clarity. During epochs of rising polar insolation, CO₂ ablates and H₂O lag covered by a thin layer of CO₂ forms at the top of the deposit. At ~510 kyr, the entire MCID ablates, H₂O 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, CO₂ accumulates, burying prior stratigraphy. Stars indicate times when all the CO₂ between two H₂O layers ablates so the H₂O layers merge.