THE ORIGIN, AGE, AND STRATIGRAPHY OF MARS' MASSIVE SOUTH POLAR CO_2 DEPOSIT AND ITS CONTROL OF MARS' ATMOSPHERIC PRESSURE.

P. B. Buhler[1], S. Piqueux[1], A.P. Ingersoll[2], B.L. Ehlmann[1,2], P.O. Hayne[3]. [1]Jet Propulsion Laboratory, California Institute of Technology (peter.b.buhler@jpl.caltech.edu). [2]California Insitute of Technology. [3]University of Colorado, Boulder.

Introduction: Mars' CO_2 atmosphere pressure varies seasonally by ± ~15% due to deposition and sublimation of polar CO_2 ice. In 2011, a buried, layered, ~1 km thick perennial CO_2 ice deposit with a mass similar to that of the current atmosphere was discovered overlying part of the principally H_2O southern ice cap, hinting at longer-term variations in Mars' pressure [1,2]. The top layer is the ~1-10 m thick Residual South Polar Cap (RPSC), which is underlain by ~10-20 m of H_2O ice, followed by three 100s m thick layers of CO_2 ice, with two ~20-40 m intervening layers of H_2O ice [1-3].

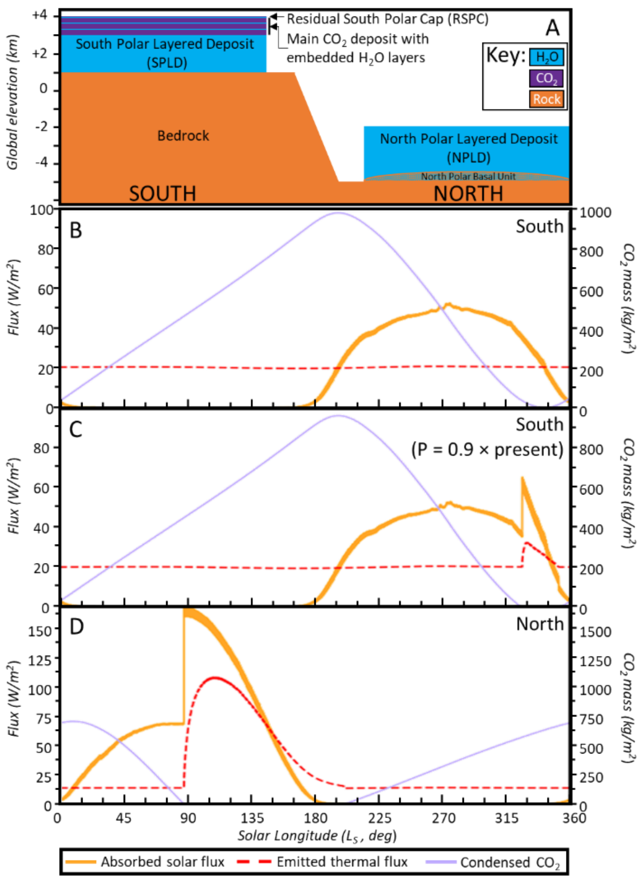

Fig. 1: A. Schematic martian polar deposit stratigraphy. **B-D:** One-year model outputs of polar cap energy fluxes and CO_2 ice accumulation for current orbit, observed stratigraphy, and observed CO_2 and H_2O optical properties. **B.** Latitude = 89.5° S, pressure = 1.0 × present, elevation = 4.75 km. **C.** Same, but pressure = 0.9 x present. Note incoming flux spike at L_S ~330 when CO_2 frost disappears, exposing darker H_2O, and smaller corresponding rise in outgoing flux as H_2O temperature rises above frost temperature. **D.** Latitude = 89.5° N, pressure = 1.00 x present, elevation = -2 km.

Previous studies hypothesized that the H_2O layers entomb the CO_2 layers. However, we show that variations in polar incident sunlight from Mars' 100-kyr orbit cycles [4] drive equilibrated evolution of the atmosphere and the CO_2 deposit in communication with each other.

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 top of the deposit through vapor pressure equilibrium. We account for changes in altitude of the top of the CO_2 deposit due to mass exchange and simultaneously solve for the deposit mass, atmospheric mass, and zero-elevation reference pressure $P_{eq,0}$ normalized to the current pressure. We calculate Mars' $P_{eq,0}$ history from a lookup table of polar insolation as a function of orbital elements.

Results: ***H_2O layer formation.*** The CO_2 deposit loses (gains) mass during epochs of rising (falling) insolation. A small amount of H_2O ice also accumulates onto the deposit [5]. Currently, mean annual insolation is rising at the south pole, so the CO_2 deposit is losing CO_2 at a rate of <~10^{-2} m yr^{-1}, leaving behind impurities (~10^{-4} m yr^{-1} dirty H_2O) that consolidate into a lag layer.

RSPC existence. The H_2O lag is darker than CO_2 [6], so net annual absorbed solar flux exceeds emitted thermal flux if H_2O is exposed at any time (Fig. 1C-D). Excess absorbed energy conducts to the CO_2 below the lag. The CO_2 sublimes up through the lag until atmospheric pressure is high enough for surface CO_2 to cover the lag throughout the year (Fig. 1B). The CO_2 covering the lag is the RSPC. Uneven CO_2 deposition [3] permits some RSPC regions to maintain perennial CO_2 cover while other regions expose bare lag at the end of summer; horizontal erosion redistributes the entire RSPC to transiently expose all areas of the lag on 10^2 yr timescales [7] (<<10^5 yr orbital timescales [4]). CO_2 loss beneath the lag layer is consistent with observed km-scale pits and troughs in the H_2O layer immediately beneath the RSPC [1,2], which we interpret as sinkholes.

Pressure history and Stratigraphy. Mars' $P_{eq,0}$ has been increasing for the past 40 kyr from a 0.7 × $P_{0,present}$ low (Fig. 2A). The current 0.01 Pa yr^{-1} increase implies ~0.4 Pa gain from Viking 1 to Mars Science Laboratory—less than the ~10 Pa measurement error—consistent with no mean annual pressure change detected between these missions [8]. By calculating the equilibrium pressure of the CO_2 ice deposit at different obliquities and eccentricities, the statistical distribution of

Mars' chaotic orbital states [4] permits a probabilistic $P_{eq,0}$ solution over the Amazonian (~3 Gyr), when the martian climate was likely similar to today [9]. Median $P_{eq,0}$ throughout the Amazonian is 1.32 × $P_{0,present}$ with an interquartile range of 0.77 to 1.67 × $P_{0,present}$ (not including secular change to Mars' CO_2 inventory).

The $P_{eq,0}$ history sets the stratigraphy of the south polar CO_2 deposit. During increasing insolation, lag (dirty H_2O) consolidates as CO_2 sublimes, subsuming lag layers from prior, lower-intensity maxima, until an insolation maximum. Condensing CO_2 buries lag layers when insolation decreases. If insolation is intense enough, the entire CO_2 deposit ablates, such that all of the H_2O-rich lag merges with the underlying South Polar Layered Deposit (SPLD; Fig. 1A, 2), resetting the CO_2 deposit's stratigraphic record. Thus, the number of lag horizons in the CO_2 deposit equals the number of monotonically decreasing insolation maxima since the most recent total ablation of the CO_2 deposit, plus an actively consolidating layer if viewed during an epoch of increasing insolation. Because lag layers grow by consolidation of all impurities deposited between $P_{eq,0}$ maxima, lag layer thicknesses depend primarily on the time between monotonically decreasing $P_{eq,0}$ maxima, while the mass of CO_2 between lag layers depends on the pressure difference between monotonically decreasing $P_{eq,0}$ maxima. Our pressure model produces a stratigraphy in good agreement with observation (Fig. 2).

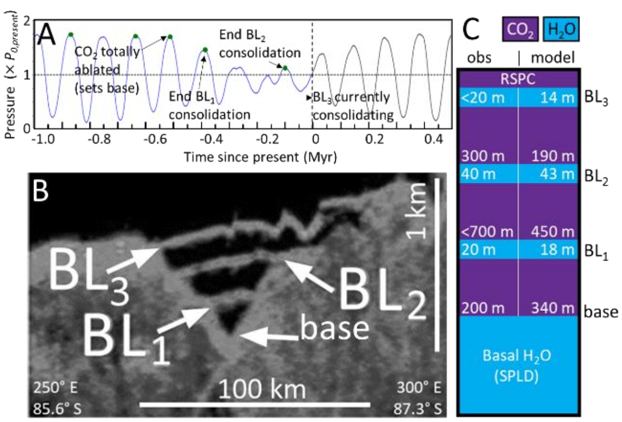

Fig. 2: A. Monotonically increasing $P_{eq,0}$ maxima (green dots) before present, which dictate the stratigraphy of the cap. **B.** Radar cross-section from [2] with H_2O ice "bounding layers" (BL) and latitude-longitude end points. **C.** Model-predicted and observed [2] stratigraphic column.

Favorable southern CO_2 optical properties protect the SPLD. When the CO_2 deposit ablates entirely, the H_2O-rich SPLD is exposed to sunlight during part of the year and erodes downward, increasing the pressure at the SPLD-atmosphere interface until, at a sufficiently low elevation, perennial CO_2 is again in thermal emission equilibrium with insolation, preventing further SPLD erosion. The albedo and emissivity of the northern and southern CO_2 ice are different, likely due to climatological factors, e.g., differences in atmospheric dust and CO_2 condensation processes between the hemispheres. Because RSPC CO_2 has the highest observed albedo of any martian CO_2 deposit and relatively high emissivity [10, 11], the RSPC achieves energy balance at the lowest temperature, and therefore lowest vapor pressure (highest altitude) of any CO_2 deposit. Perennial CO_2 with RSPC optical properties is stable at a higher altitude (3 km) than with northern CO_2 with its albedo and emissivity properties (-27 km) during Mars' maximum polar insolation. Thus, the perennial CO_2 deposit is in the south because the south's CO_2 favorable optical properties more than compensate for its ~7 km higher elevation compared to the north. Also, CO_2 protects the top of the SPLD from eroding lower than ~+3 km altitude, protecting the SPLD from total ablation, while the north PLD (NPLD) is not protected because perennial CO_2 stability (given observed albedo and emissivity) lies deep in the bedrock below the NPLD. This is consistent with both the observed ~+3 km altitude interface between the southern CO_2 deposit and the underlying SPLD and the much older surface age of the SPLD (10^7-10^8 yr) compared to the NPLD (few × 10^5 yr) [2,12,13].

Conclusions: By considering that the ~1 km thick CO_2 ice deposit is in communication with the atmosphere and modeling the co-evolution of CO_2 and H_2O ice, we successfully reproduce the CO_2 deposit's stratigraphy, calculate Mars' pressure from -21 to +11 Myr, statistically characterize Mars' 3 Gyr atmospheric pressure (median: 1.3 × present), and determine the age of the CO_2 deposit's climate record (510 kyr). Our results also resolve decades-standing questions by showing how observed north-south differences in CO_2 ice radiative properties explain: (i) why only the south polar cap hosts perennial CO_2 [14], (ii) why the RSPC exists, (iii) how the perennial CO_2 deposit formed, and (iv) how perennial CO_2 protects underlying H_2O from ablation, explaining the much older cratering age of the southern H_2O cap than the northern H_2O cap [12,13].

References: [1] Phillips, R. et al. (2011) *Science 332*, 838-841 [2] Bierson, C. et al. (2016) *GRL 43*, 4172-4179 [3] Thomas, P.C. et al. (2016) *Icarus 268*, 118-130 [4] Laskar, J. et al. (2004) *Icarus 170*, 343-364 [5] Brown, A.J. et al. (2014) *EPSL 406*, 102-109 [6] Byrne, S. et al. (2008) *PSS 56*, 194-211 [7] Byrne, S. & Ingersoll, A.P. (2003) *GRL 30*, 2-5 [8] Haberle, R.M. et al. (2014) *JGR Plan. 119*, 440-453 [9] Hu, R. et al. (2015) *Nat. Comm. 6*, 10003 [10] James, P.B. et al. (1992) in *Mars*, ed. Kieffer, H.H. et al., UA Press, 934-968 [11] Hayne, P.O. et al. (2014) *Icarus 231*, 122-130 [12] Herkenhoff, K.E. & Plaut, J.J. (2000) *Icarus 144*, 243-253 [13] Koutnik, M. et al. (2002) *JGR Plan. 107*, 10-1-10-10 [14] Murray, B.C. & Malin, M.C. (1973) *Science 182*, 437-443