Distinct CO_2 Ice Endmembers on the Northern Polar Seasonal Cap. C. P. Mount[1] and T. N. Titus[2], [1]Arizona State University, 1151 S. Forest Ave., Tempe, AZ, 85287, cpmount@asu.edu, [2]U.S.G.S. Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ, 86001-1637, ttitus@usgs.gov.

Introduction: The Polar Regions are some of the most dynamic places on Mars. Approximately 25% of the CO_2-dominated atmosphere condenses annually onto the poles as ice, driving Mars' climate [1, 2]. During fall and winter, ice condenses onto the surface via radiative cooling (slab ice) [3] or as granular particulates in the atmosphere (CO_2 snow) [4, 5]. In spring, the CO_2 sublimes. Changes in the microphysical state of CO_2 ice deposits during sublimation yield insight into the polar energy balance, which drives the CO_2 cycle and, thus, the global climate.

Depositional modes are typically defined spectroscopically by grain size [6]; however, these models produce unrealistic grain sizes for slabs. [7] showed that pores in a solid CO_2 ice matrix can explain these large model grain sizes, and provide a better conceptual framework for slab ice. Porosity translates directly to the ice density (see Methods).

The bulk density of CO_2 can be estimated by dividing the Column Mass Abundance (CMA) of CO_2 by the depth of ice on the cap. CMA is the mass of CO_2 per unit area on the surface [8], and has been derived in a variety of ways (e.g., energy balance calculations [6, 9], neutron spectroscopy [8], etc.). While most density studies of the Martian Polar Caps have used Mars Orbiter Laser Altimeter (MOLA) time-variable elevation data to measure the depth of ice on the cap [10, 11], seasonal changes in observed rock heights on the surface have been used to measure ice depths to a greater accuracy [12].

Here, we use springtime surface features, albedos, and densities to identify depositional modes and study CO_2 ice evolution over time at three locations on the North Polar Seasonal Cap (NPSC).

Methods: The presence of specific surface features may constrain the physical state of the CO_2 ice. Dust fans, fractures, and accentuated topography indicate slab ice [3], while "damped" topography (e.g., infilled troughs) indicates snow [13].

We apply the Lommel-Seeliger photometric function [14] to convert High Resolution Imaging Science Experiment (HiRISE) red-band image (0.55 – 0.85 μm) radiances into albedo to act as a proxy for grain size and dust contamination. Granular deposits have high albedos, whereas dusty or slab deposits have low albedos. However, HiRISE-derived albedos are prone to large errors (± 30%) [15].

Measurements of the ice depth are determined using the method from [12], in which rock shadow lengths are measured in HiRISE springtime images. We expand on this technique by incorporating the local slope and correcting for shadow distortions caused by sublimation of ice around and on top of rocks [16].

We use the energy-balance techniques of [6] and [9] to calculate CMA. These techniques use Thermal Emission Spectrometer (TES) thermal bolometer data.

We divide the CMA by the ice depth to determine density. A 50% porosity slab with 1-μm voids has a 25-μm brightness temperature consistent with grain sizes of ~1000 μm [7]. Assuming a threshold porosity between slab and snow of ~50%, and a maximum CO_2 density of ~1600 $kg \cdot m^{-3}$ [17], slab-ice densities are > ~800 $kg \cdot m^{-3}$ (< 50% porosity, > 1000 μm grains) and snow densities are ≤ 800 $kg \cdot m^{-3}$ (≥ 50% porosity, ≤ 1000 μm grains).

Results: Our three study locations are the Phoenix Landing Site (68°N, 233°E), Louth Crater (70°N, 103°E), and a dune field (herein labeled Dunes) at 75°N, 282°E.

Initially, both Phoenix and Louth appear to have "damped" topography. By late spring, bright material is isolated to polygonal troughs at Phoenix. Over time, this material reduces in width, but not length. Louth has bright lineations that are only loosely correlated with topography. These are detailed in Figure 1. Underlying ripple topography is accentuated and dust fans are clearly visible at Dunes in early spring. Dunes exhibits patterns similar to Phoenix, although less extreme, and dust fans have nearly vanished by late spring.

Initial albedos at Phoenix and Louth are relatively high (0.61 and 0.67, respectively), consistent with snow deposits. The albedo of ice at Dunes is much darker (0.38), consistent with dust-rich deposits. Phoenix reduces in brightness over time and the albedo distribution becomes bimodal in late spring. Louth albedo reduces in brightness to 0.61, then increases to 0.67, before reducing again in late spring. The albedo at Dunes increases over spring to 0.49.

Densities are initially low at both Phoenix and Louth, with corresponding porosities of nearly 75%. This suggests snow deposits. Conversely, ice at Dunes has an initial density just below ~800 $kg \cdot m^{-3}$ (50% porosity). This is consistent with a fractured, porous slab or highly compacted snow deposit. Densities at Phoenix and Louth remain low throughout spring, whereas Dunes ice rapidly increases in density before reducing near the end of spring.

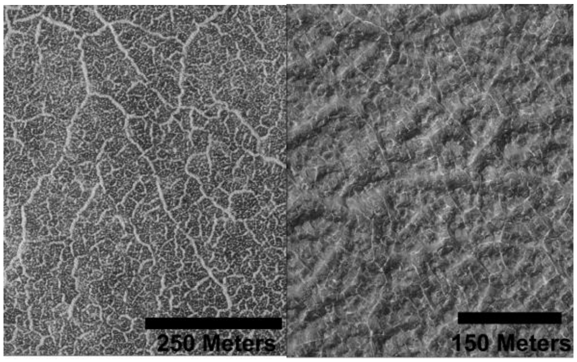

Figure 1. Late spring images of Phoenix (left) and Louth (right). Bright material is isolated to troughs, with dark material on polygons at Phoenix. Louth has bright lineations that appear only loosely correlated with topography.

Discussion: All data are consistent with snow deposition at Phoenix ("damped" topography, high albedo, and low density). The occurrence of the bright trough material, bimodality in the albedo distribution, and declining density are likely caused as follows (see Figure 2): 1) Snow is deposited during the polar night. 2) Aeolian processes redistribute the snow into topographic lows, so that polygonal troughs will contain more CO_2 ice. This "damps" the polygonal topography. 3) Sublimation and sintering of snow begin in the following spring. Because sunlight will penetrate to a relatively shallow depth, annealing will occur rapidly near the surface to produce a thin, highly porous, slab-ice layer over the top of the snow. 4) Ice sublimes and sinters preferentially at the base of the slab layer because absorption of light is higher in snow. 5) Ice depth reduces as sublimation continues, but the slab layer grows due to ongoing sintering. The albedo decreases as the layer thickens. This layer must fracture more rapidly than it metamorphoses in order to reduce the ice density over time. 6) Eventually, the snow is confined to only troughs. Polygonal high points will appear dark due to partial reflectance off of the surface (light penetrates the slab). The geometry of the troughs and growing slab layer conserves the lengths (but reduces the widths; see Figure 2d) of the trough material throughout most of sublimation.

Louth data are also consistent with snow, and this ice likely experiences the same evolution as Phoenix. However, due to the lack of bright trough material, and instead bright lineations (interpreted to be fractures), the overlying slab layer is probably much thicker with much more prominent fracturing. This study area is inside a large impact crater, so the increase in albedo during early spring may be due to wind-blown CO_2 snow that was transported via orographic lifting.

The data at Dunes are consistent with a dusty, porous slab that undergoes self-cleaning (increasing albedo) [18], metamorphism (initial densification), and fracturing (late de-densification). Despite this, the presence of bright trough material in late spring and ~50% initial porosity could indicate that this is a highly evolved snow deposit that follows the same model as Phoenix and Louth.

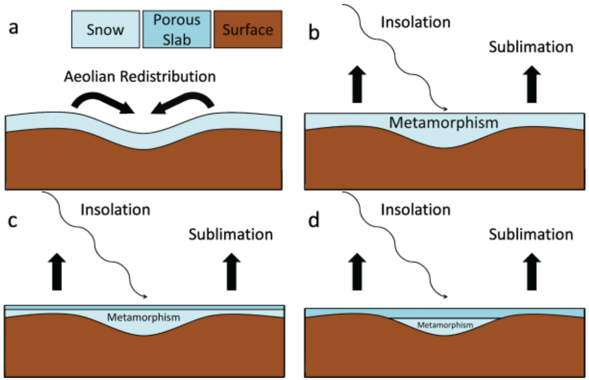

Figure 2. Model for CO_2 snow evolution. a) Deposition of fine-grained material redistributed to topographic lows. b) Insolation forces sublimation and grain growth. c) Basal metamorphism produces overlying slab layer. d) Slab layer thickens, isolating snow to topographic lows.

Conclusion: There are two distinct endmembers of the NPSC; bright, low-density deposits (snow) darken and reduce in density throughout the spring, due to metamorphism and the formation of an overlying slab layer. This slab layer fractures more rapidly than it metamorphoses, reducing the density; the slab is dark compared to the initial snow deposit and becomes darker as the slab layer thickens. Dark, relatively high-density deposits (porous slab) brighten and increase in density. These deposits brighten during spring through self-cleaning; the increase in density is due to metamorphism, until sublimation thins the ice and fracturing dominates. However, the high porosity and the presence of bright, late-spring trough material could indicate that these are highly evolved snow deposits. These endmembers indicate that slab and snow deposits have drastically different behavior, or that snow deposits evolve to a critical density such that densification processes become much more efficient.

References: [1] Leighton R. B and Murray B. C. (1966), *Science, 153, 136-144*. [2] Kelly N. J. et al. (2006), *JGR, 111, E03S07*. [3] Hecht M. H. (2008), *PSS, 56, 246-250*. [4] Forget F. et al. (1995), *JGR, 100, 21219-21234*. [5] Titus T. N. et al. (2001), *JGR, 106, 23181-23196*. [6] Kieffer H. H. et al. (2000), *JGR, 105, 9653-9699*. [7] Eluszkiewicz J. et al. (2004), *Icarus, 174, 524-534*. [8] Prettyman T. H. et al. (2009), *JGR, 114, E08005*. [9] Kieffer H. H. and Titus T. N. (2001), *Icarus, 154, 162-180*. [10] Smith D. E. et al. (2001), *Science, 294, 2141-2145*. [11] Matsuo H. and Heki K. (2009), *Icarus, 202, 90-94*. [12] Cull S. et al. (2010), *JGR, 115, EE00D16*. [13] Winstral A. and Marks D. (2002), *Hydrol. Proc., 16, 3585–3603*. [14] Hapke B. (1990), *Icarus, 88, 407-417*. [15] McEwen A. S. et al. (2007), *JGR, 112, E05S02*. [16] Mount C. P. (2013), *Thesis, N. Ariz. Univ*. [17] Titus T. N. et al. (2008), *The Martian Surface: Comp., Mineral., and Phys. Prop.*, Ed. Bell J.F., *578-598*. [18] Kieffer H. H. (2007), *JGR, 110, E08005*.