VNIR CHARACTERIZATION OF THE MARTIAN NORTH POLAR ICE CAP 2): CONSTRAINING THE SURFACE COMPOSITION.
A. C. Pascuzzo[1], J. D. Tarnas[1], J. F. Mustard[1], and H. Lin[2], [1]Dept. of Earth, Environmental, and Planetary Science, Brown University, RI, USA (alyssa_pascuzzo@brown.edu), [2]Institute of Geology and Geophysics, Chinese Academy of Sciences

Introduction: It is hypothesized that the North Polar Layered Deposit's (NPLD) distinct layers are a record of accumulation rate variability of water-ice and atmospherically deposited dust due to recent climate change over the past <1-4 Myr [1–3]. Although Mars radar data suggest the bulk composition of the NPLD and North Polar Residual Cap (NPRC), which overlays the NPLD, is ice and dust [4,5], it is likely an oversimplification of the surface composition. Several studies suggest sulfates, glasses, and mafic minerals are being eroded out of the NPLD and are present in the ice and troughs [6–11]. These additional ice impurities could be the result of present or recent past alteration, and non-climate-driven processes such as volcanism, and/or impact cratering [12]. Here we present additional theory for the origin and formation of sulfates on the north polar ice cap and our methodology for assessing spectral variability to determine compositional diversity of the NPRC and NPLD from Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) data.

Background: Despite decades of investigations, the compositional variability between the layers and climate-driven accumulation processes remain ambiguous. The interpretation of the recorded processes is complicated by the superimposition of modern aeolian surface processes (i.e., trough wall erosion and sublimation, redistribution of dust and ice, post-depositional veneer formation and induration) which modify the surface composition and topography [4,5].

Presently, the ratio of water-ice, dust, and other ice impurities of specific layers of the NPLD are unconstrained by both radar [13–15] and VNIR data. Shallow radar sounding (SHARAD; 10 m vertical resolution in ice) has inferred dust content to range from 2-30% [14,15]. No estimates of the surface composition have been made from VNIR data for the NPLD layers, therefore connections between internal and surficial layer properties remain unconstrained. Characterizing the surface composition is important because correlating spectrally interpreted composition with spatially resolved layering can aid in deconvolving these superimposed processes and constrain the accumulation history.

Previous Sulfate Detections: Before constraining the relationship between ice-to-dust ratios and stratigraphy, a thorough evaluation of spectral endmembers in the polar cap, specifically the presence of sulfates, is needed. Previous studies suggest dusty veneers, which
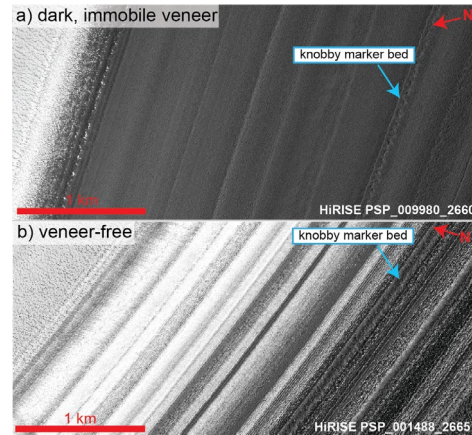

Fig 1. (a) An example of a layered trough wall covered by dark, immobile dust veneer interpreted to be sublimation lag indurated by salts or ice and a (b) veneer-free trough wall. A laterally continuous knobby marker bed is labeled for reference.

partially mantle the exposed NPLD trough stratigraphy (Fig. 1), bear weak sulfate spectral signatures, possibly gypsum [9,10] or other sulfates (identified in the icy regolith at Phoenix landing site [16,17]). Some suggest that the sulfates were deposited after forming in the atmosphere or directly from ice during accumulation and are now being eroded from the sediment-rich layers of the NPLD [9]. Other hypotheses include sulfate formation via sublimation and veneer forming/induration processes within the troughs (e.g., transient liquid phase diffusion between dust (Mg^{2+} > Ca^{2+} > Na^+) and ice grains to form sulfate crystals or frozen brines) [9]. Definitive presence and origin of trough wall sulfates remains uncertain.

Evaluating Sulfate Presence: After initial radiative transfer modeling and spectral unmixing of the NPRC and NPLD surface spectra [Companion abstract #1913] it becomes apparent that even for the most ice rich spectra simple water-ice and dust 2-component mixtures do not provide good fits. The spectral fits and residual spectra from the mixture modeling, assuming a 2-component mixture are insufficient and not fully representative of the surface composition. The largest deviations between the modeled spectra and the observed spectra occur between 1.0-1.4 μm, 1.4-1.5 μm, and 2.3-2.5 μm. This is especially true for the nearly pure ice-rich NPRC spectra. We hypothesize that there are two possible missing components that need to be evaluated: a second fine grain ice component like snow or frost and Mg-sulfate. Previous spectral studies, which investigated seasonal ice changes, used two ice components,

one of larger grain size and another for smaller grains, which produced better spectral fits [18,19]. However, the same discrepancies between the modeled spectra and data exist even when small and larger ice grain sizes were used to model the observed ice spectra [18].

It is possible that the nearly pure NPRC ice and upper ice-rich layers of the NPLD may have a significant amount of sulfate mixed with water-ice on the surface that has gone undetected. For instance, Mg-sulfates are difficult to distinguish from ice since they share diagnostic overlapping absorptions near 1.25 μm, 1.4-1.5 μm, and 2.0 μm. Sulfate bearing ice can occur as salty-ice crusts made of Mg/Na/Ca-sulfate and ice mixtures or frozen brine inclusions at the surface. Salty ice crusts are known to form on Earth's glaciers/sea ice due to a sublimation lag processes [20]. A similar process could be occurring on the martian polar water-ice cap.

We begin the assessment of compositional variability of the NPLD surface, including testing for presence of sulfates at low abundances and in complex convolutions, via application of Dynamic Aperture Factor Analysis/Target Transformation (DAFA/TT) [21–23]. This allows for detection of subtle spectral variability associated with various sulfates that are generally over-printed by the dominant water-ice and dirty water-ice spectra in this region. This allows for more robust assessment of the full suite of compositional endmembers exposed in the NPLD trough stratigraphy.

Methodology: CRISM full-resolution targeted (FRT) observations (18 m/pixel) allow for spectral measurements along the trough walls which can then be directly correlated to detailed stratigraphic sequences (down to a vertical resolution of 1-3m) from HiRISE. Before spectral analysis is performed the data are atmospherically corrected following the methods used in our companion abstract [Abs #1913].

To build a spectral library for spectral unmixing, we will use DAFA/TT to recover spectral endmembers within the CRISM scene. DAFA/TT allows for the use of large spectral libraries to minimize a priori assumptions about surface composition and grain size. It can detect spectrally active components at low abundances and complex convolutions and excels in identifying minerals with sharp vibrational absorption features like those of sulfate. DAFA/TT is unique relative to other applications of factor analysis and target transformation to CRISM images [24,25] in that it allows for detection of minerals while simultaneously constraining their location within a given hyperspectral image. DAFA/TT is performed on the CRISM reflectance data and uses a spectral library with reflectances of gypsum, hexahydrite, epsomite, meridianiite. The spectral library was curated from Reflectance Experiment Laboratory (RELAB) at Brown Univ. and the Planetary Spectrophotometer Facility (PSF) at the Univ. of Winnipeg.

Preliminary Results: We detect spectral features consistent with gypsum and or hexahydrite (Fig. 2) within the bright and dark toned water ice layers of the NPLD trough. Further investigation using a more mineralogically and spectrally diverse library for DAFA/TT, in addition to applying a constrained spectral library to Hapke spectral unmixing models will allow for more precise constraints of NPLD trough composition and its relationship to stratigraphy.
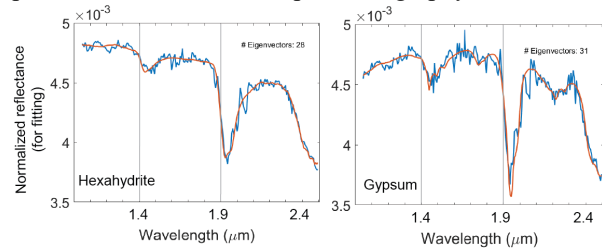

Fig 2. (left) Target transformation fit (blue) to hexahydrite library spectrum (orange). (right) Target transformation fit (blue) to gypsum library spectrum (orange). Both from DAFA/TT analysis of FRT0000beb8.

Summary: We use DAFA/TT to identify whether sulfate minerals are present within the NPLD trough. We also characterize which sulfates are likely present where their signatures are detected, in order to begin constraining the spectral library for non-linear radiative transfer modeling to estimate ice abundance and grain size, mineral composition and grain size variation, as well as the spatial variability. This provides us with more robust understanding of the hitherto ambiguous composition of the NPLD trough. Next steps will include more sulfates in our spectral library and to apply pixel-by-pixel Hapke non-linear unmixing for entire CRISM scenes.

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