THE EARLY HISTORY OF PLANUM BOREUM: AN INTERPLAY OF WATER ICE AND SAND.
S. Nerozzi[1], J. W. Holt[2], A. Spiga[3], F. Forget[3], E. Millour[3], [1]Institute for Geophysics, Jackson School of Geosciences, The University of Texas at Austin, TX 78757 (stefano.nerozzi@utexas.edu), [2]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, [3]Laboratoire de Météorologie Dynamique, Université Pierre et Marie Curie, Sorbonne Université, Paris, France.

Introduction: The Planum Boreum of Mars is composed of two main units: the North Polar Layered Deposits (NPLD), and the underlying basal unit (BU). The rich stratigraphic record of the NPLD is regarded as the key for understanding climate evolution of Mars in the last 4 My [1] and its dependency on periodical variations of Mars' orbital parameters (i.e., orbital forcing) [2-4]. Their initial emplacement represent one of the most significant global-scale migrations of water in the recent history of Mars, likely driven by climate change, yet its dynamics and time scale are still poorly understood. Recent studies revealed the composition, stratigraphy and morphology of the lowermost NPLD and the underlying BU (Fig. 1, 2; [5,6]). These findings depict a history of intertwined polar ice and sediment accumulation in the Middle to Late Amazonian, thus opening a new window into Mars' past global climate.

Here we present a summary of the latest findings on the climate-driven evolution of Planum Boreum, their significance in advancing the exploration of Mars, and new outstanding questions on Mars polar science. These studies are based on the integration of radar profiles and images acquired by the Shallow Radar (SHARAD, [7]) and the High Resolution Imaging Science Experiment (HiRISE, [8]) on the Mars Reconnaissance Orbiter, and the General Circulation Model (GCM [9]) developed by the Laboratoire de Météorologie Dynamique (LMD).

Former ice caps preserved with the cavi unit: The cavi unit is an aeolian deposit of basalt sand and water ice making up large portions of the BU. SHARAD signals penetrate through this unit revealing internal and basal reflectors. We use these detections to reconstruct the general stratigraphic structure of the unit, and obtain its bulk composition. Our exercise reveals substantial spatial variability in composition, with average water ice volume fractions comprised between 62% in Olympia Planum and 88% in its northern reaches beneath the NPLD. Similarly, internal reflectors occur more frequently closer to the pole and gradually disappear moving south. We hypothesize that the cavi unit is made of alternating ice and sand sheets, with water ice becoming prevalent towards the north pole (Fig. 2). Water ice accumulation models predict substantial ice growth during periods of low spin axis obliquity before the onset of NPLD deposition [10,11], with the thickest accumulation close to the north pole. In the models, this is soon followed by complete loss through sublimation; however, models do not include a protection mechanism against sublimation. We hypothesize that aeolian sand sheets migrated from the margins of paleo-Planum Boreum, burying portions of the remnant ice sheet and thus preventing its complete sublimation. This hypothesis is supported by observations of sand mantles extending for 10s of km on top of thick water ice along visible outcrops and radar profiles of the lowermost NPLD [5,6]. Therefore, we argue that ice caps dating to Middle to Late Amazonian are not necessarily lost due to instability during high obliquity periods, but can be partially or wholly preserved within sand sheets underneath the NPLD. These ice deposits are detected by SHARAD and can be delineated in their spatial extent. Moreover, the high water ice fraction makes the cavi unit an important water ice reservoir, potentially the third largest on Mars after the two PLDs.

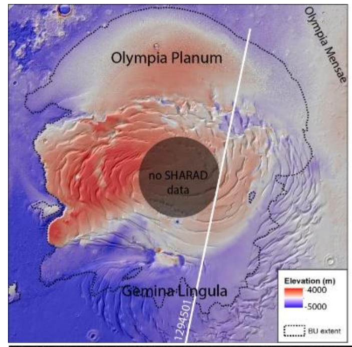

Figure 1: Topographic map of the BU and surrounding terrains revealed by SHARAD [6,7], with superimposed shaded relief of the present day Planum Boreum topography. The white line delineates the location of the SHARAD profile in Fig. 2.

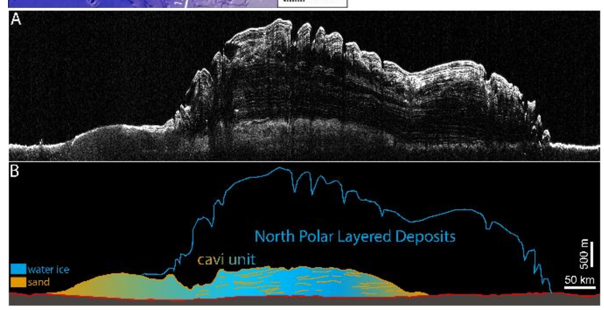

Figure 2: (A) SHARAD profile 1294501 depth corrected assuming bulk water ice composition (e=3.1 [10]), and (B) interpretation thereof [6]. The putative basal surface of the cavi unit is represented in red.

Newly mapped extent, stratigraphy, and morphology of the BU: Analysis of SHARAD profiles indicates that the BU extends over a larger area than previously thought. In particular, we detect the presence of cavi unit material extending underneath the NPLD from the western edge of Gemina Lingula to a visible exposure in the eastern end of Olympia Undae, covering an area of over 120,000 km^2 (Fig. 1). HiRISE images taken over the outcrop location reveal sub-horizontal strata forming terraces and characterized by sinuous forms and cross strata. We interpret this as a cavi unit outcrop, that we can now place into the broader stratigraphic context of Planum Boreum based on SHARAD profiles. Similarly, we combined radar observations and HiRISE-based stratigraphic mapping of visible outcrops along the margins of Planum Boreum to delineate the extent and thickness of the Rupēs and cavi units.

Our radar-based topographic mapping also reveals a series of elongated depressions tens to hundreds of meters deep along the edge of the cavi unit. In some cases, the base of these depressions are flat and appear to continue as internal reflectors for hundreds of kilometers. We interpret these findings as further confirmation of the presence of alternating ice and sand sheets within the cavi unit, delineating sequences that exhibit different resistance to erosion. The location of the elongated depressions coincides with the presence and shape of the buried chasma observed by ref. [12], suggesting that the cavi unit was eroded in the same event that shaped the chasma. We detect similar features at other locations of the BU, suggesting that many other erosional events are recorded by the unit's surface morphology.

Reconstructing the initial NPLD accumulation: SHARAD-based analysis of the lowermost NPLD stratigraphy reveals that initial water ice accumulation was not uniform, but limited in extent and confined into two areas centered around the north pole and in the present Gemina Lingula region, confirming the existence of a proto-Gemina Lingula [12]. Likewise, subsequent ice accumulation was variable in extent. We use the newly acquired information on BU composition, topography and lateral extent to accurately constrain the initial conditions and parameter space for sensitivity experiments with the LMD GCM aimed at understanding the driving forces responsible of the initial accumulation of the NPLD, and its temporal evolution. In particular, we defined parameter sets of spin axis obliquity (15-40°, 5° steps), orbital eccentricity (0-0.12, 0.03 steps), perihelion precession (0-270°, 90° steps), and atmospheric pressure (current, +106% based on ref. [13]).

The GCM output reveals that both obliquity and eccentricity play key roles in driving the amount of water ice accumulation in Planum Boreum, with low obliquity and high eccentricity scenarios resulting in the largest ice growth. Obliquity also appears to control the latitude of ice accumulation, with low obliquity driving thick ice growth at ~60°N. Local topography appears to control longitudinal patterns of ice growth in all our simulations. We find a strong similarity of the latest GCM outputs with the isolated proto-Gemina Lingula deposit (Fig. 3) and present-day icy outliers of Olympia Mensae. This suggests that Olympia Mensae may be remnant of the migration of water ice from low to polar latitudes that resulted in the initial accumulation of the NPLD. Moreover, the formation of proto-Gemina Lingula may predate the accumulation of other NPLD units closer to the north pole.

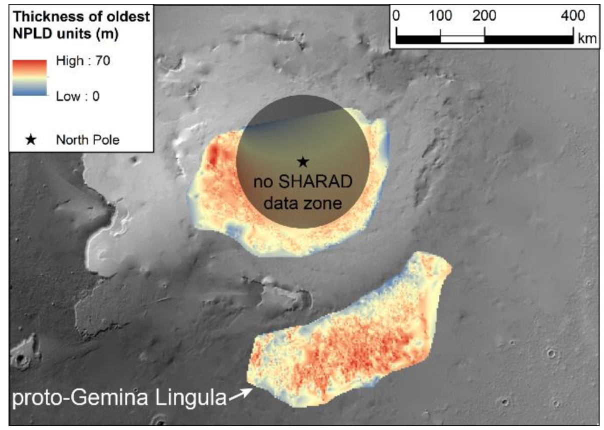

Figure 3: Earliest NPLD water ice accumulation in Planum Boreum as mapped by SHARAD [6].

Outstanding questions: Based on our latest findings in Planum Boreum, we delineate the following outstanding questions. How many episodes of past ice accumulation are recorded within the cavi unit? What is their precise age? What is the nature of western half of the BU, which is dominated by the Rupēs unit? Does this unit also record past polar ice accumulation events? Do younger unconformities in the NPLD follow a similar pattern of erosion/deposition, indicating long-term regional climate patterns?

Acknowledgments: This work was supported by NASA MDAP grant NNX15AM52G. SHARAD is provided and operated by the Italian Space Agency. The GCM was kindly provided by the Laboratoire de Météorologie Dynamique, UPMC, Paris.

References: [1] Cutts J.A. (1973) *JGR*, 78, 4231-4249. [2] Murray B.C. et al. (1973) *Science*, 180, 638-640. [3] Laskar J. et al. (2002) *Nature*, 419, 375-377. [4] Laskar J. et al. (2004) *Icarus*, 170, 343-364. Nerozzi, S. and Holt, J.W. (2018) *Icarus*. [6] Nerozzi, S. and Holt, J.W. (2019) *GRL*. [7] Seu R. et al. (2007b) *JGR, 112*, E05S05. [8] McEwen, A.S. et al. (2007) *JGR*, 112, E05S02. [9] Forget F. et al. (1999) *JGR, 104*, 155-176. [10] Levrard B. et al. (2007) *JGR*, *112*, E06012. [11] Greve R. et al. (2010) *PSS, 58*, 931-940. [12] Holt J.W. et al. (2010), *Nature, 465*, 446-449. [13] Bierson C.J. et al. (2016) *GRL, 43*, 4172-4179.