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 NPLD are the second largest water ice reservoir on Mars. Their rich stratigraphic record 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 underlying BU (Fig. 1, [5]). 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. Our studies are based on the integration of radar profiles and images acquired by the Shallow Radar (SHARAD, [6]) and the High Resolution Imaging Science Experiment (HiRISE, [7]) on the Mars Reconnaissance Orbiter, and the General Circulation Model (GCM [8]) 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 the cavi unit revealing internal and basal reflectors. We use these detections to reconstruct the general stratigraphic structure of the unit, and obtain its bulk composition with an inversion technique. 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 [9,10], with the thickest accumulation close to the north pole. In the models, this is soon followed by complete loss through sublimation. We hypothesize that some of this ice has been buried and preserved by aeolian sand sheets that prevented complete sublimation. Similar sand mantles extending for 10s of km have been observed on top of thick water ice [11], and within the lowermost NPLD [5]. Therefore, we argue that ice caps dating to Middle to Late Amazonian are not necessarily lost during high obliquity periods, but 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 cavi an important water ice reservoir, potentially the third largest on Mars after the two PLDs.

**Newly mapped extent 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 km² (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.

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 layers 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 [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 proto-Gemina Lingula region. 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.

**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 Rupes Tenuis unit? Does this unit also record past polar ice accumulation events?

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