SAND, SUN, ICE, WIND, DUST, AND TIME: AN UPDATED HISTORY OF PLANUM BOREUM, MARS.

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Introduction: Our understanding of the composition and geologic history of Planum Boreum (PB), Mars has grown extensively due to a wealth of data from recent and ongoing missions including Mars Reconnaissance Orbiter (MRO) and Mars Express (MEX), building on an extensive compilation of previous studies [1]. In particular, radar stratigraphy obtained by the Shallow Radar (SHARAD) [2] on MRO has provided a new context for interpreting high-resolution imagery, morphology, and spectral data. This review synthesizes our current understanding of the long-term evolution of Planum Boreum, starting with the cavi portion of the basal unit (BU) and moving through the overlying north polar layered deposits (NPLD), with significant updates since a review at the Sixth Mars Polar Science Conference [3]. Since then, advances have been made in constraining the composition and structure of the cavi, its relationship to earliest NPLD deposition, and the dust content of layers in the NPLD that give rise to radar reflections.

Cavi: The BU, an informal designation, consists of the Rupēs unit overlain by the aeolian cavi unit [1]. The cavi, long considered to be a roughly 50/50 mixture of sand and ice with aeolian cross-bedding, has been shown to contain transitional aeolian parasequences that stack towards a pure water–ice depositional environment, allowing the cavi and NPLD to be interpreted as a single, orbitally-forced sequence [4]. New SHARAD mapping and analyses have determined that cavi internal structure at the highest latitudes likely consists of thick (tens of meters) layers that alternate between nearly pure ice and more concentrated sand, likely dune fields that preserved the ice through periods of higher insolation [5]. The ice layers are interpreted as remnants of former polar caps predating the NPLD [5]. Furthermore, both the extent of cavi and its bulk ice content are both larger than previously thought, ranging from nearly 90% water ice at the highest latitudes observed, to approximately 60% in Olympia Planum based on SHARAD analyses [5], with bulk ice content confirmed by MRO gravity studies [6].

Cavi to NPLD: The transition from cavi to NPLD is gradational [1], and new mapping with SHARAD shows that the uppermost cavi and lowermost NPLD were in fact contemporaneous at different locations within PB [7], supporting an earlier interpretation based on outcrops alone [1]. This cavi-to-NPLD transition took place on a surface that was highly nonuniform and asymmetric about the pole [8,9], although BU morphology and structure are contiguous with that of Olympia Undae. Earliest accumulation of NPLD was likewise nonuniform, with a separate accumulation center forming a proto Gemina Lingula [7].

Composition: While bulk composition of the NPLD has been constrained by radar to be ~95% water ice [10], subhorizontal radar reflectors within the NPLD have long been assumed to arise from stratigraphic variations in dust content that modulate the dielectric properties of the layers [11,12]. Recent results combining SHARAD data with modeling have shown that this is a reasonable assumption, and reflection strength is highly sensitive to layer thickness. Observed reflectors in the uppermost NPLD are consistent with so-called “marker beds” that are meters thick [13]. Furthermore, constraints on dust content and thickness for individual layers can be obtained from SHARAD using this methodology [14], with vertical profiles and geographic distributions possible. Typical layer thicknesses resulting from this analysis are 2 - 4 m, and dust contents lie the 10% - 50% range [14]. This provides a new way to test paleoclimate models that grow NPLD with dust incorporated into the dynamics [e.g., 15].

Flow and Melt: Although ice flow has previously been proposed as a significant factor in shaping the gross morphology of Gemina Lingula [16-17], the analysis of internal radar stratigraphy including a 3-dimensional flow model [18] does not support that interpretation, nor does the presence of buried troughs within Gemina Lingula [19]. Likewise, there is no evidence yet identified in radar stratigraphy to support basal melting of NPLD from enhanced geothermal flux, or brittle deformation on large scales. Furthermore, sedimentary structures indicate that aeolian processes have played a dominant role throughout NPLD history, both within the basal unit [4] and in the uppermost NPLD during the onset and evolution of the spiral troughs [20-22].

Spiral Troughs: The spiral troughs of the NPLD are unique windows into surface/atmosphere interactions that exert strong controls on the morphology of Planum Boreum. Stratigraphic structures indicate the first appearance of the spiral troughs out halfway through NPLD accumulation, and their subsequent migration concurrent with new deposition [20]. This finding and the unique inter-trough stratigraphy supports an origin with katabatic winds as a critical driver [21]. All major characteristics of the troughs can be explained in the context of repeating katabatic jumps, otherwise known as cyclic steps [22], wherein lateral transport of material is an important process.

Accumulation History: Stratigraphy within the NPLD indicates the dominance of processes that are sedimentary in nature; therefore we use large-scale stratigraphic unconformities to define the major depositional sequence boundaries. At least three large-scale depositional sequences are preserved, each of which is bounded by an erosional event. The lower of these depositional units was mapped across Planum Boreum to reveal the early appearance of Chasma Boreale [23]. A higher unconformity found in the saddle region east of Chasma Boreale indicates a later period of regional erosion. In both instances, the lateral extension of reflectors bounding these unconformities are conformal under the main lobe of Planum Boreum, indicating that these erosional epochs may have been relatively short-lived and limited in extent. Evidence does, however, exist for significant retreat of the NPLD margin in the region of Gemini Scopuli prior to the most recent episode of deposition.

Overall, the stratigraphy indicates a relatively simple accumulation history, with continuous deposition in the center of the deposits and either two or three large- scale (but relatively brief) hiatuses interrupting deposition and creating erosional surfaces in the lower latitudes of Planum Boreum. The youngest spiral troughs initiated above the upper unconformity, but some are older, indicating that conditions required for trough formation are not necessarily connected to erosion events or sudden changes in accumulation.

Links to climate modeling: Paleoclimate modeling can link changes in orbital parameters to atmospheric conditions and surface temperatures in order to predict the temporal and spatial patterns of ice accumulation. One such model, (MAIC-2; [24]), estimates global surface-ice mass balance for the past 10 Myr. This model uses as input the periodic changes in insolation derived from predictions of Mars' orbital parameters [25]. Due to mean obliquities higher than ~35° prior to ~5 Ma, large polar ice deposits do not accumulate prior to ~4 Ma in this model. The model was modified to include only the volume of NPLD as mapped using SHARAD data. Significantly, the model predicts three large-scale erosional events that interrupt relatively continuous accumulation in the past 4 Ma, largely consistent with the accumulation and erosional events observed in the radar stratigraphy.

The most recent of these events was further studied by mapping a stratigraphic unconformity in the uppermost NPLD [26]. Following a depositional hiatus (and possible erosion), an increase in accumulation is evident from steeper trough migration paths [20] and layering that drapes the entire surface. This event is most confidently tied to the most recent shift in obliquity at 370 ka [25, 27]. The quantity of ice accumulated after this unconformity (including an equivalent package at the south pole) is within a factor of two of that predicted to have moved from the mid-latitudes to the poles poles [26], so for the first time we are beginning to match observations of ice accumulation to global climate models for specific periods in Mars' past.

Conclusions: The stratigraphy of Planum Boreum contains a rich record of deposition, erosion, aeolian processes and compositional variations. Significant challenges remain to fully link the observations to climate modeling, but the observed radar stratigraphy is consistent with a simple model predicting northern polar ice growth since 4 Ma. Aeolian processes have exerted a strong role in shaping the surface, from the cavi/NPLD transition until the present day where we can observe surface/atmosphere interactions at work.

The dynamics of dust entrainment, transport, and deposition are important areas of future work to further refine the correlation between modeled ice deposition and observed layer stratigraphy at the outcrop level [15, 28]. Accumulation patterns observed with radar can provide further constraints for mesoscale climate modeling of ice deposition and ablation in the north polar region [29] and may allow for the interpretation of radar reflectors throughout the NPLD as a climate signal linked to orbital forcing, which could yield the next leap in our understanding of polar processes on Mars.

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