ORIGIN OF THE MARTIAN NORTH POLAR BASAL UNIT AND IMPLICATIONS FOR POLAR GEOLOGIC HISTORY. K. E. Fishbaugh[1] and J. W. Head III[1], [1]Brown University, Dept. of Geological Sciences Box 1846, Providence, RI 02912, kathryn_fishbaugh@brown.edu, james_head_III@brown.edu.

Introduction: A newly discovered basal unit (BU) [1,2,3], lying stratigraphically between the Hesperian-aged Vastitas Borealis Formation and the north polar cap (consisting of layered deposits, Apl, and purer ice on top, Api), may represent the transition between formation of the VBF and Apl and thus could provide important insight into 3 billion years of "missing" north polar history.

We have expanded upon the previous work done by [3] and [4] in describing the main features of the BU using primarily MOC images and MOLA data, and have analyzed detailed outcrops and the unit's distribution. These results are summarized below and in [5,6]. Here, we examine four possible initial formation mechanisms for the BU: 1) outflow channel/oceanic deposits, 2) basal ice, 3) paleo-polar cap (mentioned by [2], and 4) eolian deposit [3]. Finally, we discuss what the age of the BU may be.

Main Characteristics of the BU: Any formation theory and post-formation modification must explain the following major characteristics of the BU: 1) generally banded with alternating light and dark, patchy (on the 100s m horizontal scale) layers with varying thicknesses and amounts and types of erosion, 2) likely significant erosion at the upper contact with the Apl, 3) likely major source of the polar dune seas [3,4], 4) differential erosion of layers, pitting, residual mesas, and eolian erosion of many layers, 5) erosion of the BU and deposition onto the early Apl, 6) confirmed existence only within bounds of the current polar deposits and the Olympia Lobe, 7) a broad, mounded shape, with a thickness of about 600 m, covering an area including the Olympia Lobe and stretching to Chasma Boreale, and comprising about 7% of the volume of the Vastitas Borealis Formation as estimated by [7].

Deposition of outflow channel/oceanic deposits: Sediment brought by outflow channels [8,9] and a possible former standing body of water [10] could provide sand and ice-rich material for the BU. Water from the outflow channels could have formed numerous standing bodies of water which froze. These ice and sand-rich deposits could then have sublimated, with the water being redeposited at the pole to form part of the north polar cap [11]. This cap would then preserve any sediments beneath it.

There are several major problems with forming the BU via this type of sedimentation. 1) The BU does not lie within the lowest part of the basin; furthermore, there is apparently little to no evidence for the existence of the BU within the rest of the North Polar Basin, especially the lowest area south of Chasma Boreale. Therefore, if the basal unit represents the approximate former thickness of outflow channel/oceanic sediments, then a large amount of material must have been removed from the rest of the north polar basin and deposited elsewhere. Where is that material now? 2) According to [12], as an ocean begins to freeze on top and loses heat to the cryosphere, convection cells modified by Coriolis forces would develop. This may lead to a circumpolar current, but by this time, there is little sediment left in suspension to be concentrated near the pole. In addition, sediment from outflow channels, if not deposited in an ocean, would end up near the channel mouths, not at the pole. 3) Details of the layering within the BU are also not consistent with formation by oceanic/outflow channel sedimentation. Following the scenario described by [12], the heavier sediments would settle out of suspension first, and the lighter ones would be entrained by the turbulent convection, settling out later. Yet, we see alternating layers of light and dark sediments with different thicknesses and material properties rather than a gradual progression. Even dust storms would be prevented from supplying the lighter layers once ice covered the ocean surface. In addition, we see evidence of varying amounts of eolian erosion which has been exhumed by exposure of overlying layers. Since eolian erosion can't occur under water, it is unlikely that these layers were formed in an ocean.

Basal Ice: *Finnegan et al.* [13] suggested that the basal unit may consist of basal ice. On Earth, some glaciers and ice sheets have one or more layers of basal ice which can range in thickness from a few millimeters to tens of meters. Basal ice can have up to greater than 50% sediment by volume and has structural, chemical, and isotopic characteristics distinct from the overlying, less sediment-rich ice layers [14]. The contact between the basal ice and overlying ice is often quite sharp. Terrestrial basal ice looks much like the BU. Basal ice can form by one or more of the following means [e.g.,15,16]: 1) Regelation or congelation, 2) net adfreezing, 3) entrainment of pre-existing ice, or 4) mixing and crevassing.

Since the BU is so thick and widespread beneath the cap, net adfreezing seems the most likely mechanism for creating such a basal ice sequence, rather than the other, more local processes. The distribution of the unit (being associated exclusively with the cap) and the irregular layering, and the sharp appearance of the contact are consistent with this mode of origin.

However, there are several difficulties with creating basal ice in the Mars polar environment. 1) A large amount of meltwater is necessary since the BU is so much thicker than any terrestrial basal ice (up to 100x). Yet the formation of the BU pre-dates Chasma Boreale, thought to be formed partly by outflow of meltwater [16,17], since the chasma walls expose the BU within them. 2) For regelation, there would have to be a means of providing small amounts of water continually or larger amounts of water cyclically. 3) Formation of the BU as basal ice does not explain how the sediment got there in the first place.

Since its initial creation, the upper portion of the BU may have been frozen on to the polar cap as a basal ice layer, and in this case would need to be taken into account when modelling the rheology of the cap. Interestingly, while basal ice on Earth is commonly deformed due to overburden stress and ice flow, we have seen no definite evidence for significant deformation in the BU; cold temperatures and high sediment content may prevent this.

Paleopolar Deposit: While not expounded upon in detail, according to [2], the BU represents a "an earlier phase of north polar deposits" (pg. 30). We interpret this to mean that the unit consists of an earlier phase of polar cap deposition and find three major observations lend support to this idea: 1) the fine-scale layering observed in the BU, 2) the exclusive association of the BU with current polar deposits (and possibly with remnants of former extents of polar deposits), and 3) the broad, mounded shape of the unit.

In this case, the BU/Apl contact represents an unconformity in polar cap deposition and an unknown amount of erosion during which time the environmental conditions changed such that one of two things happened. 1) The amount of atmospheric dust decreased (possibly suddenly) and polar deposition continued with a lower sediment/ice ratio. 2) Large-scale erosion of earlier polar cap deposits resulted in a gradually increasing sediment/ice ratio as the ice sublimated leaving sediment behind. If the BU were formed in one of these two ways, then the associated dunes would have be composed of sand-sized aggregates of dust particles [18] since the atmosphere cannot hold sand in suspension.

If the first scenario prevailed, a mechanism for deposition of greater amounts of sediment with ice needs to be invoked to explain the higher sediment/ice ratio of the BU as compared to the Apl. The atmosphere would need to be thick enough to support suspension of more dust so that they could then be deposited in layers with the accumulating snow and frost. Yet the atmosphere could not be so thick as to increase the greenhouse effect to the point where the sublimation rate exceeds the deposition rate. Why so many layers pinch-out laterally within a few kilometers is also puzzling. One might expect more laterally continuous layers in a paleopolar cap (as in the Apl).

Each BU layer could represent the lag left behind by one sublimated polar cap. *Jakosky et al.* [19] calculated that at high obliquities (60°), the current cap, ignoring its particulate content, could completely sublimate in about 10^4 years. However, as the ice sublimated, a lag from the admixed particulates would remain. Since very thin layers of dust can significantly hinder sublimation, the dust may have to be removed so as to allow more Apl layers to sublimate. Additionally, the polar cap would have had to sublimate completely each time a BU layer is created. If only partial sublimation occurred, then we would expect to find lenses of basal unit material spread stratigraphically throughout the Apl, and we have found no evidence of such lenses thus far.

Eolian Deposit: According to [3], the close geographical association of the BU with dunes indicates that it accumulated as an eolian deposit. *Anderson et al.* [20] have modeled the distribution of sand resulting from saltation, taking into account the Mars general circulation model of [21]. They find that sand from northern mid latitudes would migrate to the north pole, creating the north polar erg within 50 Ky. Our observations also support an eolian origin for this deposit. While there are a few possible problems with this origin, we feel that they are for the most part explainable.

1) *Edgett et al.* [4] have found no evidence for the cross-bedding one may expect if the BU was a major dune sea. However, most classic examples of terrestrial cross-bedding in sandstone are exposed in near vertical outcrops. The BU, on the other hand, is exposed in shallower-sloped outcrops, making the classic cross-hatching pattern difficult to recognize. However, the BU layers have been deposited in a patchy, overlapping fashion as expected from dune deposits and from a shallow slope exposure of cross-bedding. In some locations, this "patchiness" is visible on a scale close to that of individual dunes.

2) The unit is likely the major (if not the only) source for the northern circumpolar ergs. A sandy deposit supplying these sand seas is a much simpler explanation than requiring formation of filamentary sublimation residue [18] from the polar layered deposits to form the dunes, a hypothesis put forth when the existence of the basal unit was unknown. 3) The unit has been found only in the northern region, the location where migrating sand dunes would be trapped [20]. However, a southern BU could be unexposed or manifested differently. 4) *Edgett et al.* [4] have also noted the presence of semi-crescentic patches of material being exhumed near the edges of the polar cap which may be paleodunes buried in the BU (see their Fig. 4). 5) The other hypotheses of origin discussed above require much more complexity in overcoming problems with these scenarios than does the eolian hypothesis.

Assuming a sufficient sand supply, at the rate estimated by [20], to create 10 BU layers would take about 500 Ky, about 0.02% of the duration of the Amazonian Period. While the basal unit may be hundreds of meters thick, eolian sandstones of the Colorado Plateau are 3500 m thick in total [22], though some of this thickness is due to deposition in a basin. It is important to note that some of the original BU deposits may not be preserved in the strata. On Earth, often only the lower portions of the deposit are preserved [22].

Since the BU outcrops can have slopes near 40° and since more than 2.5 km of ice rests on top of the BU, cementation seems likely. As sand was accumulating (dark layers) it may have incorporated ice, though the physical mechanism by which this occurred remains a question. In this sense, the BU could be a "paleopolar deposit" which consisted of eolian deposited sand, and atmospherically deposited water and dust. *Byrne and Murray* [3] speculate that changes in obliquity could ensure that differing amounts of ice were incorporated into the different BU layers.

The thermal inertia of the north polar dunes is much lower than the dark dunes at lower latitudes, suggesting that their bulk density is lower [18]. This decreases the likelihood that the sand migrated from elsewhere, although [3] warn that high local slopes and the high emission angle of the Viking observations could complicate interpretation of thermal inertia data.

Age of the BU: Stratigraphically, the BU rests on top of the Vastitatas Borealis Formation and below the Apl and thus has an age of Early to Mid/Late Amazonian (0.1 – 3 By). It is difficult to absolutely date the BU itself since so little of its surface area is exposed. We have counted all craters greater than 5 km in diameter in areas which we consider to be candidate exposed BU surfaces and find that there are fewer than 5 craters of >5km diameter per $1x10^6$ km^2. This gives a crater age of Middle to Upper Amazonian [23]. *Tanaka et al.* [24] include more outlying deposits within Vastitas Borealis as part of the basal unit (deposits which we have not identified as part of the BU) and therefore obtain a higher crater count and older age of Early Amazonian. It is important to note that we do not know how many BU craters are buried beneath the Apl.

Conclusions: Given the observations that we and others [3,4] have made of BU characteristics, we feel that eolian deposition is the simplest, easiest way to form the north polar basal unit, supporting earlier conclusion of [3]. During the Early to Mid Amazonian, sand and dunes migrated from lower latitudes [20] and were trapped at the north pole. Ice was deposited simultaneously. The dunes thus froze, forming patchy layering. The ubiquitous planetary dust collected on top until another episode of dune migration took place, and the cycle repeated. The cause of cyclicity is unknown. It may have to do with changes in global wind patterns controlled by changes in insolation or with the periodic replenishment of the sand supply at lower latitudes (On Earth, cyclicity can be caused by variations in sand supply related to such events as glacial cycles [25]). A link with orbital parameters and thus with changing wind patterns could be modeled to test the likelihood of forming the entire thickness of the BU and the total number of layers. Since, in the absence of a large polar basin, migration of sand toward the southern pole results in trapping within craters along the way, the southern pole should not act as a trap for migrating sand [20].

Implications: Our observations and conclusions lead us to modify the scenarios of north polar Amazonian history discussed in [26]. A predominantly eolian deposit in this region implies that there was a time (enough for accumulation of the entire BU) in the Early to Mid Amazonian when the type of polar deposits we see today were not forming. Could the polar deposit accumulations have looked much different in the Early Amazonian? Ice incorporation into the BU may have been the Early to Mid Amazonian manifestation of polar cap formation. With copious amounts of sand being deposited at the same time, the older polar deposits would appear much darker. The erosional unconformity between the BU and Apl is consistent with a Late Amazonian Apl age. However, a possible reason for Early to Mid Amazonian climate conditions that precluded classic cap formation and allowed major dune migration is unknown.

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