HELLAS BASIN RIM AND WALL GLACIATION IN THE LATE NOACHIAN: ENHANCED FLOW, BASAL MELTING, WET-BASED GLACIATION AND EROSION, AND GENERATION AND FATE OF MELTWATER IN THE ABLATION ZONE. J. L. Fastook[1], J. W. Head[2], K. Scanlon[2], D. K. Weiss[2] and A. M. Palumbo[2] [1]University of Maine, Orono, ME, 04469, USA, fastook@maine.edu, [2]Brown University, Providence, RI, 02912, USA, James_Head@Brown.edu.

Introduction: In the process of exploring climate scenarios that matched the distribution of the Dorsa Argentia Formation **[1,2]** several were found that produced climates with significant accumulation zones around the rim of the Hellas Basin, with ablation zones in the interior and on the floor of the basin. Identification of glacial features in and around Hellas has been controversial since Viking times, with some arguing for a glacial scenario dominated by large continental-scale ice sheets **[3]**, while others see evidence for ice-covered lakes **[4]**, and still others credit eolian processes for producing the landscape features **[5]**. Radar data show the current existence of debris-covered glaciers in the region **[6]**.

One GCM scenario for a glaciated early Mars is shown in Fig. 1A. Using UMISM (see below) adapted for Mars **[7-12]** we investigate the behavior of ice flowing down the steep slopes from the large accumulation zone grid-south of Hellas, where accumulation rates are predicted to be several cm/yr.

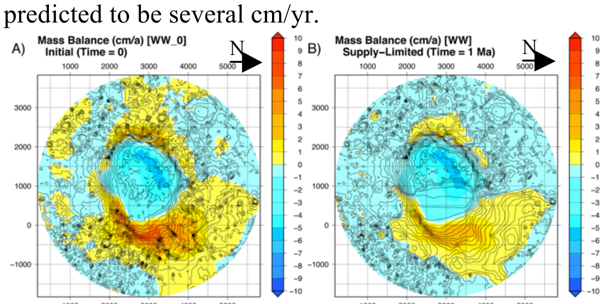

Figure 1: Mass balance distribution from a GCM [1,2] (600 mbar CO_2 atmosphere and 42° obliquity) showing accumulation zones around the rim of Hellas Basin, with an ablation zone in the deep interior. A) Directly from the GCM. B) After the "supply-limit" of 1X current water inventory is reached. Grid-south is East.

Results: UMISM is run in a "supply-limited" mode, where only a finite amount of water is available to build ice sheets. This is done by separating each individual accumulation or ablation rate into positive and negative components (the net sum of these two may be either accumulation or ablation), and reducing the positive component, while retaining the negative component, as ice volume approaches the supply limit. This generally results in a shrinkage of the accumulation areas, and can be seen in Fig. 1B for a 1X supply limit.

Runs of 1 Ma are generally sufficient for the resulting ice sheet to reach an equilibrium configuration. Fig. 2 shows profiles crossing Hellas from grid-south to grid-north (E-W) bisecting the basin. For reference, the grid origin is at the South Pole, with positive-y axis along the 0° longitude and positve-x axis along the 90°E longitude. The 4 lines show profiles for 0.5X (thinnest profile), 1X, 2X, and 5X (thickest profile), the last being more than is currently estimated for the early water budget of Mars **[13]**.

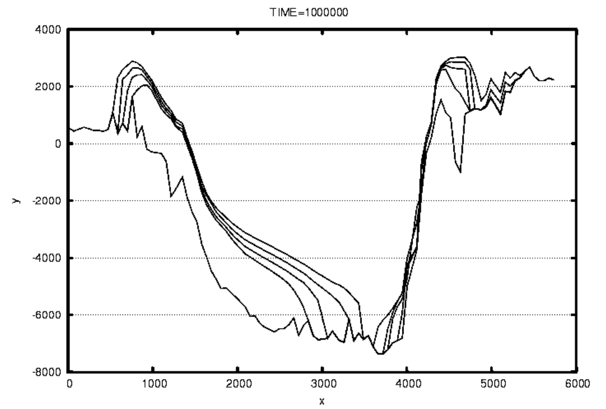

Figure 2: Profiles from grid-south to grid-north (E, left; W, right) across the center of Hellas Basin. The least thick profile is for 0.5X, the thickest for 5X, with 1X and 2X between.

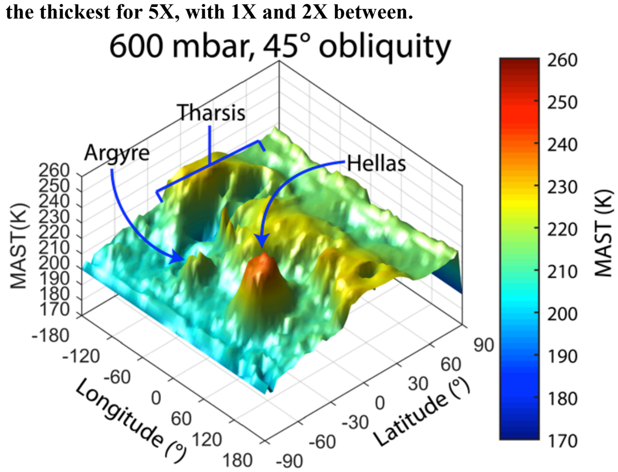

Figure 3: GCM results [23] for mean annual surface temperature (MAST) of Mars from [14] for a 600 mbar CO_2 atmosphere and 45° obliquity.

Of interest is the bed condition. Mean annual surface temperatures from the GCM for the bottom of Hellas are relatively warm, on the order of 240 K, while the rim is close to 210 K (Fig. 3). We adopt a surface heat flux of 45 mW/m^2 for the floor of Hellas following **[14]** on the basis of heat flux models of **[15, 16]**, and adopt a typical Late Noachian average heat flux of 50 mW/m^2 for the walls and 55 mW/m^2 for the rim and plateau from **[15, 17-19]**. With shear heating contributing on the steep slope, much of the bed reaches the melting point, water is produced, and enhanced flow due to sliding can occur.

Fig. 4 shows A) the computed basal melting rate and B) the resulting ice flow velocities for the 2X supply limit. Of note are the channelized flow features that follow valleys down the basin wall. With the warmer surface temperatures in the base of the basin, much of it is at the melting point as well.

Results for the 0.5X, 1X, and 5X case are similar. The thick ice at the base of the basin wall is melted at the bed, and there are regions of fast flow following topographic depressions down the basin walls. The contribution due to shear heating is significant due to the steep surface slopes producing a high driving stress. The possibility exists that some of the features apparent on the surface today may have been carved earlier in part by the flowing ice.

Conclusions: On the basis of this analysis of the accumulation and flow of ice on the rim of the Hellas Basin in a Late Noachian Cold and Icy Highlands context, we conclude:

1. On the basis of the GCMs **[1, 2]**, significant ice accumulation occurs on the eastern rim of the Hellas Basin.
2. The steep slopes of the Hellas Basin walls induce significant flow down into the basin.
3. Slopes are sufficiently steep that with shear heating included, much of the bed reaches the melting point, and wet-based glacial conditions occur.
4. Wet-based conditions further enhance flow velocities into the basin.
5. Wet-based conditions along the walls would have caused substrate erosion, and may be partly responsible for the missing mass and unusual shape of the Hellas Basin in this direction.
6. If wet-based glaciation and basal erosion occurred and persisted for a long duration, significant material may have been removed from the basin wall and deposited on the basin floor.
7. A wet-based glacier would have proceeded to flow out onto the basin floor and glaciation may have influenced a significant part of the floor, depending on supply limitations.
8. The Hellas and Argyre basins are the only locations where basal melting occurred in simulations without invoking much greater supply limits, very warm surface temperatures, or very high geothermal fluxes.
9. Basal meltwater could have readily drained onto the basin floor and may have formed a lake or sea; total volume of meltwater is supply and temperature limited.
10. Despite the relatively higher atmospheric surface temperature on the deep floor of Hellas **[1, 2]**, a lake surface on the floor of Hellas would have been above the melting temperature for only ~2% of the year, and thus would have been primarily ice covered.
11. The hydrological system is still predicted to be horizontally stratified (shear heating itself on the walls does not melt the cryosphere), except possibly in locations of thickest ice/basal melting on the eastern basin floor, where ice would be thick enough to remove the underlying cryosphere if ice remained for a sufficient duration.

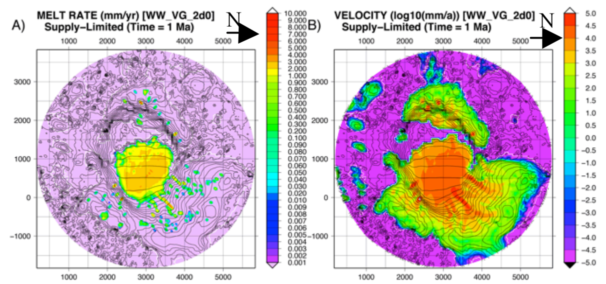

Figure 4: A) Computed basal melt rate with 55 mW/m^2 on the basin rim and plateau, 50 on the basin walls, and 45 on the basin floor, and B) Log$_{10}$ of ice flow velocities in mm/yr.

12. The emplacement of Hesperian ridged plains may have been on top of ice deposits and may have produced significant contact and deferred melting **[20]**.
13. Buried glacial and frozen lake ice may be the layer seen deforming to produce diapiric-like structures on the basin floor **[14, 21, 22],** referred to as the honeycomb terrain. The honeycomb terrain is believed to have formed prior to the emplacement of the Hesperian-ridged plains, between ~3.7 Ga and 4 Ga **[21]**, and may offer a constraint on the timing of a circum-Hellas glaciation.
14. If features within Hellas are shown to be related to Noachian top-down glacial melting, and such features are not present in Argyre, their presence would favor the Noachian climate to be ~220 K MAT because Hellas is the deepest impact basin. With higher MAT, shallower basins (e.g., Argyre) could also exhibit peak annual temperatures conducive to top-down melting.

References: **[1]** Scanlon, 2016, Ice Sheet Melting Throughout Mars Climate History: Mechanisms, Rates, and Implications. *PhD thesis*, Brown University, Providence, RI; **[2]** Scanlon et al., 2016, *LPS47*, #1315; **[3]** Kargel & Strom, 1992, *Geology*, 20,3; **[4]** Moore & Wilhelms, 2001, *Icarus*, 154, 258; **[5]** Tanaka & Leonard, 1995, *Journal of Geophysical Research*, 100, 5407; **[6]** Holt et al., 2008, *LPS39*, #2441; **[7]** Fastook & Head, 2014, *Planetary and Space Science*, 91, 60; **[8]** Fastook & Head, 2015, *Planetary and Space Science*, 106, 82; **[9]** Fastook et al., 2011, *Icarus*, 216, 23; **[10]** Fastook et al., 2013, *Icarus*, 228, 54; **[11]** Fastook et al;., 2008, *Icarus*, 198, 305; **[12]** Fastook et al., 2012, *Icarus*, 219, 25; **[13]** Carr & Head, 2015, *Geophysical Research Letters*, 42, 726; **[14]** Weiss & Head, 2017, *Icarus*, 284, 249; **[15]** Montési & Zuber, 2003, *Journal of Geophysical Research*, 108(E6), 5048; **[16]** Plesa et al., 2016, *Journal of Geophysical Research (Planets)*, 121; **[17]** McGovern et al., 2004, *Journal of Geophysical Research*, 109(E7), E07007; **[18]** Solomon et al., 2005, *Science*, 307, 1214; **[19]** Ruiz et al., 2011, *Icarus*, 215(2), 508; **[20]** Cassanelli & Head, 2016, *Icarus*, 271, 237; **[21]** Bernhardt et al., 2016a, *Icarus* 264, 407; **[22]** Bernhardt et al., 2016b, *Journal of Geophysical Research* 121 (4), 714; **[23]** Horan and Head, 2016, *LPSC47, #2394*.