

A WARMER ATMOSPHERE ON MARS NEAR THE NOACHIAN-HESPERIAN BOUNDARY: EVIDENCE FROM BASAL MELTING OF THE SOUTH POLAR ICE CAP (DORSA ARGENTEA FORMATION). J. L. Fastook¹, J. W. Head², D. R. Marchant³, F. Forget⁴, J.-B. Madeleine⁴. ¹Climate Change Institute and Computer Science, Univ. Maine, Orono ME 04469 (fastook@maine.edu), ²Dept. Geol. Sci., Brown Univ., Providence RI 02912, ³Dept. Earth Sci., Boston Univ., Boston MA 02215, ⁴LMD, CNRS/UPMC/IPSL, Paris, France.

Summary: Currently, and throughout much of the Amazonian, the mean annual surface temperatures of Mars are so cold that basal melting does not occur in ice caps and glaciers and they are cold-based. The presence in the south circumpolar Dorsa Argentea Formation of extensive and well-developed eskers, sediment-filled subglacial meltwater channels, is evidence that basal melting and wet-based glaciation occurred in the south circumpolar region near the Noachian-Hesperian boundary. We employ glacial accumulation and flow models to distinguish between melting from bottom-up heat sources (elevated geothermal fluxes) and top-down heat sources (elevated atmospheric temperatures). We show that under current mean annual south polar atmospheric temperatures (-100°C) and Noachian-Hesperian heat fluxes ($45\text{-}65\text{ mW/m}^2$), south polar ice accumulations remain cold based. In order to produce significant basal melting at these typical heat fluxes, the mean annual south polar atmospheric temperatures must be raised from today's temperature (-100°C) to the range of -50 to -75°C . This mean annual polar atmospheric temperature range implies equatorial and mid-latitude mean annual temperatures in excess of the melting point of water, perhaps explaining the concurrent development of valley networks and open basin lakes in these areas. This treatment provides an independent estimate of elevated surface temperatures near the Noachian-Hesperian boundary of Mars history.

Introduction: Current polar layered deposits [1], earlier Amazonian mid-latitude glacial deposits [2] and tropical mountain glaciers [3] all appear to be cold-based, and not to involve basal melting except where concurrent sub-glacial volcanic eruptions melted the ice [4,5]. On the other hand, the Late Noachian-Early Hesperian south circumpolar Dorsa Argentea Formation (DAF) [6] (Fig. 1) contains features interpreted to be indicative of a regional ice-rich deposit that underwent some basal melting [7-12] at that time [13].

What conditions could have led to the formation and evolution of an ice rich circumpolar deposit such as the Dorsa Argentea Formation in early Mars history? On Mars, as we know it today, water ice is expected to be less stable on average in the south polar region than in the north polar region because the global topographic asymmetry tends to favor the transport of water to the northern hemisphere [14]. Because the current atmosphere is very thin, the temperature is controlled by radiative balance rather than by the altitude of the surface, so the influence of topography is indirect. Current climate models suggest that ice would only accumulate at

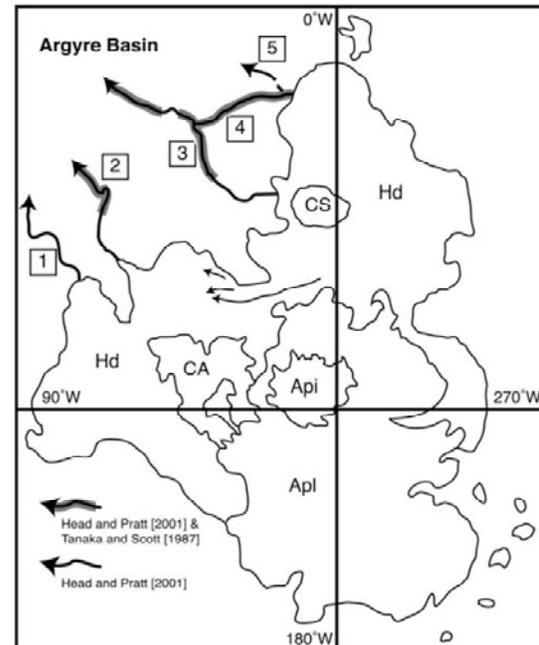


Figure 1. Sketch map [7] showing location of main eskers (arrows inside DAF) and channels draining from DAF mar-

the south pole when the season of the perihelion favors a southern summer significantly colder than in the North [15]. This may explain why the Amazonian south polar layered deposits are older than the north polar layered deposits. If the atmosphere was thicker during the Noachian and Hesperian eras than today, then conditions at the south pole may have been very different. For example, above a few hundreds Pascals, surface temperature distribution would behave much more like on Earth, with high altitude regions significantly colder than lower plains because of adiabatic cooling of the atmosphere [16-17]. Within this context, it is likely that the high southern latitudes would have become a cold-trap where ice would tend to accumulate and form a large ice cap, both because of their latitude and their altitude. It is also possible that the amount of water involved in the atmospheric water cycle was larger than today, and that consequently more water was available to form an ice cap [16-17]. For example, valley network activity, suggestive of flowing streams and a "warmer and wetter" early Mars [18-19], characterized the highlands at the end of the Noachian and into the Hesperian. The active water cycle [19] implied by these interpretations may have been able to transport large amounts of water into the southern polar region in the Late Noachian and Hesperian.

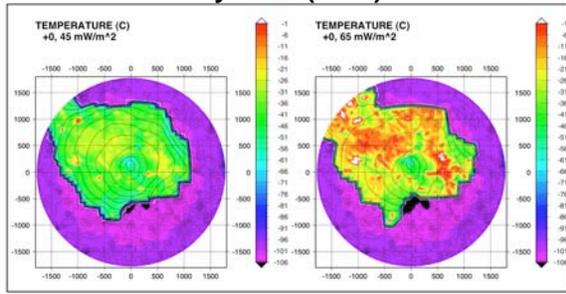


Figure 2. Calculated basal temperatures for 45 and 65 mW/m^2 using present-day surface temperatures.

Also observed in the DAF are eskers [7-11], sediment-filled subglacial meltwater channels, and thus evidence that basal melting and possibly wet-based glaciation occurred. Are these features related to top-down melting associated with elevated atmospheric temperatures, or are they related to bottom-up heat sources related to local and regional elevated geothermal fluxes? We first test the hypothesis that they could be related to bottom up melting due to enhanced geothermal fluxes linked to early thermal evolution, and that sufficient ice accumulated to raise the global melting isotherm to the base of the ice sheet. We then assess what atmospheric surface temperatures would be required to ensure basal melting.

Noachian-Hesperian Geothermal Fluxes and Ice Accumulation: Using data from [20-21] we adopt a geothermal flux of 45-65 mW/m^2 for a range appropriate for this time period. We then employ the basic assumption that the CO_2 atmosphere was thicker at this point in the history of Mars (see above), and that ice was preferentially accumulating in the south circumpolar region. We use typical ablation rates with added accumulation centered on the pole and a synthetic climate that will produce a large south circumpolar ice sheet, based on the experience that has been gained by modeling recent glacial ages with the LMD/GCM [22]. Ablation is reduced by factor of 50 and maximum accumulation is 6 mm/yr.

Results: Using current mean annual south polar atmospheric temperatures (-95 to -110°C) and the Noachian-Hesperian heat fluxes (45-65 mW/m^2) described above, south polar ice accumulations remain cold based. Fig. 2 shows calculated basal temperatures for the ice sheets grown in our synthetic climate for both 45 (left) and 65 (right) mW/m^2 . Surface elevation contours are shown at 500 m intervals. Even with the higher geothermal flux all but a few deep holes are 15°C or more below the melting point. In order to produce significant basal melting even at this high heat flux, the mean annual south polar atmospheric temperatures must be raised from today's temperature by 25°C , to the range of -70 to -85°C (Fig. 3, left). To obtain significant melting for 45 mW/m^2 the temperature must be raised by 50°C , to the range of -40 to -60°C (Fig. 3, right). At this point, basal melting will start to take place beneath the Dorsa Argentea Formation, and this will produce sufficient

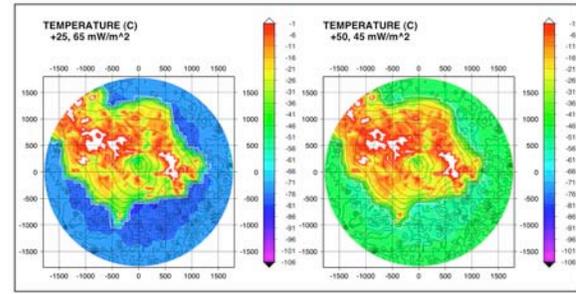


Figure 3. Basal temperatures when surface temperatures are higher than today by 25K (left, geothermal flux of 65 mW/m^2) and 50K (right, 45 mW/m^2).

melting to account for the extensive esker systems observed [7,11]. Indeed, one of the patches of calculated melting occurs close to the esker region shown by arrows in Fig. 1. Note that the surface temperatures in the circumpolar regions are still well below 0°C , and thus top-down melting is not likely to occur, consistent with geologic observations [7]. GCM results for a suite of obliquities [23] show similar polar temperature warming (25 - 50°C) as one moves from the current 23° obliquity to the extreme of 55° predicted by Laskar [24]. Excursions to such extreme obliquities are relatively brief ($\sim 100\text{Ka}$) and further would not in themselves build the observed full equilibrium icesheet of sufficient thickness to produce widespread melting at the bed.

In conclusion, the increase in surface temperatures required to explain the basal melting of a thick south circumpolar ancient ice sheet translates into higher equatorial temperatures. In fact, this annual polar atmospheric temperature range implies equatorial and mid-latitude mean annual temperatures near the melting point of water [16-17], perhaps explaining the concurrent development of valley networks [25] and open basin lakes [26] in these areas. This analysis of the Dorsa Argentea Formation provides an independent estimate of elevated surface temperatures in the mid-latitudes and equatorial regions of Mars near the Noachian-Hesperian boundary of Mars history.

References: 1) R. Phillips et al., *Science* 320, 2008; 2) J. Head et al., *EPSL* 294, 306, 2010; 3) J. Head and D. Marchant, *Geology* 31, 641, 2003; 4) D. Shean et al., *JGR* 105, 2005; 5) S. Kadish et al., *Icarus* 197, 2008; 6) K. Tanaka and E. Kolb, *Icarus* 154, 2001; 7) J. Head and S. Pratt, *JGR* 106, 2001; 8) G. Ghatan and J. Head, *JGR* 109, 2004; 9) G. Ghatan et al., *JGR* 108, 2003; 10) G. Ghatan and J. Head, *JGR* 107, 2002; 11) A. Kress et al., *LPSC 41* 2355, 2010; 13) J. Plaut et al., *Icarus* 76, 1988; 14) M. Richardson and J. Wilson, *JGR* 107, 2002; 15) F. Montmessin et al., *JGR* 112, 2007; 16) F. Forget et al., *EGU*, 2004; 17) F. Forget et al., *DPS*, 2010; 18) M. Carr, *Water on Mars*, Oxford, 1996; 19) J. Head et al., *V-B Micro* 38 ms032, 2003; 20) P. McGovern et al., *JGR* 109, 2004; 21) S. Solomon et al., *Science* 307, 1214, 2005; 22) J-B Madeleine et al., *Icarus* 203, 2009; 23) F. Forget, personal communication; 24) J. Laskar et al., *Icarus* 170, 2004; 25) C. Fassett and J. Head, *Icarus* 195, 2008; 26) C. Fassett and J. Head, *Icarus* 198, 2008.