HISTORY OF THE MARTIAN CRYOSPHERE: IS THE ICE-CEMENTED PORTION OF THE CRYOSPHERE GROUNDWATER-SUPPLY-LIMITED?

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Introduction: The present-day martian mean annual surface temperature (MAST) is below freezing at all latitudes, which produces a near-surface portion of the crust that is below the freezing point of water (i.e., permafrost, referred to as the cryosphere in the martian literature) [1]. The martian cryosphere is predicted to be a few to tens of kilometers thick depending on latitude [1]. Below the base of the cryosphere, any groundwater would be stable. Where groundwater is available, ice fills the pore space within the cryosphere; this region is known as the ice-cemented cryosphere (ICC). Groundwater will freeze directly onto the cryosphere where they are in contact. In places that the groundwater is not in direct contact with the ICC, the groundwater will diffuse upwards as vapor through the unsaturated zone and freeze onto the ICC [1]. The global ICC is the dominant thermodynamic sink for outgassed water and could thus represent a large portion of the water inventory of Mars [1-4]. Because pore ice within the ICC is sourced by underlying groundwater [1-2], evaluating the thickness of the ICC is critical to the understanding of the aqueous history of the martian subsurface. Two fundamental end-member scenarios exist for the state of the martian cryosphere and groundwater:

Thermally-limited: The volume of water in the subsurface is greater than or equal to the volume of pore space within the crust. In this case, as the planetary heat flux declines and the cryosphere freezing front advances deeper in the martian crust, the ICC grows downwards as it assimilates groundwater. The thickness of the ICC depends on the depth of the advancing freezing front.

Supply-limited: The volume of the water in the subsurface is less than the volume of pore-space within the crust. In this case, as the cryosphere freezing front advances deeper in the crust through time, the ICC will continue to grow until the supply of underlying groundwater is exhausted. The thickness of the ICC depends on the volume of water in the subsurface. At some time, the ICC will reach its maximum thickness and will not grow further as the freezing front advances. This is referred to as *ICC stabilization*.

Testing supply-limited versus thermally-limited: In order to distinguish between these two scenarios for the state of the martian cryosphere and groundwater, some knowledge on the thickness of the ICC is required. If the thickness of the ICC matches the thickness of the cryosphere predicted by Amazonian thermal models, it implies that groundwater exists below the ICC and the cryosphere is thermally-limited. If the thickness of the ICC is thinner than the predicted thickness of the cryosphere, it suggests that groundwater is not abundant in the subsurface and that the cryosphere is supply-limited. The theoretical thickness of the martian cryosphere in the Amazonian period ranges from up to ~9 km at the equator to ~10-22 km at the poles [1], but the depth to which pore-ice fills the cryosphere has remained unclear. Our recent global analysis of the layered ejecta crater populations estimated that the ICC is ~1.3 km thick at the equator and thickens to ~2.3 km at the poles [5].

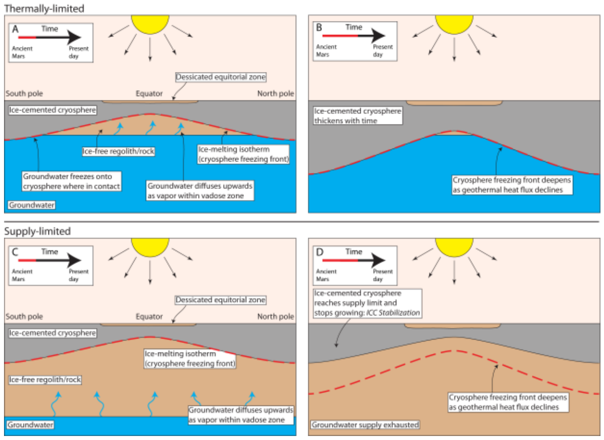

Figure 1. Schematic of the martian cryosphere (dashed red line), and the ICC (shaded in grey) for thermally-limited (top panels) and supply-limited (bottom panels) endmembers.

How does this ICC thickness estimate compare with the results of thermal models? Are these results consistent with a thermally-limited cryosphere, or a supply-limited cryosphere? If the ICC is supply-limited, when did ICC stabilization occur, and under what surface temperature, atmospheric pressure, and obliquity conditions?

In order to address these questions, we implement thermal models (following [1]) of Amazonian through Late Noachian cryosphere thicknesses for comparison with the ICC thickness inferred from the layered ejecta crater populations. We adopt surface temperatures from the results of general circulation models [6-8] for atmospheric pressures ranging from 7 mbar to 1 bar, and evaluate the best-fit cryosphere thermal models for obliquities ranging from 0° to 60° and ice melting isotherms of 273 K (pure ice) and 252 K (~23-42 wt% salt).

Obliquity: Because the obliquity of Mars varies on a 10^5-10^6 yr timescale [9], we first explore the effects of varying obliquity on the thickness of the Amazonian cryosphere (which can respond to the 10^6 yr variations; [1]). Our model results show that the R^2 values exhibit near-normal distributions around a range of surface heat fluxes for each obliquity model (Fig. 2A). It appears that the 30° obliquity (near the present day value of 25.2°) and 45° obliquity models offer the best fit to the inferred ICC thickness (R^2=0.80, 0.87), but the surface heat flux is required to be ~80-100 mW/m^2 (for 252 K and 273 K isotherms), which is a factor of ~2.5-7 too large for Amazonian estimates [10-11]. A surprising finding is that the inferred ICC thickness is far thinner than predicted by the Amazonian thermal models, regardless of the

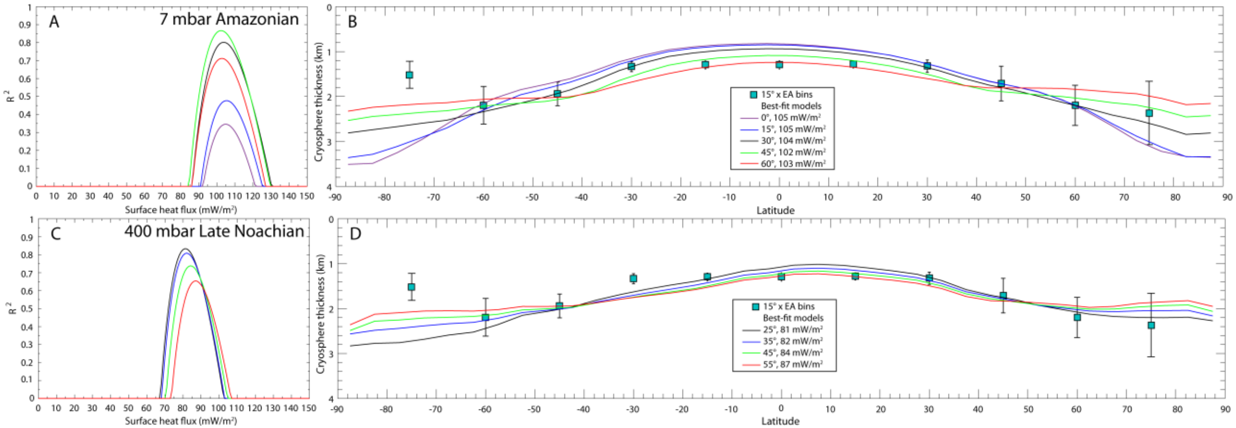

Figure 2. A) R^2 values as a function of surface heat flux for different obliquities under Amazonian conditions. (B) Best fit models from (A); green squares show the ICC thickness derived from the SLE/MLE crater excavation depths [5]. (C and D) Same as (A and B) but for 400 mbar Late Noachian conditions.

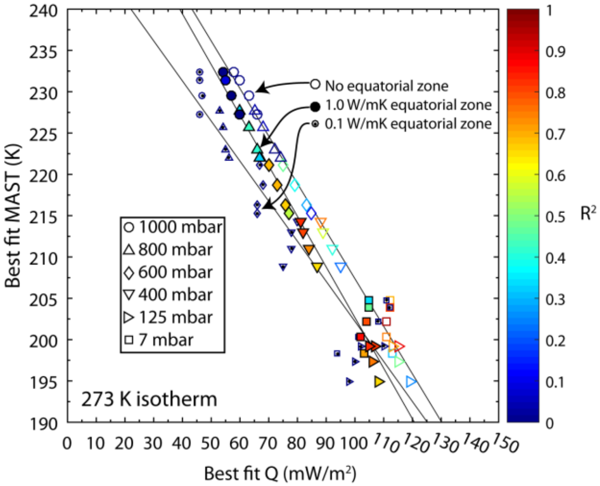

Figure 3. Mean annual surface temperature and R^2 values of the least squares fit to the different cryosphere models.

obliquity: surface heat fluxes are required to be vastly in excess of typical Amazonian heat flux estimates in order for the thermal models to reproduce the ICC thickness.

Atmospheric pressure: Mars is predicted to have had a thicker atmosphere during the more ancient Noachian period [6-8, 12]. Could a thicker atmosphere on ancient Mars allow the thermal models to better reproduce the ICC thickness? Next, we examine the effects of increasing the atmospheric pressure on the thermal models. The best-fit cryosphere models for a 400 mbar CO_2 atmosphere (solar luminosity at 3.8 Ga) are shown in Fig. 2C and D. The relationship between heat flux and R^2 is similar to that for the Amazonian models, except that the MAST produced by the increased atmospheric pressures cause the best fit models to occur at lower heat fluxes.

The entire suite of model runs for the 273 K ice melting isotherm models are shown in Fig. 3. We find that the best-fit models occur for obliquities between 25° and 45° and atmospheric pressures ≤ 600 mbar.

Discussion: The disparity between the thin inferred ICC and the thick ICC predicted by Amazonian thermal models (Fig. 2) could have important implications for the water inventory and geologic history of Mars. The difference between the inferred and modeled ICC thickness suggests that the maximum modeled cryosphere thickness [1] was not reached in the Amazonian due to a supply limit of ice (i.e., the volume of the pore space in the cryosphere exceeded the volume of ice available to fill the pores; Fig. 1C). Because the ICC thickness appears to be anomalously thin compared with the modeled Amazonian cryosphere thickness, but can be reasonably fit by thermal models with increased surface heat flux and/or atmospheric pressure, we raise the possibility that the cryosphere freezing front reached the maximum thickness of the ICC (and the supply-limit of ice) during an earlier period in martian history (Fig. 1D).

Cryosphere through time: Our model results show that the best fit cryosphere models which can match the inferred ICC thickness exhibit a linear relationship between MAST and surface heat flux (Fig. 3). Any MAST greater than shown in Fig. 3 would enable groundwater to persist beneath the ICC, and MAST equal to or below these values would lead to ICC stabilization. In concert with estimates for the decay in planetary heat flux through time [10-11], our model results offer a possible constraint on the MAST conditions through time which allow the ICC to stabilize. Adopting these heat flux estimates, **we predict the ICC must have have stabilized at or before ~3 Ga** (using an upper limit heat flux of 45 mW/m^2 [10-11]) unless MAST in the Amazonian exceeded 220 K (corresponding to a 600 mbar CO_2 atmosphere). Accounting for the decreased solar luminosity at 3 Ga [13], this would require ~20 K of warming for timescales exceeding 10^6 years, which we consider unlikely due to the cold and dry conditions believed to characterize the Amazonian [14] (modern day MAST=210 K). Our models thus predict that abundant global groundwater does not persist in the deep martian subsurface in the present day.

References: 1) Clifford et al., *JGR*, 115, E7 (2010); 2) Clifford et al., *JGR*, 98, E6 (1993); 3) Lasue et al., *Space Sci. Rev.*, 174 (2013); 4) Carr and Head, *GRL*, 42 (2015); 5) Weiss and Head, *LPSC* 47, abstract 1066 (2016); 6) Forget et al., *Icarus*, 222 (2013); 7) Wordsworth et al., *Icarus*, 222 (2013); 8) Horan and Head, *LPSC* 47, abstract 2394 (2016); 9) Laskar et al., *Icarus*, 170 (2004); 10) Montési and Zuber, *JGR*, 108, E6 (2003); 11) Ruiz et al., *Icarus*, 215 (2011); 12) Kite et al., *Nature Geosci.*, 7 (2014); 13) Gough, *Solar Phys*. 74 (1981); 14) Carr and Head, *EPSL*, 294 (2010).