LATE NOACHIAN "ICY HIGHLANDS" MARS: IMPLICATIONS FOR MELTING AND GROUNDWATER RECHARGE ACROSS THE THARSIS RISE. J. P. Cassanelli[1], J. W. Head[1], J.L. Fastook[2], [1]Brown University Department of Geological Sciences, Providence, RI 02912 USA, [2]University of Maine, Orono, ME 04469 USA. (James_Cassanelli@Brown.edu)

Introduction: Results from modeling of an early CO_2 martian atmosphere and late Noachian climate predict that at pressures greater than a fraction of a bar, atmosphere-surface thermal coupling occurs, resulting in adiabatic cooling of high areas across Mars [1]. This effect promotes the transport of water from warmer low-lying areas to the highlands where deposition and accumulation of water ice result in an "icy highlands" Late Noachian Mars [2].

Deposition of water ice by this process at predicted accumulation rates will quickly exceed the currently observed polar/near-surface water inventory on Mars [3,4]. Therefore, we assume the growth of the regional ice sheets throughout the highlands to be a supply limited process constrained by the available surface water reservoir [4,5]; we adopt a reservoir of 2 times the current available water ice in the polar/near-surface reservoirs (~60 m GEL). Distribution of this water supply across the predicted areas of deposition leads to an average ice sheet thickness of approximately 200 meters and thus predominantly cold base glaciation [3,4]. Of particular interest in the "icy highlands" model is the regional accumulation of snow and ice in the Tharsis rise volcanic provinces. The deposition of snow and ice throughout the Tharsis region coincides with a period of widespread volcanic activity [6] raising the possibility for melting through both top-down heating (climate modified by ideal insolation geometry, impacts, volcanism) and bottom-up heating (increased geothermal heat flux, thick ice accumulation).

The Tharsis Montes have been previously examined as possible centers for groundwater recharge through basal melting of ice deposits resulting from the increased geothermal heat flux [e.g. 7]. Here we assess the nature of regional ice accumulation across the Tharsis rise in the presence of an elevated geothermal heat flux and the implications that this may have for possible melting mechanisms and meltwater transport. We examine the response of regional ice deposits to a baseline Noachian heat flux [8,9,10], an elevated geothermal heat flux representative of the broader Tharsis region, and two highly elevated heat fluxes predicted to occur on specific volcanic edifices [11]. For the geothermal heat flux of the broader Tharsis region we adopt a mean value of typical geothermal heat fluxes observed in terrestrial volcanic regions [12,13,14,15,16].

In addition, we assess the configuration of the martian cryosphere under the outlined conditions in order to determine the possibility of localized vertical integration of the hydrologic system in the form of groundwater aquifer recharge.

Methods: To predict the temperature increase at the base of the regional ice deposits across Tharsis we implement the University of Maine Ice Sheet Model (UMISM) [17,18,19]. The UMISM was parameterized for Late Noachian climate conditions and used to calculate the basal temperature for ice sheets of various thicknesses at several selected geothermal heat flux values. The UMISM was also used to determine the amount of time a punctuated heating event would need to be sustained in order for the temperature increase to propagate to the ice sheet base and initiate basal melting. This places constraints on the necessary conditions that a punctuated heating event must meet in order to cause *top-down* induced basal melting.

To assess the potential for localized vertical integration of the hydrologic system we implement the one-dimensional heat equation, parameterized to the same conditions, to estimate cryosphere thicknesses.

Results: Table 1 summarizes the temperature increases calculated at the ice sheet base relative to the surface as a function of geothermal heat flux. We account for the possibility of asymmetrical ice accumulation within Tharsis [e.g., 20] by performing the calculations for ice sheet thicknesses of up to 1 km.

Ice Thickness (m)	Geothermal Heat Flux (mW/m^2)			
	55	80	100	125
200	4.32	5.77	6.94	8.42
400	6.52	8.99	11.00	13.55
600	8.15	11.40	14.05	17.41
800	9.46	13.32	16.48	20.49
1000	10.55	14.94	18.53	23.10

Table 1. Temperature increases (^{o}C) across ice sheets of varying thicknesses at nominal Late Noachian climate conditions for a background geothermal heat flux (55 mW/m^2), a general volcanic region heat flux (80 mW/m^2), and two heat fluxes characterisitic of volcanic edifices (100 and 125 mW/m^2).

These results suggest that in the nominal case, even at geothermal fluxes of up to 125 mW/m^2, basal melting cannot be achieved by *bottom-up* heating alone. As the thickness of the ice sheet grows, the amount of insulation provided increases and the basal temperatures rise accordingly. At the geothermal heat flux we assume to be representative of the broad Tharsis region in the Late Noachian period, an ice sheet would need to accumulate to thicknesses of ~3-4 km to provide enough insulation to initiate basal melting.

While melting in the nominal case is not predicted, the baseline amount of *bottom-up* heating present in the Tharsis region will render the ice sheets much more vulnerable to *top-down* induced basal melting. If a punctuated heating event increased mean surface temperatures above a 200 m ice sheet to between 264.3 and 269.2 K, for a period of time long enough to allow the

temperature increase to propagate through the ice sheet, approximately 2000 years, basal melting could begin. The same process could occur for thicker ice sheets but would require a more sustained heating event at lower temperatures.

Figure 1 displays the estimates of the mean thickness of the cryosphere along a line of longitude passing through Tharsis rise. The results indicate that cryosphere thickness in the Tharsis region in the nominal case ranges from approximately 1000 to 2000 m. This decreases to ~750 to 1250 m when we assume the regionally elevated geothermal heat flux and down to between 500 and 750 m when we apply a geothermal heat flux associated with the volcanic edifices.

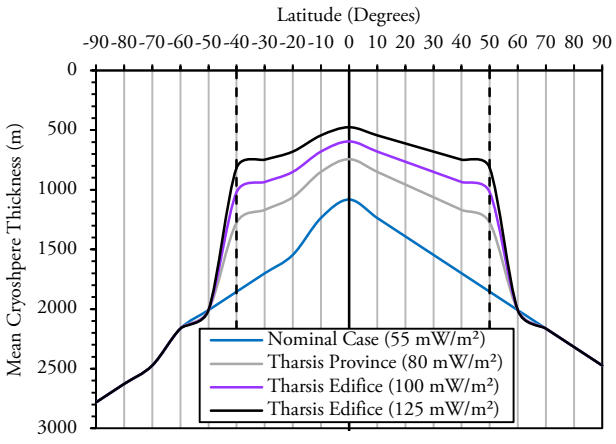

Figure 1. Mean cryosphere thickness versus latitude under nominal Late Noachian conditions [1,2,7,8,9], for the broader Tharsis region [12,13,14,15,16], and at specific volcanic edifices [7] (dashed lines represent the approximate extent of the Tharsis region).

These cryosphere thicknesses suggest that vertical integration of the hydrologic system will not typically occur over the broad Tharsis rise. In the nominal case, even with an overlying ice sheet 200 m thick, the cryoshpere will still extend to between 1150 and 1300 m below the ice sheet for the considered range of geothermal heat fluxes. The thickness of the underlying cryosphere will decrease as the overlying ice sheets become thicker and provide more insulation. For the cases in which basal melting is predicted as a result of *bottom-up* heating alone, the melting isotherm is at the base of the ice sheet and so no cryosphere should exist beneath the ice sheets.

Implications for Melting: Calculations of the basal temperatures in the various ice sheets indicate that there are two primary mechanisms by which melting can occur: 1) *top-down* climate-induced basal melting 2) exclusively under *bottom-up* geothermal heating-induced basal melting at sufficient ice thicknesses.

Top-down induced basal melting can occur for any ice sheets where basal melting does not occur as a result of bottom-up heating alone. Basal melting in this manner can proceed in two distinct manners: 1) *Top-down heating leads to induced basal melting, but the punctuated heating event is not sustained for a long enough time to melt through the ice-cemented cryosphere beneath the ice sheet.* In this case generated meltwater may produce subglacial meltwater features including tunnels which can coalesce and drain to the glacial margins through steady discharge or by episodic flooding. The melt generated in this manner can also create a lens between the overlying ice and the substrate, lubricating the base of the ice sheet, initiating wet-based glaciation and enhancing glacial flow and erosion. 2) *If the overlying ice sheet becomes thicker it will be easier to melt the cryosphere beneath the ice sheet.* This is because the underlying cryosphere will be thinner and because the overlying ice is more thermally conductive than the cryosphere material and can transmit the induced heat more readily. In this case a punctuated heating event may be able to induce basal melting and also cause the cryosphere to melt beneath the ice sheet allowing the meltwater to infiltrate down into the substrate and provide groundwater aquifer recharge to any aquifers which may underlie the cryosphere.

If basal melting can be produced by elevated geothermal heat fluxes acting alone on the base of thicker ice sheets then there will be no underlying cryosphere because the melting isotherm will have reached the base of the ice sheet. In this case meltwater generated at the ice sheet base may be able to directly infiltrate the substrate material and provide groundwater recharge depending on the permeability of the underlying material. If the material is relatively impermeable, meltwater production may exceed the capacity of the substrate to accept it. This will lead to the formation of subglacial hydrology features similar to those produced when the melting ice sheet is underlain by the ice-cemented cryosphere. **Broad-scale Tharsis basal ice-sheet groundwater recharge is only predicted to occur under very significant ice thicknesses (> ~3-4 km, at nominal geothermal heat fluxes ~55mW/m^2)[7,8,9], at an extremely high geothermal heat flux (> ~700 mW/m^2, for predicted ice thicknesses of ~200 m) [1,2,7], or a combination of these factors.**

References: [1] Forget et al. (2013) *Icarus, 222,* 81-99. [2] Wordsworth et al. (2013) *Icarus, 222,* 1-19. [3] M. Carr, J. Head (2014) *LPSC 45,* Abstract #1427. [4] J. Fastook, J. Head (2014) *LPSC 45,* Abstract #1115. [5] J. Head et al. (2014) *LPSC 45,* Abstract #1412. [6] Phillips et al. (2001), Science, 291, 2587-2591. [7] Russell P. and Head J.W. (2007) *Planetary and Space Science,* 55, 315-332. [8] J. Fastook *et al*., *Icarus,* 219, 25 (2012). [9] Solomon et al. (2005) *Science,* 307, 1214-1220. [10] Clifford et al. (2010) *J. Geophys. Res.*, 115, E07001. [11] Fasset C.I. and Head J.W. (2007) *Icarus, 189,* 118-135. [12] Blackwell D.D., and Richards M., (2004) *Geothermal Map of North America (AAPG).* [13] Blackwell D.D., (1983) *The Role of Heat in the Development of Energy and Mineral Resources in the Northern Basin and Range Province*, 13, 81-93. [14] Blackwell D.D., (1978) *Tectonics and Regional Geophys. Western Cordillera*, 152, 175-208. [15] Lee, W.H.K.., and Uyeda, S., (1965) *Am. Geophys. Union Mon.*, 8, 87-190. [16] Horai, K. and Uyeda, S., (1969) *Am, Geophys. Union Mon.*, 13, 95-109. [17] Fastook et al. (2004) *LPSC35,* Abstract #1352. [18] Fastook et al. (2005) *LPSC 36,* Abstract #1212. [19] Fastook et al. (2006) *LPSC 37,* Abstract #1794. [20] Head J.W., and Marchant D.R., (2003) *Geology*, 31(7), 641-644.