SOURCES OF WATER FOR GROUNDWATER-FED OUTFLOW CHANNELS ON MARS: IMPLICATIONS OF THE LATE NOACHIAN "ICY HIGHLANDS" MODEL FOR MELTING AND GROUNDWATER RECHARGE ON THE THARSIS RISE. J. P. Cassanelli[1], J. W. Head[1], J. L. Fastook[2], [1]Brown University Department of Earth, Environmental and Planetary Sciences, Providence, RI 02912 USA, [2]University of Maine, Orono, ME 04469 USA. (James_Cassanelli@Brown.edu).

Introduction: During the Late Noachian (LN), Hesperian, and early Amazonian periods, large outflow channels were carved into the surface of Mars [1-3]. Many are interpreted to have originated through catastrophic discharge of groundwater from pressurized aquifers [4,5]. Formation of outflow channels by this mechanism requires a predominantly cold climate during the time of aquifer discharge because a thick and globally extensive layer of perennially frozen ground (cryosphere) is needed to create an impermeable confining unit (in order for the aquifers to become pressurized). However, the impermeable cryosphere prohibits the operation of typical groundwater recharge mechanisms by preventing infiltration of surface water. Therefore, the water needed to prime the aquifers for outflow channel formation must have been supplied prior to the discharge events.

While the climate of early Mars has been suggested by some to have been "warm and wet" [*e.g.* 6], which would allow for groundwater recharge, recent Global Climate Modeling (GCM) efforts [7,8] predict an early Mars climate dominated by "cold and icy" conditions. The GCM modeling of an early, thicker CO_2 martian atmosphere indicates that, when coupled with a full water cycle, the atmosphere of Mars will behave adiabatically causing temperatures to decrease with elevation. As a result high standing areas across Mars are cooled, leading to preferential accumulation of snow and ice, and the formation of regional ice sheets throughout the Tharsis region and the Southern highlands. These predictions outline the Late Noachian "icy uplands" (LNIH) early Mars climate model [8]. Under the conditions predicted by the LNIH model, a thick global cryosphere would exist, preventing groundwater recharge. Therefore, the LNIH early Mars climate scenario appears incompatible with the later formation of groundwater sourced outflow channels through near-simultaneous recharge mechanisms.

Here we adopt the assumption that the LNIH scenario is the actual representation of the LN Mars climate in order to test this model: Can LNIH ice sheet basal melting produce sufficient groundwater recharge to provide a mechanism for the near-simultaneous formation of outflow channels by cryospheric cracking and groundwater release? Previous work has shown that groundwater recharge from the Tharsis region could have supplied the hydraulic head needed to explain the formation of some outflow channels [9], though further assessment showed that ice sheet basal melting was only likely to occur at very significant ice sheet thicknesses or geothermal heat flux values [10,11]. However, the regional ice sheet formation predicted by the LNIH model coincides with a time of intense volcanic and magmatic activity in the Tharsis region [12], which is likely to have contributed to an elevated geothermal heat flux. Here, we revisit the Tharsis region as a center for groundwater recharge given the predicted deposition of LNIH sheets in the presence of a regionally elevated geothermal heat.

Ice Sheet Basal Melting: In order for ice sheet basal melting to occur, a critical thickness of insulating ice must be accumulated for a given mean annual surface temperature and geothermal heat flux. 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 [13]. We adopt a reservoir 5X the currently observed polar/near-surface water inventory on Mars. Distribution of this reservoir across the high standing areas, above the predicted equilibrium line altitude (+1 km; [8]), gives an average ice sheet thickness of ~700m [14]. Given these predicted average thicknesses, and LN mean annual surface temperatures (~225 K; [7,8]), we assess the geothermal heat flux conditions required to initiate basal melting.

Geothermal Heat Flux: During the LN, widespread volcanic and magmatic activity throughout the Tharsis region [12,15] would have contributed to an elevation of local and regional geothermal heat fluxes. The extent to which these geothermal heat fluxes may have been elevated is unclear, but estimates of the regional geothermal heat flux in the Tharsis region during this time range from ~60-100 mW/m^2 [16]. Due to local variations, the geothermal heat flux can vary considerably from the regional average, particularly near active volcanic features. Here we assume that the geothermal heat flux values measured from active terrestrial volcanic regions (Fig. 1; [11]) are comparable to what would have occurred in the Tharsis region during the LN. We assess the potential for ice sheet basal melting in response to both regional and localized heat flux values.

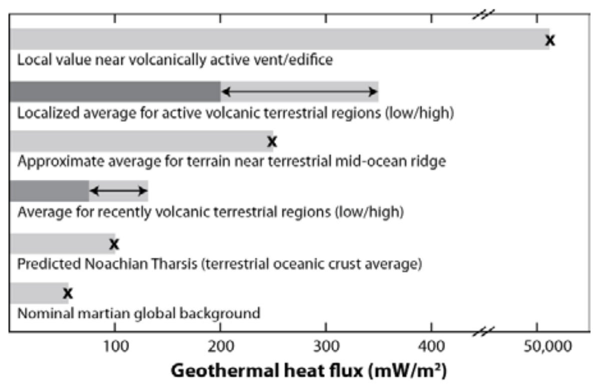

Figure 1. Geothermal heat flux values in areas of varying volcanic and magmatic activity.

Regional Basal Melting: Given a predicted LN mean surface temperature (~225 K), and a conservative estimate of the mean ice sheet thermal conductivity (2.5 W/m K; [11,17]), the geothermal heat flux required to induce basal melting at the nominal average LNIH ice sheet thickness (~700m) is ~170 mW/m^2 (Fig. 2), far above the predicted background heat flux (55 mW/m^2; [10,18,19]). While the regional geothermal heat flux in the Tharsis region would have been elevated by magmatic activity, it is unlikely that it ever approached this critical value over broad scales. Therefore, unless the LNIH ice sheets were considerably thicker (corresponding to an unreasonably large LN surface water inventory [13,14]; Fig. 2), glaciation in the Tharsis region during the LN is predicted to have been predominantly cold-based.

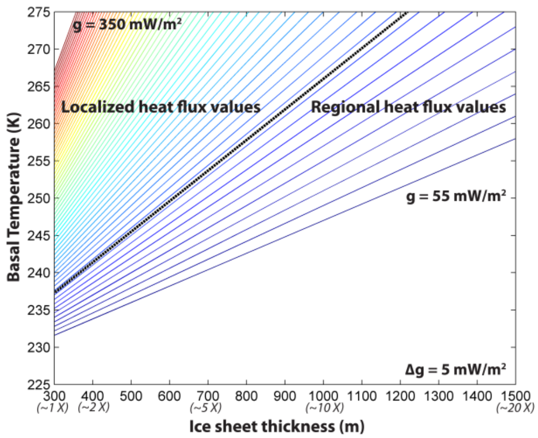

Figure 2. LNIH ice sheet basal temperatures as a function of ice sheet thickness (corresponding to ~1-20X the current available surface water inventory), and geothermal heat flux.

Localized Basal Melting: It is likely that highly elevated geothermal heat flux values were sustained near active volcanic features in the Tharsis region during the LN, potentially causing LNIH ice sheet basal melting and groundwater recharge through a "heat-pipe drain pipe" mechanism. A "heat-pipe drain pipe" mechanism is defined as a point thermal source (*e.g.* a magma reservoir in a volcanic edifice) or a linear thermal source (*e.g.* a dike-rich rift zone) which serves as "heat pipes" that locally destroys the cryosphere, causing meltwater to descend down a "drain pipe" into the groundwater system, despite the presence of a regionally coherent cryosphere.

In terrestrial volcanic environments, geothermal heat flux values elevated to the levels required for LNIH basal melting (~200 mW/m^2) are only observed over areas of limited extent (~10s of km; [20]) in (or near) highly active volcanic terrain (*e.g.* the East volcanic zone of Iceland; [21,22]). Heat flow modeling of Hecates Tholus on Mars [23] suggests that, following the emplacement of a magmatic intrusion beneath a volcanic edifice, surficial heat flows will peak at ~120-200 mW/m^2. However, the peak heat flows are confined to the summit region of the edifice (~700 km^2) [23]. We scale this result linearly to each edifice within the Tharsis region [11] to obtain a total peak heat flow area where basal melting might result in groundwater recharge through the "heat-pipe drain pipe" mechanism. We obtain a total potential "heat-pipe drain pipe" melting area of ~10,000 km^2. Given that regions of elevated heat flow in terrestrial settings can extend beyond the bounds of individual volcanic features [20], and that other martian volcanic environments might have exhibited elevated local heat fluxes (*e.g.* the possible Tempe Fossae rift zone; [24]), we assume this to be a conservative estimate of peak heat flow area. We address potential error by assessing the "heat-pipe drain pipe" recharge over a range of melting areas within a factor of 3 of our nominal estimate.

We find that for the nominal LNIH ice sheet thickness (700 m) and "heat-pipe drain pipe" melting area (10,000 km^2), a plausible peak heat flow of 200 mW/m^2 can produce a total of ~0.01 m GEL of groundwater recharge, which is on the order of the lowest estimates of individual outflow channel flood event volumes [5]. Even at the maximum conceivable ice sheet thickness (1500 m), geothermal heat flux (350 mW/m^2), and "heat-pipe drain pipe" melting area (30,000 km^2), the amount of groundwater recharge that can be produced is ~0.25 m GEL, less than half the total volume estimated for the smallest martian outflow channels [13].

Cryosphere Contribution: If the cryosphere was initially *ice-saturated*, then raising the melting isotherm throughout the Tharsis region by accumulation of LNIH ice sheets, or elevation of the geothermal heat flux, may have contributed a significant amount of water to the groundwater system. The effect of accumulating 700 m thick LNIH ice sheets across the Tharsis region in combination with an elevation of the geothermal heat flux from 55 mW/m^2 to 100 mW/m^2, will be to raise the melting isotherm from ~1.7 km to ~400 m, and the release of ~20 m GEL of water from the cryosphere (assuming a conservative crustal porosity structure; [2]). This is comparable to the estimated volume involved in the formation Kasei Valles, but is not sufficient to explain the formation of all groundwater-fed outflow channels. [13].

In localized areas where "heat-pipe drain pipe" groundwater recharge is predicted to take place, the cryosphere will have become completely diminished prior to basal melting. Again assuming an initially *ice-saturated* cryosphere and conservative porosity structure, this would liberate ~0.01-0.05 m GEL of water.

Conclusions: (1) Broad-scale Tharsis basal ice-sheet groundwater recharge is not predicted even under anomalous LN heating conditions expected in the Tharsis region. **(2)** LNIH ice sheet basal melting and "heat-pipe drain pipe" groundwater recharge is likely to occur at very local scales due to highly elevated geothermal heat fluxes near active volcanic features. Meltwater production is limited due to the local nature of heating, even with a cryosphere contribution. **(4)** If the cryosphere was initially *ice-saturated,* regional scale reduction in cryosphere thickness could have released enough water to the groundwater system to form Kasei Valles, but not enough to form all groundwater-fed outflow channels. **(5)** "Heat-pipe drain pipe" groundwater recharge is not able to supply the water required for outflow channel formation by aquifer discharge. We conclude that the LNIH climate scenario may be incorrect, groundwater recharge may have occurred earlier in Mars history, and/or there are other mechanisms of groundwater recharge and outflow channel formation.

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