DEGRADATION STATE OF NOACHIAN HIGHLAND CRATERS: ASSESSING THE ROLE OF CRATER-RELATED ICE SUBSTRATE MELTING IN A COLD AND ICY EARLY MARS.
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Introduction: The faint young sun [1,2] has led to the supposition that early Mars was cold [3-5]. The presence of valley networks and the degraded state of highland craters, however, has led many investigators to suggest that the martian climate in the Noachian was warm and wet, and that precipitation [6] in the form of rainfall [7] and fluvial activity are the likely causes of crater degradation. Recent climate models, however, have shown that climactic conditions in the Late Noachian may not have been favorable for liquid water precipitation [8,9], and that regional snow and ice deposits, much like those inferred to be present in the Amazonian (Fig. 1) [10], characterized the Late Noachian highlands [11]. These climate models have shown that unlike the Amazonian, slightly increased atmospheric pressures in the Late Noachian could allow the atmosphere to thermally couple to the surface [8], a scenario in which the Noachian southern highlands acts as a cold trap and preferentially accumulates atmospheric snow and ice deposits [8,11-13], the *Late Noachian Icy Highlands (LNIH) scenario*.

The degraded martian highland craters are a common feature of the Noachian-aged southern highlands, and may provide insight into the climatic conditions on early Mars. Martian Noachian highland craters (Fig 1) differ from fresh martian craters in that they possess (1) subdued crater rims [7,14,15]; (2) flat/shallow floors [7,14,15]; (3) a paucity of craters <~10-20 km in diameter [14,16-19]; (4) channels superposing crater rims [7,14,15,19]; and (5) a relative absence of ejecta facies [7,14,15]. These characteristics have been variously explained by (1) burial by air fall deposits [20-24]; (2) erosion by groundwater sapping [25]; (3) erosion by rainfall and surface runoff [6,7,15]; (4) impact-induced seismic liquefaction [26]; (5) a complex interweaving of erosion, deposition, and cratering [27]; or (6) erosion from melted snowpack [28].

Based on the suggestion that the Late Noachian southern highlands may have been covered with hectometers-thick snow and ice deposits [8], it has recently been proposed that the degradation state of Noachian highland craters might also be explained in the LNIH model [29]. In this scenario, impacts in the highlands occur in hectometers-thick snow/ice deposits. Investigation of formation of a hypothetical impact crater in such a deposit predicts the following candidate features: (1) structurally-uplifted rims may be partially composed of the surface snow/ice layer, and allow some of the depth of the crater cavity to be accommodated by the surface ice; (2) subsequent removal of the surface ice in a later, different climate could then lower the rim height and produce an apparently smaller crater cavity; (3) following the impact, erosion should modify the crater: back-

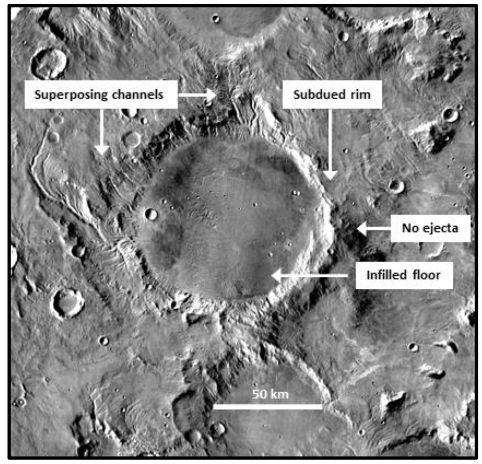

Figure 1. Noachian highland crater and characteristics.

wasting of rim material could contribute to the flat and shallow floors and subdued rims seen in Noachian highland craters [15]; (4) insolation-induced top-down melting, such as proposed for Amazonian gullies [e.g., 30,31], or melting from emplacement of hot ejecta around large craters [28] could generate runoff: such a process could further erode the rim and ejecta, infill the crater, and generate near-rim superposing channels [e.g., 32].

Impact ejecta-induced basal melting?: In addition to these candidate predicted processes, could basal melting of surface ice [29] contribute to the degradation state of highland craters formed in icy substrates? Highland craters formed on this environment would be unusual in that the snow/ice deposits in which they form would still be present beneath their ejecta facies during modification; snow and ice could also overlie the crater during periods of continuing snow deposition. If basal melting following ejecta emplacement were to occur, fluvial erosion from the melted snow/ice deposits might contribute to rim and ejecta erosion, channel formation, and crater infill. Previous investigators [5,12,33,34] have shown that it may be possible to generate basal melting only in instances of hectometers to kilometers thick ice and snow deposits. The LNIH ice budget above a 1 km equilibrium line altitude may be as low as ~300 m assuming the 34 m GEL Amazonian ice supply limit [35, 36], and thus the Late Noachian regional snow/ice deposits would likely be of insufficient thickness to generate basal melting. Recent work, however, suggests that deposition of low-thermal conductivity ejecta on top of regional snow and ice deposits is sufficient to raise basal temperatures above the melting point of water-ice [29]. In the current analysis, we explore the predicted effects of ice melting below impact crater ejecta on degradation processes and state of Noachian highland craters.

Quantitaive assessment of basal melting: We model the *crater diameters* predicted to exhibit basal-ice melting, *melting timescales*, and *erosional capability of basal ice melting* in the LNIH scenario. Preliminary calculations suggest:

(1) *Crater diameters* above ~40 km have near-rim ejecta thicknesses sufficient to generate basal ice melting (Fig. 2).

(2) *Melting timescales:* The timescale for the ice-melting isotherm to reach the base of the ice sheet (and initiate basal melting) is dependant upon heat flux (*Q*) the initial depth of the ice-melting isotherm (i.e., the thickness of the cryosphere), and the density, heat capacity, and thermal conducitivity (*K*) of the subsurface. We predict that basal melting initiates ~100-200 kyr after impact for craters 40-150 km in diameter. Because the thermal conductivity of ejecta is much lower than that of ice, the entire thickness of ice below the ejecta is generally able to melt. A lower-bound estimate for complete melting of a 300 m ice sheet below the near-rim ejecta is ~53 kyrs, or ~100 kyrs for a 600 m thick ice sheet (Fig. 3a). Basal melting is thus predicted to terminate between ~150-300 kyr following the initial impact.

(3) *Erosion*: The amount of erosion generated by basal melting is dependant upon melt production rates and substrate permeability. We predict the minimum melt production rate from basal melting to be ~4-8 x 10^{-3} m/yr per m^2 (Fig. 3b) for heat flows [37, 12] between 45 and 65 mW/m^2. Substrate permeabilities above ~10^{-16} m^2 allow infiltration rates to exceed melt production rates, favoring minimal erosion (Fig. 3b). Substrate permeabilities below ~10^{-16} m^2 produce infiltration rates below melt production rates, and thus favor erosion. Permeability models [38] show that megaregolith permeability at the surface is much less than 10^{-16} m^2. For basal melting to have an erosive effect, we predict that a low permeability substrate (i.e., bedrock) is required.

Predictions to test the LNIH model: Basal melting of ice underlying near-rim ejecta of craters is predicted to occur in the LNIH scenario. If an impact occurred in megaregolith, the ice-rich rim should be depressed by melting, but erosion of the ejecta and substrate is predicted to be minimal. If the impact occurred in bedrock, low infiltration rates would favor fluvial erosion, which could contribute to ejecta and rim erosion, channel formation, and crater infill.

The amount of erosion from basal melting is also predicted to be dependant upon the thickness of ice initially beneath the ejecta, which places a supply limit on total melt volume. Because the predicted amount of erosion will be dictated by melt volumes and rates, the validity of the LNIH scenario can be tested and constraints can even be placed on the melting-style in the hypothesized LNIH scenario. For example, if no evidence of basal melting is observed, then the LNIH scenario is not supported. If basal-melt volumes and rates are insufficient to produce the observed erosion, other (warmer) climate scenarios [e.g., 6, 7, 15] or mechanisms to produce melt (e.g., top-down melting of snow [8, 28], and/or volcanically-induced atmospheric warming pulses [39]) would be required. We are currently assessing a representatione population of Noachian highlands craters to test these predictions.

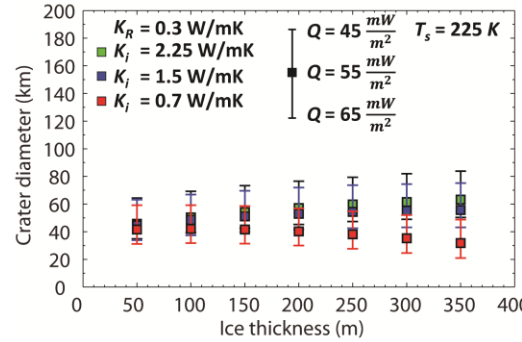

Figure 2. Minimum crater diameters predicted to exhibit basal melting.

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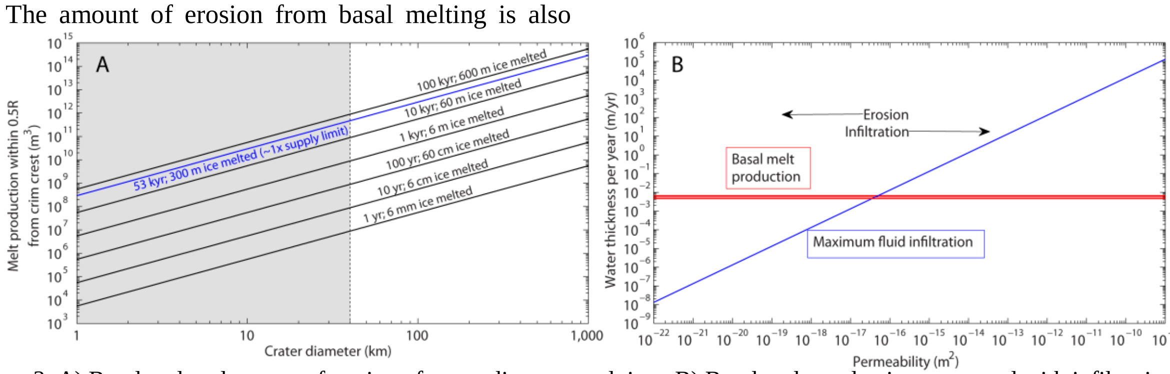

Figure 3. A) Basal melt volume as a function of crater diameter and time. B) Basal melt production compared with infiltration rates.