EVALUATING THE ROLE OF IMPACT-INDUCED BASAL MELTING OF SURFACE ICE DEPOSITS ON THE DEGRADATION STATE OF IMPACT CRATERS ON A COLD AND ICY EARLY MARS. D. K.

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Introduction: The wide array of fluvial features present on the surface of Mars, despite its current below-freezing surface temperatures, has raised many questions regarding the climate of Mars throughout its early history. Fluvial channels incised onto impact crater rims and ejecta [e.g., 1-3] are particularly interesting because these features may offer insight into the ancient martian climate, and its relationship to the impact cratering process. Could these features provide insight into the climate of Mars during the Late Noachian period? The fluvial features associated with degraded Late Noachian highlands craters (Fig. 1) [3] have typically been attributed to rainfall and fluvial erosion in a warmer and wetter early martian climate [4-6]. Noting that a warm early martian climate (and sustained rainfall) is not predicted by recent 3D global climate models [7-9], these fluvial features have been alternatively explained by snowmelt and fluvial erosion from snow deposition on hot ejecta [10], or top-down melting during peak seasonal or daytime temperatures [11] in a cold and icy Late Noachian climate. In the cold and icy climate scenario, the presence of hectometers-thick regional surface snow and ice deposits in the southern highlands during the Late Noachian period [11,12] has been proposed on the basis of recent 3D global climate models [8,9]: *the Late Noachian Icy Highlands (LNIH) scenario.* Recent work [13] has further proposed that impact-induced basal melting of surface ice is a candidate process which may contribute to some of the ancient impact-related fluvial features in such a cold and icy ancient martian climate.

Here, we investigate the quantitative characteristics of impact-induced basal melting of surface ice deposits [13] in order to assess its role in the formation of impact-associated fluvial channels on early Mars. In the basal melting scenario (Fig. 2), ejecta deposition on top of regional surface snow and ice deposits inhibits geothermal heat diffusion through the ice. As a result, following the impact event the 273 K ice melting isotherm within the shallow crust is predicted to rise to the base of the ice sheet given sufficient ejecta thicknesses. This causes the ice sheet to melt from the bottom-up, supplying a potential source of liquid water for fluvial erosion proximal to the impact crater.

We provide a quantitative treatment of the basal melting mechanism [13] using thermal modeling in order to assess whether impact ejecta-induced basal melting of surface ice deposits could have played a role in forming impact crater-associated fluvial channels during the Late Noachian period of Mars.

Quantitative assessment of basal melting: We are guided by the following questions: Could an impact event into a thick surface ice sheet in the Late Noachian
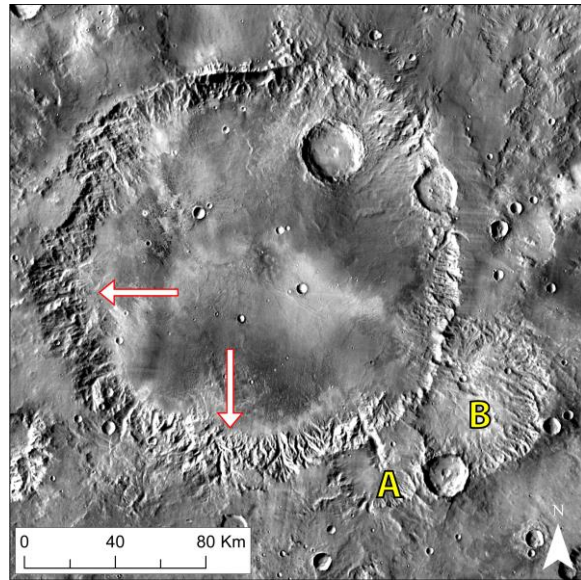

Figure 1. Noachian-aged crater exhibiting fluvial channels draining into the crater interior (arrows).
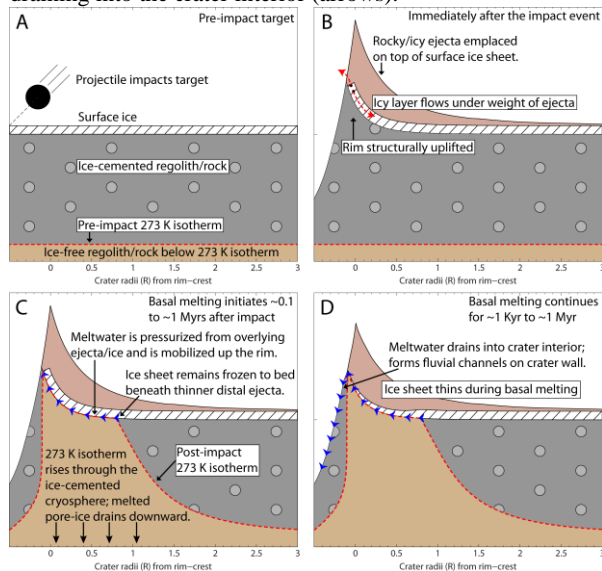

Figure 2. Hypothesized post-impact basal melting configuration used in our models. Vertical exaggeration of 55X.

period of Mars generate basal melting and contribute to the observed fluvial erosion around the rim and ejecta of these highly degraded impact craters? At what crater diameters might this process occur? What surface temperatures, geothermal heat fluxes, and ice thicknesses are required to generate basal melting? How long after impact would basal melting of the surrounding surface ice occur, and over what period of time would it continue? What volume of melt is expected, and what are the predicted melting rates?

Assuming surface temperatures of 215 to 235 K and

a heat flux of 60 mW/m^2, our models (Fig. 3) suggest that crater diameters as low as 20-40 km in diameter have sufficiently thick ejecta to produce basal melting up to 1.2R from the rim-crest. Basal melting will begin between ~0.4 to ~1 Myr after impact and will continue for ~1 kyr to ~1 Myr. Melt volumes range from 10^{-1} to 10^4 km^3, and melt fluxes reach up to 10^{-3} m/yr per m^2. On the basis of these melt fluxes, substrate permeability is required to be $\leq$~10^{-18} to 10^{-16} m^2 (i.e., crystalline or consolidated sedimentary bedrock) for melting rates to exceed infiltration rates. If the melt fluxes exceed substrate infiltration rates, the melt may be transported laterally: hydraulic head from the overlying ejecta is predicted to transport this meltwater up the crater rim, where it will drain into the crater interior and lead to fluvial erosion of the crater walls (Fig. 2). Higher permeabilities (such as expected for regolith) enhance infiltration rates, and are predicted instead to allow for the meltwater to infiltrate and drain through the substratum.

Geomorphologic assessment of basal melting: With these guidelines, are there any observed impact crater-associated fluvial channels that are consistent with such a basal melting origin? A typical example of a highly degraded impact crater located in the Noachian-aged southern highlands (Fig. 1) exhibits fluvial channels nearly circumferential around the rim, a subdued rim-crest, and a lack of observable ejecta. A crater of this diameter (180 km) is predicted to generate between 10^3 to 10^4 km^3 of meltwater, and a peak melt flux of ~40 m^3/yr into the crater interior (Fig. 3).

On the basis of the model results, we suggest that the circumferential interior wall channel morphology observed (arrows in Fig. 1) could have formed through basal melting of surface ice underlying the crater ejecta. If surface ice were present at the time of impact (Fig. 2a, b), basal melting of this deposit is predicted to lead to meltwater transported towards the crater interior (Fig. 2c). The meltwater would then be able to exit and flow down the slopes of the crater walls, where fluvial incision and/or liquid water-assisted debris flows could contribute to channel formation (Fig. 2d).

While the fluvial channels circumferential around the rim of this crater are consistent with a basal melting origin, their morphology does not exclusively require basal melting to form (i.e., other formation mechanisms, such as rainfall or surface snowmelt, cannot be ruled out). Are there other characteristics of this crater that are exclusively consistent with a basal melting origin? The crater shown in Fig. 1 partially intersected two smaller pre-existing craters located in the south-eastern quadrant of the image (features A and B in Fig. 1). Two anomalously large channels associated with these impact craters (features A and B in Fig. 1) appear to initiate at the crater center, and drain down into the larger crater. In a cold and icy early Mars, impact craters are predicted to serve as topographic lows that accumulate large thicknesses of surface ice (akin to the Amazonian debris-covered gla-
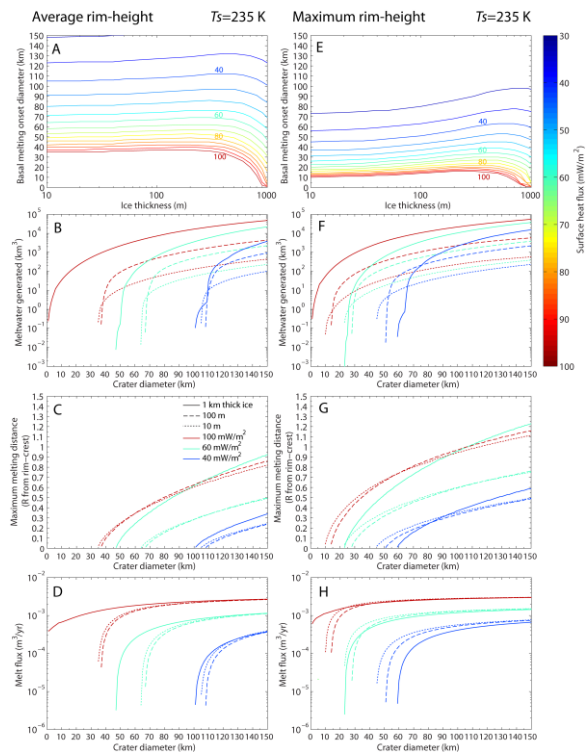

Figure 3. Model results A) Onset crater diameters for basal melting for surface heat fluxes between 30-100 mW/m^2 (contour spacing=5 mW/m^2). B) Meltwater volume generated. C) Maximum distance of basal melting from the rim-crest. D) Time-averaged basal melt fluxes. E-H) Same as A-D but for the maximum rim-height case.

cial deposits known as concentric crater fill [e.g., 14,15]). Upon impact, the ejecta of the 180 km diameter crater will superpose both the surrounding icy surface and the pre-existing ice-filled impact craters (i.e., CCF). Basal melting of any ice that infills the pre-existing craters will then produce higher volumes of meltwater (relative to the surrounding terrain), leading to greater degrees of channel incision.

Although parts of the typical impact crater discussed above (Fig. 1) are relatively unique (intersecting pre-existing impact craters with larger fluvial features), a basal melting origin is consistent with all of the other observed crater-associated fluvial features. This in turn suggests that basal melting is a viable candidate process for all impacts which exhibit fluvial channels circumferential to the rim. We are continuing to test the basal melting model under the LNIH scenario using a wider model parameter space and a larger population of Noachian-aged impact craters.

References: Morgan and Head, *Icarus* 202, 2009; 2) Mangold, *PSS* 62(1), 2012; 3) Mangold et al., *JGR* 117, E4, 2012; 4) Craddock and Maxwell, *JGR* 98, 3453, 1993; 5) Craddock et al, *JGR* 102, 13321, 1997; 6) Craddock and Howard, *JGR* 107, E11, 2002; 7) Forget et al., *Icarus* 222(1), 2013; 8) Wordsworth et al., *Icarus* 222, 1, 2013; 9) Wordsworth et al., *JGR* 120(6), 2015; 10) Kite et al., *JGR* 116, 2011; 11) Head and Marchant, *Antarctic Sci.* 26, 2014; 12) Fastook and Head, *PSS* 106, 2015; 13) Weiss and Head, *PSS* 117, 2015; 14) Levy et al., *Icarus* 209(2), 2010; 15) Fastook and Head, *PSS* 91, 2014.