PROBING GLACIERS ON MARS: CONSTRAINTS ON THE PHYSICAL PROPERTIES OF SUPRAGLACIAL DEBRIS FROM IMPACT CRATERS AND RADAR SOUNDING DATA.

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Introduction: The mid-latitudes of Mars are host to a class of features thought to be debris-covered glaciers (DCGs) [e.g., 1]. These DCGs are protected from sublimation by a layer of supraglacial debris that is hypothesized to be on the order of 10 m thick and covers nearly pure glacial ice hundreds of meters in thickness [2-4]. The supraglacial debris layer likely consists of a combination of headwall rock fall material, sublimation lag, and superposed mantling sequences. Although radar sounding and crater morphology have provided some constraints on the physical characteristics of this supraglacial debris [2-4], much is unknown about its thickness, sedimentary structure and origin, and depositional and erosional evolution.

A number of unique crater morphologies exist on the surfaces of DCGs, which have been previously documented [1,2,5]. So-called "ring-mold craters" were hypothesized to have formed their concentric ridge and central plateau morphologies during impacts into mostly glacial ice [2]. In contrast, smaller bowl-shaped craters were hypothesized to have formed mostly within the supraglacial debris; the underlying ice did not affect their final morphology.

To provide additional constraints on the physical properties of martian supraglacial debris and to test the hypothesized origins of DCG impact crater morphologies, we conducted a detailed analysis of the near-surface of DCGs within Deuteronilus Mensae (36-48.5ºN, 13-36ºE). We used MRO CTX (6 m/pixel) and HiRISE (25 cm/pixel) images for mapping of DCGs, measuring fresh crater depths and diameters, and assessing materials exposed by the craters. SHARAD radar sounding data (vertical resolution: 15 m in free space; horizontal footprint: ~0.3-1 km along-track and ~3-6 km cross-track) were used to assess DCG thicknesses and search for evidence of near-surface layering.

Morphologic Mapping: A full-resolution mosaic of CTX images was generated for regional mapping using USGS ISIS tools. Glacial deposits cover 22% of the region (166,035 km^2) and were mapped based on their topographic and textural characteristics at 1:50,000 scale in ArcMap. A variety of surface textures at the tens of meters scale are present [e.g., 5] and typically consist of relatively "fine-grained," sub-meter scale material based on HiRISE images.

Crater Depths and Diameters: We mapped and measured the rim-crest diameters (D) of 1,398 fresh craters >75 m on DCG surfaces. Fresh craters were recognized by their sharp rim-crests and their lack of significant interior fill. We also measured the depths (d) of fresh craters >250 m in diameter using wall shadow lengths observed in CTX images with 55-80º incidence angles (total of 56 craters). Measurements were calculated from equations appropriate for their assumed geometry [6] and were averaged where multiple images overlapped. Digital elevation models (DEMs) at 18 m/pixel were also generated from available CTX stereo pairs using the Ames Stereo Pipeline (ASP) [7]. Depths for 25 craters with DEM coverage were calculated as the difference between an average of rim-crest elevations and the first percentile of all interior elevations.

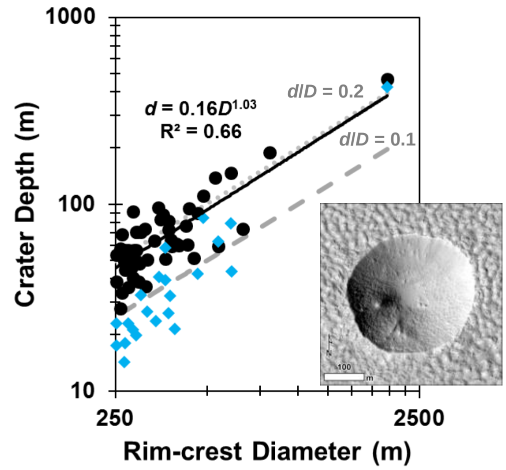

Fig. 1. Log-log plot of fresh crater depth (d) versus rim-crest diameter (D). Shadow-length measurements are shown as black circles; DEM measurements are blue diamonds. Fresh craters on DCGs (e.g., inset HiRISE image) have d/D ratios of ~0.2, typical for simple craters on Mars.

Results: Most fresh craters show typical bowl-shaped morphologies (Fig. 1). All of the craters lack ejecta blankets, suggesting that excavated material was highly erodible or volatile, consistent with fine-grained material and/or ice-rich subsurface debris. The walls of the craters also typically lack boulders and layering at the >1-m scale where HiRISE images were available.

Craters measured from shadow-lengths have an average d/D ratio of ~0.2 (Fig 1), which is consistent with the general trend of other simple craters on Mars [6,8]. If we extend this d/D ratio to all craters and assume a maximum depth of excavation $d_e \approx 0.084D$ [9], we find that all craters >75 m on DCGs have depths that exceed the proposed ~10-m thickness for the supraglacial debris layer (Fig. 2), with 35% exceeding depths of 25 m.

Depths measured from CTX DEMs are systematically shallower (~70% on average) than the shadow-length measurements (Fig. 1). We attribute these shallow depths to inaccuracies in the DEM products at small scales. Although stereo pairs were carefully selected [10], the small sizes of the measured craters (~15-20 DEM pixels) and dominant wall shadows likely precluded accurate strereo matching of crater interiors. The percent difference between DEM and shadow-length measurements generally increases with decreasing size of the crater. It is therefore advised that users of CTX DEMs exhibit caution when making morphometric measurements of craters <1 km from these products. In contrast, HiRISE DEMs have been shown to have high fidelity for crater measurements [e.g., 8].

Comparisons with Glacier Thicknesses: The identifications of strong, radar-bright reflectors at the bases of DCGs in SHARAD radargrams provide evidence that DCGs contain massive, low-loss, relatively pure ice bodies [3]. We identified 48 craters >250 m with adjacent SHARAD tracks that showed DCG basal reflectors, which allowed for estimates of DCG thicknesses, as in [3,4].

Results: DCG thicknesses range from 104-761 m with a mean of 396 m (Fig. 2). Crater depths, on average, extend to ~20% of the DCG thickness, with excavation depths reaching ~10% of the DCG. These depths are well beyond 10 m and should have extended into glacial ice (Fig. 2).

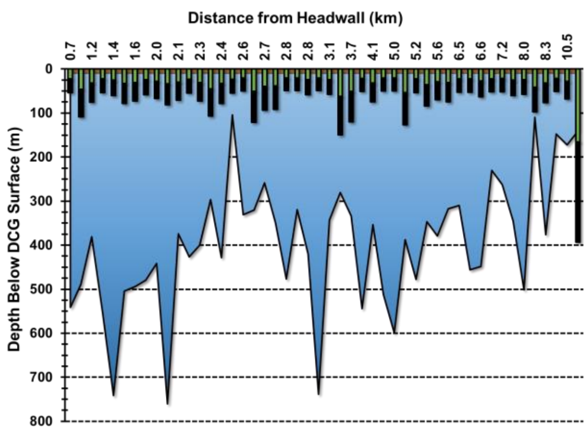

Fig. 2. Depths of excavation (green) and crater depths (black) compared to glacier thicknesses (blue) and a 10-m debris thickness (brown). Measurements of 48 craters >250 m are arranged by distance from the glacier headwall.

Fresh Crater Survival Timescale: Incremental size-frequency distributions for fresh craters were compared to Hartmann (2005) [11] isochrons to estimate a survival timescale for these crater types (Fig. 3). The fresh crater population on DCGs has a survival timescale of ~10 Myr.

Discussion/Conclusions: Hundreds of craters excavated and displaced material tens of meters into DCGs and possibly into glacial ice, yet still retain their simple, bowl-shaped morphology and d/D ratios typical of simple craters on Mars. This is at odds with the hypothesized formation of "ring-mold craters" [2] and should be a focus of further testing.

In addition, the 10-Myr survival timescale for craters on DCGs is greater than predicted from recent modeling of craters formed into ice-rich targets. Dundas et al. [12] show shallowing and substantial widening and rounding of the

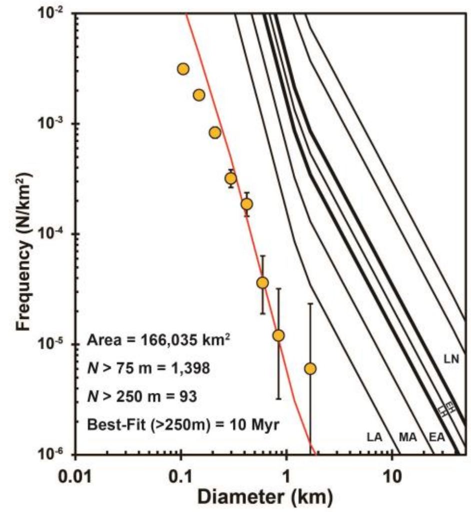

Fig. 3. Survival timescale of fresh bowl-shaped craters on DCGs is ~10 Myr. Incremental size-frequency distribution with Hartmann (2005) isochrons [11].

rims of craters subjected to sublimation on timescales of tens to hundreds of thousands of years. Preliminary results from Dombard and Noe Dobrea [13] also suggest that crater shallowing and widening can be achieved through viscous relaxation on timescales of a few million years. Considering these timescales, it is unlikely that many of the craters on DCGs have formed into pure-ice targets; a more debris-rich, ice-poor target material is more consistent with the observed fresh crater population.

The above observations suggest that the thickness of supraglacial debris is greater than previous estimates and probably on the order of tens of meters. The apparently fine-grained nature of the crater walls and erodibility of the ejecta also suggest that much of the supraglacial material may not be rockfall shed from DCG headwalls. However, we cannot rule out the possibility that headwall material is present with grain sizes < 1 m, which would not be resolved in HiRISE images. Overall, the observations are consistent with the surfaces of DCGs being highly modified by tens of meters thick mantling materials through their history [e.g., 14].

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