FORMATION OF IMPACT CRATER LANDFORMS WITHIN GLACIAL DEPOSITS ON MARS. David M. H. Baker[1] and Lynn M. Carter[2], [1]NASA Goddard Space Flight Center, Greenbelt, MD 20771 USA (david.m.hollibaughbaker@nasa.gov), [2]Lunar and Planetary Lab, University of Arizona, Tucson, AZ 85721 USA.

Introduction: A suite of landforms in the mid-latitudes of Mars interpreted to be debris-covered glaciers (DCGs) consist of nearly pure glacial ice protected by a cover of supraglacial debris [1,2]. These features are important non-polar ice reservoirs that record the recent climate evolution of Mars and are valuable resources for future landed and manned missions.

Impact craters formed within DCGs are generally <1 km in diameter and possess a range of interior landforms that are distinct for these deposits [3] (**Fig. 1**). One hypothesis [4] suggests that many of the landforms are produced by impacts into glacial ice. Large impacts were able to penetrate into the glacial ice, while smaller impacts remained within the supraglacial debris layer to form simple bowl-shaped craters. Other hypotheses [e.g., 5] suggest that the deposition of ice-rich dust, or “mantle”, combined with e and surface deflation could be responsible for the range of crater morphologies.

We tested these hypotheses by conducting a comprehensive study of DCG crater landforms within Deuteronilus Mensae (36-48.5°N, 13-36°E). We mapped the diameters and classified the morphologies of 16,458 impact craters ≥125 m located on DCGs and using a mosaic of >500 CTX images at 6 m/pixel. This study includes observations of 13 times more craters over an area 66 times larger than a previous detailed study within this region [4].

Crater Classes and Diameters: Two groups of craters consisting of nine types were identified (**Fig. 1**) (median diameters in parenthesis). *Bowl-shaped craters* include: 1) Well-preserved bowl-shaped (167 m) and 2) Degraded bowl-shaped (169 m). *Modified craters* include: 1) plateau (181 m), 2) etched plateau (168 m), 3) torus (253 m), 4) mound (160 m), 5) filled torus (190 m), 6) ring (190 m), and 7) pit (238 m). We also find numerous isolated knobs that resemble landforms in friable material interpreted to be the remnant, compressed floors of craters [6].

Transitional landforms also occur, indicating that many of the craters can be formed by degradation of only three types: bowl-shaped, plateau, and torus. This is in contrast to the previous study by [4] where no such degradation sequence was found.

Except for torus and pit craters, we also find no statistically significant difference in diameters between bowl-shaped craters and modified craters, in contrast with [4]. These trends are consistent on both regional and local scales, indicating minimal control by variations in supraglacial debris thickness.

Spatial Distributions: The spatial density of crater types varies across the study region. Bowl-shaped craters are evenly dispersed, while the density of modified craters decreases with increasing latitude. Modified craters are also more concentrated on DCGs with more developed surface textures, such as the presence of “brain terrain” and flow lineations. These observations suggest that processes affecting the surface modification of DCGs are also important in controlling the development of modified crater landforms.

Relationship with Flow Lineations: Flow lineations completely cross-cut many torus and etched plateau type craters but not the centers of other crater types (**Fig. 1a**). However, most torus craters preserve their circular planforms, indicating little deformation by glacial flow. To reconcile these observations, we suggest that torus craters are formed completely within a mantle unit that superposes lineated supraglacial debris at depth (**Fig. 2**). In this way, crater formation does not destroy the continuity of the lineations and subsequent fracturing and inheritance of the lineations within the mantle can produce the observed cross-cutting structure. Degradation of torus craters or variation in mantle strength contrasts can form etched plateau craters.

Modified Craters on Non-DCG units: We find landforms analogous to modified craters within non-DCG units, including adjacent plains and mantle units within the study area and in Arcadia Planitia. Glacial ice is therefore not required to form modified craters. Embedded depressions and terraces within craters in Arcadia Planitia [7] are plausible analogs to torus craters (**Fig. 2**). Terraces in Arcadia craters are interpreted to have formed by strength contrasts between an ice-rich layer and ice-poor regolith below [7].

Formation Scenario: The inconsistencies between our observations and those of [4] reduce support for the influence of glacial ice and supraglacial debris thickness in the formation of modified crater types. Instead, we find most consistency with formation by deposition and modification of at least two ice-rich mantle units (**Fig 2**). Torus craters and some bowl-shaped craters are formed in an initial mantle unit overlying the supraglacial debris, with other modified types produced by superposition and erosion of a second, later mantle unit. Flow lineations are produced within the initial mantle unit through topographic inheritance of flow structure at depth [3].

Implications: If correct, our formation scenario further emphasizes the importance of mantle layers in the development and evolution of the near-surface of DCGs [3] and other terrains within the mid-latitudes of Mars. Crater retention ages for DCGs mostly document the deposition of mantle, and necessarily only provide minimum ages for DCG formation. Mantle layers were likely tens of meters in thickness to support crater formation. While surface deflation has occurred, it is possible that substantial portions of these mantle units are still preserved and superpose glacial ice in many locations within the study area**.**

References: [1] Head, J.W. et al. (2010) *EPSL*, 294, 306–320. [2] Holt, J.W. et al. (2008) *Science*, 322, 1235–1238. [3] Mangold, N. (2003) *JGR*, 108(E4), 8021. [4] Kress, A.M. and Head, J.W. (2008) *GRL*, 35, L23206. [5] McConnell, B.S. et al. (2006) *LPSC 37*, no. 1498. [6] Kerber, L. A. and J. W. Head (2010) *Icarus*, 206, 669–684. [7] Bramson et al. (2015) *GRL*, 42(16), 6566–6574.

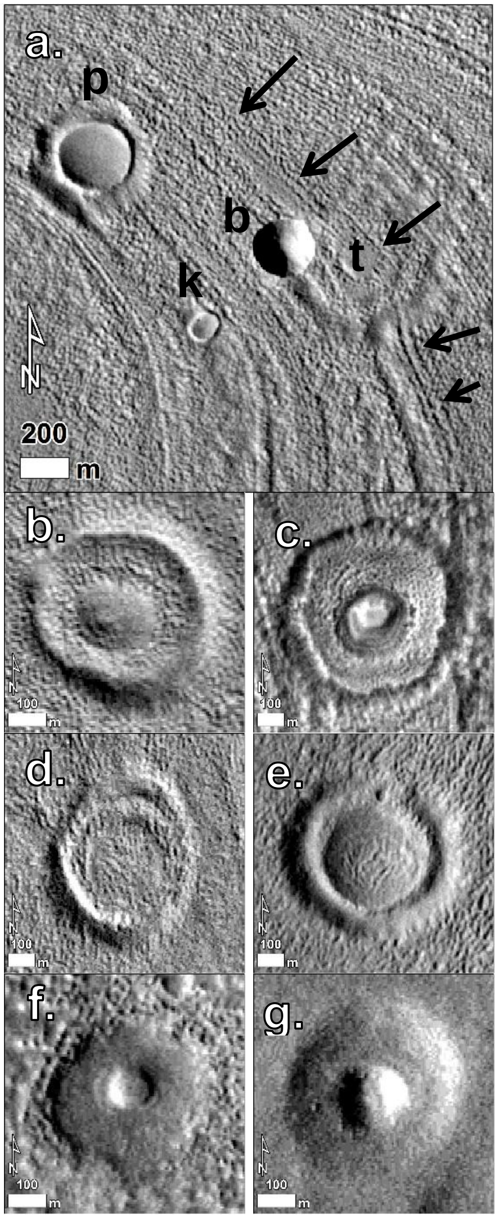

Figure 1. DCG crater types: **a)** plateau (p), well-preserved bowl-shaped (b), torus (t), and knob (k). Lineations (arrows) cross cut the torus crater. **b)** torus, c) filled torus, d) etched plateau, e) ring, f) mound, and g) pit. Scale bars in b-g are 100 m.

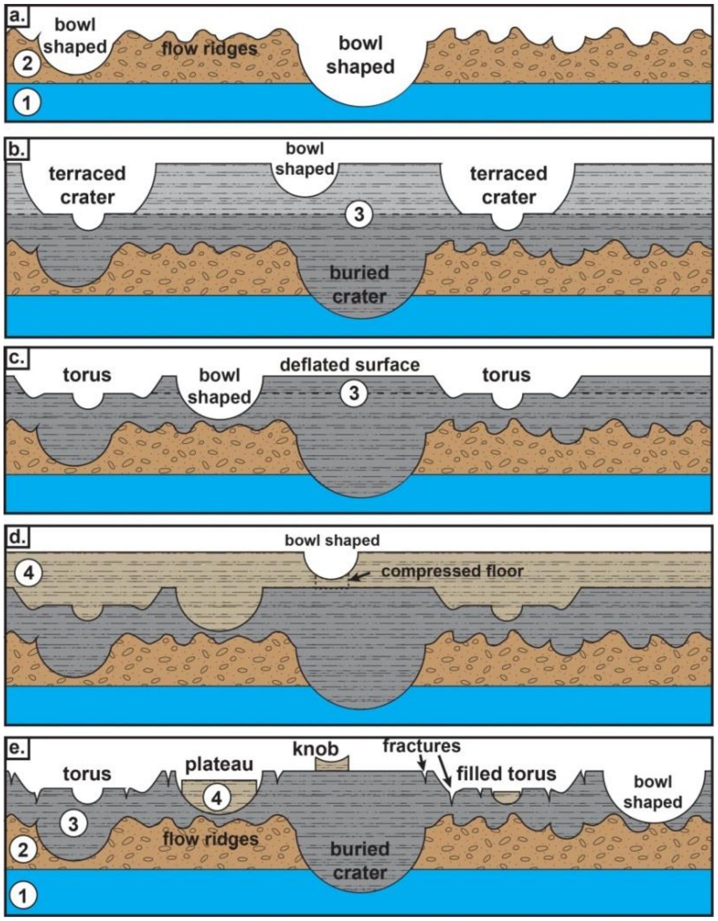

Figure 2. Schematic formation scenario for crater morphology on debris-covered glaciers. **a)** Glacial ice (1) is superposed by supraglacial debris (2) composed of boulder-rich rockfall and deformed by flow ridges. **b)** Mantle unit one (3) is emplaced, with strength contrasts (dashed line) due to variations in ice/dust content causing terracing in craters. **c)** Deflation of mantle unit one through sublimation of internal ice reduces topography and forms torus shape. Subsequent craters are bowl-shaped due to reduction in internal strength contrasts. **d)** Mantle unit two (4) is emplaced, is more erodible, and buries surface topography. Small impact craters form compressed floors that remain post-erosion. **e)** Erosion of mantle unit two leaves remnant patches to form plateau craters, filled torus craters, and knobs. Fracturing within mantle unit one (3) is controlled by underlying topography in supraglacial debris (2), including flow ridges, producing lineations that cross-cut torus craters. Subsequent degradation of torus, plateau, and bowl-shaped craters can produce the remaining crater morphologies.