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Ring-mold craters in lineated valley fill and lobate debris aprons on Mars: Evidence for subsurface glacial ice

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[1] Ring-mold craters (RMCs), concentric crater forms shaped like a truncated torus and named for their similarity to the cooking implement, are abundant in lobate debris aprons (LDA) and lineated valley fill (LVF) in the northern mid-latitudes on Mars, but are not seen in surrounding terrain. LDA and LVF have been interpreted to form by flow of debris, but uncertainty remains concerning the mechanism of flow, with hypotheses ranging from pore-ice-assisted creep of talus to debris-covered glaciers. RMCs average less than a few hundred meters in diameter and occur in association with normal bowl-shaped impact craters whose average diameters are commonly less than RMCs. On the basis of their morphologic similarities to laboratory impact craters formed in ice and the physics of impact cratering into layered material, we interpret the unusual morphology of RMCs to be the result of impact into a relatively pure ice substrate below a thin regolith, with strength-contrast properties, spallation, viscous flow and sublimation being factors in the development of the ring-mold shape. Associated smaller bowl-shaped craters are interpreted to have formed within a layer of regolith-like sublimation till overlying the ice substrate. Estimates of crater depths of excavation between populations of bowl-shaped and ring-mold craters suggest that the debris layer is relatively thin. These results support the hypothesis that LDA and LVF formed as debris-covered glaciers and predict that many hundreds of meters of ice remain today in LDA and LVF deposits, beneath a veneer of sublimation till. RMCs can be used in other parts of Mars to predict and assess the presence of ancient ice-related deposits. **Citation:** Kress, A. M., and J. W. Head (2008), Ring-mold craters in lineated valley fill and lobate debris aprons on Mars: Evidence for subsurface glacial ice, *Geophys. Res. Lett.*, *35*, L23206, doi:10.1029/2008GL035501.

1. Introduction

[2] Lobate debris aprons (LDA), lobate landforms with convex upward profiles that commonly surround massifs, and lineated valley fill (LVF), material on the floors of valleys that is characterized by patterns of parallel ridges and grooves, are common in the northern and southern mid-latitudes of Mars [*Squyres*, 1978]. Two end-member models have been proposed for the mode of origin of LDA/LVF: 1) Dry talus or debris flows mobilized by pore ice at times of enhanced water-ice deposition [*Squyres*, 1978], and 2) Debris-covered glaciers, with a layer of sublimation till overlying flowing glacier ice [*Head et al.*, 2006].

[3] In the course of analysis of the nature, origin and age of LDA/LVF in the northern mid-latitudes of Mars in the 950-km-long Mamers Valles, a fretted channel located along the dichotomy boundary in Deuteronilus Mensae, we found evidence for two populations of impact craters superposed on the LVF and LDA [*Kress and Head*, 2008]. One population consists of normal bowl-shaped craters (Figure 1a), but the other is characterized by an unusual concentric morphology like a truncated torus that we named "ring-mold craters," for their similarity to the cooking implement (Figure 1a). We mapped the 12,800 km^2 area of Mamers Valles [*Kress et al.*, 2006] and specifically analyzed the characteristics of these two populations of craters through the description and classification of over 1,300 craters in 65 MOC images covering nearly 2,500 km^2 of the valley.

2. Definition of Crater Types

[4] Bowl-shaped craters (Figure 1a) are typical of the morphology of relatively fresh craters on planetary surfaces. We have only found RMCs, however, on LDA/LVF-type terrain. RMCs are generally rimless and consist of a circular moat surrounding a variety of complex interior morphologies. Most RMC morphologies can be assigned to one of the following morphological groups: 1) central pit or bowl; 2) central plateau; 3) multi-ring; and 4) central mound (Figure 2). RMCs form almost 80% of the total crater population on LDA/LVF, and they are typically larger than bowl-shaped craters. RMC diameters reach ~750 m in diameter, with a mean of ~102 m, while the largest bowl-shaped crater diameter is ~356 m and the mean is ~77 m.

[5] Other workers studying craters seen on LDA/LVF have interpreted differing morphologies as a degradational sequence, considering bowl-shaped craters "fresh" and unmodified, and those with unusual "oyster-shell" morphologies (like RMCs) "degraded" and more highly modified [*Mangold*, 2003]. The size distribution of different crater types plotted by *Mangold* [2003, Figure 8] shows that "fresh" craters represent 10% of the total population, that most fresh craters are less than ~60 m in diameter, and that "degraded" (generally "oyster-shell" and RMC types) reach ~400 m in diameter. *McConnell et al.* [2007] similarly interpreted unusual craters observed on LVF as the result of sublimation and degradation, invoking crater infill and subsequent surface deflation to explain a transition from "fresh" bowl-shaped craters to "inverted impact craters." In our analysis, we were unable to establish a clear degradational sequence; on the basis of the differences in size-frequency distribution between the two crater types we explore the hypothesis that the difference between bowl-shaped craters and RMCs is not solely a degradational

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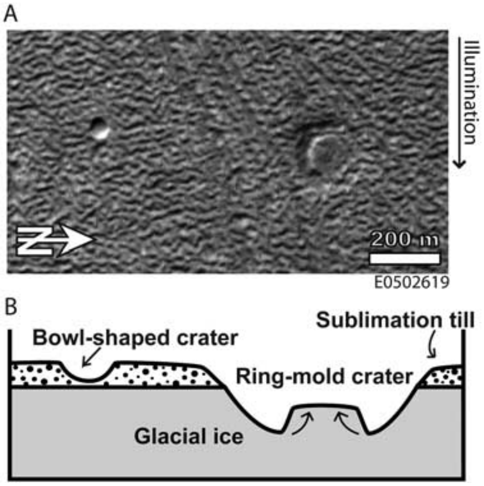

Figure 1. (a) Comparison of (left) a bowl-shaped crater and (right) a ring-mold crater on LDA/LVF in the Mamers Valles region (MOC image E0502619). (b) Diagrammatic cross-sectional model for the relationships of bowl-shaped and RMC craters; bowl-shaped craters penetrate into, but not through, the regolith. Ring-mold craters penetrate through the regolith into underlying glacial ice and are modified by local short-term viscous flow, and then modified by sublimation.

sequence, but instead may be related to the response of the substrate to increasing crater size and changing substrate characteristics. "Fresh" craters are small because they form in the relatively ice-poor silicate-debris-rich sublimation till above an ice substrate, while RMCs owe their shapes to the behavior (or process) of crater-formation in the deeper ice substrate [*Kress and Head*, 2008]. We now explore impact cratering experiments into ice and ice-rich substrates to assess this hypothesis.

3. Experimental Impacts Into Ice Substrates

[6] Two stages characterize the impact process: formation and modification. The formational stage produces the initial crater morphology, which is a function of the impact energy of the projectile (depending on material properties, size, velocity, and angle of incidence) and the material and structural properties of the target material (e.g., composition, density, porosity, layering). The primary crater morphology may experience different modification processes after emplacement. We distinguish short-term modification (slumping or gravitational collapse) from long-term modification (impact, eolian, volcanic, tectonic, or fluvial degradation). Viscous relaxation of craters can bridge short- and long-term modification time scales due to its dependence on crater size, energy coupling, geothermal gradient, and material properties of the substrate.

[7] Impacts into water ice and ice-silicate mixtures produce distinctly different landforms [*Croft et al.*, 1979; *Croft*, 1981; *Kawakami et al.*, 1983; *Cintala et al.*, 1985; *Kato et al.*, 1995; *Shrine et al.*, 2000; *Senft and Stewart*, 2008]. Impacts into pure water ice show unusual patterns due to the low melting point and the brittle nature of the target. Crater volumes in pure ice are one to two orders of magnitude larger than those in pure silicates [*Lange and Ahrens*, 1987; *Koschny and Grun*, 2001], and crater diameters are two to six times larger in ice than in basalt for the same range of impact energies [*Croft et al.*, 1979; *Kawakami et al.*, 1983; *Cintala et al.*, 1985; *Lange and Ahrens*, 1987]. Experimental impacts show a distinctive conical spallation zone around any of a variety of interior structures (Figures 2 and 3) [*Croft et al.*, 1979; *Cintala et al.*, 1985; *Lange and Ahrens*, 1987; *Kato et al.*, 1995; *Koschny and Grun*, 2001; *Grey et al.*, 2002]. Spallation terrace depths were typically found to be half the total depth of the crater [*Grey et al.*, 2002]. Some variations in morphology are observed as a function of impact velocity [*Croft et al.*, 1979; *Shrine et al.*, 2000].

[8] Types of morphologies observed [*Kato et al.*, 1995] include: 1) central pit; 2) tabular plateau; 3) bowl with central peak; 4) bowl with tabular plateau; 5) flat floor; and 6) double bowl (Figure 2). In some experiments, the cratered ice targets were kept in a cold room for a month to accentuate large cracks by the healing of fine cracks. The sharp edges and rims of the craters disappeared due to sublimation of the ice, but the crater shapes and sizes were preserved [*Kato et al.*, 1995]. Experimental impacts into ice-saturated sand and pure ice show considerable differences, craters in ice-saturated sand being generally bowl-shaped [*Croft et al.*, 1979; *Croft*, 1981]. Fracturing beyond the crater rim crest was about the same in ice-saturated sand and competent basaltic rock, but was more extensive in ice targets. Crater diameters in ice were greater than in ice-saturated sand and basalt.

[9] Impact into layered targets also contributes to variations in crater morphology. The changes in crater morphology in the lunar maria (thin regolith overlying solid basalt)

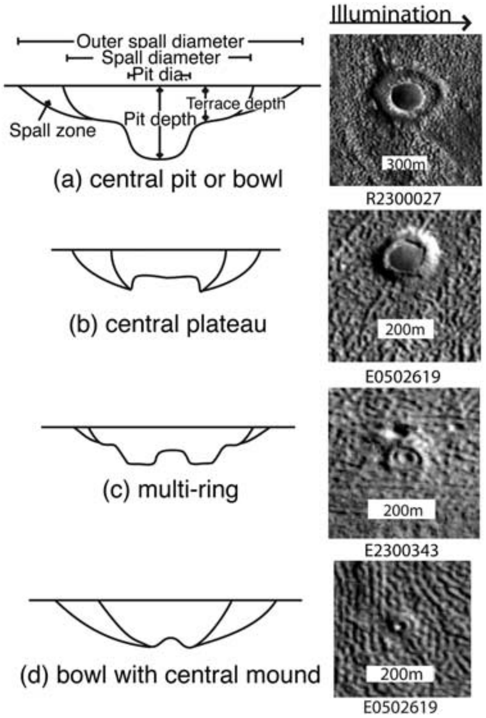

Figure 2. Types of RMCs observed in LDA/LVF (right, MOC images R2300027, E0502619, and E2300343) and comparisons to cross-sections observed in experimental impacts (left, modified from *Kato et al.* [1995]).

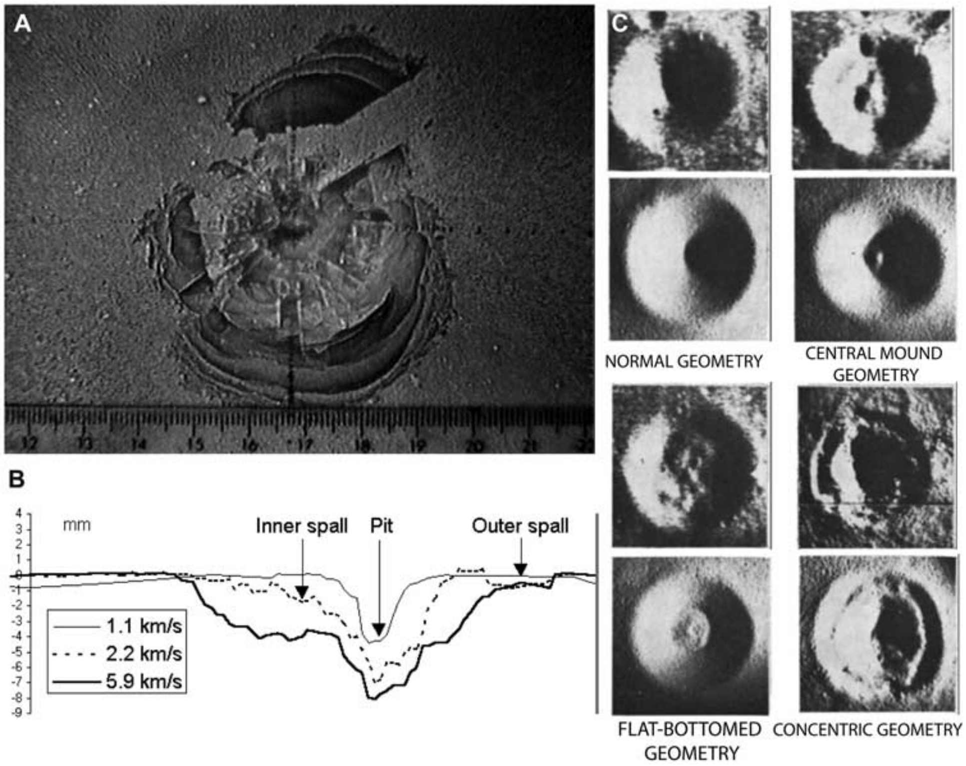

Figure 3. Effects of target characteristics on crater morphology. (a) Impact crater from a 2.2 km/sec impact showing inner pit and outer spall zone. (b) Depth profiles from impacts at different velocities [from *Shrine et al.*, 2000]. (c) Lunar craters (top of each vertical pair) with normal, central mound, flat bottomed, and concentric morphology in Lunar Orbiter images, and in the laboratory (bottom of each pair) [from *Quaide and Oberbeck*, 1968].

are well-known; bowl-shaped craters in the regolith transition to flat-floored and concentric craters as the coherent substrate is encountered [*Quaide and Oberbeck*, 1968]. Numerical modeling of silicate regolith overlying ice suggests that similar morphologies can be produced due to both shock impedance and strength mismatches between debris and ice layers [*Senft and Stewart*, 2008].

[10] In summary, these data indicate that during the formational stage of impacts into icy substrates, primary crater landforms are observed that differ from the simple, bowl-shaped craters seen in silicate, regolith, and ice-cemented regolith targets. A range of interior morphologies, including central bowl, pit, peak, flat plateau, or bowl with raised rim, forms at the sub-impact point. Spallation forms an outer annular moat in small-scale laboratory experiments, though the scaling of this process to larger sizes to account for the transition from spallation to bulk movement of fragmented target material is uncertain [e.g., *Melosh*, 1984; *Burchell et al.*, 2001]. Shock impedance and strength mismatches between debris and ice layers contribute to variations in crater interior morphology [e.g., *Quaide and Oberbeck*, 1968; *Senft and Stewart*, 2008]. During emplacement, fracturing and shear heating elevate ice temperatures in the substrate in the vicinity of the crater interior, potentially favoring viscous flow, and some impact melt may form. Freshly exposed ice ejecta and talus rapidly sublimate, removing the rim and rounding major features.

[11] What features are likely to form in the short-term and long-term modification stages of cratering events? Viscous relaxation of impact craters on Mars and other bodies with icy or ice-rich substrates is to be expected, and the level of relaxation is related to crater size (imparted energy) and geothermal gradient [*Parmentier and Head*, 1981]. Craters on icy satellites show upwelling of the crater floor and central peak, flattening of the crater profile, and viscous domes forming in central crater pits [*Schenk et al.*, 2004]. Profiles and images of experimental viscous relaxation of craters exhibit similar features to the interior morphologies of some craters on LDA/LVF [*Parmentier and Head*, 1981; *Schenk et al.*, 2004]. On the basis of the scale of craters on LDA/LVF (less than 1 km), broad-scale viscous relaxation is unlikely; however, localized viscous flow related to impact heating could occur. Recent numerical simulations have shown that a warm core of heated ice exists below the impact point, and that ice can form a central uplifted region that can also flow outward [*Senft and Stewart*, 2008]. Impact-induced heating of an ice substrate would dissipate by conduction after the initial impact event, leading to a time-dependent short-term modification process.

[12] A further aspect of immediate crater modification in a debris-covered glacial model for LDA/LVF has to do with the fracturing and ejection of ice and the exposure of fresh fragmented and spalled ice. On the basis of latitude-dependent ice stability on Mars [*Mellon and Jakosky*, 1995], it is clear that freshly exposed ice would sublime in a geologically short period of time. If the impact experiments are a guide [*Kato et al.*, 1995], we would anticipate removal of ejecta deposits, rounding of sharp features, and deepening of topographic differences until sublimation tills developed on spalled and exposed surfaces. Furthermore,

sublimation of underlying ice via vapor diffusion through the relatively porous till substrate would lead to the thickening of the sublimation till overlying the ice by addition of debris from below [e.g., *Marchant et al.*, 2002].

[13] Formation of craters in ice-rich substrates has implications for impact crater size-frequency distributions; impacts into ice produce larger craters than in basalt or regolith for otherwise comparable impact energies, due principally to the material properties of ice, spallation, and strength contrasts [*Croft et al.*, 1979; *Kato et al.*, 1995; *Kawakami et al.*, 1983; *Lange and Ahrens*, 1987]. The low tensile strength of ice allows the formation of craters with relatively larger diameters. Spallation may contribute to an increase in diameter at smaller scales, but extrapolation to larger scales is uncertain [e.g., *Burchell et al.*, 2001]. Thus, crater counts performed on impact craters in ice will yield ages greater than the true age [*Lange and Ahrens*, 1987] if the larger diameters of craters formed in ice are not accounted for.

4. Interpretation of Craters in Mamers Valles

[14] Experimental crater data show that craters formed in ice and regolith-over-ice substrates have shapes that are very similar to the RMCs seen in the LDA/LVF (Figures 1–3). Specifically, the convex-downward annulus surrounding the central structure (with various shapes and configurations) is strikingly similar in both cases, and is in contrast to craters formed in ice-cemented soils, silicate regolith, or basalt. The ring-mold shape is interpreted as a primary landform due to the inherent tensile strength of the target, strength mismatches during impact (with potential contributions from spallation), as well as from short-term viscous flow from heat deposited in the ice below the crater. Degradation of the primary landform smoothes the margins but does not radically alter the structure itself.

[15] The characteristics of RMCs permit us to assess models for the nature of the internal structure and origin of LDA/LVF. The ice-impact origin for RMCs directly implicates the presence of nearly pure subsurface ice at the time of formation of the crater. A dry regolith-only target would not produce such morphologies, and craters formed in ice-cemented regolith are similar in morphology to those formed in solid rock (basalt) [*Croft et al.*, 1979]. Of the two end-member models for the origin of LDA/LVF, 1) dry debris aprons mobilized by pore ice [*Squyres*, 1978] and 2) debris-covered glaciers with a superposed layer of sublimation till overlying glacier ice [*Head et al.*, 2006], the presence of RMCs in LDA/LVF strongly suggests that glacial ice comprised the substrate at the time of crater formation. Flow lineations and other features preserved in LDA/LVF support a debris-covered glacier model [*Head et al.*, 2006]. Only a very small percentage of craters on LDA/LVF are non-circular, and we interpret the superposed craters to have formed after glacial flow ceased, in the manner described by *Dickson et al.* [2008]. If this interpretation is correct, the presence of RMCs can be used to detect glacial ice elsewhere on Mars, and to determine the depth to buried ice.

[16] We interpret the smaller sizes of craters forming the bowl-shaped population (Figure 1) to indicate that small impact craters do not penetrate through the debris cover to the ice-rich layer of the LDA/LVF. In such a model, sublimation till develops on top of flowing glacial ice due to progressive concentration of silicate debris by sublimation, and the till subsequently thickens non-linearly as a function of age [*Marchant et al.*, 2002]. Bowl-shaped craters form when impact energies are insufficient to excavate to the underlying ice, and RMCs form when impactors excavate down into the glacial ice underlying the regolith till (Figure 1b).

[17] Bowl-shaped crater sizes can thus be used to estimate a minimum till thickness. The mean bowl-shaped crater diameter in our survey is ~77 m, corresponding to an average regolith layer thickness of ~15 m, if crater excavation depth is taken to be ~20% of the crater diameter (after the depth-diameter ratios obtained by *Croft* [1981] and *Kato et al.* [1995]). MOLA data suggest LDA in Mamers Valles may be greater than 400 m thick for over half the length of the valley. Studies of sublimation on both Earth and Mars [*Marchant et al.*, 2002, *Helbert et al.*, 2005] suggest that an insulating surface layer can protect underlying ice for millions of years (and yield numbers comparable to the surface ages and till thicknesses we see in Mamers Valles); thus it is likely that several hundred meters of relatively pure ice still exist within the LDA and LVF today.

5. Summary and Conclusions

[18] Experimental impacts into ice substrates yield a plausible model for the formation of RMC morphologies as primary landforms. RMCs provide important clues to the origin and evolution of LVF and LDA in Mamers Valles and potential insight into detection of buried ice elsewhere on Mars. Surface textures and geological relationships of RMCs and bowl-shaped craters suggest that the lineated surface is a sublimation till and that buried glacial ice lies at shallow depths below the present surface of LVF and LDAs. RMCs support the hypothesis of extensive glacial activity in the mid-latitudes during the Late Amazonian and suggest that a significant amount of the glacial ice is preserved beneath these LDA/LVF surfaces today.

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