

**RING-MOLD CRATERS ON LINEATED VALLEY FILL (LVF) AND LOBATE DEBRIS APRONS (LDA) ON MARS (II): IMPLICATIONS FOR THE PRESENCE OF SUBSURFACE ICE.** A. M. Kress<sup>1</sup>, J. W. Head<sup>1</sup>, and D. R. Marchant<sup>2</sup>, <sup>1</sup>Dept. of Geological Sciences, Brown University, Providence, RI 02912; <sup>2</sup>Dept. of Earth Sciences, Boston University, Boston MA 02215 (ailish\_kress@brown.edu)

**Introduction:** Craters with unusual morphologies commonly characterize the surfaces of lineated valley fill (LVF) and lobate debris aprons (LDA) on Mars [1-5]. We assessed the characteristics and distribution of impact craters superposed on LVF and LDA within the 950-km-long Mamers Valles, a fretted channel at the border of the northern lowlands covering an area  $\sim 12,800$  km<sup>2</sup>. We studied 54 MOC images covering an area of  $\sim 1500$  km<sup>2</sup> in the valley and located and analyzed 326 craters. Elsewhere [4] we describe the nature of the impact cratering process in ice and ice-rich substrates and compare these predictions to crater forms (ring-mold craters, RMC; Fig. 1) observed in the LVF/LDA. We show that the unusual ring-mold craters are plausibly interpreted to be primary landforms due to the role of spallation in the formation of impact craters in ice. We show these primary relationships [4], and discuss the range of modification processes likely operating on RMCs and the implications.

**Definition and Characterization of Crater Types:** We recognized two fundamental crater types in the LVF/LDA of Mamers Valles (Fig. 1): 1) *Bowl-shaped craters* (typical of relatively fresh craters in regolith in most areas of Mars), and 2) *Ring-mold craters* (generally rimless craters with a circular moat surrounding an inner generally circular raised plateau or mesa with a variety of different morphologies). Ring-mold is a purely descriptive term that refers to the shape of a common kitchen item used for shaping gelatin or baking certain types of bread and cake. Ring-mold crater plateau morphologies can be flat, depressed, crater-like, have scalloped margins (the "oyster-shell" craters of [1]), and annular rings (Fig. 1). The variations in the interior plateau structure of the RMCs show analogs to experimental craters produced with different projectiles [4], and may also be related in part to post-formation degradation processes.

**Size-Frequency Distribution of Superposed Craters:** The range of morphologies of craters seen on LDA [1] has been interpreted as a degradational sequence, with bowl-shaped craters being "fresh" and unmodified and those with ring-mold morphologies being "degraded" and more highly modified. The size distribution of different crater types plotted in [1; Fig. 8] shows that "fresh" craters represent only 10% of the total population, that most fresh craters are less than  $\sim 60$  m in diameter, and that "degraded" (generally ring-mold types) extend out to  $\sim 400$  m in diameter. We interpret this difference not in terms of a degradation sequence, but in terms of the characteristics of the substrate (Fig. 2): "fresh" craters are small because they are forming in the relatively ice-poor silicate debris-rich sublimation till on top of the ice substrate, while "degraded" craters are simply ring-mold cra-

ters that owe their shape to excavating into an icy substrate below a thin sublimation till [4].

**Implications of the Buried Ice Model of Ring-Mold Crater Formation:**

**1) Ring-mold crater formation indicates the presence of buried relatively pure ice:** The spallation origin for ring-mold craters directly implicates the presence of subsurface ice at the time of formation of the superposed crater. A dry regolith-only target would not produce these, and craters formed in ice-cemented regolith look like those formed in solid rock (basalt) [4].

**2) The subsurface ice is at a relatively shallow depth, below a thin protective layer of till:** The small size of craters forming the bowl-shaped population (less than  $\sim 60$  m) indicates that the overlying layer is less than several tens of meters thick.

**3) Impact crater morphology can be used as a guide to the depth of ice deposits, and thickness of overlying till, at present and in the past:** Impact craters can be used to measure depth to ice in space and time; the onset diameter of ring-mold craters provides clues to the boundary between ice and overlying debris-rich sublimation till layers. If sublimation till continues to thicken due to vapor diffusive loss of buried ice, this should be recorded in the crater population. The largest and most pristine bowl-shaped craters should be an indication of the most recent thickness. A population of ring-mold craters overlapping with this size crater could indicate that the till was thinner in the past.

**4) RMCs as Clues to Glacial Movement:** Ridges in the sublimation till above the flowing glacial ice are formed by differential movement along streamlines in the subsurface ice, accentuated by ice loss and sublimation in the overlying till. The presence of generally circular ring-mold craters in the LVF/LDA till is an indication that the ice forming the glacial substrate has stopped shearing, because RMCs are not deformed.

**5) RMC Diameters and Dating of Surfaces:** Due to spallation, the diameter of ring-mold craters is not the primary crater diameter as is the case in bowl-shaped craters. Ring-mold diameters will be relatively larger, and thus, if not accounted for, will tend to give older ages for the surface [4].

**6) RMCs and Crater Degradation-Based Studies:** Ring-mold craters should not be used for simple degradation studies [1,5] because, if the interpretation outlined here is correct, then they are not degraded from "fresh" bowl-shaped craters, but represent a different type of primary crater landform [4]. In some previous studies [e.g., 1] the difference between bowl-shaped ("fresh") and various RMC morphologies ("degraded")

was explained by mantling of dust, accumulation of interstitial ice, and subsequent removal of ice by sublimation [1], and crater counts were interpreted to mean that the sublimation occurred in the last tens of millions of years, up to the recent past. Although most craters have been degraded to some degree, the interpretation outlined here attributes the difference in morphology to the nature of the cratering process in the two substrate types (till and ice) (Fig. 2), and thus is sensitive to excavation depth, rather than to age and degree of degradation.

**7) Crater Ages Record When Ice Flow Ceased:** Properly calibrated for spallation, the size-frequency distribution, including ring-mold craters, is a measure of the age of the surface after flow has generally ceased. Glaciation may have gone on for a much longer period of time, with craters only being preserved after flow has stopped.

**8) RMCs on LVF/LDA Implicate Glacial Ice in the Substrate During their Formation:** Three models exist for LVF/LDA: 1) Rock-glacier-like dry debris flows which are mobilized at times of enhanced water ice deposition in pore spaces [6]; 2) Rock-glacier-like debris flows which still retain ice in pore spaces [7]; 3) Debris-covered glaciers with a superposed layer of sublimation till overlying previously flowing glacier ice [8]. Thus, most models for the formation of LVF/LDA involve an icy substrate at some time in their formation or evolution, but differ in the current presence or degree of ice. Options 1) and 2) imply small amounts of secondary ice, while option 3) envisions thick glacial ice. The presence of RMCs in LVF/LDA strongly suggests that glacial ice is currently in the substrate, or was at the time of crater formation. RMCs can thus be used to assess the role of glacial ice in other LVF/LDA, and if a sufficient population is available, to determine the depth and evolution of buried ice.

**9) RMCs Show Differences in Degradation State:** Although generally a "fresh" crater landform, RMCs also show evidence of degradation, including sublimation and loss of crater ejecta, viscous relaxation of the crater interior, and sublimation and scalloping of "oyster-shell-like" floor material.

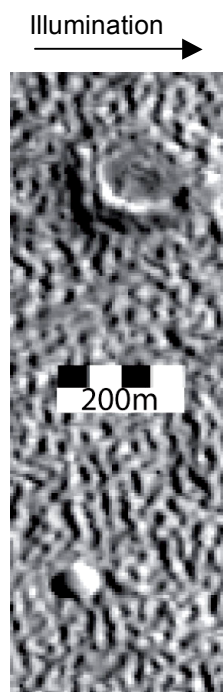
**10) RMCs Provide Clues to the Development of Sublimation Till:** Viewing RMCs as "degraded" craters yields a complex scenario for the formation and evolution of the LVF/LDA surface textures [e.g., 1, 5]. Interpretation of the lineated textures as preserved flow features in LVF/LDA, and RMCs as evidence of thick glacial ice below thin sublimation till provides a simpler scenario: sublimation till developed on top of flowing glacial ice [8] due to the progressive concentration of silicate debris by sublimation (Fig. 2), and the development of a sublimation till that thickens non-linearly as a function of age [9]. In this scenario, craters could be used to track the development of the sublimation till as a function of distance from the accumulation zone and in time.

**11) Origin of the "Oyster-Shell" Features and Their Importance:** "Oyster shell" features [1] are interpreted to

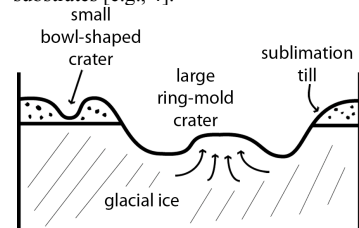
be the modified remnant of the inner crater floor (sintered and cemented by proximity to the sub-impact point). This material would be preferentially dehydrated, solidified, cemented and thus would be a much more impenetrable vapor barrier than surrounding exposed ice, and adjacent undisturbed sublimation till. Thus, this structure is largely a primary feature, and its presence suggests that the RMC has not undergone much modification or burial. Many oyster-shell (and other) crater interior structures appear perched above the crater floor and this position may be enhanced by the relative sublimation that might occur between the glacial ice exposed by spallation (very high sublimation rates), the oyster-shell-like structure (very low sublimation rates), and the undisturbed exterior till (intermediate sublimation rates).

**Summary and Conclusions:** Ring-mold craters provide important clues to the origin and evolution of Lineated Valley Fill and Lobate Debris Aprons in Mamers Valles, and potential insight into the nature and evolution of LVF/LDA on Mars. Surface textures and geological relationships of RMCs and bowl-shaped craters suggest that the lineated surface is close to a primary surface of sublimation till, and that buried glacial ice lies less than several tens of meters below the present surface of LVF and LDAs.

**References:** [1] N. Mangold (2003) *JGR*, 108, 8021. [2] A. Kress et al. (2006) *LPSC* 37, #1323. [3] A. Kress and J. Head (2007) *B-V* 46, #44. [4] A. Kress and J. Head (2008) *LPSC* 39, #1273. [5] B. McConnell et al. (2007) *Mars* 7, #3261. [6] M. Carr (1996) *Water on Mars*, Princeton, 229 p. [7] S. Squyres et al. (1978) *Icarus*, 34, 600. [8] J. Head et al. (2006) *EPSL*, 241, 663. [9] D. Marchant et al. (2002) *GSAB*, 114, 718.



**Fig. 1.** Small bowl-shaped crater (bottom; diameter = ~70 m) on lineated valley fill (LVF) on the floor of Mamers Valles. Ring-mold craters (RMC) in adjacent part of the LVF (top; 230 m wide with a central plateau diameter of ~120 m). RMC morphology is similar to that of experimental craters formed in ice substrates [e.g., 4].



**Fig. 2.** The two-substrate model for the origin of bowl-shaped and ring-mold craters in the LVF and LDA. Small impact events penetrate only the sublimation till and form typical bowl-shaped craters. Larger impacts penetrate to shallow glacial ice, causing spallation and forming larger ring-mold craters. Arrows show uplift of crater floor following impact heating and time-dependent viscous relaxation.