RING-MOLD CRATERS ON LINEATED VALLEY FILL (LVF) AND LOBATE DEBRIS APRONS (LDA) ON MARS (I): EVIDENCE FOR THE PRESENCE OF SUBSURFACE ICE. A. M. Kress and J. W. Head, Department of Geological Sciences, Brown University, Providence, RI 02912 (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. Mangold [1] interpreted a series of craters on LDA to range from fresh to highly degraded and attributed these to sublimation processes operating on craters formed in an ice-rich substrate. Kress et al. [2] and Kress and Head [3] classified and described unusual crater forms superposed on LDA/LVF and discussed the differences between candidate formational and degradational processes to explain the observed morphologies [4]. McConnell et al. [5] reviewed crater morphology on LVF in the Ismenius Lacus region and described a feature they termed "inverted impact craters", interpreting these to be due to very recent surface deflation of ice-rich targets and interaction with deposition of dust-rich layers. We have 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 ~12,800 km^2. We studied 54 MOC images covering ~1500 km^2 and located and analyzed 326 craters. Here we outline the nature of the impact cratering process in ice and ice-rich substrates and compare these to crater forms (ring-mold craters; Fig. 1) observed in the LDA/LVF; in [4] we discuss the implications.

The nature of impacts into icy substrate: The impact process is characterized by two stages: formation and modification. Important formational stage variables include those associated with the projectile (e.g., type, size, velocity, angle of incidence) and the substrate (e.g., composition, density, porosity, layering). Short-term modification (e.g., slumping, gravitational collapse) is distinguished from long-term modification (e.g., impact, eolian, volcanic, tectonic and fluvial degradation); crater viscous relaxation can bridge short and long term modification time scales (e.g., depending on crater dimension, energy coupling, geothermal gradient, substrate composition and state).

Three models exist for LDA/LVF [4]: 1) Rock-glacier-like dry debris flows which were mobilized at times of enhanced water ice deposition in pore spaces; 2) Rock-glacier-like debris flows which still retain ice in pore spaces; 3) Debris-covered glaciers with a superposed layer of sublimation till overlying previously flowing glacier ice. Thus, most models for the formation of LDA/LVF involve an icy substrate during their evolution, and we thus assess two end-members: 1) impacts into a debris-covered glacial ice substrate, and 2) impact into ice-cemented substrate.

Impacts into water ice and ice-silicate mixtures produce distinctly different landforms [6-14]. Impacts into pure water ice show unusual patterns due to the low melting point and the brittle nature of the substrate. Experimental impacts show a distinctive conical spallation zone surrounding a central crater with a raised rim (Fig. 1; [6-7, 11-13]). Crater volumes in pure ice are ~two orders of magnitude larger than those in pure silicates [6, 11], and crater diameters are ~2-3 times larger in ice than basalt for the same energy range [10-11]. Spallation terrace depths were typically found to be about half the total depth of the crater [7]. Some variations in morphology are observed as a function of impact velocity [9]. Central peaks and central pits are observed, and the central pit (a near-circular feature that has a diameter close to the projectile diameter) has been interpreted to mean that the initial highly compressed target material is not removed by subsequent tensile stresses that might lead to target failure and excavation [11]. Differences in crater excavation and morphology are readily attributable to the ~two order of magnitude difference in quasi-static compression and tensile strength between ice and basalt [11]. Differences in crater diameters are attributed largely to spallation in ice. Differences in the central *tabular plateau-type* craters were also observed (Fig. 1), including 1) *central pit*, 2) *central peak*, 3) *tabular plateau*, 4) *ringed tabular plateau*, 5) *flat floor*, and 6) *simple double bowl* [12]. In some of the experiments, the cratered ice targets were kept in a cold room for a month to accentuate large cracks by the healing of fine cracks. During this time, the sharp edges and rims of the craters disappeared due to sublimation of the ice, but the crater shapes and sizes were preserved [12].

These data indicate that the dimensions of craters produced in an icy substrate are not the same as those in a basaltic or granular substrate under similar conditions because of different target strengths and the role of spallation [10,12] (Fig. 1). Experimenters defined *pit diameter* [5, 7] as the diameter of the moat in the tabular-plateau type, the central pit in the pit-type, the central flat floor, and the central bowl in the double-bowl type craters. *Spall diameter* is the distance between the rim edges of the excavated crater. *Outer spall diameter* is the distance between the outer edges of the cracks leading to the surface (concentric spall fractures). *Pit depth* was defined in two parts: the maximum depth of the terrace and central pit (pit-type craters) and the maximum depth and depth to the top of the tabular plateau (tabular plateau-type craters).

Experimental impacts into ice-saturated sand and pure ice show considerable differences [13-14]; fracturing beyond the crater rim crest was about the same in ice-saturated sand and competent basaltic rock, but was considerably larger in ice targets. Crater diameters were greater in ice than in ice-saturated sand and basalt, due in large part to spallation.

In summary, during the formational stages of impacts into ice substrates, landforms different than the simple bowl-shaped craters of silicate, regolith, and ice-cemented regolith targets are observed: a variety of morphologies (central bowl, pit, peak, flat plateau, annular flat plateau) are formed at the sub-impact point, and spallation in the ice substrate causes formation of an outer annular depression (Fig. 1). Fracturing and shear heating elevate ice temperatures in the substrate in the vicinity of the crater interior, and some impact melt forms. Freshly exposed ice ejecta and talus rapidly sublime, removing the rim and rounding the major features.

What features are likely to form in the short 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 and geothermal gradient [15-16]. Craters on icy satellites show upwelling of the crater floor and central peaks, flattening of the crater profile, and viscous domes forming in central crater pits [17]. On the basis of the scale of craters in the LVF/LDA (generally much less than a km), broad-scale viscous relaxation is unlikely. Localized viscous flow related to impact heating could occur, however. Profiles and images of experimental viscous relaxation of crater forms show many similarities to the floor structures of some of the impact craters on LVF/LDA [15-18]. In contrast to a landform created in a geothermal gradient conducive to viscous flow, however, impact-induced heating of the shallow substrate would conduct away and dissipate after the initial impact event, leading to a time-dependent relaxation process.

A further aspect of immediate crater modification in the debris-covered LVF/LDA has to do with the spallation and ejection of ice and exposure of fresh fragmented and fractured ice. On the basis of latitude-dependent ice stability on Mars [19], it is clear that freshly exposed ice would sublime in a geologically very short period of time. If the impact experiments are a guide [7], 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., 20]. Subsequent degradation and modification processes could include: 1) deformation (differential movement of the surface and shearing of the landform), 2) sublimation; 3) eolian deflation and burial; 4) heating, thawing and melting processes associated with climate change; 4) deposition of dust and ice layers due to subsequent climate change.

Comparison of experimental impact craters and those observed in the LVF/LDA: Experimental crater data show that craters formed in ice substrates have shapes that are very similar to the ring-mold craters seen in the LDA/LVF (Fig. 1). Specifically, the ring-mold-shaped annulus surrounding the central plateau (with various shapes and configurations) is strikingly similar in both cases, and is in contrast to craters formed in ice-cemented soils or silicate regolith. The ring-mold shape is interpreted as a primary landform component due to spallation of ice during impact. Degradation of the primary landform smooths the margins but does not radically alter the structure itself. This interpretation differs from others in which the unusual landform is due to degradation [1,5]. We explore the implications of this interpretation in [4].

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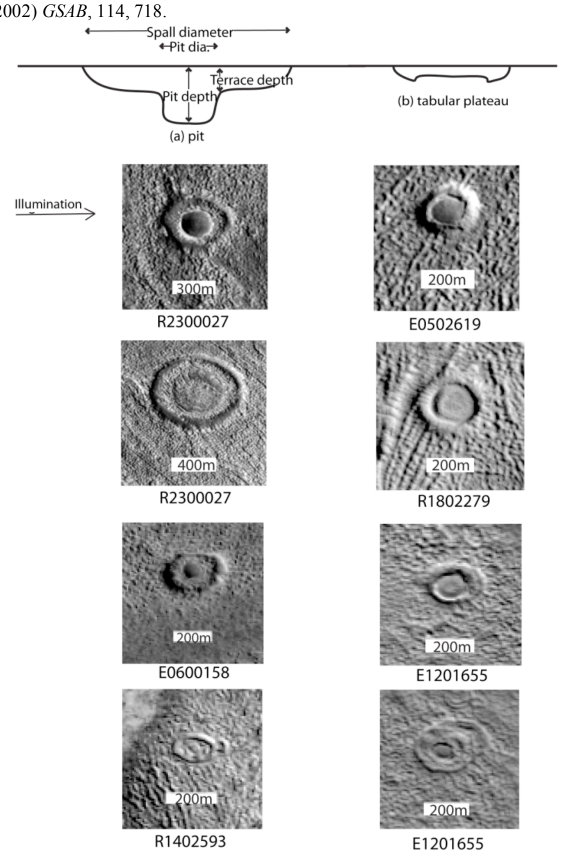

Fig. 1. Ring-mold craters on LVF/LDA in Mamers Valles compared to profiles of experimental craters formed in ice substrates [e.g., 12].