Implications of the Morphology of Flow Features on Martian Layered Ejecta: Joseph M. Boyce, and Peter J. Mouginis-Mark, Hawaii Institute of Geophysics & Planetology, University of Hawaii, Honolulu, HI 96822.

Introduction: There is a range of types and scales of landforms on Martian layered ejecta deposits that formed by fluid flow, including 1) radial grooves, 2) rampart ridges that form at the distal edge of ejecta layers, 3) transverse graben-like troughs, and 4) roll waves. Except for the troughs, these features have morphologic analogs on landslides, and other granular geophysical flows [1, thru 10].

Radial Grooves: All types of Martian layered ejecta exhibit closely spaced sets of grooves oriented radial to the crater center (see Fig.1 [ref. 8]). Boyce et al., [8], and [4] presented evidence, e.g., difference in their interaction with low-relief topography, timing of their formation, and in average groove width that suggests the radial grooves on ejecta of single layered ejecta (SLE), double layer type-2 (D), and multilayer ejecta (MLE) craters (together SDM) are similar to each other, and to grooves formed on landslides, debris flows, laboratory granular flow experiments. But the grooves on inner ejecta layers of DLE type-1 crater are similar to grooves produced by scouring by high-velocity base surge. Based on these data [4, 8, 9] suggested that SDM ejecta behaved similar to the granular debris in geophysical flows, while the radial grooves on the inner ejecta layers of DLE type-1 craters are similar to those produced by high-velocity surges like the one at Mount St Helens, and hence, could be the result of such a surge. They also proposed that the material eroded by these surges are deposited on the outer ejecta layer to form the unique surface features found there. In addition, [4, 8, 9] presented evidence that the radial grooves on the inner ejecta layer of DLE type-1 craters formed after the ejecta's surface had stabilized, whereas the radial grooves on SDM crater ejecta formed in the ejecta as its surface stabilized.

Ramparts: Each ejecta layer ends in a distal rampart ridge [see 1, 4, 6, 11, 13, 14, 15, and16]. Ramparts develop at the leading edge of flows as coarse debris is pushed up and forward by the body of the flow behind. Boyce et al., [13] measured the widths of Martian ramparts and found that the ones on the inner ejecta layers of DLE type-1 craters are about 4-5 times wider than ramparts on similar size SDM craters. We extended this work, and find the trends in width are more complicated than that described by [13]. For example, the ramparts of SLE and the outer ejecta layer of DLE type-1 craters are systematically wider (~ 1.2 and 1.4 times, respectively) than those of DLE type-2 and MLE craters (which are approximately the same width). Also, field and laboratory observations show that after flowing water-rich, poly-dispersive granular debris (e.g., debris flows) halts, it deflates as water leaks out of the flow body, but the terminal ramparts do not deflate because they tend to be dry during flow [17, 18]. This provides a test to estimate the amount of deflation on each type of Martian layered ejecta. We measure the thickness (using MOLA PDER data) of the ejecta behind the ramparts (h_b) and rampart thickness (h_r) of fresh Martian test craters of each type of crater, and for calibration purposes h_b and h_r for a well-preserved, dry geophysical flow (i.e., Tsiolkovskiy landslide on the Moon) [16, 17]. The h_r/h_b ratio for the dry flow is ~ 0.75, while the h_r/h_b ratio for SLE craters is ~ 0.65 ± 0.20, but for DLE type-1, MLE and DLE type-2 craters this ratio is ~ 0.30 ± 0.15 (note: the accurate measurement of the h_r/h_b ratio of the inner ejecta layer of ramparts of DLE type-1 craters is not possible because the shape of the rampart). These data combine to suggest that the ejecta of SLE craters only modestly deflated, while those of DLE type-1, DLE type-2, and MLE craters outer ejecta layers likely underwent substantially more deflation. Assuming that the deflation is due to water loss, approximately, as much as, half of the original flow volume of the outer ejecta layers of DLE type-1, DLE type-2, and MLE craters could have been water, and ~ 10 to 15 % of the volume of SLE ejecta also could have been water [17, 18, and 19].

Transverse Graben-like Troughs: Steep-sided, flat floored, troughs that resemble grabens are common on the inner ejecta layers of all types of layered ejecta craters (see Fig. 2, 6 [ref. 7]). These features occur as straight segments that connect to form chevron-like patterns around the parent craters. Each segment is a few hundred meters to >1 km long (depending on crater size), but averaging ~ 250 m wide but modestly increases with parent crater diameter, while their average width and average distance from the crater rim remains nearly constant with increased crater diameter (Fig. 5, [ref. 8]). They are most frequently located at about 0.4 R. The graben-like morphology and transverse orientation to the direction of flow suggests that they are probably extensional features that result from the nearly reverse velocity distribution of particles in the ejecta compared with landslides and debris flows [23]. The velocity of impact ejecta particles striking the surface typically increases progressively outward [21] suggesting that, at least initially, the velocity of ejecta closest to the rim is less than that of ejecta further from the rim. Hence, flowing ejecta should tend to thin, and depending on its rheology, even pull apart as it flows outward. Assuming this is the case, then the width and depth of these troughs is likely a direct function of the thickness of the ejecta where they formed.

Roll waves*:* Wave-like sets of closely spaced ridges and troughs whose long axes are generally transverse to ejecta flow direction are common on all ejecta layers. Bologa and Bruno [22] propose that these are roll waves (also called Kapitza waves) (Fig. 4, [ref. 8]). Although ejecta is not a viscous fluid, roll waves also form in flowing granular materials [17 - 32]. Recent studies suggest that the wavelength (λ) of these features is approximately three time the thickness (*h*) of the flow in which they form [e.g., see 25 - 30], but because individual roll waves tend to overtake one another and merge where eventually, this coarsening is interrupted at intermediate scales creating patterns with preferred λ not related to *h* [31, 32, 33, and 34]. Hence roll waves provide little information that is useful in measuring deposit thickness or deflation.

Summary: There are three types of radial grooves on Martian layered ejecta, those on SDM ejecta, those on the inner ejecta layer of DLE type-1 craters and those on the outer layer of DLE type-1 craters. The grooves on SDM ejecta exhibit characteristics like those on landslides and debris flow [35, 36, 37]. The radial groove on the inner ejecta layer of DLE type-1 craters shows characteristic similar to those scoured by the surge at Mount St Helens [37], but this does not mean that the ejecta was emplaced by a surge, only that its surface was eroded by a surge. The curvilinear grooves on the outer ejecta layer of DLE type-1 craters are morphologically similar to ones formed on debris flows [19]. Rampart morphology also provide valuable information about ejecta, such as rampart widths suggest two major types of layered ejecta, i.e., SDM craters and DLE type-1 craters (but may be more complicated). In addition, the difference in thickness of ejecta behind the outer ramparts and the height of those ramparts suggest that the material of MLE and both types of DLE craters deflated considerably after they halted. The amount of this deflation suggests that these ejecta likely contained a substantially high proportion of water (~ 50%), while the targets of SLE craters contained considerably less (i.e., ~ 10-15%). These data also suggests that although SLE craters are members of the SDM group, they also show important differences.

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