Why are the ramparts of Martian impact crater so high relief? Joseph M. Boyce, and Peter J. Mouginis-Mark, Hawaii Institute of Geophysics & Planetology, University of Hawaii, Honolulu, HI 96822.

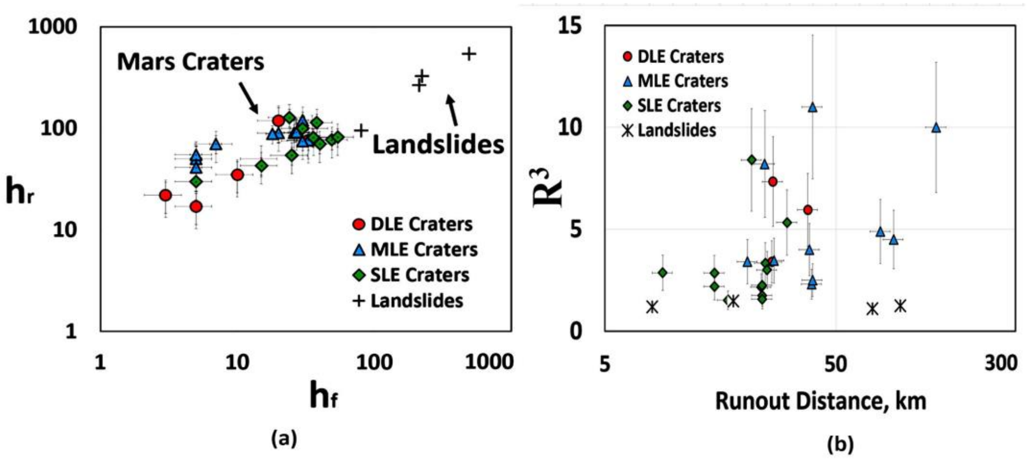
Introduction: Rampart ridges at the distal edges of Martian ejecta flows are typically higher relief than similar ridges formed on the distal edges of dense, long runout, gravity-driven geophysical flows, such as landslides [1, 2]. Because Martian ejecta are composed of granular debris of multiple-grain size (i.e., poly-dispersive), their flow is governed by the same physics and flow processes as are dense, natural geophysical flows. There is considerable evidence from observational, experimental and theoretical studies of the development of terminal ridges on such dense geophysical flows that particle size-segregation is a critical process in the development of these ridges [3-6] This mechanism forms the foundation of our model, presented here, for the formation of Martian ejecta rampart and why they are higher relief than terminal ridges on dense geophysical flows.

Data: To document the difference in relief between Martian ramparts and the terminal ridges on dense, geophysical flow, we measure the height (i.e., rampart thickness) of these ridges above the pre-flow surface (h_r), and the thickness of the flow body (h_f), immediately behind these ridges to calculate the relief between the flow and he rampart. This was done on the outer ejecta layer of 26 fresh Mars layered ejecta craters (i.e., 12 SLE, 4 type 1 DLE, and 10 MLE fresh Martian craters), and four well-preserved long runout landslides on different planetary bodies. For the Martian data, we used Mars Orbiter Laser Altimeter shot data for these measurements. In addition, to determine h_r and h_f for the geophysical flows in this study, we used topographic data cited in the literature. These flows include the Blackhawk landslide [7] on Earth, Tsiolkovsky landslide on the moon [8], a Martian landslide in Valles Marineris [9], and a landslide on Ceres [10]. We note that the ramparts of many terrestrial long runout landslide are very subdued and cannot be accurately measured or if on glaciers may be produced by plowing instead of particle segregation (e.g., Sherman glacier landslide).

Results: Figure 1a is a plot of h_r as a function of h_f that shows that ramparts on Martian layered ejecta are higher (and thicker) relative to their flow thickness and compared with the terminal ridges on geophysical flows. It shows that the thickness of the geophysical flows increases at approximately the same rate as the height of their terminal ridges increase, but ramparts on Martian ejecta increase in height at a slightly lower rate relative to the increase in thickness of their flows. We used the h_f and h_r data to calculate h_r/h_f, i.e., the Relative Relief Ratio (R^3). This ratio is a measure of the relative relief of ramparts and terminal ridges relative to their flow thickness. Figure 1b is a plot of this function relative to runout distance of their flows, and shows that the average R^3 ratio of terminal ridges on long runout landslides on different planetary bodies is ~ 1.25, no matter the runout distance. In contrast, the average R^3 of Martian ejecta ramparts is substantially larger, at ~ 4.60, although there is considerable scatter in the Martian ramparts data because of the topographically irregular nature of Martian ramparts [11].

Model for development of high relief Martian ejecta ramparts: We propose that the relatively high relief of Martian ejecta ramparts compared with the relief of ramparts on dense, geophysical flows is due to differences in their origins that cause different flow conditions. Typically, nearly all of the mass of dense, geophysical flows (like landslides) begins movement from a local source at essentially the same time (unsteady flow) with only gravity driving movement and controlling its velocity [12]. In contrast, during impact crater formation, the ejected fragments travels along ballistic trajectories in a cone-shaped ejecta curtain where the first material ejected from the crater (i.e., at its center) is the highest velocity and thrown the furthest, while the last material ejected is the lowest velocity, and barely makes it out of the crater. This means that close to the crater, the velocity of the ejecta flows may be nearly the same, or less, than if it were gravity-driven alone [13]. However, a substantial portion of the ejecta further away from the crater will strike the surface and start its ground-hugging flow at a substantially higher velocity than if it were a gravity-driven geophysical flow (e.g., ejecta at ~ 0.5 radius (R) from a 10 km Martian crater strike the surface at nearly 150 m/sec. horizontal velocity, far greater than known gravity driven landslides [13]). This results in higher average particle velocity of debris outward in ejecta flows**.** Although abundant large particles are required to build large ramparts and likely supplied by target material eroded by impact of the primary ejecta [14], probably of greater importance is the typically higher average velocity of ejecta flows. The high velocity of ejecta flows has two major effects on producing high ramparts. These are: 1) a greater drive to push the growing ramparts along for a greater distance providing more time and distance for it to accumulate additional large particles, and 2) the driving force to push the flow front to the top of even a high rampart where the flow can deposit its load of large particles. This enables ramparts to grow relatively large on ejecta flows, while the relatively lower velocity geophysical flows lack the same drive to build their terminal ridges large and high before stopping. Adding to the relative relief of the ramparts, like on debris flows, typically the body of the ejecta flow elongates markedly and accelerates less rapidly than the flow front [15]. This causes the profile of the flow to stretch in length and attenuate in height with increase time and distance traveled. When the flow halts due to friction, the head of the flow that had been pushed up against the rampart to its height, then drains back away from it. This leaves a relatively high relief rampart standing above the relatively thin ejecta flow and surrounding surface. In addition, even if the ejecta is water-rich, this likely add only about 10 % of relief to the rampart as the flow densifies [16].

References: [1] Carr et al., 1977. JGR., 82, 4055 – 4065.; [2] Baratoux, et al., 2005.JGR, v. 110. E04011,doi:10.1029/2004 JE002314.; [3] Middleton, 1970. Geol. Assoc. Can. Spec. Pap., 7, 253–272; [4] Forterre, Y., Pouliquen, O., 2008. Ann. Rev. Fluid Mech. 40, 1-24.; [5] Johnson et al., 2012. JGR., 117, F01032, doi:10.1029/2011JF002185.; [6] Gray, J, 2019. J. Fluid Mech., 50, 407-433; [7] Shreve, R., 1966. Natl. Acad. Sci. Publ., 1603, 395-4012; [8] Boyce J., Mouginis-Mark, P., 2019. Icarus, 337, 113464. [9] Boyce J., Mouginis-Mark, P., 2018. LPSC. XXXXIX Abs. # 1116.; [10] (Schmitt B., et al., 2017. Nature Geoscience, DOI:10.1038/ NEO2936; [11] Mouginis-Mar k, P., Baloga, S., 2005.MAPS. 41, 10, 1469-1482); [12] Simpson, 1997. Cambridge Univ. Press; [13] Melosh, J., 1989. Oxford U. Press, 245 p; [14] Bart, G., Melosh, J., 2007. GRL. V. 34, L07203, doi:10.1029/2007 GL029306; [15] Iverson, R., 1997. Rev. Geophys., 35(3), 245–296, doi:10.1029 /97RG00426.; [16] Branney, M., Kokelaar, P., 2002. Memoir of the Geological Society of London, 152.



(a) (b)

Figure 1. Graph a shows that the height/thickness of the geophysical flows increases at about the same rate as the height/thickness of their terminal ridges increase, while Martian ejecta ramparts are higher and thicker than the ridges on geophysical flows, and increase in height/thickness at a lower rate relative to the thickness of their flow. Figure 1b is a plot of R^3 (h_r/h_f) and shows that compared to terminal ridges on geophysical flow, the relief of rampart on Martian layered ejecta is considerably greater relative to the thickness of their flow body.