A NEW PHENOMENOLOGICAL EJECTA EXCAVATION AND EMPLACEMENT MODEL FOR DLE CRATERS.

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Introduction: The ejecta blankets of impact craters in volatile-rich environments often possess characteristic ejecta morphologies. Martian impact craters are typically surrounded by layered ejecta deposits that terminate in ramparts [1]. The so-called "layered" or "rampart" craters are commonly classified as single-layer ejecta (SLE), double-layer ejecta (DLE), and multiple-layer ejecta (MLE) craters [2]. Martian DLE craters are typically 5 to 25 km in diameter and can be found at a variety of terrain types, elevation levels and surface ages and are located in both hemispheres of Mars, though they are concentrated at mid-latitudes, preferentially in the northern lowlands [3-6]. The deposition chronology of the two layers is still controversial. Some authors have supposed that the inner layer overlays the outer layer which indicates a successive deposition [1, 7, 8], whereas other authors have assumed that the inner layer was deposited first, followed by the outer layer after a hiatus, e.g. involving a high-velocity outflow of materials from tornadic winds and the change from a supersonic to a subsonic flow generated by the advancing ejecta curtain or a base surge [3, 6]. The analysis of high-resolution image data, especially HiRISE (High Resolution Imaging Science Experiment) and CTX (Context Camera), provide new insights into the formation of DLE craters. We present a detailed case study of the Martian Steinheim crater (11.2 km diameter), a textbook like, pristine DLE crater, including geological mapping, morphological, morphometric and hyperspectral analyzes. The results are focused on the crater ejecta and are combined and extended to other DLE craters to build a sound and comprehensive basis for a new phenomenological formation and ejecta emplacement model.

Observations: Our results show that outer ejecta layer is the result of a multitude of relatively thin debris flow like geological mass movements. The varying positions and characteristics of the different flow tongues of the theses granular flows indicate varying source areas as well as velocities and thus long transportation paths and mobilization of the outer ejecta after landing. The granular flows take place in a debris avalanche or debris flow mode depending on the respective water content (saturation) and velocity. The crater nearest source areas are buried underneath the outer parts of the inner ejecta layer that clearly overlays the outer layer.

The inner ejecta layer is deposited as a geological mass movement in a landslide mode that starts at least partially within the present day crater rim and extents over the entire inner layer building longitudinal striations as depositional features. This ejecta landslide had to set into motion nearly simultaneously around the crater rim as a coherent body because otherwise interactions between flows in terms of time and space would lead to large-scale overlapping zones, which were not observed.

Discussion: A new ejecta excavation and emplacement model for DLE craters is developed that is constrained by the observation of abundant novel ejecta morphologies and surface features in high-resolution that allow to derive a deposition chronology and emplacement mechanisms (Fig. 1). The key results are:

(1) DLE craters on Mars are the result of an impact event into a rock/ice mixture that produces large amounts of shock-induced vaporization and melting of ground ice which leads to high ejection angles, relatively proximal landing positions, high ejecta thicknesses in the most proximal part of the ejecta deposition, and an ejecta curtain with relatively wet (in terms of water in liquid form) composition in the distal part and dryer composition in the proximal part.

(2) The ejecta of the medial and distal landing zones possesses significant amounts of liquid water and strong outwards directed horizontal components of movement leading to a propagation as "wet" granular flows after ejecta deposition in which the relative amount of molten ice determines whether the flow take place in a debris avalanche mode or (if saturated) in a debris flow mode. In the process of flowing, the outer ejecta layer overruns numerous early formed secondary craters, that are partly still visible.

(3) The ejecta of the proximal landing zone is characterized by relatively low amounts of liquid water and initial low horizontal velocities. During the emplacement stage, the large and slow-moving ejecta volumes at the transient crater rim and outer crater slope induce increased frictional heating at a critical loading pressure that finally leads to basal melting of the ice components of the ejecta. The localized reduction of the internal friction in the basal part of the ejecta body initiates an ejecta landslide that overrun and superimpose the medial parts of the ejecta deposits forming the today visible inner ejecta layer with its morphological landslide characteristics.

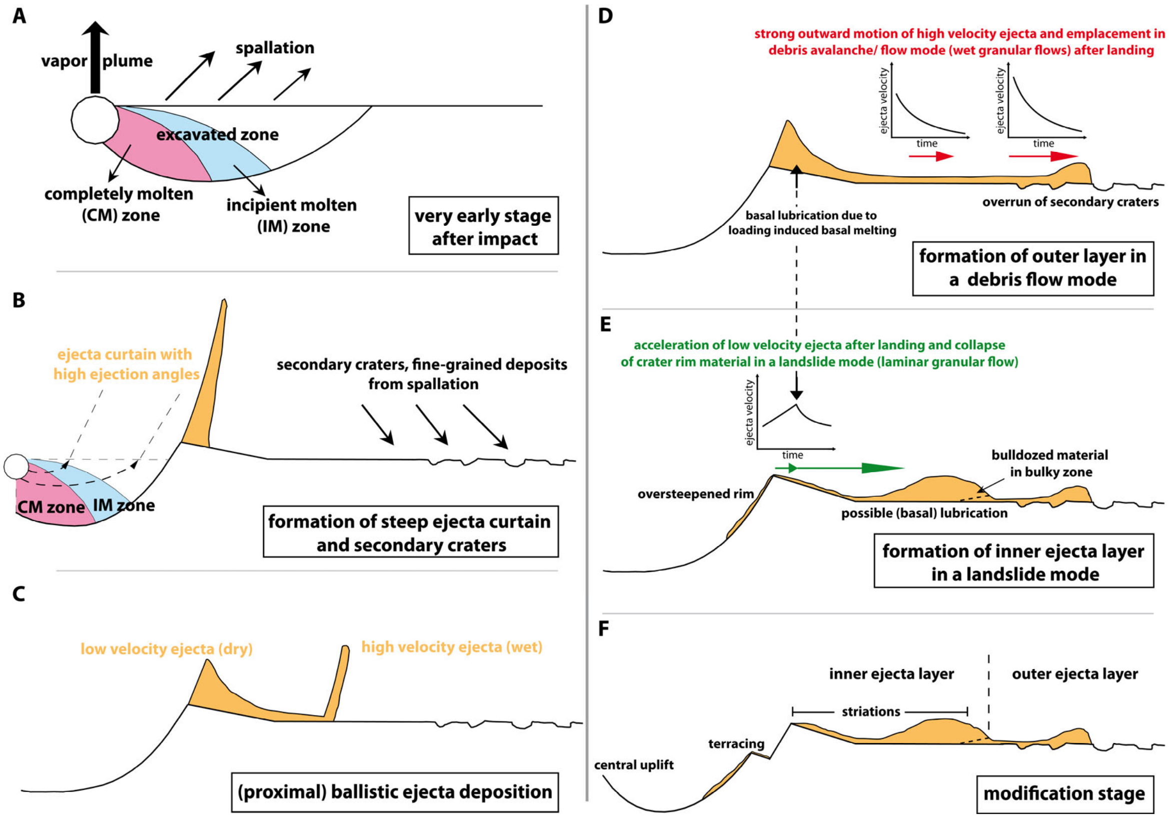

Fig. 1: Excavation and emplacement model for DLE craters: (A) In the very early stage after impact a small vapor plume is formed, spallation and shock-induced vaporization and melting of ice from the pore spaces occur (modified after [9]). (B) The excavated zone includes large amounts of molten and vaporized ice that lead to high ejection angles. In addition, secondary craters are formed by spallation fragments. (C) The high ejection angles lead to relatively proximal landing positions. The relative amount of molten ice within the ejecta curtain decreases from the early to the late stage leading to a ballistic ejecta deposition with relatively dry (in terms of water in liquid form) proximal ejecta in comparison to the "wetter" distal ejecta. (D) The ejecta of the medial and distal landing zones possess significant amounts of liquid water and strong outwards directed components of movement leading to a propagation as "wet" granular flows after landing in which the relative amount of molten ice determines whether the flow take place in a debris avalanche mode or (if saturated) in a debris flow mode. (E) The ejecta of the proximal landing zone is characterized by relatively low amounts of liquid water and initial low horizontal velocities. The large and slow-moving ejecta volumes at the transient crater rim and slope and the resulting loading pressure induce increased frictional heating and thus a basal melting of the ice components of the ejecta leading to a reduction of the internal friction in the basal part of the ejecta body. As a consequence, the ejecta in this area starts to slide and accelerates inducing an ejecta landslide that overrun and superimpose the medial parts of the ejecta deposits forming the inner ejecta layer. (F) The outer parts of the transient crater rim and slope, and thus of the landslide's source area, are collapsed into the crater cavity forming the final crater. (all dimension are not in scale)

Our results indicate that the outwards directed collapse of crater rim ejecta in a landslide mode take place not only for DLE craters but also for several MLE and SLE craters on Mars as well as possibly for the terrestrial Ries crater. Additional numerical and experimental studies are required to verify the functionality of our ejecta emplacement model and the existence of ejecta landslides also for other crater types and planetary bodies with volatile-rich environments, such as Ganymede and Europa.

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References: [1] Carr, M. H. et al. (1977) J. Geophys. Res., vol. 82, p. 4055-4065. [2] Barlow, N. G. et al. (2000) J. Geophys. Res., vol. 105, p. 26.733-26.738. [3] Mouginis-Mark, P. J. (1981) Icarus, vol. 45, p. 60-76. [4] Barlow, N. G. and Bradley, T. L. (1990) Icarus, vol. 87, p. 156-179. [5] Barlow, N. G. and Perez, C. B. (2003) J. Geophys. Res., vol. 108, p. 5085. [6] Boyce, J. M. and Mouginis-Mark, P. J. (2006) J. Geophys. Res., vol. 111, E10005. [7] Osinski, G. R. (2006) Meteoritics & Planet. Sci., vol. 41, p. 1571-1586. [8] Weiss, D.K. and Head, J.W. (2013). Geophysical Research Letters 40 (15), 3819-3824. [9] Stewart, S.T. et al. (2003). In Shock Compression of Condensed Matter, Am. Inst. of Physics (2003), pp. 1–4.