EMPLACEMENT CHRONOLOGY OF DOUBLE LAYER CRATER EJECTA ON MARS.
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Introduction: Martian double layer ejecta (DLE) craters occur preferentially in the mid-latitudes in regions displaying evidence of periglacial features; hence, their formation is thought to involve volatiles in some manner [e.g., 1–5]. Their ejecta morphology consists of a distinct inner layer and a significantly thinner (~<35 m [5]) outer layer. However, the timing of the emplacement of these layers relative to one another has been a subject of debate. Some authors have proposed that the outer layer is deposited first via ballistic emplacement and is subsequently overlain by a more viscous ground-hugging flow forming the inner layer based on observations of both terrestrial and martian craters [6,7]. Others propose that the inner layer is deposited first, followed by a base surge phenomenon or tornadic winds to form the more areally extensive outer layer [1,5]. To address this question, we have inspected the contact between the inner and outer ejecta layers of three DLE craters using Mars Reconnaissance Orbiter (MRO) Context Camera (CTX, ~6 m/pixel resolution) and High Resolution Imaging Science Experiment (HiRISE, ~0.3 m/pixel) data.

Methods: Three relatively youthful-looking/well-preserved (based on morphology and the presence of pitted materials [8] on the crater floor) DLE craters were chosen for our analysis in order to look for examples of ejecta layer contacts that had experienced minimal amounts of post-emplacement modification: Maricourt, Steinheim, and an unnamed crater at 43.07°N, 225.70°E. Image analysis was conducted using Java Mission-planning and Analysis for Remote Sensing (JMARS) software [9].

Results, Interpretation, and Discussion:

Contact morphology. The morphology of the contact between the inner and outer ejecta layers of all of the DLE craters analyzed is highly variable, ranging from sharp and well-defined (Fig. 1a–c) to poorly defined (Fig. d–e) or turbulent (Fig. 1f), varying spatially around each single crater. This variation can lead to challenges in identifying syn- vs. post-impact modification processes at the layer contact. Mars Orbiter Laser Altimeter (MOLA) elevation profiles across the ejecta blankets show the inner layer sits topographically higher than the outer layer in all cases, with a sharp downward slope at the layer contact regardless of the state of the contact.

The radial features, a prime characteristic of DLE craters [5], are highly linear atop the inner ejecta layer, seemingly unaffected by topography. Conversely, the radial features associated with the outer layer are clearly deflected by pre-existing topography [5]. These features and the transition are consistent with terrestrial observations of base surges [10] formed in nuclear explosion craters and volcanic settings. These surges are capable of significant erosion with or without significant deposition of material and exhibit a change in morphology occurring at the point where the surge velocity shifts from supersonic to subsonic [5,10].

Emplacement Chronology. Based on the variability of contact morphology around each of the DLE craters analyzed and the presence of apparent base surge scouring features, we propose the following sequence of events for the emplacement of DLE crater ejecta following the initial impact event:

1. Outer ejecta layer emplacement via ballistic sedimentation and radial flow [e.g., 11]
2. Inner ejecta layer emplacement as a viscous ground-hugging flow
3. Base surge formation and subsequent radial flow across the inner and outer ejecta layers

Ejecta sourced from the uppermost portion of the target region [12] is emplaced via ballistic sedimentation and radial flow [e.g., 11] during the excavation stage of the impact process to form the outer layer and secondary craters. The inner ejecta layer, potentially sourced from deeper portions of the target region [12], is emplaced during the modification (final) stages of the impact process as a melt-rich ground-hugging flow (note that "melt" can take the form of water from molten ground ice).

As crater modification ceases, material entrained in the ejecta plume above the crater begins to fall and move radially outwards from the crater as a base surge [13], scouring the radial features into the inner and outer layers of the ejecta blanket and overprinting the original ejecta morphology. The deeper the crater, the smaller the base surge produced by the impact event [14,15]. As the surge passes over the viscous melt-rich inner layer, portions of the layer edge are modified, destroying the well-defined contact between the inner and outer layers and resulting in the turbulent morphologies seen in Fig. 1d–f. Variations in the size/density of the base surge in different impact events may explain the range of contact morphologies observed around DLE craters, with very weak surges leaving the contact relatively intact and well defined.

This sequence of events, with the inner layer being deposited after the emplacement of the outer layer as proposed by Osinski [6] and Wulf et al. [7], followed by modification by a late-stage base surge, explains several observed features including: 1) the sharp contact observed along some portions of the ejecta layers, 2) the modified appearance in other portions, and 3) the formation of the radial features extending across both ejecta layers. This proposed emplacement sequence builds on earlier suggestions [1,5] that DLE craters involve some kind of base surge; however, it differs in that the base surge in our sequence is unrelated to the emplacement of the outer ejecta layer.

Boyce and Mouginis-Mark [5] propose that the outer ejecta layer is emplaced after the inner layer via a base surge; however, for this to be a viable source for the outer layer, 30–40% of the total ejecta volume would need to be lofted into the explosion column to form the surge [5]. The sharp contacts observed in many locations do not support the deposition of such a large amount of material atop the inner layer. More detailed mapping of ejecta layer contacts around well-preserved DLE craters will be conducted in order to help better constrain the mechanism behind their formation. As DLE occurrence is thought to be linked to volatile content of the target rock [e.g., 1–5], and base surge formation requires the presence of volatiles and the size is controlled in part by crater depth [14,15], analysis of other factors such as the target properties and excavation depth may also help to answer the question of why base surges only appear to be associated with DLE craters and not other fluidized ejecta craters based on the lack of radial scouring features around other fluidized ejecta craters [5].

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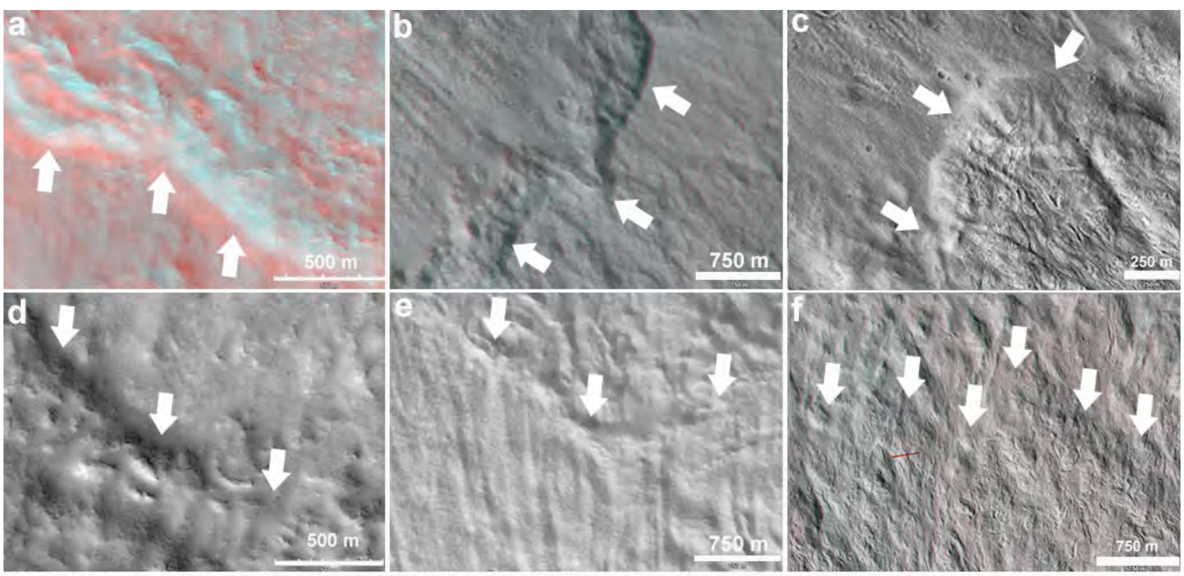

Figure 1: DLE crater ejecta layer contacts showing well-defined (upper row) and poorly defined/modified (lower row) examples. Columns from left to right are Maricourt, Steinheim, and an unnamed crater at 43.24°N, 225.79°E. **a)** HiRISE anaglyph ESP_024848_2335_ESP_019547_2335. **b)** HiRISE anaglyph PSP_008303_2345_PSP_00736_2345. **c)** HiRISE ESP_25892_2235. **d)** HiRISE ESP_018268_2335. **e)** HiRISE PSP_007235_2350. **f)** HiRISE anaglyph ESP_020156_2235_ESP_028714_2235. Image credit: NASA/JPL-Caltech/University of Arizona.