Formation of double-layered ejecta craters on Mars: A glacial substrate model

David K. Weiss1 and James W. Head1

Received 27 June 2013; revised 15 July 2013; accepted 19 July 2013; published 7 August 2013.

[1] A class of Martian impact craters with particularly unusual ejecta characteristics (double-layered ejecta (DLE) craters) are preferentially located in the midlatitudes in both hemispheres of Mars. Unlike today, decameters thick deposits of snow and ice occupied these same latitudes for significant periods during the Amazonian period. We assess the hypothesis that the unusual double-layer morphology could be related to impact into a snow and ice glacial substrate followed by landsliding of ejecta off of the structurally uplifted rim. We find that many characteristics of DLE craters (e.g., latitudinal distribution, lack of secondaries, landslide-like textures, evidence for overthrusting, relation to other crater types, etc.) are consistent with such an origin. Citation: Weiss, D. K., and J. W. Head (2013), Formation of double-layered ejecta craters on Mars: A glacial substrate model, Geophys. Res. Lett., 40, 3819–3824, doi:10.1002/grl.50778.

1. Introduction

[2] Martian impact craters often possess unusual ejecta characteristics relative to ballistically dominated lunar and Mercurian impact crater ejecta: lobate ejecta deposits appear to have been fluidized during their emplacement, although the mode of fluidization is debated [Carr et al., 1977; Gault and Greeley, 1978; Mouginis-Mark, 1979, 1981; Woronow, 1981; Boyce and Mouginis-Mark, 2006].

[3] Particularly enigmatic amongst the fluidized ejecta craters are double-layered ejecta (DLE) craters (Figures 1a and 1b), located in the mid-high latitudes of Mars in both hemispheres (Figure 1e) [Boyce and Mouginis-Mark, 2006] and characterized by two ejecta facies (Figure 1a): the inner facies possesses a distinctive radial texture of parallel ridges and grooves. The major unusual features of DLE craters include the following (Figure 1): (1) a regional, midlatitude-dependent distribution [Boyce and Mouginis-Mark, 2006]; (2) a paucity of secondary craters [Boyce and Mouginis-Mark, 2006]; (3) a characteristic radial grooved texture [Boyce and Mouginis-Mark, 2006] and megablock distribution (see supporting information) [Wulf et al., 2013]; (4) apparent superposition of the inner ejecta facies over the outer [Carr et al., 1977; Barlow and Perez, 2003; Osinski et al., 2011; Wulf et al., 2012]; (5) an unusual annular depression at the base of the rim structural uplift and enhanced positive annular topography at the distal edge of the inner facies [Boyce and Mouginis-Mark, 2006]; (6) an association with other distinctive crater types (pedestal (Pd) craters, excess ejecta (EE) craters [Kadish and Head, 2011]; Figure 1f), and (7) a sharp rim crest.

[4] Many of these unusual characteristics have been interpreted to be related to several factors: (1) the presence of the Martian atmosphere [Schultz and Gault, 1979; Schultz, 1992], (2) the presence of volatiles within the regolith target materials [Mouginis-Mark, 1981; Barlow and Bradley, 1990; Costard, 1994; Barlow and Perez, 2003; Barlow, 2005; Osinski, 2006; Boyce and Mouginis-Mark, 2006], (3) some combination of these factors [Barlow et al., 2005; Boyce and Mouginis-Mark, 2006, Komatsu et al., 2007], (4) a base surge [Boyce and Mouginis-Mark, 2006], (5) impact melt overtopping the crater rim [Osinski, 2006; Osinski et al., 2011], or (6) impact into a subsurface ice layer [Senft and Stewart, 2008]. Prior models, however, have been unsuccessful in reconciling their predictions with observations (see supporting information).

[5] Noting the latitudinal distribution (Figure 1e), we explore a new hypothesis, the glacial substrate model, which attributes the unusual characteristics of DLE craters (Figure 1b) to the presence of decameters thick surface snow and ice (glacial deposits) that existed periodically in mid-high latitude regions due to spin-axis/orbital variations [Laskar et al., 2004]. Recent work (synthesized in Head and Marchant [2009]) shows that nonpolar regions have often been covered with decameters of snow and ice [Head et al., 2005; Meresse et al., 2006; Head et al., 2006; Kadish et al., 2009; Pedersen et al., 2010; Dickson et al., 2008; Kress and Head, 2008]. Could the presence of a glacial substrate, such as these regional ice layers, in earlier Martian history have been a factor in producing the unusual morphology of DLE craters?

2. Testing the Hypothesis

[6] We examine each of the seven unusual characteristics of DLE craters enumerated above (Figure 1b) and test these against the glacial substrate model to assess its plausibility and usefulness for further analysis.

2.1. Latitude Dependence

[7] DLE craters are primarily located in the mid-high latitudes of Mars (Figure 1e) [Boyce and Mouginis-Mark, 2006], and new mapping [Barlow and Boyce, 2013] has shown that DLE craters are present in the latitudinal bands 25°N–80° N and 30°S–70°S. A wide variety of studies of different landforms, summarized in Head and Marchant [2009], have established the presence of nonpolar surface snow and ice deposits during extended periods of the
Amazonian in these latitudinal bands (Figure 1e). These landforms include latitude-dependent mantles [Mustard et al., 2001; Head et al., 2003], Pd craters [Kadish et al., 2009], EE craters [Black and Stewart, 2008], lobate debris aprons, lineated valley fill, and plateau ice deposits [Head et al., 2010]. We hypothesize that the icy substrate layer beneath Pd and EE craters, often at least 50 m thick, may also be related to DLE craters.

2.2. Paucity of Secondary Craters

DLE craters exhibit a scarcity of evident secondary craters [Boyce and Mouginis-Mark, 2006]. This has been explained by the fragmentation of ejecta blocks due to (1) atmospheric turbulence [Schulte, 1992], (2) volatiles within the regolith ejecta blocks and target material [Boyce and Mouginis-Mark, 2006], (3) crushing of ejecta blocks by dynamic pressure in high-velocity outflow of gas during ejection [Boyce and Mouginis-Mark, 2006], in addition to (4) burial of secondary craters by ejecta flow [Mouginis-Mark, 1979; Osinski, 2006], and (5) primarily near-rim ejecta deposition [Senft and Stewart, 2008]. Alternatively, in the glacial substrate model, if secondary craters were emplaced when decameters of ice were present, the small size and relatively shallow depths of the secondary craters would be likely to prevent their preservation subsequent to the sublimation loss of the glacial substrate during a later climate regime.

2.3. Radial Textures

DLE craters exhibit radial striations that extend from the crater rim to the outer edge of the inner ejecta deposit. These striations have been suggested to result from radial scouring of wind vortices by the advancing ejecta curtain...
to be the origin of the landslide. The location of this zone induced landsliding occurred due to the lubrication of a outer ejecta layer (Figure 1b). The annuli around DLE DLE annuli depressions lie at an elevation very close to that Boyce and Mouginis-Mark with the larger sizes of the landforms themselves (Sherman Martian grooves (~100 m across; Figure 1c) is consistent annuli farther out as far as ~1.5 \( R \) from the rim [Settle and Head, 1979].

2.6. Relation to Other Crater Types

[12] DLE craters are linked by their areal distribution and their glacial substrate [Kadish and Head, 2011] to other crater types, Pd craters [Kadish et al., 2009], EE craters [Black and Stewart, 2008], and perched (Pr) craters [Meresse et al., 2006; Kadish and Head, 2011] which have latitudinal distributions similar to that of DLE craters. Kadish and Head [2011] proposed that Pd/EE/Pr craters (Figure 1f) share the common theme of formation on a glacial snow and ice layer. The classification of EE craters shows that the majority of EE craters have DLE morphology [Kadish and Head, 2011].

[13] Excess ejecta (EE) craters as identified by Black and Stewart [2008] are craters with volumes of material above the pre-impact surface \( (V_{above}) \) larger than the crater cavity volumes \( (V_{cavity}) \) by factors of 2.5 to 28.5 [Kadish and Head, 2011]. In the proposed EE crater formation, an icy surface layer is present at the time of impact [Black and Stewart 2008]. The impact excavates material below the icy surface layer, and the resultant ejecta deposit covers the icy layer proximal to the crater cavity. Black and Stewart [2008] propose that the ejecta deposit will insulate the underlying icy layer proximal to the crater cavity and slow sublimation. Climate change causes the regional icy layer to sublime, and the terrain outside the crater ejecta deposit will disappear, leaving an anomalously large volume: that of the persistent underlying icy layer protected by the ejecta deposit.

[14] Kadish and Head [2011] observe that there may exist EE craters too large to detect: the volume of “excess” ejecta becomes proportionately smaller as the crater diameter (and thus ejecta volume) increases, making the positive identification of an EE crater more difficult at larger diameters (>25 km). Since most EE craters are also DLE craters and since large EE craters would be difficult to recognize as EE craters, larger DLE craters may also be EE craters that formed through impact into an icy surface layer.

[15] On the basis of the substrate thickness crater diameter relationships for these craters (Figure 1f), it is clear that DLE craters exhibit a larger average crater diameter and larger upper limit in crater diameter than EE craters. This is consistent with formation in a glacial substrate: the larger DLE craters are not classified as EE craters because their \( V_{above}/V_{cavity} \) signal is drowned out by their larger ejecta volumes.

2.7. Rim Crest

[16] The outer rim crests of DLE craters appear to be steep [Boyce and Mouginis-Mark, 2006]. In concert with the other lines of evidence, this is consistent with the sliding of ejecta off of the structurally uplifted inner rim facilitated by a glacial substrate, resulting in the production of the inner facies.

3. Toward a Quantitative Glacial Substrate Model

[17] If the morphological characteristics of DLE craters can be explained through a landslide mode of ejecta off an underlying glacial substrate, does the angle of the structural uplift play a role in governing ejecta stability? An analysis of the force balance of ejecta sliding on a glacial substrate at the proximal edge of the structurally uplifted rim crest constrains the structural uplift angles of DLE and EE craters which would facilitate a landslide of the near-rim ejecta.
Figure 2. (a) Structural uplift relationship approximated using the rim height and structural uplift functions adapted from Stewart and Valiant [2006] and Craddock et al. [1997]. (b) Force balance calculation for a 1 kg mass of ejecta under two conditions: overlying a glacial substrate (blue line) and overlying a regolith substrate (black line). For \( \mu = 0.1 \), a structural uplift angle of \(-5.7^\circ\) will cause ejecta overlying a glacial substrate to be unstable (net force > 0). (c) Crater diameter-frequency distribution: DLE craters fall off beyond \(-25\) km.

[18] If the ejecta is considered to be a distinct unit overlying the pre-impact substrate, the balance of forces acting on the ejecta can be divided into (1) normal force upwards into the ejecta, (2) gravitational force acting downwards parallel to the sliding plane, and (3) frictional force (governed by the static coefficient of friction, \( \mu \)) between the ejecta and the substrate. Thus, the outer rim crest angle (\( \theta \)) at which ejecta overlying a glacial substrate becomes unstable can be represented by \( \theta = \tan^{-1}(\mu) \). Terrestrial landslides on glaciers generally have dynamic \( \mu \) values ranging from 0.03–0.1 [Sosio et al., 2008]. While terrestrial landslides occur much closer to the melting point of ice than surface temperatures of Mars in the Amazonian, the high temperature environment of the area proximal to the crater following the impact [e.g., Wrobel et al., 2006] will serve to decrease the static \( \mu \) by producing melt which may trigger the landslide, a process which would be enhanced by deposition of even a moderately heated ejecta facies. Alternatively, if the landslide occurred in the latter stages of crater formation, the initial horizontal velocity of ejecta at the time of deposition may be enough to overcome the friction, facilitating the landslide, and so we apply dynamic terrestrial coefficients of friction to post-impact landslides on Mars.

[19] The force balance has been calculated for a 1 kg mass of ejecta overlying a glacial substrate to determine what rim crest angles produce an ejecta instability (i.e., the angle at which net force on the ejecta is > 0; Figure 2b). We find that ejecta overlying a glacial substrate (\( \mu = 0.1 \)) is unstable at crater rim structural uplift angles that exceed \(-5.7^\circ\) (Figure 2b).

[20] Comparing our calculation results with an approximation for structural uplift [Stewart and Valiant 2006] as a function of crater diameter and crater radii (\( R \)) from the rim crest (Figure 2a), we find that the ejecta instability angle (\(-5.7^\circ\)) is reached on the structural uplift of craters 0.1 \( R \) to 0.5 \( R \) from the rim crest up to a crater diameter of \(-25\) km. This suggests that beyond \(-25\) km, the structural uplift angle values for craters are too low for ejecta overlying a glacial substrate to be unstable, predicting that craters >25 km in diameter should not exhibit DLE morphology. The crater diameter-frequency distribution for DLE craters (Figure 2c) shows that DLE craters do indeed fall off drastically >\(-25\) km, suggesting that EE craters beyond \(-25\) km do not have DLE morphology because their low structural uplift angles prevent landsliding of the ejecta proximal to the rim crest. DLE craters are generally not present in the \(-1\) km diameter range (Figure 2c) because their excavation depths are too shallow to excavate beneath the glacial substrate. Because the value of \( \mu \) is uncertain, we acknowledge the possibility that the ejecta instability angle may be even higher, thus predicting DLE morphology to fall off at smaller crater diameters: Figure 2b shows that the diameter-frequency of DLE craters may begin falling off after \(-15\) km.

4. Conclusions

[21] The proposed glacial substrate model (Figure 3) for DLE crater formation is interpreted to have involved the following steps: (1) Deposition of a snow and ice layer, producing a glacial substrate (Figure 3a). (2) Impact of a projectile, penetrating down into the regolith below the glacial ice, causing excavation, rim structural uplift, and ejecta emplacement (Figure 3b); secondary craters form primarily in the glacial substrate. (3) In the latter stages of formation of the ejecta facies, the inner facies is emplaced in a landslide mode, enhanced by the glacial substrate-lubricated, structurally uplifted rim (Figure 3c). This produces the sharp crater rim crest and the distinctive annular topographic low. (4) Following this emplacement, global climate change leads to removal of the surrounding icy substrate, destroying evidence of superposed secondary craters (Figure 3d).

[22] We conclude that numerous characteristics of Martian DLE craters can be plausibly explained by the presence of a glacial substrate (snow and ice layer) present during the impact events. Further analysis and testing of this model can be undertaken by (1) dating of individual DLE craters and comparison of these ages with the chronology of ice deposits [e.g., Head and Marchant, 2009] and (2) comparison of the diameter distribution of EE craters with SLE morphology to the predicted size range.
Figure 3. Interpreted sequence of events in the glacial substrate model: (a) pre-impact target surface, (b) immediately following crater formation, (c) following the landslide on icy substrate, and (d) subsequent to sublimation of the glacial substrate.

References
Dickson, J. L., J. W. Head, and D. R. Marchant (2008), Late Amazonian glaciogluation at the dichotomy boundary on Mars: Evidence for glacial thickness maxima and multiple glacial phases, Geology, 36(5), 411–414.
Kadish, S. J., and J. W. Head (2011), Impacts into non-polar ice-rich paleodeposits on Mars: Excess ejecta craters, perched craters and pedastal...


Weiss and Head: A Glacial Substrate Model
