Emplacement of Martian rampart crater deposits

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[1] We present a basic continuum flow model for the emplacement of the distal rampart crater deposits on Mars. Assuming cylindrical symmetry, analytic solutions of the volume and momentum conservation equations yield time-dependent flow thickness and velocity profiles. The momentum equation has an inertial term, and a frictional resistance term that is proportional to the local volumetric flow rate. We find that only a few basic physical processes are necessary to form sharp distal ramparts. First, there must be sufficient material to form a continuum overland flow. Then, for simple choices of boundary conditions at the source of the flow, distal ramparts form naturally due to the cylindrical geometry, the inertia of the flow, and local frictional resistance. THEMIS images of rampart deposits show that the ejecta flow velocities were relatively slow, being diverted by preexisting obstacles even within \( \sim 0.2 \) crater radii from the rim of the parent crater. To develop inferences about rampart deposit emplacement, we require measurements of the crater radius and flow distance, and assumptions about the maximum source flow velocity and depth. We measured nine clearly expressed rampart deposits for craters with diameters of 3.4–17.0 km. The model provides estimates of the emplacement time, the rampart width, and the shape of the radial flow depth profiles. We find that modest velocities of \( \sim 27–116 \) m s\(^{-1}\), maximum source flow depths of 10–40 m, and emplacement durations of 12–31 min adequately explain the morphologies of selected rampart craters.


1. Introduction

[2] The rampart craters on Mars are thought to provide a unique diagnostic of target properties and the ambient conditions at the time of impact. These craters commonly possess lobate deposits that appear to have been fluidized during emplacement (Figure 1) [Carr et al., 1977; Gault and Greeley, 1978; Mouginis-Mark, 1978, 1981, 1987; Melosh, 1989]. Typically this has been attributed to the presence of volatiles (water or ice) within the target material at the time of crater formation. Alternative models that emphasize atmospheric effects have also been proposed [e.g., Schultz and Gault, 1979; Schultz, 1992; Barnouin-Jha and Schultz, 1996, 1998]. The spatial and temporal variations in ejecta characteristics can best be ascribed to target variations (e.g., volatile content), the latitude and altitude of the parent crater, and possible temporal changes in the climate [Mouginis-Mark, 1979; Horner and Greeley, 1987; Schultz, 1992; Barnouin-Jha and Schultz, 1998; Barlow et al., 2000; Barlow and Perez, 2003].

[3] Several different classifications of rampart craters have been identified previously in the literature. The three most common types have been formally classified by Barlow et al. [2000] as single layered ejecta (SLE), double layered ejecta (DLE), or multilayered ejecta (MLE) craters. The wider coverage and better resolutions of the Thermal Emission Imaging Spectrometer (THEMIS) and Mars Orbiter Camera (MOC) data reveal that MLE craters are more numerous than previously thought. On the basis of morphologic considerations, rampart deposits appear to be more closely associated with the processes that formed the SLE and MLE craters, and are distinct from DLE craters, which typically possess no ramparts.

[4] Our analysis here focuses on craters having well-defined and relatively simple distal ramparts. These craters typically have diameters in the range 4–18 km for SLE craters and 15–35 km for MLE craters. Characteristic features of these craters include (1) a distal ridge, or “rampart,” around the perimeter of the ejecta (Figure 1) and (2) ejecta that appear to have been emplaced as ground-hugging flows. The distal ramparts have typical heights of about 100 m, with a range of 25–180 m, and apparent widths of 0.5–2 km (P. J. Mouginis-Mark, unpublished data, 2005). Very little relief is observed in the crater-ward portion of ejecta deposit.

[5] In this study, we investigate the hypothesis that rampart deposits were emplaced as a continuum fluid that...
emanated from the rim and flowed over the surface. We also explore the possibility that the onset of continuum flow occurred at a significant distance from the rim. We first present morphologic evidence supporting the former hypothesis for three rampart craters with particularly well-expressed diagnostics of ground-hugging surface flow. Subsequently, we present a basic quantitative continuum flow model to determine the minimum set of physical processes and conditions that produce ramparts. This model is used to derive quantitative inferences about emplacement times, initial velocities, and flow thickness profiles. We use the most basic forms of volume and momentum conservation equations and consider the simplest plausible forms for boundary conditions on the flow thickness and velocity at the source of the continuum flow regime. We then present and analyze data for nine relatively fresh rampart craters located in Lunae and Solis Planum. These rampart craters all have well-defined ejecta deposits and crater rims suitable for detailed morphometric analysis.

We make no attempt to develop a theoretical model of the detailed structures of the ramparts or surface morphologies found on the ejecta. At present, the model is not sufficiently developed to provide any inferences about the role of volatiles, deposition or entrainment of sediments during emplacement, or the possible influence of atmospheric effects or target properties. Such issues are reserved for later investigations.

2. Emplacement Hypothesis

There has been abundant evidence in the literature for many years [e.g., Carr et al., 1977; Gault and Greeley, 1978; Mouginis-Mark, 1979; Melosh, 1989; Baratoux et al., 2005] that rampart deposits are associated with ground-hugging surficial flow. THEMIS and MOC imaging continue to support this viewpoint. In Figure 2, we show three examples of rampart craters in the diameter range 8.2–11.1 km, where ejecta have encountered a topographic obstacle. These obstacles are either preexisting mesas that were partially surrounded by the radial ejecta flow, or they are the rim crests of preexisting impact craters. Figures 2a and 2b show two examples indicating flow around
Figure 2. Three examples of rampart craters in the diameter range 8.2–11.1 km where obstacles close to the rim of the parent crater have diverted the surface flow of ejecta. See Table 1 for morphometric data. (a) THEMIS frame V10292014; (b) subframe of Figure 2a, showing location of each MOLA shot used to estimate the height of the mesa south of the crater rim. Elevations are in meters. Open white circles show traces of individual MOLA orbit numbers 11722, 12231, 12464, and 19863. (c) THEMIS frame V02685008; (d) subframe of Figure 2c, showing individual point heights from MOLA orbit numbers 10943, 12182, 12427, 13339, 13911, 14238, 19305, and 20304. (e) THEMIS frame V09878006; (f) subframe of Figure 2e, showing individual point heights from MOLA orbit numbers 11785, 17561, 18177, and 19798. The height of the small (2.5 km diameter) crater is estimated from the rim crest elevation of 3366 m and the 3281 m elevation of the terrain to the southwest.

obstacles both near the crater rim and distally. Figure 2c shows infilling of the small adjacent crater to the southwest, as well as flow diversion around it.

[8] In all three cases, the deposited ejecta layers appear to have been emplaced essentially as solitary sheets of material that can be traced from the distal ramparts approximately to the crater rims. There is virtually no evidence beyond the distal ramparts for a ballistic emplacement of a significant component of the ejecta that comprises the remaining deposit.

[9] The mechanism of proximal transformation from ejecta excavation to overland flow is unknown, but conceivably might involve collapse of steeply ejected volatile-rich target material or ballistic ejection of fluidized slugs [e.g., Gault and Greeley, 1978; Melosh, 1989]. However, regardless of the details of the transformation process, the morphologic evidence suggests that continuum flow appears to start from close to the crater rim in many cases, or somewhat further out in the cases where some form of inner deposit is evident (e.g., Figure 1).

[10] The simplest choice for an emplacement hypothesis suggested by these examples is one of a continuous flow that moved across the preexisting surface from a point near the rim out to the distal locations observed today. Although there may be minor anomalies, the material comprising the distal ramparts generally issued from the crater rim earlier than proximal deposit constituents that now reside behind it.

[11] The morphometric data (Table 1) that can now be obtained from THEMIS and the Mars Orbiter Laser Altimeter (MOLA) are particularly diagnostic of the flow thicknesses and their abilities to surmount preexisting obstacles. Using the MOLA Precision Experiment Data Record topographic data coregistered to the THEMIS VIS images, we have been able to constrain the height of the obstacle in each case (Table 1). These heights range from 85–235 m. We point out that these values are only minima, as it is
unlikely that the MOLA footprint fell on the exact top of the obstacle. We have also measured the radial distance from the rim crest of the rampart crater to the point where these obstacles diverted the ejecta flow. These distances vary from 0.17–0.68 crater diameters. The relationships of the flows to the obstacles suggest that the flow thicknesses were comparable to, or smaller than the obstacle heights. In addition, the inability to surmount these obstacles suggests that the flows had limited velocities.

[12] The example of the crater on Alba Patera (Figures 2e and 2f) is particularly intriguing. The radial ejecta flow was evidently unable to surmount the rim of the smaller (2.5 km diameter) crater to the southeast, which lies only 14 km (or 0.17 crater diameters) from the rim of the larger crater. The highest point on the rim of the smaller crater is at most ~85 m above the preexisting surface. Yet, the relatively high depth/diameter ratio (~0.1) indicates that it has escaped significant infilling by the ejecta from the larger crater. Further examples of this diversion of ejecta by small obstacles close to the parent crater have also been found elsewhere on Mars.

3. Mathematical Model

[13] Having presented evidence for ground-hugging fluidized emplacement, we model the ejecta flow as a continuum fluid, as is often done for complex multicomponent flows of geologic materials (e.g., debris flows, pyroclastic flows, volcanic plumes). That is, the internal motions of particulates and fluid components within a control volume are considered to have some single value for mean flow velocity that is a function of distance and time. The fluidizing medium could be water in a vapor or liquid phase, such that the ejecta flows might resemble pyroclastic flows at one extreme of the spectrum of possible behaviors [Wohletz and Sheridan, 1983] or debris flows at the other extreme [Carr et al., 1977; Fink et al., 1982; Ivanov, 1996]. In either case, there are numerous precedents for modeling such flows as continuum fluids [e.g., Sparks et al., 1978; Chen, 1987; Bursik and Woods, 1996; Iverson, 1997; Iverson and Denlinger, 2001; Baloga and Bruno, 2005; Barnouin-Jha et al., 2005].

[14] The flow in our model is considered to have a mean velocity that is essentially parallel to the preexisting surface and may vary in magnitude from the source to the distal rampart. At any given location along the path of the flow, the only vertical component of the mean flow velocity results from the local volume conservation equation due to the spatial gradient of the horizontal volumetric flux. This same concept has been employed [Barnouin-Jha et al., 2005] in comparing the emplacement of rampart ejecta blankets to large landslides on the Earth and Mars.

[15] Once a ground-hugging flow is established, it is considered to have a well-defined thickness that may vary with distance and time. It is possible that there could be many types of particulate and fluid exchanges between the flow and the preexisting subsurface [e.g., Barnouin-Jha et al., 2005], and/or interactions with the ambient atmosphere similar to those discussed with vortex-ring propagation [Barnouin-Jha and Schultz, 1996, 1998], entrainment by volcanic plumes [e.g., Glaze and Baloga, 1996], or degassing by lava flows [Baloga et al., 2001]. In our initial formulation here, such complex processes are ignored. For the present, we make the further simplifying assumption that the bulk density of the flow is a constant.

[16] Thus, for an overland ground-hugging fluidized flow, the primary dependent variables of interest are the time-dependent thickness of the flow \( h = h(r,t) \) and its velocity \( u = u(r,t) \), where \( r \) is distance from the crater center and \( t \) is time. Definitions of the mathematical symbols are provided in Table 2. By formulating and solving appropriate volume and momentum conservation equations involving these variables, we would hope to gain insight into the basic processes required to produce the dimensions and shapes of the observed deposits. The formulation below assumes cylindrical symmetry, although some of the most interesting structures of the deposits have systematic azimuthal variations. We assume that the flow volume is conserved during the emplacement of the deposit and use the standard expression for cylindrical coordinates

\[
\frac{\partial h}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (ruh) = 0. \tag{1}
\]

This is the primary equation for determining the time-dependent profile \( h(r,t) \). To obtain the solution, one must specify a boundary condition at the source (e.g., the crater

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Units</th>
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<tbody>
<tr>
<td>( h )</td>
<td>Ejecta flow depth</td>
<td>m</td>
</tr>
<tr>
<td>( h_{\text{max}} )</td>
<td>Maximum flow depth at crater rim</td>
<td>m</td>
</tr>
<tr>
<td>( H )</td>
<td>Flow depth at crater rim</td>
<td>m</td>
</tr>
<tr>
<td>( r )</td>
<td>Radial distance</td>
<td>m</td>
</tr>
<tr>
<td>( r_0 )</td>
<td>Crater radius</td>
<td>m</td>
</tr>
<tr>
<td>( r_{\text{front}} )</td>
<td>Distance to flow front</td>
<td>m</td>
</tr>
<tr>
<td>( r_{\text{max}} )</td>
<td>Distance to distal rampart</td>
<td>m</td>
</tr>
<tr>
<td>( t )</td>
<td>Time</td>
<td>s</td>
</tr>
<tr>
<td>( t_0 )</td>
<td>Emplacement duration</td>
<td>s</td>
</tr>
<tr>
<td>( v_{\text{avg}} )</td>
<td>Average ramp width</td>
<td>m</td>
</tr>
<tr>
<td>( u )</td>
<td>Flow velocity</td>
<td>m s(^{-1})</td>
</tr>
<tr>
<td>( v_0 )</td>
<td>Velocity at crater rim</td>
<td>m s(^{-1})</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Characteristic time coordinate</td>
<td>s</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Velocity decay rate constant</td>
<td>s(^{-1})</td>
</tr>
<tr>
<td>( \Gamma )</td>
<td>Source depth time constant</td>
<td>s</td>
</tr>
</tbody>
</table>

Table 2. Notation
h(r = r₀, t) = H(t), that describes how the source flow depth changes as a function of time. Furthermore, one must know the local flow velocity in equation (1). As concepts for modeling rates of entrainment or deposition emerge, this equation will have to be modified by adding source or sink terms to the right-hand side. A full treatment of the dynamics of the fluid-particles mixture would require a separate set of governing equations for each phase.

We have formulated a momentum conservation equation by assuming that the resistance to flow is proportional to the local volumetric flow rate. Conceptually, this suggests that the faster the flow goes, the more resistance it experiences. Similarly, thicker flows experience proportionally more resistance to flow. We have introduced a velocity decay rate constant, \( b \), with dimensions of 1/time, to describe this proportionality. It is shown in Appendix A that momentum conservation leads to the following equation for the flow velocity,

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} = -\beta u. \tag{2}
\]

Equations (1) and (2) constitute the mathematical model for the flow. When these equations are solved simultaneously for plausible boundary conditions at the flow source, the mathematical solutions describe how \( h \) and \( u \) change with time and distance.

For the present, we make the simplest choice that the flow velocity at the crater rim is a constant given by \( u_0 \). Thus the solution of equation (2) has the simple form

\[
u(r, t) = u_0 - \beta(r - r_0). \tag{3}\]

This shows that the effect of friction, as we have formulated it, is simply to slow the flow linearly with distance. We note from equations (2) and (3) that if the constant \( \beta = 0 \), there is no frictional resistance to flow. Thus it would continue to flow indefinitely.

Of course, other more complicated boundary conditions on the velocity are possible. We have also considered a velocity boundary condition at the source of the flow that begins with \( u_0 \), then decays monotonically with time according to a separate time constant. We have found that ramparts are produced only when this new time constant is much greater than the emplacement time (i.e., the source velocity decays only very slowly). In effect, this means that our fortuitous choice of the simplest boundary condition \( (u_0 = \text{constant}) \) was the correct one for producing ramparts. However, further investigation of other admissible boundary conditions remains warranted.

The rate constant \( \beta \) in equation (3) describes the dissipation of velocity along the flow path. We may estimate this parameter by measuring the radial distances from the crater center to the crater rim \( r_0 \) and to the distal rampart \( r_{\text{max}} \). Then, by setting the velocity of the flow to zero at \( r_{\text{max}} \) for an assumed initial velocity at the crater rim, \( u_0 \), we have

\[
\beta = \frac{u_0}{r_{\text{max}} - r_0}. \tag{4}
\]

While equation (3) tells us where the velocity goes to zero, it does not tell us how long it takes to get there. Equation (3) can be integrated directly to find the radial distance of the front of the ejecta flow as a function of time

\[
r_{\text{front}}(t) = r_{\text{max}} - \frac{u_0}{\beta} e^{-\beta t}. \tag{5}
\]

We use equation (5) to determine an approximate time range for the ejecta emplacement. Figure 3 shows a graph of the advance of the flow front. It shows that the flow front initially moves outward very rapidly, before slowing and approaching the maximum radius asymptotically. While strictly speaking, it takes an infinite time to get to the maximum radial distance according to equation (5), Figure 3 shows that after 5 dimensionless time steps, the
flow has reached a location within 1% of \( r_{\text{max}} \). It is therefore sufficient to describe the emplacement duration, \( t_e \), as \( 5/\beta \).

[25] We now return to the determination of the flow depth profile. Substituting the velocity given by equation (3) into (1) gives

\[
\frac{\partial h}{\partial t} + \frac{\partial}{\partial r} (ru_0 - \beta(r - r_0))h = 0. \tag{6}
\]

[26] Equation (6) can be solved in the general case, i.e., for any form of time-dependent boundary condition behavior, by the method of characteristics [e.g., Whitham, 1974; Zauderer, 1983]. The general solution is provided in Appendix B.

[27] To simulate the transient flow of material past the crater rim, we have adopted a specific model for the time dependent behavior of the depth at the source, given by

\[
h(r = r_0, t) = \frac{h_{\text{max}}t}{\Gamma} e^{1 - t/\Gamma} = H(t). \tag{7}
\]

[28] This boundary condition is shown in dimensionless terms in Figure 4. A single time constant, \( \Gamma \), characterizes the timescale by which the flow depth at the crater rim rises relatively rapidly to its maximum value (at \( t = \Gamma \)) and then decays at a more gradual rate. We discuss below how this time constant can be estimated. This type of boundary condition behavior is commonly observed in catastrophic mass movements that feature a relatively rapid rising phase compared to the tail. This particular mathematical form is useful because it implies a finite total discharge. However, most literature that deals with similar issues [e.g., Glaze et al., 2002; Fagents and Baloga, 2004; Barnouin-Jha et al., 2005] ignores the waxing phase of the “hydrograph” as being overridden by other uncertainties in the physics and the measurements of the geologic variables. [29] With this boundary condition, the solution of equation (6) can be put in the compact form

\[
h(r, t) = \left( \frac{t_0}{r} \right) \frac{u_0}{u(r)} \frac{h_{\text{max}}}{\Gamma} e^{1 - t/\Gamma}, \tag{8}
\]

where

\[
\tau = t + \frac{1}{\beta} \ln \left[ 1 - \frac{\beta(r - r_0)}{u_0} \right]. \tag{9}
\]

[30] As we show in section 4, our model, as embodied by the governing equations (1) and (2), naturally produces a flow thickness profile featuring a sharp frontal peak that grows as the flow advances.

[31] Equations (3), (4), (8), and (9), together with plausible assumptions about the maximum flow depth \( h_{\text{max}} \) and velocity \( u_0 \) at the crater rim, allow us to make elementary comparisons with observed rampart crater dimensions. Once we know the crater radius and the extent of the rampart, we can derive estimates of \( \Gamma \) and \( \beta \) for any plausible source velocity \( u_0 \). Using equation (4) to calculate \( \beta \), we then know by equation (5) the total time for emplacement, i.e., 5 times the quantity \( 1/\beta \). The decay of the boundary condition on the flow depth (controlled by \( \Gamma \)) is much slower than that of the advance of the flow front (controlled by \( \beta \)). Indeed, the model we have used theoretically continues for an infinite time unless artificially truncated. By inspection of the boundary condition on the flow depth, essentially all the volume passes the crater rim after 8\( \Gamma \) has passed. Thus, knowing the emplacement time (\( t_e = 5/\beta \)), we can approximate the time constant of the flow depth boundary condition by

\[
\Gamma \approx \frac{5}{8\beta}. \tag{10}
\]

[32] In effect, we set the transit time of the flow front equal to the discharge time with this method of approximation. Further refinements are possible but are not presently...
warranted by the data and the level of sophistication of the theory.

In this work, we investigate different assumptions about the maximum flow depth at the crater rim. Once we specify $h_{\text{max}}$, the mathematical solution of equation (7) for $h(r, t)$ describes how the flow depth profile advances and evolves in time.

In summary, if we prescribe two plausible constants $h_{\text{max}}$ and $u_0$, and measure two others, $r_0$ and $r_{\text{max}}$, we have all the information required to identify the primary controls on rampart formation and to provide a basis for comparison with observed rampart deposits.

4. Observations

Nine examples of rampart craters are shown in Figures 1, 5, 6, and 7. Although some of these craters are SLE craters and others are MLE, the mode of ejecta transport and rampart formation appears to have been very similar. These craters are all located in Lunae and Solis Planum, in an area running from the north to the south of Valles Marineris between latitudes 21°S to 29°N and longitudes 280°E to 320°E. All of the examples chosen have clearly-defined, relatively simple rampart deposits, and are covered by multiple THEMIS infrared (IR) images at 100 m/pixel resolution and, in some cases, THEMIS visible (VIS) images at 19 m/pixel.

Table 3 shows representative data taken for the nine craters, including the crater radius $r_0$, the extent of the ejecta deposit, $r_{\text{max}}$, measured from the origin (i.e., the crater center), the ejecta width, $r_{\text{max}}-r_0$, measured from the crater rim to the distal rampart margin, and the rampart width, $w_{\text{av}}$. The radii of the craters here range from 1.68 to 8.5 km, the ejecta deposits extend 3.79 to 21.3 km beyond the crater rim, and the average rampart widths lie between 0.75 and 2.03 km.

It is clear from the images that the margins of the ejecta deposits exhibit varying degrees of lobateness and crenulation. Therefore, in order to derive a representative ejecta width, $r_{\text{max}}-r_0$, measurements of the distance from the crater rim to the distal margin were made 10° radial increments around the crater. This led to a maximum of 36 measurements from which average values were calculated. Portions of the ejecta deposit that were incoherent or disrupted by other impacts, wrinkle ridges, etc., were excluded. The values of $r_{\text{max}}-r_0$ shown in Table 3 for each crater represent the averages plus or minus the standard deviations of the measurements.

Radial rampart “widths” are more difficult to measure accurately, as a large degree of subjectivity enters into the determination of the rampart extent in the image data. The outer slope of the rampart is quite steep, so it is relatively easy to identify the distal extent. However, the inner slope is much shallower, so it is much harder to ascertain the location at which the deposit begins to ramp up to form the rampart, due to the illumination geometries of the surfaces under study. The $w_{\text{av}}$ values given in Table 3 are averages (plus or minus one standard deviation) of several measurements taken for each crater. We consider these values to be only rough approximations of the actual widths in spite of the precision of our measurement methodology (i.e., the relatively modest standard deviations).

5. Application of Model

In addition to the measured values of $r_0$ and $r_{\text{max}}$, we require plausible estimates of $u_0$ and $h_{\text{max}}$ to apply the model. For the initial flow velocity, we have considered values ranging from 10 m s$^{-1}$ to 200 m s$^{-1}$. The lower limit was selected on the basis of terrestrial experience with catastrophic mass movements such as landslides, debris
flows, and lahars [Shreve, 1968; Goguel, 1978; Eppler et al., 1987; Iverson, 1997; Glaze et al., 2002; Fagents and Baloga, 2004; Baloga and Bruno, 2005]. The upper limit was chosen because it approaches the speed of sound in the Martian atmosphere.

[40] Table 4 shows the calculated values of the time constants $\beta$ and $\Gamma$ (from equations (4) and (10)) and the total emplacement duration ($t_e = 5/3$) for each of the craters and four assumed flow velocities at the crater rim. These computations show that the emplacement times range from $<2$ min to about 3 hours for the velocity limits we have assumed.

[41] However, we can further refine the parameter combinations by computing flow profiles as a function of time from equation (8). Figure 8 illustrates the application of model to craters 1 and 8 as examples of large and small rampart craters. Dimensionless flow depth ($h(r, t)$) normalized to $h_{\text{max}}$ is plotted as a function of distance at three different times (equal to 1/4, 1/2 and 3/4 of the total emplacement duration). Multiplying the vertical axis by an assumed $h_{\text{max}}$ yields the flow depth profile in meters. It is clear that as the flow progresses away from the crater rim and slows, the flow front forms a sharp peak. In addition, we can see that values of $h_{\text{max}}$ in excess of 30–40 m start to produce unreasonably steep and high flow fronts ($>200$–$300$ m) by the time $6\Gamma$ have passed, inconsistent with typical rampart heights of about 100 m [Barnouin-Jha et al., 2005]. Furthermore, at times approaching $t_e (=8\Gamma)$ the flow front, growing exponentially, becomes extremely high.

[42] The elementary treatment presented here does not contain enough physics to compare in detail the theoretical profiles with the observed shapes of the deposits. We have required the flow front to stop at $r_{\text{max}}$, but the theory presently contains no mechanism to slow or stop the trailing upstream parts of the flow in response. Consequently, the theoretical frontal peaks can continue to steepen without bound as trailing elements of the flow encounter our imposed barrier at $r_{\text{max}}$. However, by analogy with relatively dense fluid-particulate mixtures such as debris flows or block-and-ash flows, the thickness profile characteristics of the resulting deposit should bear a reasonable resemblance to the depth profile of the ejecta flow as it comes to rest.

[43] We can obtain a crude prediction of the radial rampart width by investigating the validity of the solutions in equations (3), (8), and (9) to the governing equations (B1) and (A3) (see Appendices A and B). Our fundamental assumption in this work is that the ejecta flow as a continuum that resembles a fluid. When this is true, one might expect fluid pressure terms in equation (A3) to play an important role in limiting the growth of topographic gradients toward the flow front, i.e., in smoothing out very steep slopes and limiting flow front height. This cannot be true indefinitely, however, because image and topographic data confirm that significant gradients are retained in the deposits after all motion has ceased.

### Table 3. Morphometric Characteristics of Nine Rampart Craters

<table>
<thead>
<tr>
<th>Location</th>
<th>Crater Radius $r_0$, km</th>
<th>Ejecta Extent $r_{\text{max}}$, km</th>
<th>Ejecta Width $r_{\text{max}} - r_0$, km</th>
<th>Rampart Width $w_{\text{max}}$, km</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.9°S 285.3°E</td>
<td>8.50</td>
<td>29.8 ± 2.96</td>
<td>21.30 ± 2.96</td>
</tr>
<tr>
<td>2</td>
<td>2.7°N 281.7°E</td>
<td>7.89</td>
<td>25.6 ± 2.23</td>
<td>17.80 ± 2.23</td>
</tr>
<tr>
<td>3</td>
<td>28.4°N 316.9°E</td>
<td>7.76</td>
<td>21.23 ± 2.11</td>
<td>13.47 ± 2.11</td>
</tr>
<tr>
<td>4</td>
<td>16.4°N 294.6°E</td>
<td>6.95</td>
<td>16.46 ± 0.85</td>
<td>9.51 ± 0.85</td>
</tr>
<tr>
<td>5</td>
<td>14.8°N 299.8°E</td>
<td>5.23</td>
<td>11.44 ± 1.19</td>
<td>6.21 ± 1.19</td>
</tr>
<tr>
<td>6</td>
<td>21.5°N 316.8°E</td>
<td>4.97</td>
<td>10.39 ± 0.74</td>
<td>5.42 ± 0.74</td>
</tr>
<tr>
<td>7</td>
<td>9.9°S 279°E</td>
<td>4.83</td>
<td>15.41 ± 1.52</td>
<td>10.58 ± 1.52</td>
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<tr>
<td>8</td>
<td>22.5°N 312.5°E</td>
<td>4.29</td>
<td>10.13 ± 0.53</td>
<td>5.84 ± 0.53</td>
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<tr>
<td>9</td>
<td>13.8°S 279.6°E</td>
<td>1.68</td>
<td>5.47 ± 0.25</td>
<td>3.79 ± 0.25</td>
</tr>
</tbody>
</table>

### Table 4. Model Parameters and Computed Characteristics for Select Rampart Craters

<table>
<thead>
<tr>
<th>Crater</th>
<th>$t_e$, min</th>
<th>$\beta$, s$^{-1}$</th>
<th>$\Gamma$, s</th>
<th>$u_0 = 10$ m s$^{-1}$</th>
<th>$u_0 = 50$ m s$^{-1}$</th>
<th>$u_0 = 100$ m s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>178</td>
<td>$4.7 \times 10^{-4}$</td>
<td>426</td>
<td>79</td>
<td>52</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>148</td>
<td>$5.6 \times 10^{-4}$</td>
<td>356</td>
<td>1.1 $\times 10^{-3}$</td>
<td>1.6 $\times 10^{-3}$</td>
<td>1.8 $\times 10^{-3}$</td>
</tr>
<tr>
<td>3</td>
<td>112</td>
<td>$7.4 \times 10^{-4}$</td>
<td>269</td>
<td>190</td>
<td>124</td>
<td>108</td>
</tr>
<tr>
<td>4</td>
<td>79</td>
<td>$1.1 \times 10^{-3}$</td>
<td>190</td>
<td>1.6 $\times 10^{-3}$</td>
<td>1.8 $\times 10^{-3}$</td>
<td>2.6 $\times 10^{-3}$</td>
</tr>
<tr>
<td>5</td>
<td>52</td>
<td>$1.6 \times 10^{-3}$</td>
<td>124</td>
<td>9.5 $\times 10^{-4}$</td>
<td>9.7 $\times 10^{-4}$</td>
<td>1.7 $\times 10^{-3}$</td>
</tr>
<tr>
<td>6</td>
<td>45</td>
<td>$1.8 \times 10^{-3}$</td>
<td>108</td>
<td>1.7 $\times 10^{-3}$</td>
<td>1.3 $\times 10^{-2}$</td>
<td>6.3</td>
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<tr>
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<td>$9.7 \times 10^{-4}$</td>
<td>211</td>
<td>7.6</td>
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<td>8</td>
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<td>$1.7 \times 10^{-3}$</td>
<td>117</td>
<td>1.3 $\times 10^{-2}$</td>
<td>3.2</td>
<td>3.2</td>
</tr>
<tr>
<td>9</td>
<td>32</td>
<td>$2.6 \times 10^{-3}$</td>
<td>76</td>
<td>3.2</td>
<td>6.3</td>
<td>6.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Crater</th>
<th>$t_e$, min</th>
<th>$\beta$, s$^{-1}$</th>
<th>$\Gamma$, s</th>
<th>$u_0 = 100$ m s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18</td>
<td>$4.7 \times 10^{-3}$</td>
<td>43</td>
<td>5.2</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>$5.6 \times 10^{-3}$</td>
<td>36</td>
<td>4.5</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>$7.4 \times 10^{-3}$</td>
<td>27</td>
<td>8.8</td>
</tr>
<tr>
<td>4</td>
<td>7.9</td>
<td>$1.1 \times 10^{-2}$</td>
<td>19</td>
<td>4.9</td>
</tr>
<tr>
<td>5</td>
<td>5.2</td>
<td>$1.6 \times 10^{-2}$</td>
<td>12</td>
<td>3.2</td>
</tr>
<tr>
<td>6</td>
<td>4.5</td>
<td>$1.8 \times 10^{-2}$</td>
<td>11</td>
<td>3.2</td>
</tr>
<tr>
<td>7</td>
<td>8.8</td>
<td>$9.5 \times 10^{-3}$</td>
<td>21</td>
<td>5.3</td>
</tr>
<tr>
<td>8</td>
<td>4.9</td>
<td>$1.7 \times 10^{-2}$</td>
<td>12</td>
<td>3.2</td>
</tr>
<tr>
<td>9</td>
<td>3.2</td>
<td>$2.6 \times 10^{-2}$</td>
<td>11</td>
<td>3.2</td>
</tr>
</tbody>
</table>

8 of 12
Our criterion for estimating the predicted rampart width is to determine (at $t_e = 8 \Gamma$) the distance at which the contribution of the pressure terms in the momentum equation becomes comparable to the flow resistance term. The distance from this point out to $r_{\text{max}}$ is then taken as our rampart width prediction.

There are clearly difficulties in defining actual rampart widths from imaging data or topographic profiles because of shallow slopes and the horizontal spacing of MOLA shots, respectively. However, by requiring that the widths predicted using the pressure term criterion are comparable to those shown in Table 3, we are able to refine the combinations of $h_{\text{max}}$ and $u_0$ that produce the ejecta deposits for two of our crater examples (craters 1 and 8; Figure 9).

Given that the pressure terms act to “relax” the topographic gradients in the flow within this distal annular zone, we might expect flow front heights up to a factor of two greater than typical rampart deposit thicknesses measured in the data sets (25–178 m). For crater 1, this implies $h_{\text{max}}$ in the range 10–40 m, $u_0$ in the range 58–116 m s$^{-1}$ (Figures 8a and 9) and an emplacement duration $t_e$ of 31–15 min. For $h_{\text{max}} = 50$ m, the narrowness of the rampart implies a totally unrealistic thickness approaching a kilometer. Applying the same criterion to the smaller crater 8 yields the corresponding parameter ranges: $h_{\text{max}} = 10–20$ m, $u_0 = 27–39$ m s$^{-1}$ (Figures 8b and 9), and $t_e = 18–12$ min.

Thus far we have based our calculations on the assumption that ejecta flow commences from the crater rim. However, in some cases, the presence of interior deposits adjacent to the crater rim (e.g., Figures 1 and 2a) suggests that continuum flow may have started at some distance beyond the crater rim. We have therefore explored how our results would differ if our assumption of a near rim flow source were relaxed. We have rerun the computations for Crater 1 with the continuum flow regime beginning at 15 km, roughly twice the average crater radius. In general, this has the effect of decreasing the required initial flow velocity by about half or less. Corresponding distal peak

Figure 8. Dimensionless ejecta flow depth profiles ($h(r, t)/h_{\text{max}}$) at three times. (a) Crater 1 (crater radius $r_0 = 8.5$ km, ejecta extent $r_{\text{max}} = 21.3$ km, rampart width $w_{\text{av}} = 2$ km, rampart height = 178 m). (b) Crater 8 (radius $r_0 = 4.3$ km, ejecta extent $r_{\text{max}} 10.1$ km, rampart width $w_{\text{av}} = 0.89$ km).

Figure 9. Plot showing the pairs of $h_{\text{max}}$ and $u_0$ required to calculate rampart widths consistent with those observed for Crater 1 (solid line) and Crater 8 (dashed line). Thick black lines denote admissible $h_{\text{max}}$, $u_0$ combinations based on maximum likely rampart heights.
heights increase by about 80%. Specifically, admissible velocities range from 39–61 m s\(^{-1}\) for \(h_{\text{max}} = 10–25\) m. Maximum distal flow thicknesses for \(h_{\text{max}} = 30\) m produce unrealistic distal flow heights above 380 m. In summary, there is only modest sensitivity of the model output to the choice of starting location for continuum flows.

[43] Thus our elementary model constrains the source conditions to flow thicknesses of only a few tens of meters and modest velocities ranging from a few tens of meters per second to perhaps 116 m s\(^{-1}\), regardless of the specific location of the onset of continuum flow.

6. Discussion

[49] In this study, we have addressed only rampart deposits exhibiting simple morphologies and a prominent distal rampart. Typically, larger craters on Mars develop more complicated eject blankets with multiple, overlapping rampart deposits (i.e., MLE craters [Mouginis-Mark, 1979; Barlow et al., 2000]). These more complex deposits could result from multiple ballistically emplaced slugs of ejecta [Gault and Greeley, 1978], or multiple flow pulses being discharged at the source. Alternatively, it is possible that fluid dynamic instabilities disrupt the coherence of the ground-hugging, continuum flow [Baratoux et al., 2002]. Finally, we speculate that target heterogeneities or differential entrainment of external sediments, and/or deposition could produce radially and azimuthally varying deposits.

[50] For the simple rampart deposits under consideration here, we find that there are three factors in our model that lead to the formation of sharp distal peaks. First, there must be sufficient material ejected so that transport resembles a continuum fluid flow. Second, there must be some form of local resistance to flow that dissipates the momentum along the flow path. Then third, the basic processes of flow momentum and volume conservation, combined with elementary boundary conditions at the source, naturally produce flow thickness profiles with sharp frontal peaks. This behavior is essentially independent of the form of the flow depth boundary condition. Even if the boundary condition has only a monotonic decay with time, the advancing flow still features a sharp prominent peak that ultimately forms the rampart.

[51] Our model cannot yet describe the final transition from a flowing continuum to stationary rampart deposit. There are a variety of plausible processes that could cause this transition. The most likely candidates are intergranular locking, devolatilization, or some combination thereof. Setting or subsidence could be additional factors that need to be considered in developing a model of the transition phase of emplacement that is suitable for detailed comparison with topographic profiles. These issues require additional physical modeling that is beyond the scope of the present work.

[52] We have adopted a simple flow resistance term that is proportional to the velocity of the flow. It is likely that a more nonlinear resistance term would compress the radial width of the final deposit and act to produce a taller rampart. However, this would be offset by the inclusion of higher-order fluid dynamic pressure terms, which would act to suppress the exponential flow front growth currently predicted, and spread the flow front over a greater radial distance. The need to include both nonlinear flow resistance and pressure terms in the governing equations is clearly warranted, particularly to address the very final stages of emplacement.

7. Conclusions

[53] Morphologic evidence and the quantitative inferences from our elementary emplacement model suggest that only thin ejecta flows, moving at relatively low velocities, are needed to produce distal ramparts. Our model predicts that the emplacement times range from approximately 12–31 min for rampart craters with diameters in the 4–17 km range considered. Our inferred values of maximum flow depth at the source (\(h_{\text{max}} = 10–40\) m) imply that seemingly plausible values up to 100 m are precluded. Furthermore, relatively low flow velocities (\(u_0 = 27–116\) m s\(^{-1}\)) are predicted at the location where the ejecta can be treated as a ground-hugging continuum. These results are consistent with previous conventional interpretations [e.g., Melosh, 1989] that the characteristics of rampart deposits are more suggestive of a relatively dense, ground-hugging flow similar to a debris flow or pyroclastic flow (block-and-ash or ignimbrite type), rather than a highly dispersed granular suspension of base-surge type.

[54] For the crater diameter range we have studied here, it is difficult to ascertain unambiguously from deposit images where the continuum regime actually began. However, there are clear suggestions that continuum flows occurred within a fraction of the parent crater radii. Moreover, these flows had difficulty surmounting preexisting topographic obstacles with relative elevations suggestive of modest flow velocities consistent with our model. Our theoretical constraints on flow thicknesses and velocities are not significantly altered whether the continuum flow regime begins immediately at the crater rim or approximately halfway between the crater rim and distal rampart.

[55] Our conclusions argue that there is indeed something unique about the emplacement of rampart crater deposits. From longstanding concepts of the crater excavation process and ejection velocity arguments [e.g., Gault and Greeley, 1978; Housen et al., 1983; Melosh, 1989], one might expect flow velocities exceeding those we have obtained, perhaps by as much as a factor of two. Given the prodigious energies of the impact process, the mechanism for producing modest flow boundary conditions is unclear. At present, our model is not sufficiently developed to explain this issue. Thus our approach and results do not necessarily conflict with conventional views of the ejection processes. However, it is likely, a fortiori, that the rampart deposits result from a presently unrecognized atmospheric interaction or target property that affects the boundary conditions at the source of the continuum flow regime.

Appendix A: Derivation of the Velocity Equation

[56] Subject to the assumptions cited in the text, a general form for the expression of momentum conservation for a control volume \(r \, dr \, d\theta\) is given by

\[
\frac{\partial (urh)}{\partial r} \, dr \, d\theta + \frac{\partial}{\partial r} (u r^2 rh) \, dr \, d\theta = -\rho r \, dr \, d\theta + \frac{\rho g}{2} \frac{\partial}{\partial r} (r h^2) \, dr \, d\theta.
\]
The first term on the right-hand side indicates that there is an opposing resistance to flow that is proportional to the basal area, \( r \, dr \, \partial h/\partial r \), of the control volume. The proportionality is expressed by the function \( R \), which must be prescribed or determined by empirical means. The second term on the right-hand side is the cylindrical form expressing the role of a fluid pressure. A detailed discussion of this term in planar coordinates is found in numerous texts that treat mass flows as two-dimensional problems. See, for example, Whitham [1974], or other texts on the St. Venant equations.

Equation (A1) can be simplified by expanding the derivatives on the left-hand side, canceling common terms (\( \partial \rho /\partial t \), \( \partial r /\partial t \), and \( \partial \beta /\partial t \)), and using the volume conservation equation

\[
\frac{r}{\partial t} + \frac{\partial}{\partial r} (rhu) = 0. \tag{A2}
\]

We thus obtain

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} = -\frac{R}{h} - \frac{g}{2r} \frac{\partial (rh^2)}{\partial r}. \tag{A3}
\]

The governing equation for the flow velocity given in the section 3 is obtained by setting \( R = \beta u h \) and considering the pressure term in (A3) to be negligible.

**Appendix B: General Solution of the Volume Conservation Equation**

The volume conservation equation can be readily solved in the general case for an arbitrary boundary condition, \( h(r = r_0, t) = H(t) \), on the flow depth at the crater rim using the method of characteristics. This gives us the flexibility to look at other influences, such as a rising flow depth at the crater rim, on the shape of the propagating wave.

The volume conservation equation

\[
\frac{r}{\partial t} + \frac{\partial}{\partial r} (rhu) = 0. \tag{B1}
\]

can be put in the form

\[
\frac{r}{\partial t} + ru \frac{\partial h}{\partial r} + h \frac{\partial}{\partial r} (ru) = 0. \tag{B2}
\]

So we have the canonical form

\[
\frac{\partial h}{\partial t} + u \frac{\partial h}{\partial r} = -\frac{h}{r} \left( u + r \frac{\partial h}{\partial r} \right) = -\frac{h}{r} (u - \beta r). \tag{B3}
\]

This is equivalent to the system of ordinary differential equations

\[
\frac{dt}{T} = \frac{dr}{u} = -\frac{dh}{\beta r (u - \beta r)}. \tag{B4}
\]

The characteristics are obtained by solving

\[
\frac{dt}{T} = \frac{dr}{u} = \frac{dr}{[u_0 - \beta (r - r_0)]}. \tag{B5}
\]

The characteristic immediately tells us that information from the boundary condition on \( h \) propagates along the characteristic with the velocity \( u \). Upon integrating, we have

\[
t = \int_{r_0}^{r} \frac{dr}{u_0 - \beta (r - r_0)} + \tau = -\frac{1}{\beta} \ln \left[ 1 - \beta/u_0 (r - r_0) \right] + \tau. \tag{B6}
\]

where \( \tau \) is the parameter of the curve \( H(t) \) on the vertical plane \( h, r = r_0 \). We write this in the form

\[
\tau - t = +\frac{1}{\beta} \ln \left[ 1 - \beta (r - r_0)/u_0 \right]. \tag{B7}
\]

noting that each side is positive because \( t \) must be less than or equal to \( \tau \). We can put this equation of the characteristics in the form

\[
r(t) = r_0 + \frac{u_0}{\beta} \left( 1 - e^{\beta (\tau - t)} \right). \tag{B8}
\]

Because we have

\[
r_{\text{max}} = r_0 + \frac{u_0}{\beta}, \tag{B9}
\]

we see that by setting to \( \tau = 0 \) at the start of the emplacement,

\[
r_{\text{flow}}(t) = r_{\text{max}} - \frac{u_0}{\beta} e^{-\beta t}, \tag{B10}
\]

for any arbitrary boundary condition on the flow depth.

We return now to the second integration required by equation (B4) to obtain the general solution of (B1).

\[
\frac{dr}{u} - \frac{dh}{\beta (u - \beta r)} \tag{B11}
\]

can be rearranged as

\[
\frac{dh}{h} = -\left( \frac{u - \beta r}{ru} \right) dr = -\frac{dr}{r} + \beta dr/u. \tag{B12}
\]

Upon integration, we have

\[
\ln \left( \frac{h}{H(\tau)} \right) = -\ln \left( \frac{r}{r_0} \right) \ln \left( \frac{u_0 - \beta (r - r_0)}{u_0} \right). \tag{B13}
\]

Thus our general solution is

\[
h(r, t) = H(\tau) \frac{r_0}{r} \frac{u_0}{u_0(r)} \tag{B14}
\]

where

\[
\tau = t + \frac{1}{\beta} \ln \left[ 1 - \beta (r - r_0)/u_0 \right]. \tag{B15}
\]

Given any boundary condition on the flow depth, \( H(t) \), we simply replace the \( t \) by the right-hand side of
References


