Atmospheric Effects On Ejecta Emplacement

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Laboratory experiments allow the investigation of complex interactions between impacts and an atmosphere. Although small in scale, they can provide essential first-order constraints on the processes affecting late-stage ballistic ejecta and styles of ejecta emplacement around much larger craters on planetary surfaces. The laboratory experiments involved impacting different fine-grained particulate targets under varying atmospheric pressure and density (different gas compositions). During crater formation, ballistic ejecta form the classic cone-shaped profile observed under vacuum conditions. As atmospheric density increases (for a given pressure), however, the ejecta curtain bulges at the base and pinches above. This systematic change in the ejecta curtain reflects the combined effects of deceleration of ejecta smaller than a critical size and entrainment of these ejecta within atmospheric vortices created as the outward moving wall of ejecta displaces the atmosphere. Additionally, a systematic change in emplacement style occurs as a function of atmospheric pressure (largely independent of density): contiguous ejecta rampart superposing ballistically emplaced deposits (0.06 to 0.3 bar); ejecta flow lobes (0.3 to 0.7 bar); and radial patterns (>0.8 bar). Underlying processes controlling such systematic changes in emplacement style were revealed by observing the evolution of the ejecta curtain, by changing target materials (including layered targets and low-density particulates), by varying atmospheric density, by changing impact angle, and by comparing the ejecta run-out distances with first-order models of turbidity flows. Three distinct ejecta emplacement processes can be characterized. Ejecta ramparts result from coatset clasts sorted and driven outward by vortical winds behind the outward moving ejecta curtain. This style of "wind-modified" emplacement represents minimal ejecta entrainment and is enhanced by a bimodal size distribution in the ejecta. Such "eddy-supported flows" are observed to increase in run-out distance (scaled to crater size) with increasing atmospheric pressure. By analogy with turbidity flows, this scaled distance should increase as $R^{1/2}$ for a given atmospheric pressure and degree of entrainment. Ejecta flows with much greater run-out distances develop as the turbulent power in atmospheric response winds increase. Such flows overrun and scour the inner ejecta facies, thereby producing distinct inner and outer facies. The degree of ejecta entrainment depends on the dimensionless ratio of drag to gravity forces acting on individual ejecta and the intensity of the winds created by the outward moving curtain. Entrainment increases with increasing atmospheric density and ejection velocity (crater size) but decreases with ejecta density and size. The intensity of curtain-generated winds increases with ejection velocity (crater size). The dimensionless drag ratio characterizing the laboratory experiments can be applied to Mars since the reduced atmospheric density is offset by the increased ejection velocities for kilometer-scale events. For a given crater size (ejection velocity) and atmospheric conditions, a wide range of nonballistic ejecta emplacement styles could occur simply by varying ejecta sizes even without the presence of water. Alternatively, the onset crater diameter for nonballistic emplacement styles can reflect the range of ejecta sizes possible from the diverse martian geologic history (massive basalts to fine-grained aeolian deposits). Scaling considerations further predict that ejecta run-out distances scaled to crater size on Mars should increase as $R^{1/2}$; hence long run-out flows dependent on crater diameter need not reflect depth to a buried reservoir of water. On Venus, however, the dense atmosphere maximizes entrainment and results in ejecta flow densities approaching a constant fraction of the atmospheric density. Under such conditions, ejecta run-out distances should decrease as $R^{-1/2}$.
testing first-order interpretations and computational codes but also reveals controlling variables that can be then incorporated into testable physical models of selected processes or phenomena. With this philosophy, a wide range of experiments allow the exploration of the possible role of an atmosphere in modifying the emplacement of impact crater ejecta.

Earlier studies of ejecta dynamics focused largely on explosion craters [Sherwood, 1967; Wisotzki, 1977]. Large backpressures created by chemical explosions drive early-time excavation, thereby complicating direct applications to impact cratering [Herr, 1971]. Impact craters, however, are produced by the mechanical transfer of energy and momentum to the target. Melt, vapor, comminution, and crater excavation are all in response to shocks created by the collision. This is the basis for using particulate targets to investigate late-stage crater excavation: passage of intense shock waves transforms a solid target into a particulate assemblage [see Gault et al., 1968]. Introduction of an atmosphere should not significantly modify this fundamental aspect of crater excavation, except under extreme conditions leading to projectile disruption prior to impact [Melosh, 1981; Schultz and Gault, 1985] or interactions with the trailing wake [Schultz, 1990a].

Atmospheric interactions separate into early- or late-time processes. Early-time interactions reflect the energy partitioned to the atmosphere prior to and just after contact during the compression stage of crater growth. Late-time interactions concern the final stages of crater formation (2/3 complete) and ejecta emplacement. Early-time processes may affect late-time interactions if shocks during first contact temporarily heat and drive away the atmosphere. Such interactions are often modeled as an intense cylindrically expanding shock associated with the impactor [Ivanov et al., 1986] or a point source explosion [Jones and Kodis, 1982; Vickery, 1986], both of which contain an assumed fraction of the original impactor energy. Both approaches, however, exaggerate the early-time atmospheric response by ignoring the role of the early-time crater cavity in containing and redirecting wake-heated atmospheric gases or impact-generated vapor into an upward directed jet, rather than a hemispherical explosion [Schultz and Gault, 1979, 1982, 1990]. Experiments exploring the more complex early-time coupling between the collision and atmosphere at high impact angles (>45°) reveal that only a small fraction of energy available actually directly couples with the ambient atmosphere around the crater, even for easily volatized targets [Schultz, 1988]. Consequently, this paper emphasizes late-time interactions with an atmosphere, which is assumed to resemble ambient conditions; a future paper will explore this assumption in more detail.

Late-time interactions comprise most of crater excavation and ejection: one half of the ejected mass leaves the cavity after the crater has achieved 85% of its final excavation diameter. Schultz and Gault [1979] explored the response of ejecta to an atmosphere by incorporating a first-order model of crater growth with aerodynamic deceleration of individual ejecta. Such an approach predicted the unrealistic conclusion that most ejecta below a critical size for a given crater diameter (and atmosphere) never leave the crater. Consequently, they concluded that ballistic ejection during ejection must lessen the full effect of aerodynamic drag. Hence calculations and predictions based only on trajectories of isolated particles [e.g., O’Keefe and Ahrens, 1982] will not reproduce observed phenomena; nevertheless, they provide a useful upper limit for aerodynamic drag effects. Additionally, a distinction was made between ballistic ejection and nonballistic emplacement. Nonballistic emplacement represents a two-stage process involving aerodynamic deceleration to near-terminal velocity and then entrainment in atmospheric turbulence created by the outward moving wall of ballistic ejecta. Consequently, conditions leading to nonballistic styles of emplacement depend on a critical ejecta size that depends on crater size (i.e., ejection velocity), ejecta size, and atmospheric pressure (i.e., density). Schultz and Gault [1979] compared this critical ejecta size for craters in the laboratory and on Mars, Earth, and Venus.

A subsequent study [Schultz and Gault, 1982] explored atmospheric effects on ejecta dynamics in the context of a major terrestrial impact. Laboratory experiments provided a basis for assessing phenomena that would stress the terrestrial environment, possibly leading to massive extinction of life species. While Alvarez et al. [1980] emphasized lofting and long-term suspension of finer ejecta fractions, Schultz and Gault [1982] proposed that such ejecta would be largely entrained in near-rim ejecta flow and deposition. More critical to global environmental stress would be the effects of hypervelocity ejecta (particularly from oblique impacts) that escape significant deceleration at early times due to the finite scale height of the atmosphere and ballistic shadowing; nevertheless, enormous quantities of thermal energy will be deposited in the upper atmosphere far from the impact during reentry.

Although such laboratory experiments were performed to investigate complexities of ejecta dynamics, they also provided distinctive evidence indicating the role of the early-time crater cavity in containing and redirecting wake-heated atmospheric gases or impact-generated vapor into an upward directed jet, rather than a hemispherical explosion [Schultz and Gault, 1982, 1985; Schultz, 1986, 1989]. The presence of an atmosphere, then, was proposed to be an essential ingredient for diversity of emplacement styles on Mars [Schultz, 1989], in addition to the presence or absence of water [Carr et al., 1977; Gault and Greeley, 1978; Greeley et al., 1980; Mouginis-Mark, 1979]. With this perspective, fluidized ejecta lobes do not necessarily indicate the presence of water but only that the flow properties resembled a fluid. Because systematic changes in emplacement style with atmospheric pressure paralleled changes in cratering efficiency and crater shape, energy lost to crater excavation appeared to be expressed in the complexities of ejecta dynamics and ejecta emplacement. Such energy losses could reflect a variety of early- or late-time processes. Hence companion papers first emphasized atmospheric effects on crater scaling [Schultz, 1990a, 1992] and crater shape [Schultz, 1990b; Schultz, Atmospheric Effects on Crater Shape, submitted to Icarus, 1991] before addressing styles of ejecta emplacement in greater detail.

This paper first reviews the effects of impactor, target, and atmospheric environment on ejecta facies morphology in the laboratory. The effect of these variables on ejecta curtain efficiency and crater shape, energy lost to crater excavation, and atmospheric interactions. Ejecta dynamics and ejecta morphology are then considered in terms of processes of ejecta emplacement, thereby forming a basis for physical models (analogous to turbidity flows) developed in the final discussion section. Analysis of the laboratory results can then be applied to ejecta emplacement styles on Mars where the range in lithologies and atmospheric conditions allows a unique test for the derived models.

2. EJECTA MORPHOLOGY

Impact environment. Ejecta morphology systematically changes with increasing atmospheric pressure. For compacted pumice targets, a contiguous ridge or "rampart" begins to appear about a crater radius from the rim for pressures as low as 0.06 bar and becomes very well defined at pressures of 0.25 bar (Figure 1a) The rampart begins to break into individual ejecta lobes above 0.4 bar, and these lobes can extend over 6 crater radii from the crater rims (Figure 1b). In several experiments, a scoured, faint rampart can be identified about a crater radius from the rim even as other characteristic emplacement styles dominate. A narrow moatlike depression typically encircles the
Fig. 1. The effect of atmospheric pressure (density) on ejecta emplacement for hypervelocity impacts into compacted pumice. (a) At 0.25 bar, a distinctive ejecta rampart (arrow) encircles the craters. (b) At 0.5 bar, lobes of ejecta (arrow) extend over four radii from the crater rim. A narrow scoured moat often develops adjacent to the raised rim. (c) Near 1 bar, a radial pattern characterizes the inner raised crater rim for pressures above 0.4 bar. Impacts under a 1 bar atmosphere produce an extensive, radially scoured ejecta deposit with a more pronounced rim depression (Figure 1c). In all cases, the amount of ejecta fallback and fallout is minor since remnants of the projectile and sintered target material remain clearly visible on the floor. Subtle lineations in the preimpact target remain clearly preserved at pressures below about 0.6 bar up to the continuous facies and even through the ejecta deposits with distal ejecta thinning without identifiable boundaries. Targets in Figures 1b and 1c had a thin veneer of dry temper sprinkled on the surface. All impacts were 0.635 cm aluminum spheres impacting from 5.0 to 5.4 km/s under an argon atmosphere. Scale bars correspond to 10 cm.

The use of different gas compositions (helium, air, nitrogen, argon, and carbon dioxide) allowed the atmospheric density to be varied while a constant pressure is maintained (see Table 1). Figure 2a summarizes the dependence between
ejecta morphology and atmospheric pressure. The onset and style of ejecta emplacement did not appear to vary significantly with density. Impacts into a helium atmosphere at 0.06 bar, which corresponds to an atmospheric density 0.01 p0 (P0 is the density of air at 1 atm, 1.293 x 10^3 g/cm^3), produced a faint contiguous rampart that was not enhanced by a CO2 atmosphere at the same atmospheric pressure (0.12 P0). The much denser CO2 atmosphere also did not affect the transition to more complex ejecta morphologies at higher pressures. Nevertheless, ejecta ramparts tended to persist to higher atmospheric pressures of helium.

Separate contributions summarize atmospheric effects on cratering efficiency [Schultz, 1990a] and crater shape [Schultz, 1990b]. Figure 2b correlates such atmospheric effects with ejecta emplacement style. As ejecta emplacement style becomes less ballistic and more turbulent, cratering efficiency relative to vacuum conditions is reduced. In addition, the crater diameter-to-depth ratio is reduced as the atmosphere restricts late-stage lateral crater growth. Hence energy lost in crater formation appears to be transferred to turbulent ejecta emplacement. Table 2 provides a listing of empirical data shown in Figure 2.

A series of experiments explored the effect of a stratified atmosphere. It was not possible to create a gradient in atmospheric pressure, but it was possible to produce a gradient in density. Sublimation of dry-ice blocks surrounding the target created a high-density vapor layer above the surface that was contained by a 5 cm barrier enclosing the target. The presence of the higher-density layer of CO2 in air (factor of 1.5) enhanced the production and size of the contiguous ejecta rampart. This trend was less evident for high-velocity impacts producing large craters relative to the CO2 gas layer thickness. Shadowgraphs made during impact demonstrated that the CO2 layer was neither removed nor appreciably disturbed by an impact-induced air shock at late times [Schultz and Gault, 1982]; consequently, the importance of the density gradient appears to decrease as the scale of the crater appreciably exceeds the scale of the CO2 layer.

In summary, ejecta morphology becomes increasingly more complex with increasing atmospheric pressure but is relatively independent of atmospheric density for a given pressure. A contiguous rampart characterizes impacts into compacted pumice from 0.06 to 0.25 bar. The development of the rampart is enhanced by the presence of a density gradient in the atmosphere provided that the thickness of the higher-density layer is not significantly less than a crater radius. Extending these empirical and phenomenological observations to different planetary environments requires further understanding of the underlying processes revealed by varying impactor and target properties as well.

### TABLE 1. Atmospheric Properties

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<tr>
<th>Constituent</th>
<th>Density (P/P0)</th>
<th>Viscosity (g/P0)</th>
<th>Sound Speed (C/Co)</th>
<th>Ratio of Specific Heats</th>
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Density and viscosity values are given with respect to air: p0 = 1.29 x 10^3 g/cm^3; c0 = 331 m/s.

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**Fig. 2a.** Effect of atmospheric pressure and composition on ejecta morphology for 0.635 cm aluminum spheres impacting compacted pumice at low and high velocities. Atmospheric density at a given pressure does not appear to be as important. Transitional or examples with both facies are positioned between categories. Ballistic facies represent gradually decreasing ejecta thickness with distance from rim, characteristic of vacuum conditions. Rampart ejecta facies indicate the formation of a contiguous ridge on top of ejecta. Long run-out flow lobes (flow style) and radial scouring (radial style) occur under higher atmospheric pressures. Radial facies do not appear to develop under a helium atmosphere. Use of a thin layer of dry egg tempera (parentheses) appears to enhance flow and radial ejecta morphology.

**Fig. 2b.** Relation between ejecta morphology and cratering efficiency referenced to the expected value for the same impactor under vacuum conditions. Increasing atmospheric pressure dramatically decreases cratering efficiency in particular targets with small (or low density) grain sizes [see Schultz, 1992]. This reduction in crater excavation is expressed in increasingly nonballistic ejecta morphologies from rampart to radial styles (Figure 1). Empirical data are given in Table 2.
<table>
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<th>Impactor Velocity</th>
<th>Atmosphere</th>
<th>Type</th>
<th>Ejecta Morphology</th>
<th>Crater Morphology</th>
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All experiments given in Table 2 used 0.635 cm aluminum spheres impacting compacted pumice; launch (V_0) and impact (v_1) velocities are given in units of kilometers per second. Atmospheric pressure is given in bars. Ejecta morphologies correspond to ballistic (B), rampart (Rmp), flow (F), and radial (RA). Cratering efficiency is given by displaced target mass (M) divided by projectile mass (m) and is scaled to expected values under vacuum conditions based on derived scaling [see Schultz, 1992]. Asterisks indicate impacts into targets with a thin veneer of dry tempera.

**Impactor variables.** The style of ejecta emplacement for a given environment and target does not change significantly with impactor size, velocity, or density. Figure 3 shows the formation of the distinctive ejecta rampart at impact velocities of 0.2, 2.0, and 6.0 km/s. The other characteristic patterns shown in Figure 1 also develop at higher atmospheric pressures, but the ejecta rampart tends to persist to higher atmospheric pressures for lower-velocity impacts (same projectile size). Such results further indicate that the distinctive ejecta patterns are not the result of a projectile-induced air shock but must reflect a response of ballistic ejecta moving through an atmosphere.

Nonvertical impacts result in a similar pressure-dependent change in ejecta morphology for compacted pumice targets. Figure 4 contrasts such changes for impact angles of 60° and 30° from the horizontal at 0.25 and 0.9 bar. At 60°, the ejecta morphology is visible at both atmospheric pressures. At 0.25 bar (Figure 4a), the rampart is slightly offset downrange with considerable asymmetry in the radial clumps. At 0.9 bar (Figure 4b), however, the rampart borders a butterfly pattern of continuous ejecta, a pattern more characteristic of much lower angle impacts (i.e., 5°) under vacuum conditions [see Gault and Wedekind, 1978]. The crater in Figure 4b also displays a downrange flow-lobe. Projectile fragments commonly are strewn downrange on top of the emplaced ejecta. At 30° impact angles (Figure 4c), ejecta deposits form a complex deposit fanning downrange at both atmospheric pressures. At the higher atmospheric pressure (Figure 4d), the ejecta is more restricted along the downrange axis. As was illustrated and discussed by Schultz and Gault [1982], ejecta from oblique
impacts are drawn by strong atmospheric flow trailing ricocheted projectile material. It should be noted that the craters formed at 30° exhibit an oblong shape, perpendicular to the trajectory. Again such a shape is more characteristic of lower angle impacts (~10°) under vacuum conditions.

Target variables. Significant effects of the environment on ejecta emplacement occur only for targets with grain sizes sufficiently small to be aerodynamically decelerated at laboratory scales [see Schultz and Gault, 1979]. Table 3 lists the different characteristics of various targets used in this study. Pumice provided the smallest modal particle size (80 μm) but had to be compacted in order to minimize porosity. Without compaction air pockets and cohesion resulted in ejecta clumping which resulted in decreased aerodynamic drag effects. For comparison, sand targets with different characteristic particle sizes were used. Particle size ranges were selected through use of U.S. standard sieves with mesh openings denoted by number. Sand passing through a U.S. no. 24 sieve are hereafter labeled 24 sand, and sand passing through a no. 140 sieve but blocked by a no. 200 sieve are labeled 140-200
Fig. 4. Effect of impact angle on ejecta emplacement under 0.25 bar (left) and 0.9 bar (right). Figures 4a and 4b contrast the effects at 60° with the effects at 30° from the horizontal shown in Figures 4c and 4d. At high impact angles, the contiguous rampart is slightly offset downrange at 0.25 bar (Figure 4a). Under a 0.9 bar atmosphere, a butterfly pattern emerges with maximum dimensions perpendicular to the impactor trajectory (Figure 4b). Such a pattern is typical of much lower angle (5°) impacts under vacuum conditions. A rampart-bordered lobe also extends downrange. At 30° impact angles (Figures 4c and 4d), the characteristic ejecta patterns are partly destroyed by the effects of residual downrange airflow created by the obliquely impinging wake and ricochet. Nevertheless, an ejecta rampart exists at 0.25 bar. Both low and high pressures result in oblong craters with maximum dimensions perpendicular to the trajectory. This response to impact angle is more characteristic of lower angle impacts (10°) under vacuum conditions. Impact velocities at the target were approximately 4.7 km/s (Figure 4a) 5.5 km/s (Figure 4b), 5.6 km/s (Figure 4c), and 5.5 km/s (Figure 4d). Ambient atmosphere was argon. Scale bars correspond to 10 cm.

TABLE 3. Target Properties

<table>
<thead>
<tr>
<th>Type</th>
<th>Grain Size, †</th>
<th>Density, g/cm³</th>
<th>Porosity, ‡</th>
<th>Angle of Internal Friction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumice</td>
<td>81 (25)</td>
<td>1.52</td>
<td>39</td>
<td>~80°</td>
</tr>
<tr>
<td>Microspheres</td>
<td>100</td>
<td>0.5</td>
<td>~40</td>
<td>20°</td>
</tr>
<tr>
<td>140-200 sand</td>
<td>125</td>
<td>1.55</td>
<td>40</td>
<td>32°</td>
</tr>
<tr>
<td>24 sand</td>
<td>457</td>
<td>1.70</td>
<td>35</td>
<td>30°</td>
</tr>
</tbody>
</table>

† Grain size is size of ejecta where cumulative fraction (by weight) is coarser than 50%; pumice exhibits a bimodal distribution (see Schultz [1992] for complete distribution).

‡ Density of constituent grains for pumice is 2.5 g/cm³; microspheres, 0.7 g/cm³; 140-200 and 24 silica sand, 2.6 g/cm³.

sand. Size distributions of these target materials are illustrated in Schultz (1992). Targets composed of 140-200 and 24 sand exhibited larger modal particle size (125 μm and 450 μm, respectively), thereby providing a wide range in drag effects due to particle size. Since particle density also should affect aerodynamic drag, targets of low-density (0.7 g/cm³) microspheres were also tested. Table 3 reveals that the pumice, microsphere, and 140-200 sand targets all exhibit comparable porosities. These three targets, however, exhibit very different angles of internal friction. The irregular particle shapes of pumice resulted in friction angles sufficient to preserve the postimpact crater profile, whereas the much lower internal angles of friction of sand and microsphere targets resulted in rim collapse, particularly at higher ambient pressures [see Schultz, 1990a, b, 1992].

Figure 5a illustrates an impact into 140-200 sand only. In general, the development of distinctive rampart-bordered ejecta facies persists for impacts into sand to higher ambient pressures, but at 1 bar, the radial scoured pattern of grooved inner ejecta is clearly established. Experiments performed at equivalent pressures of both 0.25 bar and 1 bar but contrasting densities (helium and carbon dioxide atmospheres) produced virtually identical ejecta patterns. Thus the trends previously described for pumice targets also occur for slightly coarser grained sand targets. Impacts into 24 sand, however, failed to produce any significant change from near-vacuum conditions.

Aerodynamic drag force relative to gravity increases if either particle size or particle density (for given impactor conditions) is decreased. Figure 5b illustrates an impact crater formed in a target composed of low-density (δₚ = 0.7 g/cm³) microspheres (median size of 100 μm) with a carbon dioxide atmosphere near 0.9 bar. Such a target and atmosphere should exhibit aerodynamic drag effects greater than even pumice. The
resulting ejecta deposits exhibit a very well defined rampart similar to but extending to greater distances from the rim than for sand (Figure 5a). In addition, the distal ejecta are deposited in lobes with splayed termini extending more than 10 crater radii from the rim (Figure 5c). The crater rim in this example was lost through rim/wall collapse immediately after formation.

Particle sizes in pumice exhibit a bimodal distribution with the greatest fraction centered near 81 µm and a secondary peak near 25 µm. Hence the pronounced contiguous rampart might reflect differential sorting during emplacement. Mixtures of pumice with coarse sand (16 and 24) enhanced the bimodal distribution and resulted in a distinctive modification of the crater with exaggeration of the ejecta rampart (Figures 6a and 6b). A pumice component as small as 8% by weight mixed with 24 sand produced progressively smaller craters and larger ramparts with increasing atmospheric pressure. In contrast with pumice-only targets, however, the rampart-style pattern dominated the emplacement style to a pressure of 1 bar and was evident at pressures as low as 3 mbar. Sieving the ejecta facies revealed that the rampart was composed primarily of the coarser 24 sand fraction, whereas ejecta emplaced uprange was a relatively unsorted pumice/sand mixture veneered with pumice (Figure 6c). Further dissection of the target beyond the rampart revealed that the red coarse sand fraction formed a distinctive deposit thinning with distance and resembling unmodified ballistic deposition. Consequently, it appears that a wide range of bimodal distribution in ejecta (target grain) sizes enhances the development of the ejecta rampart over a wide range of environments. The limiting atmospheric pressure and the minimum pumice (fine-grained) component required for onset of this style, however, remains to be established.

The effects of layered pumice and sand further help to identify processes responsible for the distinctive style of ejecta emplacement but may have limited relevance at broader scales. Impacts into targets with pumice overlying sand produced craters resembling impacts into sand alone, even at 1 bar atmospheric pressure. Impacts into a 1 cm layer of sand overlying compacted pumice, however, produced dramatically different results. At pressures of 1 mbar, a bowl-shaped crater was formed that resembled an impact into pumice alone (Figure 6d). Impacts under increasing atmospheric pressures (above 30 mbar) produced a nested crater appearance: a raised-rim crater in the pumice subtarget surrounded by a ridge of sand (Figure 6e). The sand layer between the crater rim and sand rampart was removed during impact with radial grooving evident in the exposed pumice substrate. The diameter of the sand rampart relative to the pumice crater increased with increasing atmospheric pressure. The process responsible for the sand rampart will be examined in more detail in subsequent sections.

A thin veneer of dry egg tempera paint on the pumice targets appeared to enhance the development of ejecta flow lobes at higher atmospheric pressures. The tempera provided a useful stratigraphic marker but also appeared to ignite when mixed with the hot wake gases. Consequently, carbonate targets were also used in order to examine the possible effects of impact vaporization. High-frame-rate imaging clearly documented vapor release and allowed the estimate of the energy in the vapor cloud [see Schulz, 1988; Schulz and Gault, 1990]. Under vacuum conditions, the released vapor cloud did not create any of the ejecta flow patterns. Under modest atmospheric pressures (0.25 bar), neither the rampart nor the flow morphology was particularly enhanced. Hence impact-generated volatiles alone will not create ejecta flow; atmospheric interactions are necessary. The enhancement of run-out resulting from powdered tempera, however, appears to reflect added turbulence created by its fine size or exothermic reaction.
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2. EJECTA SORTING

Fig. 6. Effect of mixing red-stained 24 sand (median size of 450 μm) with 8% pumice (median size of 81 μm) by weight. The development of the ejecta rampart is enhanced with concentrated coarse fractions (darker red component): (a) low-angle illumination enhancing the rampart and (b) high-angle illumination revealing distribution of lighter colored pumice. Dissection of ejecta facies reveals a mixture of pumice and sand inside the rampart with a dusting of pumice on the surface. Beyond the rampart, the coarser sand fractions dominate. (c) Sorting of ejecta sizes as referenced to the preimpact bulk particle size distribution [see Schultz, 1992].

In summary, the characteristic styles of ejecta emplacement were most affected by target particle (ejecta) size or particle density for given impactor conditions (Table 4) but could be enhanced by increased entrainment or turbulence.

The coalescing in the rampart is believed to reflect terminal deposition of larger clasts suspended by winds created during crater growth. (d and e) Effect of layered targets in the presence of an atmosphere for 0.635 cm aluminum spheres launched at about 2.2 km/s. Impacts into pumice overlain by a layer of 20 sand under 1 mbar (Figure 5r) and 30 mbar (Figure 6e) produce contrasting results due to scouring action by impact-generated winds. Experiments using pumice overlaying sand did not create this pattern even at a 1 bar atmosphere. Scale bar corresponds to 10 cm.

TABLE 4. Effect of Target Type and Atmospheric Pressure on Ejecta Emplaeement Style in Laboratory Experiments

<table>
<thead>
<tr>
<th>Target Type</th>
<th>Pressure</th>
<th>Ballistic</th>
<th>Rampart</th>
<th>Lobes</th>
<th>Radial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumice (uncompacted)</td>
<td>all P</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Pumice (compacted)</td>
<td>-0.05</td>
<td>0.06-0.3</td>
<td>0.3-0.7</td>
<td>&gt;0.8</td>
<td>--</td>
</tr>
<tr>
<td>Pumice (compacted)</td>
<td>-0.01</td>
<td>0.04-0.4</td>
<td>0.4-0.7</td>
<td>&gt;0.7</td>
<td>--</td>
</tr>
<tr>
<td>Microspheres</td>
<td>&lt;1 mbar</td>
<td>&gt;2 mbar</td>
<td>&gt;0.1</td>
<td>*</td>
<td>--</td>
</tr>
<tr>
<td>140-200 sand</td>
<td>&lt;0.09</td>
<td>&gt;0.1</td>
<td>--</td>
<td>&gt;1.0</td>
<td>--</td>
</tr>
<tr>
<td>24 sand + pumice (8%)</td>
<td>&lt;0.02</td>
<td>&lt;0.03</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>24 sand</td>
<td>all P</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

At full atmospheric pressures, radial pattern is masked by thin veneer from basal ejecta flow.

3. EJECTA CURTAIN EVOLUTION

The contrast in evolution of the ejecta curtain under a vacuum and with an atmosphere is illustrated in Figure 7a through a paired sequence of high-frame-rate photographs (400 frames per second (fps)). Both impacts were produced by 0.635 cm aluminum spheres impacting at about 1.6 km/s into compacted pumice with the left and right sequences occurring at less than 1 mbar pressure and 1 bar, respectively. The ejecta curtain for the impact at 1 bar remains relatively undisturbed throughout crater growth, although a small disturbance is observed to move progressively up the curtain with time. The ejecta curtain under 1 bar (right side) progressively increases from 57° at 2.5 ms after impact to 65° at 10 ms. In contrast the ejecta curtain under 1 mbar (left side) decreases from 44° to 40° over the same time interval. At later times, the curtain develops a distinctive bulge at its base with a flared upper curtain. The only significant difference for impacts at much higher
velocities (6 km/s) is the enhancement of the upward moving kink in this curtain at early times [see Schultz and Gault, 1982]. This kink reflects an eddy exhibiting outward airflow at top and inward flow at bottom.

Impacts into mixtures of sand and pumice (Figure 7b) graphically demonstrate the effects of differential air drag on different size ejecta. At high atmospheric densities, the coarser size fraction retains the undistorted funnel-shaped curtain profile, whereas the fine size component creates a separate curtain characteristic of an impact into this component alone or equivalently under vacuum conditions. The two curtains merge, however, at the base. Consequently, aerodynamic sorting during ballistic ejection and flight may not result in aerodynamic sorting during deposition, except for very late stage fallout.

In order to directly compare the sequential growth of the ejecta curtain, individual frames from the film record were digitally imaged. Digital subtraction of successive imaged frames through a computer left an image for only those portions of the ejecta curtain that changed through time. Two approaches were used. First, individual frames ($f_j$) were selected such that $f_{j+1} = 2f_j$ in order to enhance differences at late times when relative motions decrease (Plate 1a). Second, changes over a constant time interval of 5 ms were examined at the end of each $f_j$ in order to examine velocity changes with both time and position. Different colors were assigned to different time intervals from cool colors (black, blue) at early times to warm colors (yellow, red) at late times (Plate 1b). Consequently, continuous growth of the curtain is depicted in Plate 1a for the intervals 7.5-15 ms, 15-30 ms, 30-60 ms, 60-120 ms, and 120-240 ms, whereas changes in growth at 7.5, 15, 30, 60, 120, and 240 ms over the 5 ms interval are shown in Plate 1b. Additionally, crater profiles taken after impact were scaled to the film record and digitally superimposed. The successive sequence shown in Figure 7 can now be compared more directly over a wide range of atmospheric pressures.

Plate 1a reveals the systematic change in ejecta curtain evolution for four different impacts, all at about 1.5 km/s but with progressively increasing atmospheric pressure (top to bottom). As the crater forms, the ejecta curtain retains its conical shape at all atmospheric pressures as indicated by the base of the undistorted curtain tied to the raised crater rim (superimposed profile). After crater formation, however, the base of the curtain bulges outward while the upper portion converges inward. At 1 bar, the curtain evolves into a basal ejecta flow clearly revealing the nonballistic style of emplacement. The companion sequence (Plate 1b) documents the effect of pressure on the velocity of the curtain at a given time as indicated by the width of each color slice. During crater growth, the outward velocity of the curtain rapidly decreases until only a sliver remains at the base. Just prior to the end of crater formation, the width of the color slice corresponds to an outward curtain velocity of about 50 cm/s. After crater formation under vacuum conditions, the color slices increase in width with time, thereby indicating an increase in curtain velocity due to higher velocity ballistic ejecta comprising the curtain. With increasing atmospheric pressure, ejecta curtain velocities at the bulge not only increase but appear to be greater than under vacuum conditions. Additionally, these images reveal the inward flow well above the crater at late times. Hence the presence of an atmosphere appears to decelerate and redirect the curtain above, but enhances advance near the surface.

Comparisons of ejecta curtain growth for pumice and 140-200 sand targets are shown in Plate 2. Here, constant time intervals (at the same successive sample times shown in Plate 1b) permit focusing on the rate (as well as the form) of growth. Plate 2a contrasts curtain evolution at 0.25 bar for sand (top) and pumice (bottom) under atmospheres of helium (left) and carbon dioxide (right). Impacts into fine sand produce a slightly less bowed curtain with less irregularities at the same atmospheric pressures. The former phenomenon can be attributed to the slightly larger ejecta size for sand targets; the latter, to the narrower range in particle sizes for sand relative to pumice. Plate 2 demonstrates that the observed atmospheric effects are not the result of some unique property of pumice. The effect of gas density is illustrated in Plate 2b by the use of helium and air. For reference, ejecta curtain evolution from
Fig. 7b. Effect of different particle sizes on the evolution of the ejecta curtain. A mixture of coarse sand and pumice under a 1 bar atmosphere (air) resulted in both undistorted and distorted components of the ejecta curtain resembling impacts under a vacuum and atmosphere, respectively, as shown in Figure 7a. Resulting crater resembled example in Figure 6a. Scale bars correspond to 10 cm.

Fig. 7c. Effect of a layer of coarse sand over compacted pumice on ejecta curtain evolution under vacuum (left side) and atmospheric (right side) conditions. Under vacuum conditions, the classical conical ejecta curtain advances well after crater formation (left). Under a 1 bar atmosphere (air), the coarse sand forms the same undisturbed conical shape, whereas the finer pumice fraction resembles the shape produced by impacting into pumice alone (right). Resulting crater under vacuum conditions is shown in Figure 6b; crater at 1 bar resembled example in Figure 6a.

Impacting 140-200 sand under vacuum conditions is shown in the upper left. Ejecta curtain angle and curtain distortion are generally unchanged, but more detailed examination demonstrates that curtain growth under high pressures of helium (~1 bar) resembles growth in air at lower pressure but comparable ambient density. Although not shown, impacts in a CO2 atmosphere produce the opposite trend. Thus air drag, revealed here by the effect of atmospheric density, controls the growth of the ejecta curtain. The separate effect of atmospheric pressure can nevertheless be seen by the relative sizes of the final craters, as discussed by Schultz [1990a, 1992].

At early times (within 7.5 ms) the conical ejecta curtain shape typifying vacuum conditions remains evident at all pressures, but higher atmospheric pressures result in higher angles (with respect to the horizontal). Figure 8 documents this evolution as a function of both time and atmospheric pressure for sand and pumice targets. The curtain angle for both sand (140-200) and pumice targets under vacuum conditions...
Plate 1. Computer-digitized film record showing evolution of ejecta curtain under different atmospheric conditions. (a) Overall growth between 7.5-15 ms (purple), 15-30 ms (blue), 30-60 ms (green), 60-120 ms (yellow) and 120-240 ms (red). (b) Incremental advance over a constant time interval of 5 ms ending at about 7.5 ms (black), 15 ms (purple), 30 ms (blue), 60 ms (green), 120 ms (yellow), and 240 ms (red). Atmospheric conditions range from 0.125, 0.25, 0.50, to 1.0 bar of air with impact velocities of about 1.5 km/s (0.635 cm aluminum spheres). Width of color slices in b indicate the outward velocity of the ejecta curtain that decreases during crater growth but increases afterwards.
Plate 2. Comparison of atmospheric pressure, density, and particle size on ejecta curtain evolution. (a) Effect of atmospheric density at a given pressure (0.25 bar) for 140-200 sand (top pair) and pumice (bottom pair) by the use of a helium atmosphere (left) and carbon dioxide atmosphere (right). (b) Effect of atmospheric density on ejecta curtain evolution for impacts into sand (top) and Pumice (bottom) under a pressure of 1 bar of air (right, top and bottom) and helium (left, bottom). Top left sequence shows the evolution of the ejecta curtain for 140-200 sand under vacuum conditions as a reference. The color coded stages of curtain evolution are the same as in Figure 8. Scale bar corresponds to 10 cm.
Fig. 8. Contrasting ejecta curtain angles as a function of time, atmospheric pressure, atmospheric density, and target particle size. (a) Time evolution of the ejecta curtain for 140-200 sand (top) and pumice (bottom) targets. Under vacuum conditions, the curtain angle for sand and pumice gradually decreases from near 50° to 43°. As atmospheric pressure increases, ejection angle also increases. Comparison of a helium atmosphere at 1 bar with air at 0.125 bar reveals a very similar evolution. Moreover, curtain angle in pumice is greater than in sand. Both responses should be expected if atmospheric density (aerodynamic drag) controls curtain angle. (b) Evolution of ejecta curtain angle 25 ms (+2 ms) after impact as a function of atmospheric pressure for air and helium using sand (top) and pumice (bottom) targets. Ejecta curtain angle is more affected in pumice than in sand. Use of helium has little effect. Impact velocities were all about 2 km/s.

decreases only slightly with time (from 50° to 42°). The addition of an atmosphere increases the curtain angle. Use of helium allows the comparison of the effect of atmospheric pressure and density and reveals that atmospheric density is the controlling variable for both pumice and sand: helium at 0.84 bars exhibits the same curtain evolution as air at 0.125 bar, both conditions resulting in nearly identical densities (0.116 and 0.125 air at STP, respectively). Figure 8b further establishes the difference between helium and air at common times (25 ms). At high atmospheric pressures the curtain continues to move outward at the base after crater formation but ceases above the surface. Comparisons of the vacuum and nonvacuum cases (Plate 1) reveal that the base of the curtain under high pressures moves outward at a velocity higher than the curtain under vacuum conditions. Consequently, a base-surge-like motion develops after the crater finishes forming. The nature and cause of this motion will be discussed in a subsequent section.

In summary, an ensemble of ballistic debris composes the ejecta curtain during crater growth even at high atmospheric pressures and densities. Both particle size and atmospheric density affect the shape and evolution of the ejecta curtain after crater formation, thereby indicating the role of aerodynamic drag. Under high atmospheric densities, a basal ejecta surge develops and advances outward at velocities that exceed the ballistic ejecta curtain under vacuum conditions.

4. EJECTA EMBOLMENT PROCESSES

The preceding descriptions focused on the variables controlling the observed ejecta patterns and ejecta curtain profiles in different atmospheric environments. This section reviews specific observations and experiments that can provide clues for possible processes producing contrasting ejecta emplacement styles in the laboratory. Possible processes unrelated to crater formation are considered before examining the origins for the contiguous ejecta rampart, ejecta flow lobes, and radial scour pattern.

Nonimpact processes. Could the various ejecta patterns and ejecta curtain modifications reflect disturbances created by launch design, the preimpact passage of the projectile through an atmosphere, or the release of gases trapped in the target? Several procedures and observations minimize or constrain such possibilities. Muzzle blast by gases trailing the projectile can occur in both two-stage light-gas guns and conventional powder guns.
This effect was minimized in these experiments by the use of thin mylar diaphragms mounted both at the exit port from the launch tube and at the entrance port in the impact chamber. A mylar diaphragm is necessary for experiments with the light gas gun in order to prevent atmospheric gases from entering the launch tube. A further benefit, however, is the containment of muzzle blast. For example, the self-luminous ionized wake left behind the projectile at high velocities (>5 km/s) exhibits fine-scale turbulence that remains unmodified (see Schultz and Gault, 1982), thereby confirming the absence of a launch-related blast disturbance. Failed experiments producing large muzzle blast break the mylar and produce visible effects; such occurrences are excluded from this analysis.

Turbulence created by the projectile air shock represents a second possible nonimpact process that might modify ejecta emplacement. Several observations, however, indicate that this effect is minor. First, air shock effects did not modify a dry-ice vapor cloud suspended above the impact surface (Schultz and Gault, 1982). Second, air tracers (threads) showed the passage of the air shock well above the impact but also showed rapid equilibration. Third, the characteristic ejecta patterns and curtain evolution occur for impacts at subsonic (30 m/s) as well as supersonic velocities. Signatures of the projectile shock wave and trailing wake appear to exist in early-time turbulence in the ejecta curtain [Schultz and Gault, 1979, 1982], in cratering efficiency [Schultz, 1990a, 1992], and in crater shape [Schultz, 1990b]. Such signatures, however, do not extend to late-time evolution of the ejecta curtain when near-rim emplacement occurs.

Compacted pumice exhibits nearly the same density (1.5 g/cm^3) and porosity (~40%) as 140-200 sand but has lower permeability. Consequently, sudden-impact-released gases trapped in pore spaces might play a role in modifying the expression and maximum radial extent increases with increasing aerodynamic drag controlled by the atmospheric density, drag coefficient, target particle size and density, and ejection velocity (i.e., crater size). Third, ramparts can develop even without significant modification of the ejecta curtain shape (i.e., at low densities, Plate 2). Fourth, impact into targets where grain size radially decreased from the impact point did not produce the rampart pattern. Fifth, impacts into sand-over-pumice targets (Figure 6d) produce sand ramparts outside a sand-cleared zone in a manner analogous to rampart formation. And finally, off-vertical impacts (Figure 4) produce a rampart-bordered, butterfly ejecta pattern.

The first three observations indicate that entrainment of fine ejecta plays an important role. Too much entrainment results in the onset of more complex ejecta morphologies; less entrainment supersedes the complex ejecta morphologies, even at high pressures. Mixtures of relatively small fractions of fine-sized pumice with coarser sand produce analogous rampartlike ridges at very high atmospheric pressures (Figures 6a and 6b) but not in a vacuum. The fourth observation indicates that rampart formation is a late-stage process and requires finer fractions. The fifth observation suggests that impact-related, outward-moving winds may play a role. The sand rampart in sand-over-pumice layered targets develops by accumulation of the coarse sand rather than uplift of the substrate. This interpretation is consistent with observations of the basal ejecta surge (Plate 1). The low-shear strength of the sand permitted its radial displacement well beyond the rim of the crater formed in pumice substrate. Finer pumice ejecta were piled on the crater-facing side of the rampart. Finally, the sixth observation indicates that rampart formation is tied to emplacement of ejecta, not to vapor release or wake effects.

While Plate 1 suggests that outward winds result from impacts in an atmospheric environment, the formation of the rampart in pumice targets appears related to a depositional process. Profiles of the ejecta deposits (Figure 9a) show that the rampart occurs on top of the continuous ejecta. The rampart can be seen to cross ejecta clumps, and obstacles placed near the rim were found to suppress the development of the rampart downrange (Figure 9c). Thus the rampart does not result from preemplacement scouring of the preimpact surface but from deposition. Figure 6c revealed that coarse ejecta are concentrated in the ejecta rampart with finer fractions dominating the inner continuous deposits. This pattern of deposition is consistent with ballistic ejection and emplacement of the coarse fraction but modified emplacement of the finer fraction. Moreover, it is consistent with the onset of rampart formation without significant distortion of the ejecta curtain (Plate 2).

Although perhaps counterintuitive, the ejecta rampart increases in distance from the rim with increasing atmospheric pressure. The rampart typically becomes much more subtle, however, as the turbulent ejecta overruns and scour the inner facies (Figure 9b). Thus ejecta ramparts and ejecta flow morphologies are not exclusionary processes.

**Ejecta flow.** At higher atmospheric pressures (0.4-0.7 bar), the contiguous rampart developed in compacted pumice increases its diameter and commonly breaks into tongues of ejecta (Figure 1b). Ejecta ramparts may be broken or over-run by these flow lobes under transition conditions. The ejecta lobes extend as far as six radii from the crater rim and reflect deposition from a ground-hugging flow witnessed in the film record. This turbiditylike flow behavior can be illustrated by the effect of topographic barriers on its advance. A crater-facing scarp 2 cm high constructed in the target was overrun by individual flow lobes. Consequently, the ejecta exhibited fluidlike behavior even in the absence of water.
Ejecta flow did not develop in either 140-200 sand or in sand-pumice mixtures. Moreover, it was not particularly enhanced by the use of easily volatized target material. The use of low-density microspheres with comparable ejecta sizes, however, resulted in both an inner ejecta rampart and distal run-out lobes (Figures 5b and 5c). The distal ejecta lobes form a distinctive divergent pattern resembling a cauliflower (Figure 4c). Consequently, the development of ejecta flow seemed to require only a sufficient ambient pressure and a target having small (<80 μm) or low density constituent grains.

The development of ejecta flows therefore appears to reflect a three-stage process of ejecta deceleration, entrainment within turbulent vortices, and run-out as a ground-hugging density flow. Such a description mirrors the observed basal flow of ejecta that outpaces ballistic ejecta for identical impactor conditions in the absence of an atmosphere (Plate 1). While the formation of the ejecta rampart reflects a broad-scale vortex pattern trailing behind the wall of ejecta at lower pressures, ejecta flows represent ejecta kinetic energy being converted to atmospheric convective turbulence near the rim and the formation of a turbidity flow.

**Ejecta scour (radial pattern).** At the highest ambient pressures possible in the vertical gun (i.e., 1 bar), material is still ejected in ballistic trajectories during crater formation, thereby indicating response to the collisional shock and rarefaction in the target. Emplacement of ejecta, however, now is severely modified by an intense, tight eddy forming an expanding donutlike toroid. This vortex scours ballistically emplaced ejecta near the rim, thereby creating a characteristic moat surrounding the raised rim (Figures 9a and 9b). Entrained ejecta are carried and dispersed many crater radii from the rim by this process. The long run-out lobes in Figure 5c further underscore the process. Such distal ejecta deposits, however, are characteristically thin and principally composed of very fine grained ejecta. While subtle preimpact textures remain preserved beyond the ejecta rampart at lower atmospheric pressures, these textures are muted or lost at high pressures due to the intense scouring action witnessed in the film record. Thus high atmospheric pressures do not prevent crater formation but result in nearly complete transfer of energy from ejecta kinetic energy (arresting ejecta curtain advance soon after crater formation) to turbulent power within the atmosphere which scours the surrounding surfaces.

**Crater and ejecta dimensions.** The change in emplacement style with atmospheric pressure appears to reflect increased entrainment of the atmosphere with ballistic ejecta at interparticle scales and increased intensity of turbulence at broader scales. In order to extend these laboratory-scale results to kilometer-scale craters on Mars, ejecta entrainment and the emplacement process need to be quantified.

The diameter of the ejecta rampart relative to the crater diameter appears to increase with increasing atmospheric pressure for a given composition and for the same impactor conditions (Figure 9). The specific physical processes affecting crater growth during excavation, however, are different from processes controlling ejecta emplacement after excavation. Consequently, observed crater dimensions
principally serve as reference. Crater size under vacuum conditions actually provide a more relevant comparison since momentum of the impactor.

this dimension can be related to the initial energy and vertical barrier placed in the preimpact target interrupted the advancing ejecta pressure and density represent the only remaining relevant crater for two different impact velocities but identical impactor size. Although the data are not shown in dimensionless form, Fig. 9c. Effect of obstacles on ejecta rampart formation in compacted pumice. A vertical barrier placed in the preimpact target interrupted the advancing ejecta curtain and suppressed the formation of the rampart. A small scoop (top) also affected rampart formation. Impact velocity (0.635 cm aluminum) was 5.2 km/s with an atmospheric pressure of 0.25 bar (argon). Scale bar corresponds to 10 cm. Illumination is from the upper right.

Figures 10 and 11 permit contrasting the effects of ambient pressure and density on the diameter of the ejecta rampart and crater for two different impact velocities but identical impactor size. Although the data are not shown in dimensionless form, pressure and density represent the only remaining relevant controlling variables. Atmospheric pressure does not appear to affect rampart diameter for different constituent atmospheres (Figure 10a). Increasing atmospheric density (Figure 10b) systematically increases rampart diameter with decreased scatter. Since atmospheric density affects aerodynamic drag, entrainment of ejecta in the atmospheric response appears to control the observed run-out. Parallel effects of atmospheric conditions on rampart and crater diameter for sand targets and more complex stratigraphies and mixtures are shown in Figure 11. Table 5 provides a listing of empirical data used in Figures 10 and 11.

Controlling processes. The film record provides critical information about ejecta emplacement processes. First, high-frame-rate photography from cameras positioned above the impact reveal that the region inside the ejecta curtain is visible throughout crater growth. Only after crater formation does the crater cavity become obscured. At this time, ejecta well above the impact surface rapidly converge inward and appear to be drawn downward. Second, stereo imaging by a side camera further reveals an upward motion behind the leading wall of ejecta. And third, a thick plexiglass window placed parallel to the impactor trajectory and perpendicular to the camera literally bisected the cratering event. Such configurations are termed quarter-space experiments and reveal the pattern of circulation inside the ejecta curtain.

The quarter-space experiments graphically demonstrated ballistic ejection and unobscured transient cavity growth well after passage of the shock wave (Figure 12). The impact point is necessarily offset from the window (about a projectile diameter away) and results in ejecta streaming along the plexiglass without atmospheric distortion. Nevertheless, the sequence of views reveals that the base of the ejecta curtain is carried outward by the rolling vortex inferred from stereo photography. Once the vortex no longer can mobilize and support the ejecta, it collapses to form a rampart while smaller ejecta entrained in the rolling vortex help to identify its continued outward advance. After the ejecta curtain dissolves, suspended ejecta above the crater simply fall directly to the surface without evidence for any thermal buoyancy effects.

The pressure-controlled onset of different emplacement styles yet the density-controlled run-out distances suggest that pressure differential created in the basal vortex controls the onset of a particular emplacement style while the degree of entrainment in the vortex controls the run-out distance. Ejecta entrainment depends on the relative role of aerodynamic and gravitational forces:

\[ d/g = (3/8)C_D p v_e^2/\delta g a \]  

where \( d \) is the decelerating force, \( g \) is gravitational acceleration, \( C_D \) is the drag coefficient, and \( v_e \) is late-stage ejection velocity for an ejected particle of density \( \delta \) and diameter \( a \). The abscissa in Figure 10, then, can be viewed equivalent to equation (1) with all variables constant, excepting density. At laboratory scales, the small size of the ejecta (<80 \( \mu \)m) and low velocity of ejecta at late stage (<50 cm/s) result in low Reynolds numbers \( (R_e) \) approaching unity where the drag coefficient varies as \( 1/R_e^0 \). For given impactor and target conditions, the range in density and gas viscosity controls the variation in \( C_D \). The complex conditions and distribution of shapes preclude estimating \( C_D \) directly. In the limiting case where \( \omega \) is unity, the role of \( d/g \) reduces to a dependence on only viscosity of the ambient atmosphere. The relative viscosities listed in Table 1 reveal that such a case would still remain consistent with the trends in Figure 10.

The onset of nonballistic ejecta emplacement also can be viewed analogous to conditions necessary for aeolian transport. Greeley and Iversen (1985) examined the threshold friction speeds necessary for particle motion on Earth. For particle sizes comparable to pumice, the threshold friction speed was 20 cm/s, a value comparable to the outward velocity of the ejecta curtain as it advances beyond the rim (Plates 1 and 2). Entrainment in a vortex, however, was found to be independent of viscous effects (i.e., particle diameter and wind speed); rather, the pressure difference created in the vortex lofted and entrained particles. Wind velocities are created and controlled by the pressure difference in front of and behind the ejecta curtain; consequently atmospheric pressure controls the onset of rampart formation. As noted by Greeley and Iversen (1985), however, viscous drag effects do become important as particle size and density increase beyond a critical value, that is, as the laboratory craters are scaled to much larger Martian craters.

Different ejecta emplacement styles in laboratory experiments, then, reflect different processes that largely depend on the atmospheric response (turbulence or winds) and the degree of entrainment of ejecta into this response. The various styles have not been placed into a taxonomic matrix, as is commonly done for Martian craters, in order to emphasize underlying processes and to acknowledge that such processes
may not scale to much larger dimensions in a simple or direct way. Moreover, different combinations of processes can lead to multiple emplacement styles around a single crater resulting in different taxonomic classes without changing the underlying cause. Table 6 summarizes the various emplacement styles observed in the laboratory, specific examples cited in the text, observed processes, controlling variables, and interpretation.

5. DISCUSSION

The various styles of ejecta emplacement bear striking similarities to ejecta facies surrounding Martian craters. Such similarities have greater utility if they can be incorporated into a testable model of the emplacement process. The following discussion develops such a working model and explores possible implications for understanding ejecta emplacement on Mars, Earth, and Venus.

Emplacement model. Three different styles of late-stage ejecta emplacement with increasing atmospheric pressure can be recognized from the laboratory experiments: rampart, multilobed, and radial. These styles correspond to processes reflecting the increasingly intense atmospheric response to crater formation resulting in increased modification of the ballistic ejecta curtain and entrainment of ejecta. A fundamental assumption must be made at the outset: the cratering flow field and eventual ballistic ejection from the crater cavity reflect the mechanical response of the target to the impact shock and consequent rarefaction waves from the free surface as summarized by Gault et al. [1968]. In other words, material is ballistically excavated, not simply driven by explosive backpressures. Such an assumption can be justified by the observed evolution of the ejecta curtain, an observation discussed in previous sections. Although backpressures created by the impinging wake trailing the projectile may augment crater growth [Schultz, 1990a, 1992], this process is assumed to be a second-order effect modifying early-time ejecta. Consequently, growth and ejection is a systematic, not chaotic process under atmospheric conditions just as it is under a vacuum.

Interaction between ejecta and atmosphere can be divided into two time scales. Early-time impact processes occur when the crater has achieved only 40% of its final diameter. As reviewed previously [Schultz and Gault, 1982], a complex air shock must develop in response to jetted material and an early-time supersonic ejecta plume (Figure 13a). Such interactions appear to be restricted to within the first millisecond of impact,
Layered sand targets, examples of which are shown in Figures 5b and 6c, respectively. Confronting the ejecta curtain, thereby creating a strong precursor wind. Low-density styrofoam spheres placed across the preimpact surface documented passage of this vapor cloud front. Most of the vapor, however, is partly contained in and redirected by the growing transient cavity [see Schultz and Gault, 1979, 1982; Melosh, 1982; Schultz and Gault, 1990]. Consequently, the early-time vapor cloud resembles an upward directed jet exhaust for high-angle impacts [see Schultz, 1988]. In the presence of an atmosphere, this upward moving and expanding cloud is retarded both by the ambient gas and the incoming wake trailing the projectile. Such processes, however, are all early-time phenomena and do not appear to affect later-stage ejecta emplacement processes at laboratory scale.

At low impact angles (<30°), the early-time jetting component and vapor cloud travel rapidly downrange, thereby becoming decoupled from the initial ejecta plume and growing transient cavity [Schultz, 1988; Schultz and Gault, 1982, 1990]. Under low atmospheric pressures the resulting cloud expands hemispherically while traveling downrange. Under high atmospheric pressures, the vapor cloud, early-time jet, and ricocheted projectile fragments combine in a tight fireball that scours the downrange target surface prior to emplacement by late-stage ejecta.

The evolution of the later stage ejecta curtain and subsequent ejecta emplacement are illustrated in Figure 13b. The intensity of the later-stage curtain is similar from subsonic to hypersonic impact velocities, the observed distortion of the ejecta curtain is interpreted as a response of the atmosphere to the outward moving wall of ejecta coupled to the effect of drag on individual ejecta as they leave the cavity. Specifically, a partial vacuum develops behind the outward moving curtain, but recovery to ambient conditions occurs as the atmosphere rushes through (and over) its thinnest upper portion. Moreover, airflow responding to the inclined ejecta curtain is analogous to a well-known hydrodynamic problem of flow impinging on an inclined plate. In the frame of reference of the moving plate, the redirected airflow develops compressed streamlines as it passes over the top, thereby producing augmented velocity and pressure. If the curtain is viewed as a flexible plate, then a bowed profile should develop. Behind the curtain, a rolling circulation pattern develops with inward flow at top and outward flow at the base. The intensity of this circulation (wind velocity) should depend on the velocity of the outward moving curtain at late times, which in turn depends on the ejection velocity. As depicted in Figure 13, at some point recovery winds entrain and mobilize ejecta landing behind the ballistic ejecta curtain. The circulation will be sustained, however, only as long as a pressure differential exists.

With increasing atmospheric pressures, turbulence increases and sustains long run-out distances of individual flows. Eventually, the intensity of the entrained atmosphere at higher pressures erodes the crater rim, scours ballistically emplaced inner ejecta deposits, and disperses the distal ejecta. The effectiveness of this process can be inferred from the deep scours surrounding the rim and the reduced ejecta thickness shown in Figure 9c. Erosional scouring is further indicated by the basal ejecta flow, which exceeds ballistic velocities (Plate 1), the radial grooving characteristic of the near-rim (<2R) ejecta deposits, and the rounding of the inner facies.

The scenario in Figure 13 depicts two different modes of emplacement. After the crater has finished forming, ballistic ejecta form the inclined, outward moving curtain. Near the rim (<0.5 R), impacting ejecta create a debris flow that is limited in advance at laboratory scales owing to low potential energy. This first phase, however, resembles qualitatively experimental subaqueous debris flows [e.g., Hampton, 1972]. Flow separation in the lee of such advancing debris flow creates a turbulent cloud of debris mixing with the ambient fluid;
In Table 5 the impact velocity $v_i$ has been corrected for drag that reduces launch velocity $v_o$. Pressure is in bars. Target types include compacted pumice (P), no. 140-200 sand (S), no. 24 sand mixed with 8% by weight pumice (PS), and layer over compacted pumice (S/P). Rim to rim crater diameter (DC) and "rampart" diameter are (DR) in centimeters. Asterisks indicate impacts into targets with a thin veneer of dry tempera.

enough turbulence generates a turbidity flow. In the laboratory impact experiments, recovery winds created by the temporary vacuum behind the ejecta curtain enhanced an analogous turbidity flow: the greater the pressure differential, the greater the winds, the greater the power in the turbulence. This analogy permits exploring the various modes of emplacement and factors controlling ejecta run-out in the context of a physical model.

Run-out by flow of emplaced ejecta in the absence of a fluidizing agent (e.g., entrained air, water, or released gas) can be divided into two components:

$$S = S_0 + S_t$$  \hspace{1cm} (2)

where $S_0$ is the distance traveled where the supply of turbulent energy created by the ejecta curtain moving through the atmosphere goes to zero and where $S_t$ is the run-out distance following this turbulent influx. Here the effect of basal shear drag on the run-out is ignored. Under limited turbulence, $S_0$ should correspond to the distance where the suspended load is suddenly deposited, thereby forming the ridge of coarser ejecta on top of the ballistically emplaced ejecta deposit. Under enhanced turbulence, run-out will be extended by a distance ($S_t$) until energy in the flow has fallen below a critical value. As discussed in more detail below, this distance could be further augmented by an autosuspension process [Bagnold, 1962, 1963; Pantin, 1979] in which the moving ejecta cloud creates more turbulence, thereby increasing its power.

The distance $S_0$ depends on the wind velocities ($w$) generated by the ejecta curtain moving at a velocity, $v_{e}(x/R)$. At a given
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\[ S_0 = \frac{1}{2} (w^2 g) = kR \]  

This result predicts that rampart distance scaled to crater size should be approximately constant. Because \( R \) is calculated on the basis of late-stage gravity-controlled growth, it is implicitly assumed that it refers to crater radius had it formed in a vacuum (i.e., material flow created by the impact without any modification due to presence of an atmosphere). At low atmospheric densities (low Reynolds numbers) turbulence generated by the moving ejecta curtain should be minimal, as graphically illustrated in Plate 2b for impacts under an atmosphere of helium. Ejecta ramparts nevertheless form above a critical pressure, and Figure 14a reveals that equation (3) is consistent with this model of entrainment and deposition from turbulent-generated winds.

As atmospheric density increases, turbulence increases (Plate 1), and the distance to rampart formation or run-out of individual lobes increases. In the absence of continued influx, the head of the density current created by ejecta entrained in the turbulent atmosphere behind the ejecta curtain should initially continue to advance outward at a horizontal velocity \( u \) (if frictional forces along the surface are considered negligible). Under these conditions, conservation of energy gives the following relation:

\[ \frac{1}{2} \rho_o u^2 = (\rho_e - \rho_o) gh \]  

where \( \rho_o \) is the ambient density, and \( \rho_e \) and \( h \) are the density and height of the turbulent ejecta cloud, respectively. This density cloud should travel a distance given by

\[ x = \frac{1}{2} \rho_o u^2 \]  

where \( \rho_o \) is defined as an entrainment factor. The distance traveled before forming a rampart therefore is augmented by a factor dependent on the degree of ejecta entrained in the recovery wind circulation.

The degree of entrainment depends on the deceleration of individual ballistic ejecta as given by equation (1). Two limiting conditions can be derived. The first considers the drag coefficient to be constant; the second assumes that \( C_D \sim \frac{1}{Re} \): \n
\[ F_e = (1/2) \rho e R^2 \]  

where \( \mu \) is the eddy viscosity of the atmosphere introduced through the Reynolds number \( (Re = \rho va) \), and \( a \) and \( \alpha \) are the size and velocity of individual ejecta fragments. Velocity in equation (1) and in the Reynolds number has been replaced by the approximation \( va^2 = gR \), as required for late-stage gravity-controlled ejection velocities. The eddy-driven rampart distance predicted for different ranges of Reynolds numbers becomes

\[ z/R \sim (\rho_e R \delta a)(R/g)^{1/2} - \rho_o R^{1/2} \]  

for \( C_D = \text{const} \).
Fig. 13. Processes affecting ejecta emplacement at early and late times as inferred from high-frame-rate imaging, changing target and atmospheric conditions, and special experimental designs (quarter-space experiments and layered targets). (a) At early times the ionized wake trailing the projectile fills the growing impact cavity. Interactions between the ionized wake and high-velocity ejecta create a turbulent disturbance that moves up the curtain. (b) At late times evolution of the ejecta curtain is largely controlled by response of the atmosphere to the outward-moving ballistic ejecta curtain. Targets resulting in a wide range of ejecta sizes (factor of 100) result in a two component curtain: larger size fractions define the classic conical profile observed under vacuum conditions; smaller fractions become entrained in an ejecta cloud (see Figure 10). The ejecta cloud is turbulent at small scales but reflects an atmospheric circulation at large scales induced by the outward-moving ejecta curtain.

\[ x/R = (\mu/g \alpha)^{1/2} \left( R^{1/4}/\delta_a \right) = (\mu)^{1/2} R^{1/4} \quad (8b) \]

for \( C_D \sim (1/R_a)^{1/2} \), and

\[ x/R = (\mu/\delta a^2)(1/g)^{1/2} \sim \mu \quad (8c) \]

for \( C_D \sim (1/R_a) \) where it is assumed that \( F_e (g/R)^{1/2} \gg k \) and that \( \delta, a, \) and \( g \) are constant. Equation (8a) accounts for the observed dependence between rampart diameter and atmospheric density for given impactor size and velocity revealed in Figure 10. Small residual offsets, however, for different atmospheric compositions suggest that a viscosity-dependent drag coefficient (introduced by a dependence on the Reynolds number) also may apply.

Figures 14b and 14c show the range of possibilities given by equation (8) for different Reynolds numbers and reveal that the proposed scaling of the rampart is generally consistent with the observations. Figure 15 correlates ejecta run-out distances with formation of the crater cavity as revealed by crater profile (diameter/depth). Greater run-out distances characterize smaller values of diameter/depth, i.e., arrested crater growth. Consequently, energy expended in reducing crater diameter is nevertheless expressed in enhanced turbulent power of ejecta flows.

As atmospheric pressure increases, the intensity of turbulence behind the ejecta curtain increases. The resulting eddy-driven flow overrides deposition of the suspended load and channelizes into individual lobes (Figures 1c and 5c). Divergent flow within the flow head creates continued vertical
motion, mixing with local material; eventually a rampart-bordered terminus forms as turbulent energy dissipates. The observed ejecta lobes in the laboratory no longer grow proportionally and perhaps indicate an autosuspension process described by Bagnold [1962, 1963] and Pantin [1979]. Autosuspension is a feedback condition wherein suspended material causes motion, thereby producing further turbulence and more suspension. In rivers and certain avalanches, gravity and slope control advance of the density current. For impacts in an atmosphere, movement down the radially thinning continuous ejecta deposits partly control this process. Gravity also plays an indirect (but perhaps more important) role through the impacting ejecta at the base of the advancing ejecta curtain. Since the ballistic ejecta curtain increases in velocity with increasing distance from the rim (Plate la), autosuspension should be a natural consequence as leading ballistic ejecta add kinetic energy to the flow.

Pantin [1979] found that turbidity currents must either decelerate, thereby depositing their load, or accelerate into autosuspension. Conditions leading to autosuspension were given as

$$e_x \beta \omega / v_t \geq 1$$  \hspace{1cm} (9)

where $e_x$ is an efficiency factor, $\beta$ is the slope, $\omega$ is the flow velocity, and $v_t$ is the fall velocity in the entrained flow. The efficiency factor represents the degree of excess power available for suspending the load relative to the power expended along the base. As the overriding turbidity current runs off the continuous ejecta, $\beta$ may be replaced by an effective-gradient factor reflecting the increased outward velocity in the ejecta curtain with distance. Such a factor also would go to zero, however, as the ejecta curtain thins sufficiently. The basal surge observed at laboratory scales

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**LATE-TIME PHENOMENA**

![Diagram](image_url)
Fig. 14. The effect of crater size and atmospheric conditions on run-out of ejecta ramps. (a) Distance from crater rim to rampart as a function of crater diameter had the impact formed in a vacuum. Data are for very small Reynolds numbers with minimal drag (viscous effects). (b) Comparison of rampart run-out distance scaled to crater diameter (vacuum conditions) as a function of entrainment as given in equation (8). Entrainment depends on the drag coefficient, which also depends on the Reynolds number. Figure 14b considers a range in Reynolds numbers over Table 5 for listing of empirical data.

indicates that a large e due to increasing turbulence, entrainment, and small \( \nu \) all can contribute to excessive run-out. The possible role of increased turbulence is illustrated by the effect of adding a thin veneer of tempera over compacted pumice, whereas the role of entrainment and small \( \nu \) is clearly demonstrated by the long distal lobes for impacts into a target of low-density microspheres (Figure 5c). In the latter example, the fanlike terminus characterizes sudden termination of channelized autosuspended flow. Conversely, the absence of flowlike lobes in coarser grained targets or mixtures (Figure 6) reflect fall velocities of coarse ejecta that are too high to meet this condition.

Oblique impacts. The various modes of ejecta emplacement should not fundamentally change with impact angle: eddy-suspended and autosuspended flows resulting in ramparts or lobes should and do (Figure 4) develop. Nevertheless, a distinctive asymmetry and even the butterfly pattern develop under 0.25 bar pressure at much higher angles (60° from horizontal) relative to vacuum conditions (5°). The ionized wake and point of impact clearly establish that the impact angle has not changed [see Schultz and Gault, 1982]. The enhancement of ejecta asymmetry can be attributed to three causes. First, the development of an ionized wake trailing the projectile at higher atmospheric pressures creates an early-time turbulent barrier for uprange ejecta [see Schultz and Gault, 1982]. Gases within the projectile wake are observed to continue to impinge on the impact cavity even after contact. These two nonaxisymmetric processes result in an exaggeration of the emplaced ejecta pattern at modest atmospheric pressures. Second, despite a relatively symmetric appearing crater and ejecta distribution for impacts into particulates between 15° and 60°, there is considerable asymmetry in the evolution of the ejecta curtain under vacuum conditions [e.g., see Gault and Wedekind, 1978; Schults and...
Third, oblique impacts result in low downrange ejection angles. The relevant scaling ratios include the Froude (inertia:gravity forces), and Weber (inertia:surface tension forces), Reynolds (inertia:viscous friction forces), and Euler (pressure:inertia forces) numbers. These scaling ratios must be considered for both the outward moving ejecta curtain and the ejecta particle moving through the atmosphere.

Scaling laboratory results. Impact craters in the laboratory can be scaled over many orders of magnitude through dimensionless scaling parameters as discussed by Holsapple and Schmidt [1982]. Their derived principal scaling parameter can be viewed as Froude-scaling where inertial forces are ratioed to gravity forces. An explicit assumption is made that details of the transfer of energy from impactor to target at early times can be ignored at late times when gravity controls crater growth. The use of loose particulate targets is implicitly based on this assumption where the initial passage of the shock wave converts solid target material into broken debris. Shock-broken target material may be further comminuted by the shearing action resulting from the redirected material flow field [e.g., Schultz and Mendell, 1978] or perhaps vaporization [Wohletz and Sheridan, 1983]. Froude-scaling predicts that late-stage ejection velocities and time should scale as the square root of linear dimension and gravity as derived in various studies [e.g., Post, 1974; Schultz and Gault, 1979; Housen et al., 1983] and as used in derivations in the present study. Table 7 explores the implications of this scaling principle on late-stage ejection velocities and representative peak pressures over a wide range of crater sizes on Mars. For reference, an impact producing a 16-cm-diameter crater in the laboratory with late-stage ejection velocities of 50 m/s would correspond to velocities of 77 m/s for a 10-km-diameter crater (apparent diameter of transient crater) on Mars in order to maintain the same relative radial distribution of ballistic ejecta (without atmospheric effects).

Interactions between ejecta and the atmosphere also require scaling inertial forces to viscous friction forces, that is, the Reynolds number, in order to extend the model. It is desirable to have the Reynolds number matched at laboratory and actual scale but this is not possible for impacts in the laboratory since two interaction scales must be considered. The movement of the curtain of ejecta through the atmosphere establishes one scale of interaction; the interaction of individual ejecta and that energy lost to crater formation is represented in atmospheric turbulence leading to greater run-out of the ejecta rampart. See Table 5 for listing of empirical data.

Gault, 1979, 1985], The downrange ejecta curtain advances at a higher velocity and contains more ejecta than the uprange curtain. Consequently, both ejecta rampart and run-out lobes should extend to greater distances in the downrange direction. Third, oblique impacts result in low downrange ejection angles and high uprange angles under vacuum conditions. Introduction of an atmosphere results in vertical ejection curtain angles, thereby amplifying asymmetries in emplacement distribution.

At high atmospheric pressures and low impact angles, the emplacement process becomes disrupted by two additional processes: projectile ricochet and effects of vaporization. Impact angles less than 30° result in ricochet of large fractions of the projectile at high velocities [Gault and Wedekind, 1978; Schultz and Gault, 1990] as graphically revealed in high frame-rate photography [see Schultz and Gault, 1982], the downrange ricochet creates a strong turbulent wake and wind that draws considerable ejecta downrange. Thermal effects from this wake and from impact-induced vaporization create significant thermal turbulence behind the downrange ejecta. As a result, projectile and target material are drawn downrange, even at late times. At laboratory scales, these two processes significantly disrupt the emplacement process.

6. POSSIBLE IMPLICATIONS

Although the laboratory impact craters are clearly at a small scale, they nevertheless reveal phenomena and processes that can be scaled to the planets. Future work will explore specific aspects in greater detail; the following discussion considers selected testable predictions for ejecta emplacement styles on Mars with implications for the Earth and Venus. Interactions between late-stage ejecta and the atmosphere require evaluating a variety of dimensionless scaling relations depicting relative forces in order to maintain similarity between the laboratory "model" and planetary scale processes [e.g., Langhaar, 1951]. The relevant scaling ratios include the Froude (inertia:gravity forces), Reynolds (inertia:viscous friction forces), Euler (pressure:inertia forces), and Weber (inertia:surface tension forces) numbers. These scaling ratios must be considered for...
### TABLE 7. Effect of Crater Size (Relative to 0.5 km)

<table>
<thead>
<tr>
<th>Apparent Excavation Diameter (km)</th>
<th>Observed Apparent Diameter (km)</th>
<th>Ejecta Velocity</th>
<th>Maximum Ejecta Size</th>
<th>Median Ejecta Size</th>
<th>Peak Shock Pressure</th>
<th>Dynamic Pressure</th>
<th>Atmospheric Pressure</th>
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<td>1</td>
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<td>8200</td>
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<td>0.002</td>
</tr>
</tbody>
</table>

1. Observed rim-rim diameter $D_o$ is derived from excavation apparent diameter $D_E$ by assuming $D_o = 1.25 D_E$. For craters larger than 5 km, rim/wall failure (slumping) enlarges the crater an additional 33%, that is, $D_F = 1.33 D_o$.

2. Scales approximately as $D_E^{1/2}$ for crater excavation diameter $D_E$.

3. Scales as $D_E^{2/3}$.

4. Depends on lithology: aeolian dust (<16 μm), loess (60 μm), moving sand (200 μm), fluvial transport (<10 mm), shock-broken basalt (0.1-20 cm).

5. Scales approximately as $D_E^{1.7}$ for the same stage of crater growth.

6. Scales as (ejecta velocity)$^2$ for given atmospheric pressure (no ballistic shadowing).

7. Assumes exponential decrease of atmospheric density with altitude results in a decreasing atmospheric effect as $exp(-D_F/H)$, where $a = 0.66$, $D_F$ is final crater size (for 33% enlargement of excavation crater), and $H$ is atmospheric scale height of 10 km.

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**Fig. 16.** Dynamic pressure experienced by ejecta encountering ambient Martian (top), terrestrial (bottom left scale), and Venusian (bottom right scale) atmospheres at different stages of crater growth for different diameter excavation craters. This idealized representation is based on scaling ejection velocities $v_e$ calculated from numerical codes described by Orphal et al. [1980] to larger craters with the assumption that $v_e = (gD)^{1/2}$ at the same stage of growth. Different stages of growth provide a measure of the fraction of ejecta subject to high dynamic pressure. Shock-weakened ejecta should be further fragmented during ejection (or during reentry if they escape the impact region). Note that liquid water should be atomized and dispersed as craters exceed about 5 km in diameter on Mars. Moreover, dynamic pressures experienced by ejecta from large craters on Earth (hence Venus) should exceed the strengths of shock-weakened debris, thereby augmenting entrainment.
when drag forces due to aerodynamic drag are scaled to gravity forces as indicated in equation (1). In order to maintain a given ratio of drag-to-gravity forces for larger ejecta particles, however, drag forces may exceed their internal strength. Figure 16 provides a summary of the maximum expected dynamic pressures for ejecta encountering an atmosphere at different conditions, respectively. Equation (10) indicates that crater formation serves to underscore the fact that large ballistic masses do not overwhelm the atmosphere but can be aerodynamically decelerated through turbulence acting on the constituent particles.

On the basis of such scaling considerations and the laboratory results, processes affecting late-stage ejecta emplacement on Mars can be considered. The formation of ejecta ramparts is interpreted as the least degree of entrainment, and onset of this style should be constrained by equation (1). If craters are too small, ejection velocities and curtain-induced vortices are too low to modify ballistically emplaced ejecta. Appearance of rampart-style emplacement should be dependent on local substrate properties. Equation (1) predicts that comparable ejecta entrainment in the laboratory and on Mars requires

\[ R_M = (C_{D_M}/C_{D_0})^{(p_L/p_M)(a_M/a_L)}R_L \]  

(10)

where the \( L \) and \( M \) subscripts refer to laboratory and Martian conditions, respectively. Equation (10) indicates that substrates leading to millimeter-sized ejecta would have onset diameters (rim-rim) approaching 0.5 km (\( C_{D_0} = 25; C_{D_M} = 0.8; p_L \) corresponding to 60 mb of air; \( a_L = 80 \mu \)). As craters exceed 1 km, gravity-scaling dominates and minimum ejecta sizes tend to approach the average size of the component mineral grains in the impacted substrate, that is, the inherent flow size discussed by Curran et al. [1977]. Impacted lithologies characterized by windblown materials, however, should exhibit significantly smaller onset diameters of nonballistic emplacement styles.

Table 8 provides first-order estimates of particle sizes potentially entrained by winds created by an advancing ejecta curtain for different size craters on Mars. The outward curtain velocity is calculated on the basis of the horizontal component of ejecta velocities at late stages of growth in a particulate target (see Plate 1b). For this calculation, an ejecta velocity of 50 cm/s corresponds to late-stage growth of a crater 16 cm in apparent diameter [see Schultz, 1992]. Ejecta particles reduced to terminal velocities are readily entrained in winds and turbulence, thereby producing nonballistic ejecta emplacement styles. Such conditions can be met for 1- to 2-km-diameter craters only if the substrate is dominated by airfall deposits with particle sizes less than 100 \( \mu \). Such substrates would result in crater ejecta with a radial scour pattern and basal ejecta flow (Plate 1, bottom) based on extrapolation from equation (10). Craters surrounded by contiguous ejecta ramparts (Figure 1a) would be expected in lithologies characterized by much coarser debris (e.g., sand size).
Fig. 17. Comparison of ejecta emplacement styles around small craters (<5 km) in contrasting lithologies on Mars. (a) Three-kilometer-diameter crater formed in a basaltic plain (13.8°N, 151.5°W; Viking frame 693A03) west of Olympus Mons (left) and in an 0.8-km-diameter crater in sedimentary deposits near the northern highland/lowland border (47°N, 346°W; Viking frame 458B71). The crater formed in basalt resembles craters of comparable size on the Moon, whereas the crater formed in sediments exhibits long ejecta run-out lobes (arrows). From extrapolation of laboratory experiments, the ballistic ejecta emplacement style at left is consistent with modal ejecta sizes exceeding 10 cm, whereas the multilobed pattern at right is possible for a target composed of fine-grained (<100 μm) debris. Scale bar indicates 1 km. (b) Five-kilometer-diameter crater in mottled plains (43.4°N, 134°W; Viking frame 9B35). The anomalously large secondaries around such a small primary crater are believed to indicate a porous, fine-grained lithology. Impacts into uncompacted pumice produce unusually large ejecta clumps that are relatively unaffected by aerodynamic drag. Such a lithology would be consistent with gently accumulated air fall deposits, which also can be inferred from muted terrains and craters. Scale bar corresponds to 10 km.

Figure 6 revealed the importance of finer constituent fractions (less than 10%) entraining large ejecta. Consequently, in the absence of other mobilizing substances, lithologies leading to bimodal ejecta size distributions (e.g., basalts over sediments) may produce craters surrounded by contiguous ejecta ramparts. Substrates characterized by well-sorted finer material (wind, fluvial deposits) should exhibit craters with ejecta emplacement styles progressing systematically from rampart styles at the smallest diameters to more fluid lobate emplacement styles as turbulent eddies and, eventually, the autosuspension process create greater run-out distances of channelized flows (see Table 9). As this process increases in importance, the continuous ejecta deposits near the rim should show increased evidence for scouring, including traversing radial grooves and near-rim depressions created by the strong toroidal winds. Further variety in ejecta morphology can result from variations in target porosity, as indicated by impacts into uncompacted pumice.
Fig. 18. Comparison of ejecta emplacement styles at different sizes for impacted lithologies likely composed of (a) lava and (b) sediments. Craters in the ridged plains of Hesperia Planum exhibit progressively more complex ejecta facies with increasing size (Figure 18a). The 10-km-diameter crater at left (28.3°S, 240.2°W; Viking frame 418S39) is surrounded by a contiguous ejecta rampart extending about a crater radius from the rim. The 15-km-diameter crater at right (30°S, 241°W; Viking frame 418S40) exhibits an inner continuous facies out to a crater radius with rampart-bordered lobes extending to two crater radii. Although frequently cited as evidence for increased volatiles excavated from depth, the large ejecta run-out is also expected for increased atmospheric entrainment due to ejection velocities increasing with size or excavation of fine-grained debris at depth. Scale bar corresponds to 10 km. Craters at high latitudes exhibit greater run-out distances without rampart-bordered termini (Figure 18b). Available resolution often prevents detailed characterization of ejecta facies as around 9-km-diameter crater at left (Viking frame 676B13) but scouring of preexisting terrains out to 10 crater radii is common. The 8-km-diameter crater at right exhibits both scouring and multilobed facies (73°N, 232°W; Viking frame 676B33). The inner facies extend to 1.2 crater radii from the rim, whereas the outer continuous facies extend over three crater radii. Additionally, scouring extends to nearly 11 crater radii with faint rampart termini. The inner continuous facies is believed to indicate ballistic emplacement (possibly with postformation flow), whereas the multilobed facies reflects deposition from a turbiditylike flow created by atmospheric entrainment of very fine-grained (<100 μm) airfall deposits. Release of near-surface volatiles by frictional heating due to colliding ejecta would enhance this process. The outer, scoured facies may reflect the effects of early-time vapor blast. Scale bar corresponds to 5 km.

Even though the various dimensionless scaling ratios may allow extending selected aspects of the cratering process to much broader scales, the partitioning of impactor energy at the 1-6 km/s velocities available in the laboratory might fundamentally change the atmospheric environment around the impact at the 10-30 km/s on Mars or Venus, thereby affecting ejecta emplacement. In the laboratory, energy transferred to the atmosphere either by the projectile bow shock or during impact was consumed during the earliest stages of crater growth as discussed in a previous section. A first-order comparison can be made between the response time of the atmosphere and response time of target. Impactor energy is coupled to the atmosphere through the accompanying bow shock, high-speed ejecta, and vapor cloud expansion. If it is assumed that the specific mode of energy transfer to the atmosphere is eventually lost at late times, then an analogy can be made with strong explosions in an atmosphere with a source energy assumed to be a fraction of the initial impactor energy. Analytical expressions have been derived to treat this problem [e.g., Taylor, 1950]. The intense blast with an energy $E_A$ rapidly expands hemispherically with atmospheric pressure returning to ambient conditions on a time $t_E$ given by:

$$t_E = (1.5 \times 10^{-6})E_A^{1/2}p_a^{-1/2}$$

(11a)
Fig. 19. Comparison of eroded ejecta facies indicative of contrasting size fractions. (a and b) Ejecta ramparts generally remain as the last surviving relics of the ejecta facies. Figure 19a (14°N, 159°W) shows survival of distal ejecta rampart yet loss of other ejecta flow textures. Superposed pedestal craters indicate that region once may have been covered by a surface layer, now largely removed. Contrasting survival of rampart is consistent with a less mobile fraction composed of coarser debris. Scale bar corresponds to 20 km; Viking frame 886A-11. Figure 19b illustrates a smaller crater 4 km x 5 km (7.4°S, 313°W; Viking frame 751A15) with degraded facies but preserved rampart. This survival is also consistent with larger, more resistant ejecta clasts. (c) Craters in the Catina fractured plains (36°N, 25°W; Viking frame 538A04) where the outer facies are nearly uniformly and completely removed (arrows). This erosional style is consistent with outer ejecta facies composed of finer grained debris emplaced as a thin unit from a turbidity-like flow. Finer grained ejecta would be more susceptible to aeolian removal under present Martian conditions. Scale bar corresponds to 10 km.

with a distance $R_E$,

$$R_E = \left(0.5 \frac{E_A}{\rho_o} \right)^{1/3} c^{2/3}$$  \hspace{1cm} \text{(11b)}

where $c$ and $\rho_o$ indicate the ambient sound speed and density of the atmosphere, respectively, under ambient conditions. If it is assumed that the energy fraction coupled to the atmosphere in such a blast is 10% of the initial impactor energy, then the blast zone for a laboratory experiment ($m_p = 0.376 \text{ g}$ and $v = 5$
kin/s) would be limited to about 8 cm in 0.04 ms. Hence a 30-
cm-diameter crater in a particulate target forming in about 150
ms would be largely unaffected by the blast during late-stage
ejecta emplacement. Early-time interactions with ejecta,
however, should be expected and are observed [Schultz and
Gault, 1979, 1982]. For comparison, a 10 km-diameter
(apparent excavation diameter) crater on Mars would take about
30 s to form, but the atmospheric disturbance would last only
about a second when the blast front had expanded to nearly 100
km. Even if considerable vaporization had occurred with 50%
of the impactor energy coupled to the atmosphere, the
equilibration time would increase only 23%. Consequently,
late-stage ejecta emplacement should not be dramatically
affected.

Such estimates implicitly assume that the energy fraction is
coupled to the atmosphere without any moderating effects of
the growing crater cavity. Experiments reveal that the energy
fraction coupled with the atmosphere strongly depends on
impact angle. At high impact angles (>45° from the horizontal)
a large fraction of the energy represented by impact
vaporization is contained and redirected upward as a jet rather
than as a point-source atmospheric explosion [Schultz and
Gault, 1979, 1982; O'Keefe and Ahrens, 1982]. At lower angles
(<30°), the transfer of energy may be coupled more efficiently
but is offset downrange from the crater [Schultz and Gault,
1984, 1990]. A future paper will assess in more detail the
relative efficiency of atmospheric coupling as a function of
impact angle and vaporization.

Ejecta emplacement on Mars. Contrasting ejecta
emplacement styles at small crater diameters in contrasting
lithologies on Mars are shown in Figure 17. The left half of
Figure 17a shows a 3-km-diameter crater formed in lava plains
west of Olympus Mons. The mode of ejecta emplacement is
especially ballistic with hummocky facies resembling crater
ejecta on the Moon. In contrast, the right half of Figure 17a
shows crater 0.8 km in diameter formed in distinctly
sedimentary deposits near the lowland/highland contact. This
smaller crater exhibits a nonballistic style of ejecta
emplacement with long run-out lobes. From equation (10) and
Table 8, such an emplacement style at such a small diameter
would require in situ particle sizes less than 80 μm
(corresponding to loess or aeolian dust. Figure 17b illustrates a
further possible contrast in emplacement style characterizing
lithologies at high latitudes. The bulbous inner ejecta facies
with a near-rim moat suggests high ejection angles reflecting
aerodynamic effects. The ubiquitous large secondary craters,
however, usually surround much larger crater diameters (>30
km). On the basis of laboratory experiments with uncompacted
pumice, the contradictory inferences of strong aerodynamic
effects yet large secondaries can be reconciled for a surface
composed of a high-porosity, fine-grained lithology where
large ejecta assemblages are created. Impacts of such clumps
into porous substrate will produce large compression craters.

The ridged plains on Mars are widely believed to be
analogous to the basaltic maria on the Moon and should result
in largest ejecta sizes for a given size crater. Rampart-
terminated ejecta deposits in the ridged plains of Hesperia
Planum exhibit a general increase in run-out distance with
increasing crater size (Figure 18a). At the smallest sizes (<5
km), the rampart forms a contiguous ridge on top of the inner
ejecta deposits. At larger sizes, the ramparts form the terminus
for lobes extending over (Figure 18a, left) and beyond (Figure
18a, right) the inner continuous deposits. In contrast, the
stippled plains at high latitudes may be covered by a fine-
grained sedimentary cover as indicated by the high erosion rates [Arvidson et al., 1979; Schultz and Lutz, 1988]. Figure 18b illustrates the more fluidized-appearing ejecta typifying craters formed in this lithology. Insufficient image resolution commonly prevents characterization of the emplacement style of distal ejecta around smaller craters (Figure 18b, left), but the bulbous inner facies and mottled outer deposits are suggestive of a nonballistic emplacement style. The 8-km-diameter crater at right (Figure 18b), however, clearly exhibits successive flow lobes extending to much greater distances than lobes around comparably sized craters in the ridged plains (Figure 18a, left). Additionally, pristine examples exhibit evidence for scouring and thin distal ejecta lobes extending as far as 11 crater radii from the rim (Figure 18c). In contrast with Figure 17b, secondary craters are less frequent around craters with such fluidized facies [see Schultz and Singer, 1982].

The style and rate of destruction of their contrasting ejecta facies are also consistent with the inferred modes of emplacement. The oldest rampart-bordered ejecta facies typically exhibit nearly complete removal of the flowlike textures yet preserve the distal rampart. If the rampart represents large clasts (centimeter and larger) entrained in an eddy-driven flow, then they would form a wall-like barrier of erosion-resistant debris (Figures 19a and 19b). In contrast, the oldest craters in inferred sedimentary deposits quickly lose their outer facies (Figure 19c). At high latitudes, such craters commonly evolve into pedestal craters as aeolian processes first remove the surrounding wind-sensitive substrate. For surface wind velocities of 2 m/s, wholesale removal of the outer ejecta facies would suggest well-sorted debris with grain sizes between 50 μm and 200 μm. Broad regions surrounding the impact are more resistant to aeolian reworking, possibly due to scouring from strong (300 m/s) vapor blast winds (Schultz, 1988), as well as deposition of very fine fractions (<10 μm) behind the autosuspended ejecta flow closer to the crater. The proposed role of atmospheric effects on ejecta emplacement can be further tested for consistency by comparing the observed with the expected flow distances as a function of crater size and impacted lithology. From equation (3), wind-driven ballistic emplacement resulting in a near-rim, contiguous rampart should result in a rampart distance that is proportional to crater diameter. As turbulent eddy-driven entainment becomes important (equation (8a)), rampart distance scaled to crater diameter (D) should progressively increase as D^{1/2}, provided that ρ_a > ρ_p. If autosuspension occurs, then distal ejecta run-out will be sustained until equation (9) is no longer satisfied. For Mars, autosuspended flow will be controlled by substrate properties that enhance suspension of debris in the flow (ε_p) or decrease the fall velocity (ν_f). Degassing volatiles within the primary ejecta debris flow or entrained by secondary mixing and turbulence illustrate processes that could enhance suspension. Decreased fall velocities in the ejecta flow will occur for very fine grained, entrained debris and for flows containing devolatizing fractions. For a given impacted target with essentially a constant ratio of ε_p/ν_f, autosuspension will be controlled by the flow velocity (u) and the gradient factor (K), each of which should scale as D^{1/2}. If the ejecta flow is not further driven by precursor impacting ejecta, then autosuspension is largely controlled by the initial flow velocity, that is, the eddy-driven mechanism.

Figure 20a provides a qualitative summary of the relative ejecta run-out distances expected for various modes of emplacement. A given crater could exhibit multiple emplacement styles depending on the ejecta size distribution and crater size: an inner continuous ballistic ejecta facies can be overrun by eddy-driven ejecta flows, while sufficiently small (or low-density) ejecta may continue to be entrained in an autosuspended flow with large run-out distances as depicted in Figure 20a (e.g., Figures 5b and 5c). If the effective density (ρ_e) of the ejecta flow greatly exceeds the ambient atmospheric density, (ρ_a), then the flow can be characterized as an atmosphere- or gas-entrained debris flow. This condition should apply to Mars.

Figure 20b shows data for pristine craters on the ridged plains of Lunae Planum and on the sedimentary northern plains. The upper limit of the ejecta run-out on Lunae Planum matches the expected D^{1/2} dependence for eddy-driven flow mechanism. For comparison, Horner and Greeley [1982] found that the diameters of the outer ejecta lobes around craters larger than 30 km increased as D^{1.47}. When expressed as run-out distance from the crater rim and scaled to crater diameter to match convention in the present discussion, the scaled run-out distance increases as D^{0.47}, again consistent with eddy-driven flows. Because considerable local variation in coarse fractions can exist (basalt thickness, overlaying sediments, etc.), considerable dispersion should exist for craters in Lunae Planum as crater size decreases as shown in Figure 20b. A factor of 2 in average ejecta size could account for the observed dispersion in rim-rampart distance for craters smaller than 10 km in diameter. Because run-out distance should be scaled to the excavation crater, varying degrees of crater enlargement by rim-wall failure near the simple-complex transition (3-8 km) will offset data downward to the right, thereby also increasing scatter at smaller sizes. If some of the observed scatter indicates variations in atmospheric density through time, the observed run-out distances indicate that such variations did not exceed a factor of 2 or 3. Run-out distances from craters larger than 20 km in diameter in the northern plains at high latitudes closely match data for Lunae Planum, but smaller craters exhibit enhanced run-out distances indicative of ejecta sizes a factor 10 smaller in size.

It is important to reemphasize that interpretation of Figure 20b does not require water as a fluidizing agent but only ejecta entrained in a turbulent fluidlike flow with a run-out that increases with D^{1/2}. Impact craters 10 km in diameter on Mars should develop recovery winds exceeding 100 m/s, more than capable of transporting impacting ejecta. Since the present Martian atmosphere generates 20 m/s winds [Hess et al., 1977] and transports fine-size material, this scenario should not seem unreasonable. Adding lubricants such as atomized water, finely broken ice, and even devolatizing clays should (and probably does) contribute to the full range of observed morphologies across Mars, but these lubricants are not necessary for craters in Lunae Planum.

A general comparison of results for different atmospheric and gravitational environments is shown in Figure 20c. Ballistic ejecta facies on the Moon and Mercury scale nearly geometrically, that is, the outer limit of the continuous ejecta increases nearly linearly with crater diameter. The inner ejecta facies on Mars also scale geometrically but extend further than on Mercury, even though it has the same gravity. This enhanced run-out could indicate postemplacement flow due to volatiles as concluded by Horner and Greeley [1982] or to atmospheric entrainment. Under the extreme atmospheric conditions on Venus, entrainment is maximized, and the ejecta flow densities ρ_e will approach a constant fraction of the surrounding atmospheric density ρ_a, which is about 0.1 g/cm^3. From equation (6a) such ejecta-entrained flows should result in run-out distances that decrease as D^{1/2} if ρ_e > ρ_p, but approach a constant value as ρ_e approaches ρ_a (Figure 20c). Nevertheless, flow separation and autosuspension of fine-grained ejecta with large run-out distances beyond the inner facies also might occur (Figure 20a).

**Modes of ejecta emplacement on Mars.** On the basis of experiments, ejecta emplacement processes reflect the degree of entrainment conditions in a turbulent flow created by the ejecta curtain moving through an atmosphere. Three emplacement
Fig. 20. Predicted and observed run-out of rampart-bordered ejecta controlled by wind and eddy-suspended emplacement mechanisms. (a) Summary of the expected relation between the distance from crater rim to rampart as a function of crater diameter based on discussion in text. If the moving ejecta curtain creates strong winds that remobilizes ejecta without extensive entrainment, then the rim-rampart distance should be proportional to crater diameter (i.e., a constant value when distance is scaled to crater diameter). The onset of rampart formation should depend on ejecta density $\beta$ and size $a$ for a given atmospheric density $\rho$, i.e., ambient pressure. As aerodynamic drag increases due to increases in ejection velocity (given substrate), entrainment in turbulent eddies develop with a run-out distance proportional to $D^{1.5}$ ($D^{0.5}$ when scaled to diameter). At any diameter, the autosuspension process can enhance run-out. (b) Data for Lunae Planum. The rampart run-out distances are generally consistent with eddy-driven run-out flows. Between 3 and 5 km, however, variations in substrate and crater widening processes (rim/wall slumping) will result in considerable scatter. Open circles represent data for craters in northern lowland plains (35°-60°) as in Figure 1b (right). Their longer run-out distances are consistent with an autosuspension process for craters smaller than 20 km in diameter due to much finer constituent ejecta, (c) Summary of the contrasting run-out distances expected for different styles of emplacement. Run-out distance represents the distance between the rim and the edge of the ejecta facies and is scaled to the crater diameter. The outer limit of the continuous ejecta facies on the Moon and Mercury representing ballistic emplacement under two different gravitational fields (from Gault et al., 1975). Inner continuous ejecta around Martian craters (from Horner and Greeley, 1982) extend to greater distances than continuous ejecta around Mercurian craters with identical gravity, perhaps as a result of continued outward flow. Outer ejecta facies driven by atmospheric interactions may take on two different relations. Turbulent eddy-driven emplacement with an ejecta flow density ($\rho_e$) much greater than the ambient atmospheric density ($\rho_a$) should exhibit crater-scaled run-out distances increasing as $D^{1.5}$. Ejecta flows with maximum entrainment (as on Venus), however, should decrease as $D^{-1.5}$ (equation 6a) provided that additional turbulent energy (e.g., thermal effects) is not introduced. As $\rho_e$ approaches $\rho_a$, a constant run-out distance is expected.

styles are proposed here for Mars, as illustrated in Figure 21: curtain-wind flow, eddy-suspended flow, and autosuspended flow. All styles begin with ballistic ejection, emplacement of near-rim ejecta, and the development of recovery winds (Figure 21a). Impact-generated vapor expanding in advance of the ejecta curtain would have scoured the surface with supersonic winds, and atmospheric densities would have returned to near ambient values well before the crater had finished forming [Schultz, 1988]. Much of the impact-generated vapor is contained and redirected upward by the growing transient cavity behind the curtain, thereby being partly isolated from the atmosphere except for oblique impacts as discussed by Schultz and Gault [1979, 1982, 1990]. Later stages of crater growth, then, are believed to take place under near-ambient conditions. The advancing ejecta curtain resembles a moving solid wall and creates a pressure differential that induces strong recovery
Fig. 21. General scenario detailing processes that may control run-out of ejecta through atmospheric interactions. (a) Starting conditions for alternative modes of emplacement depicted in Figure 21b. At the final stages of crater growth, ejecta follow ballistic trajectories within an ejecta curtain. The principal contrast with vacuum conditions is the development of a large ejecta-curtain angle and vortices created along the curtain due to redirected air flow. Experiments and theoretical considerations suggest that any impact-generated vapor cloud would have expanded to large distances by this time and may have created a strong precursor scouring of the surface [see Schultz, 1988]. As the wall of ejecta moves outward, it creates a large differential pressure, thereby inducing strong recovery winds that entrain decelerated fines into a turbulent flow. (b) Three emplacement processes discussed in the text. Curtain-wind suspended flow with minimal entrainment results in temporary suspension of ballistic ejecta. As the wind-driving curtain dissipates, suspended clasts are deposited in an ejecta ridge, that is, a rampart. With increasing turbulence due to greater induced wind velocities or enhanced entrainment of fines, turbulent eddies overrun and scour the inner ejecta surfaces. This process can form multiple lobes with terminal ramparts. Flow separation may create additional, thin distal ejecta lobes. Lithologies composed of very fine grained particles result in greater entrainment and increased turbulent power. The turbulent power may increase as the flow travels down and off the inner ejecta, as it picks debris perhaps already mobilized by precursor blast or secondaries, or as entrained debris devolatilizes due to collisions. The resulting autosuspended flow may extend to great distances, leaving behind a very thin veneer of ejecta. The role of volatiles in the proposed scenarios would enhance ejecta run-out, but long ejecta flows are possible from lithologies largely composed of loess or silt-size deposits.
emplacement style depend on the average ejecta size. If the ejecta exhibits a bimodal size distribution, entrainment of the finer fraction in the turbulent atmospheric response creates a two-phase flow (atmosphere and fine ejecta) that further enhances transport of coarser fraction. As a result, bimodal ejecta size distributions (e.g., created by layered lithologies with contrasting strengths) will enhance the development of the contiguous rampart. The net outward momentum of the ejecta and structural rim uplift may result in basal shearing and a postemplacement debris slide within the inner ejecta, particularly if a fluidizing agent is present.

Eddy-suspended flow develops as ejecta entrainment increases. For small craters (<1 km) in fine-grained (<100 μm) substrates, this process can extend the continuous deposits and ejecta rampart. For larger craters (>5-10 km), it is characterized by overrunning and partial scouring the inner continuous ejecta deposits in its course over the surrounding plains. As the eddy loses energy, the suspended load is suddenly deposited. In a well-mixed debris flow of fine-grained ejecta, the deposit forms a lobate deposit. The distal lobes of ejecta recently recognized at Meteor Crater [Schultz and Grant, 1989; Grant and Schultz, 1989a] most likely reflect this process. If a significant quantity of coarse clasts (>500 μm) is present or becomes entrained during run-out, however, the lobe will form a rampart terminus. The inner ejecta deposits also may continue outward movement, due to either a lubricating agent or simply residual lateral momentum. In general, however, this emplacement style should characterize a dry lithology. Both wind-suspended and eddy-suspended flows should create erosion-resistant ramparts, since subsequent ambient winds will not approach the intensity of crater-generated winds.

As turbulent eddies run-out beyond the continuous ejecta, they may entrain surface materials with the appropriate size distribution. Material can be set in motion by a precursor atmospheric blast, by the pressure differential created in vortices, by preceding impacting ballistic ejecta, and by size fractions susceptible to saltation/suspension. On Mars, particles less than about 200 μm appear to be susceptible to suspension [Greeley and Iversen, 1985], and curtain-induced wind speeds should greatly exceed the necessary threshold speeds. Consequently, regions on Mars that have been long-term sinks for wind-blown debris (e.g., high latitudes) may contribute a significant local component to the ejecta run-out, thereby enhancing the appearance of both excessive ejecta fluidity and a mass-balance paradox (ejecta versus crater volume).

Autosuspended flow can result from extremely fine grained ejecta entrained by turbulence created in the ambient atmosphere. Impact-generated water vapor [Wohletz and Sheridan, 1983] or vapor released by mechanical friction created by impacting ejecta could significantly enhance this process as indicated by equation (9) and illustrated by experiments involving powdered tempers. Additional studies are needed, however, to assess such processes quantitatively. Diagnostic features associated with this style include a scoured inner rim creating a moatlike depression, radial grooving of the continuous deposits, a bulbous rounded profile of the inner ejecta deposits, absence of secondary craters (except for very porous targets), and a thin, fluid-appearing outer ejecta with long run-out. Lithologies characterized by a narrow size distribution of fine material (loess or silt) should produce little, if any, rampart-bordered ejecta facies.

The proposed scenario emphasizes the response of the atmosphere to the ejecta, thereby complementing the scenario by Schultz and Gault [1979] that focused on the response of ejecta to the atmosphere. Nevertheless, both approaches distinguish between ballistic emplacement of the inner ejecta deposits but nonballistic emplacement of the outer deposits. Carr et al. [1977] concluded that deflection of martian ejecta flows by obstacles indicated a slurry-like mode of emplacement, not a gas-supported ground surge. This conclusion does not challenge the interpretations here. Observations cited by Carr et al. [1977] referred to the inner facies where ballistic deposition (with possible development of a debris slide) is expected as depicted in Figure 21. They noted, however, that fluidized flow associated with the outer facies commonly overrun obstacles similar in height to the deposit and thin inward from the flow termini. The emplacement sequence proposed by Schultz and Gault [1979], observed in the laboratory, and generalized in Figure 21, therefore is completely consistent with the conclusion of Carr et al. [1977].

High-energy chemical and nuclear explosions provide a possible test for laboratory-scale phenomena at a much larger scale. Parallel aspects of aerodynamic effects on ballistic ejecta (including aerodynamic sorting) can be documented [see Wisotzki, 1977]. Nevertheless, the process of energy transfer and the degree of atmospheric coupling are significantly different [Gault et al., 1968; Cooper, 1977; Knowles and Brode, 1977; Schultz and Gault, 1982], and this difference can significantly modify the processes affecting ejecta emplacement observed in the laboratory. Comparison of the evolution of ejecta cloud from a 0.5 ton (TNT) half-buried explosion from the Pre-Mine Throw IV series in desert alluvium (left side of Plate 3) with a laboratory impact experiment under full atmospheric pressure illustrates this point (right side of Plate 3). A half-buried explosive charge transfers only about 10 to 20% of its energy to the target, in contrast with an impact which transfers about 80% [Cooper and Sauer, 1977]. Consequently 80-90% of the released explosive energy is directly coupled with the atmosphere in contrast with less than 1% for the lower velocity (1.5 km/s) impact shown in the right side of Plate 3 and the 20% possible for much higher velocity (20 km/s) impacts on the planets. Although an outward moving conical ejecta curtain develops from an explosion (Plate 3, left), the rising fireball carries decelerated debris upward and creates inward flow at the base. The laboratory impact experiment shows decelerated fractions suspended above, but
Fig. 22. Contrasting ejecta emplacement styles for identical size, nearby craters. (a) Two 5-km-diameter craters in the ridged plains of Hesperia (28.5°S, 241.9°W; Viking frame 41837). The example at bottom exhibits a well-developed contiguous ejecta rampart, whereas the example at top exhibits rounded inner continuous facies with thin distal ejecta lobes. Scale bar corresponds to 10 km. (b) Comparison of a crater with rampart-bordered multiple lobes above with smaller craters surrounded by more fluidized ejecta below, all within about a 20 km distance in the Tempe region (45°N, 60°W; Viking frames 70536 and 70537). Such contrasts in emplacement styles could represent a change in atmospheric pressure, a change in a volatile reservoir at depth, and/or a subtle contrast in in situ particle size occurring over small distances. Scale bar corresponds to 20 km.

...
In general, different modes of ejecta emplacement with distance from a crater reflects the level of energy and momentum associated with deposition. On planets without atmospheres, the depositional energy field (energy per unit area at a given distance) is controlled by the ballistic range as underscored by progressive change from continuous ejecta facies to secondary crater fields on the Moon [Shoemaker, 1962; Oberbeck et al., 1975; Oberbeck, 1975] and Mercury [Gault et al., 1975]. As a result, ejecta facies should be separated into annular zones [e.g., see Schultz, 1976]. On planets with atmospheres, increasing distances from the crater rim also must reflect increasing levels of the depositional energy field, but the mode of emplacement can range from ballistic kinetic energy to potential energy controlling a ground-hugging debris surge. The latter style reflects the degree of entrainment and the power contained in induced atmospheric turbulence, whether mechanically transferred by the wall of ejecta or augmented by stored energy (e.g., released volatiles during entrainment).

An important implication of the proposed scenario in Figure 21 is that ejecta emplacement styles could be used to characterize lithologies in the absence of other clues. Moreover, contrasting styles in a given lithology could
Ballistic
Contiguous ramparts
Lobed rampart
Multilobed
Inner bulbous facies (outer radial or thin distal flows)

Fig. 23. Schematic representation of the effects of crater size, ejecta size (lithology), atmospheric pressure, and presence of volatiles on different emplacement styles of ejecta on Mars. Arrows reflect systematic change in emplacement style as a function of increasing the values of the selected variable while holding other variables constant.

indicate past changes in atmospheric pressure in addition to (or even instead of) the presence of buried water. Figure 22 provides two of many examples of the latter possibility where a factor of 5 change in ambient pressure could induce the observed changes in ejecta emplacement style. Such variations are possible from orbital forcing and the global redistribution of polar-trapped volatiles e.g., Fanale et al., 1986.

7. SUMMARY AND CONCLUDING REMARKS

A wide range of fluidlike ejecta emplacement styles is possible on planets with atmospheres, even in the absence of water or volatiles in the target. This conclusion does not preclude the possible role of volatiles in enhancing ejecta flow run-out but raises the possibility that the morphology of ejecta facies on Mars could reflect local lithology and past atmospheric conditions as schematically summarized in Figure 23. Mars, in fact, provides ideal conditions for recognizing atmospheric effects since the present atmospheric pressure is sufficient to decelerate and entrain particles sensitive to aeolian reworking for craters larger than about 0.5 km in diameter. With this perspective, the following general conclusions and implications emerge for Mars.

1. Ejecta flows around Martian craters may reflect entrainment of ejecta in winds and turbulence generated in response to the outward moving ejecta curtain.

2. Different emplacement styles may reflect the degree of ejecta entrainment in the dynamic atmospheric response which in turn depends on crater size (controlling ejecta curtain velocity) and ejecta size (controlling drag and sensitivity to winds). Consequently, increased ejecta run-out with increasing crater size need not indicate greater amounts of crater-excavated water-rich substrates.

3. Onset diameter for nonballistic ejecta emplacement styles may indicate critical conditions required for drag deceleration and entrainment of ejecta rather than presence of volatiles. Under present atmospheric conditions on Mars, onset diameter may prove useful to characterize impacted lithologies.

4. Rampart-bordered ejecta facies are expected to characterize basaltic bedrock lithologies with diameter-scaled run-out distances increasing as $D^{1/2}$, whereas multilobed ejecta patterns are expected for well-sorted, fine-grained sedimentary lithologies. Variations in lithology (controlling average grain size and size distribution) far exceed variations due to atmospheric pressure with elevation.

5. Systematic trends in ejecta emplacement styles and ejecta run-out distances with latitude could reflect latitude-dependent lithologies characterized by aeolian deposition of fine-grained material rather than volatiles buried at depth. Surface materials with adhered frozen volatiles (frost) or bound volatiles (clathrates) could significantly enhance ejecta run-out through the auto-suspension process as these volatiles are released within a turbulent run-out flow.

6. Unbound water excavated at impact may be best identified by its role in reducing basal shear within the inner ejecta deposits, thereby causing enhanced run-out of the inner facies [see Horner and Greeley, 1982], although gas entrainment also could play a role. Aerodynamic disruption of excavated water droplets will produce finer sizes that are even more susceptible to entrainment.

7. Variations in atmospheric pressure exceeding a factor of 5 could change the style of emplacement from rampart to run-out flow for a given lithology at a given crater diameter over the last 3 billion years.

8. The large number of asymmetric ejecta facies indicating oblique impact trajectories (45°-15° from the horizontal) is an expected consequence of atmospheric modification of ejecta emplacement.

The extreme atmospheric pressure on Venus will result in flows entraining ejecta of nearly all sizes [see Schultz and Gault, 1979]. Extrapolation of laboratory results indicates that aerodynamic drag should create a near-vertical curtain of ballistic ejecta throughout crater growth with ejecta exceeding 100 m across. As the ballistic component impacts the structurally uplifted outer rim slope, it should resemble a massive air-entrained rock avalanche. The high atmospheric density results in near-rim ejecta flows that should decrease in run-out distance (scaled to crater radius) with an increase in crater size, thereby contrasting with ejecta flows on Mars as illustrated in Figure 20c. Although decelerated “finer” fractions for conditions on Venus could include meter-sized blocks, drag forces and mechanical interactions should produce much smaller debris that will be entrained in turbulent autosuspended flows with much greater run-out distances extending over and beyond the coarse inner facies. The distal eddy-driven and autosuspended flows should be highly channelized with fan-shaped termini analogous to ejecta flows developed in targets of low-density microspheres. Because the salutation-suspension boundary on Venus occurs for particles only 30 μm in diameter [Greeley and Iversen, 1985], entrainment of local materials by residual eddies (e.g., after flow separation) should create distinct but thin “secondary” flows around the most pristine craters. Just as the coarse rampart termini on Mars are more erosion resistant than the outer facies, the extremely coarse inner ejecta around craters on Venus should persist over long times, whereas finer fractions in the distal facies would be more susceptible. From the experiments, subtle differences in ejecta asymmetry due to impact angle should be accentuated.

Experiments with easily vaporized targets (dry ice and carbonates) at different impact angles [Schultz, 1988; Schultz and Gault, 1990] provide additional clues for atmospheric effects on early-time processes perhaps uniquely revealed on Venus. At higher impact angles (>60°), impact-generated vapor is partly contained within the crater cavity and early-time ejecta plume. In contrast with the later stage mechanically driven ballistic ejection, this early-time cloud of hot vapor should resemble a short-lived gas-driven plinian eruption column. At lower impact angles (<45°), however, increasing fractions of the early-time vapor cloud and entrained projectile become decoupled from the later stage processes and travel downrange [see Schultz and Gault, 1990]. Under the extreme atmospheric pressures on Venus, lateral expansion of this early-time cloud will be prevented, while the downrange
distance will be arrested by aerodynamic drag acting on the ensemble (as observed in the laboratory). On Mars, the tenuous atmosphere cannot restrain this expanding cloud [Schultz, 1988], whereas on Earth the atmosphere serves to localize such effects into a broad "fireline" [Schultz and Gault, 1990]. On Venus, however, the downrange complex of vapor and projectile debris would create a turbidity flow extending to great distances. As in laboratory experiments, later stage ejecta will be emplaced on top of this component but may be drawn downrange by strong recovery winds trailing the flow of hot vapor and projectile debris. Such laboratory observations provide qualitative yet specific predictions for the style and sequence of emplacement that may be uniquely tested to the extreme atmospheric conditions on Venus.

The intent of this study was not to simulate directly all the conditions for ejecta emplacement on the various planets with atmospheres. Rather, the intent was to demonstrate that the atmosphere can play a critical role in modifying emplacement, and to explore controlling processes revealed in laboratory experiments. This perspective challenges the widely held view that buried water controls ejecta morphologies on Mars and proposes instead that both lithology (grain size) and near-surface volatiles (e.g., frost) play equal (if not the dominant) roles, particularly for distal facies. The observed processes also allow formulation of simplified theoretical models and tests of the very complex interactions acting from micron to kilometer scales.

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REFERENCES


Schultz, P.H., Moon Morphology, University of Texas Press, Austin, 1976.


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