TRANSITION DIAMETERS FOR CRATER SHAPE IN LABORATORY EXPERIMENTS
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Laboratory experiments indicate that impact craters in granular targets become shallower as projectile penetration time increase (1, 2, 3). Further analysis has characterized specific domains and transitions for crater aspect ratios (D/d for diameter, D, and depth, d) as functions of a wide range of projectile/target parameters: impactor velocity (v), size (mass, m, radius, r, or length, l), density (\(\rho_p\)), strength (\(Y_p\)), shape (2r/l), sound speed (c_p), and target density (\(\rho_t\)), sound speed (c_t), porosity (P), grain size (a), and strength (Y_t). Impacts into non-porous ductile targets reveal similar systematic changes in the aspect ratio for impact velocities from 6 to 11 km/s. These results have potentially important implications for crater excavation depths, dimensional scaling relations, crater morphology, and flux rates derived from observed crater diameters on the planets.

Granular Targets:  Crater aspect ratio and impactor parameters follow three distinct relations. For a given projectile impacting a given target, D/d increases with increasing impact velocity until exceeding the target sound velocity. Thereafter D/d varies inversely with v. Above a critical velocity, however, D/d varies directly as \(v^2\). This systematic change in the aspect ratio occurs over a wide range in projectile sizes and compositions and can be shown to be related to projectile size divided by the impact velocity, which is related to the time for projectile penetration (2, 3). Figure 1 illustrates the different relations between crater aspect ratio and 2r/v where \(r_v = (m/\rho_p)\frac{1}{v^2}\). The crater aspect ratio in the low velocity regime (Regime A, Figure 1a) reflects the effect of compression in porous targets and depends on the momentum/area or \(\delta_p l v\). After maximum pore compaction is achieved, D/d varies inversely as \(\delta_p (2r_v/v)\). The quantity \(\delta_p(2r_v/v)\) can be viewed as the penetration time or as the ratio between momentum/area divided by the specific kinetic energy (KE/m). In this domain (Region B) projectile deformation and comminution are observed. Undeformed projectiles will follow this relation provided that v < c. Data in Region C generally exhibit less scatter if D/d depends on the \(\pi_2\) parameter (4), but the specific power-law relation depends on the style of failure of the projectile in a given target: brittle impactors typically exhibiting little change in the aspect ratio with increasing impact velocity. For fine-grained (No. 24) targets, the dependence in Region B can be more generally expressed as \(\eta = (2r_v/v)(c_p/c_t)(\delta_p(\delta_t)(2r_v/l)\) which includes a shape factor and ratios of projectile/target sound speed and density (Figure 2). The transition from B to C is labeled \(\eta_c\).

Coarse targets (No. 6-8 mesh sand) exhibit considerable scatter and little dependence between 2r_v/v and D/d for large values of 2r_v/v. This can be interpreted as the result of individual grain disruption as sand grain size exceeds projectile size. Such an interpretation is supported by comparisons of data with similar ratios between projectile and average grain size. The increase in D/d with decreasing \(\pi_2\) more generally may reflect internal energy losses by comminution since it has been documented that impact-induced failure of brittle spheres increases with increasing specific energy, KE/m_p where m_p is the mass of the sphere (5, 6). Moreover, data reveal that the increase in aspect ratio primarily reflects a constant scaled depth (d/r) with increasing impact velocity while the scaled diameter increases as \(\pi_2\).

Ductile Targets: Data for various non-porous, ductile targets have been re-examined in order to determine if similar changes in crater aspect ratio occur. Impacts by polyethylene and aluminum projectiles over a wide range of sizes (0.159 cm - 1.27 cm) into hard and soft aluminum targets from 2-11 km/s (7, 8) have been compared with polyethylene into polyethylene impacts (7). For a Al-Al impacts, the crater aspect ratio rapidly decreases with increasing velocities until about 3 km/s. Between this velocity and the target sound speed, the aspect ratio increases or plateaus. This "knee" has been attributed to a change in cratering physics from compression to hydrodynamic flow (8). At higher velocities (6-11 km/s), D/d increases as 2r_v/v provided that \(\delta_p v\) is below a critical value; however, aluminum targets (1100-0) exhibit an inverse relation. Data for different combination of projectiles and impactors coincide if the same dimensionless ratios used to describe \(\eta_c\) for granular targets are multiplied by the target yield strength for 6-11 km/s.
impacts. Moreover, the three regimes described for granular targets apply for ductile targets except for velocities well below \( c \) (Figure 1b).

**Discussion:** The similarity in crater shape dependences for non-porous and porous targets indicates that the observed late-stage aspect ratio is controlled by the early-time transfer of energy and momentum. Since the cratering flow field is controlled by shock rarefaction at the free-surface, the observed change in the aspect ratio may reflect a transition from an extended shock wave profile (including perhaps elastic precursors) controlled by projectile-penetration time to the “instantaneous” point-source analogy implicitly incorporated in the \( \pi_2 \) analogy (4).

The critical value \( \eta_e \) for gravity-controlled granular targets can be more generally expressed as \( \eta_e \left( Y_g / \delta, u^2 \right) \) where \( Y_g / \delta, u^2 \) is a dimensionless strength ratio, including both the lithostatic overburden \( Y_g = \delta, g, y \) for gravitational acceleration \( (g) \) and depth \( (y) \) and the limiting cratering flow field velocity \( (u) \). Because \( y \) is proportional to \( D \) and \( u \) depends on \( D^{1/2} \), the dimensionless strength parameter simplifies to \( k, g \). If this result is combined with scaling relations \( D/r \) using the \( \pi_2 \) parameter (4), then it can be shown that the transition diameter between a near constant \( D/d \) and \( D/d \) increasing with \( 2r_e / v \) is simply expressed as: \( D_t = k v^{1/12} g \). This expression can be used to accurately compare the \( D/d \) transitions for different planets (9) and provides a new perspective for interpreting changes in crater shape, morphology, and statistics (10).


![Figure 1a](image1a.png) **Figure 1a.** Different relations between diameter \((D)/depth \( (d) \) and projectile-diameter \( (2r) /impact-velocity \( (v) \) for sand targets. Region A reflects drag-controlled penetration; B, rate-dependent energy-momentum transfer; C, point-source energy-momentum release and internal energy losses by comminution.

![Figure 1b](image1b.png) **Figure 1b.** Different relations between \( D/d \) and \( 2r/v \) for non-porous ductile targets. Region A Includes non-hydrodynamic compression cratering with a transition zone as impact pressure exceeds target strength; B, hydrodynamic cratering and rate-dependent energy-momentum transfer; C, hydrodynamic cratering and point-source transfer.

![Figure 2](image2.png) **Figure 2.** Diameter \((D) \) to depth \((d) \) ratio as a function of penetration time multiplied by projectile/target ratios of sound velocity and density for impacts by \( Al, Fe, Pb, \) and pyrex spheres into No. 24 sand.