Impactor Control of Central Peak and Peak-Ring Formation. Peter H. Schultz, Department of Geological Sciences, Brown University, Providence, RI 02912. D.E. Gault, Murphys Center of Planetology, Murphys, CA

Introduction: The relation between the depth and diameter of excavation for impacts typically is assumed to be proportional. Such an assumption is consistent with the constant aspect ratio (diameter: depth) observed for simple craters found in a wide range of planetary settings (1,2) and crater-scaling laws derived from laboratory experiments (e.g., 3,4). Although complex craters exhibit evidence for floor uplift and rim collapse of a transient profile, they are typically thought to resemble initially smaller, simple crater (5,6). At large scales, however, early-time processes consume a greater fraction of crater growth (7) and the assumption of late-time equivalence of energy release as a point source becomes inappropriate. We propose instead that crater diameter, depth, and impactor penetration represent separable dependent variables that underscore the fundamental difference between impact and point-source explosion excavation process. An important consequence of this perspective is that central pits, peaks, and rings may represent contrasting target responses to impactor penetration and could provide an important indicator of impactor dimensions.

Declaration of Independence: Crater aspect ratios from laboratory experiments are not constant, whether in gravity-controlled particulate targets (9,10) or non-porous strength-controlled targets (11). Three simple experiments dramatize how lateral crater growth (diameter) can be independent of penetration (depth). First, a 0.635 cm-thick aluminum plate was buried at different depths in a No. 24 sand target and impacted with a 0.635 cm-diameter polyetheline sphere at 2km/s in a vacuum. If lateral growth reflects the total energy coupled to the particulate target, crater diameter should increase as the burial depth of the plate decreases. Instead, crater diameter (normalized to impactor size) remains nearly constant until the burial depth approaches 2 projectile diameters when crater diameter decreases. Hence crater diameter is simply controlled by the energy coupled at first contact and shock rarefaction from the free surface (8).

A second experimental series impacted a ridged particulate target obliquely. Ridges with faces comparable in size to the impactor were oriented perpendicular to the trajectory. An oblique impact (30°) into a smooth surface produces a crater with diameter scaling as \((v^2\sin^2\theta)(g/\rho g)^{2/3}\), whereas an oblique impact into the ridged surface is largely independent of angle. This result again underscores the importance of both the energy coupled at first contact and the fate of impactor ricochet.

A third series examined the parameters controlling the size and formation of "penetration pits" in solid, ductile targets by hypervelocity impactors. Penetration pits represent an inflection in crater profile correlated with a distinct transition between lateral and downward flow. Penetration depth \((p)\) is often cited as crater depth and can be expressed as \((L/\delta p)/(\delta p/\delta t)\beta/3\) where \(L\) indicates impactor length, \(\delta\) the density for target \((t)\) or projectile \((p)\), and \(\delta t\) target strength (12). The diameter of the pit \((x_0)\) depends simply on impactor diameter \((2r)\), impactor/target strength ratio \((\delta t/\delta p)\), impactor velocity \((v)\) and target sound speed \((c_t)\) as shown in Fig. 1:

\[
(x_0/2r)(\delta t/\delta p)^{1/3}-(v/c)^{\mu}
\]

where \(\mu\) is an exponent characterizing the pressure-decay law as derived in (13) and discussed further in (14). If \(v \sin \theta > c_p\), experiments reveal that the dimensions of \(x_0\) (perpendicular to the trajectory) do not depend on impact angle in contrast with earlier conclusions (15). Comparisons with numerical codes (16,17) reveal that \(x_0\) corresponds approximately to the diameter of the deformed impactor when the shock detaches laterally. Such experiments reveal that the diameter of the penetration zone depends simply on impactor diameter for a given mach number (i.e., independent of target strength in contrast with diameter or depth). Consequently, pit diameter relative to crater diameter increases as impact angle decreases.

These three experiments reveal that crater diameter, depth, and penetration exhibit separable dependences. Moreover, resisting forces acting on crater diameter (strength or gravity) can act independently of maximum penetration depth. This is further illustrated by three other studies. First, dynamic atmospheric pressure can restrict lateral crater growth in particulate targets without affecting crater depth (18,19). Second, impacts by low-density debris clouds into particulate targets produce craters with diameters following scaling laws for high-density, solid impactors but depths controlled by impactor density (10). Third, experiments involving gravity-controlled particulate and strength-controlled ductile targets reveal a systematic effect of impactor penetration time on diameter/depth for hypervelocity impacts (11).
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Discussion and Implications: For small hypervelocity impactors at laboratory scales, the transfer time of energy/momentum from impactor to target (10μs) is a small fraction of the time for crater formation (10-100ms). As a result, late-stage growth can consume signatures of penetration and produce a simple crater with a nearly constant aspect ratio. Such a profile is not diagnostic of strength-controlled growth but only the validity of the point-source approximation. As the time for energy/momentum transfer comprises an increasing significant fraction of growth at large scales, the penetration phase becomes more evident and persists to later times. This phenomenon is also documented in computational experiments as an inflection in the growing crater profile but is often masked by allowing late-stage growth to "coast" to a more symmetrical form (17). Survival of the zone of maximum penetration depends on material properties and its size relative to the impactor. Large, low velocity impactors (>6km/s) produce a compressed penetration zone only slightly larger than the projectile, whereas very high velocity objects produce a much larger zone relative to the projectile. If the over-all limit of this zone follows the simple experimental relation where $x_0 = r(v/c)^n$, as indicated above, then target response may not affect dimensions significantly but could affect the morphology. It is proposed that central pits, peak pits, peaks, and peak rings are contrasting manifestations of this common zone.

Three simple tests at planetary scales are consistent with this suggestion. First, central peak or peak ring diameter normalized to an impactor diameter calculated from scaling relations should remain approximately constant for a given impact angle over a limited range of crater diameters. Second, crater size normalized to observed peak ring diameter should decrease with decreasing impact angle. Third, craters formed by oblique impacts (<20°) should exhibit central peaks offset upward corresponding to point of maximum coupling and breaching downrange due to impactor failure and ricochet. All three tests have been successfully tested for Venus where the preserved cratering record allows recognizing impact angle but also can be documented on the Moon and Mercury (14).

If the diameter of central relief features in craters simply depends on $(v/c)\delta d$, then existing crater scaling relations can be recast in terms of an observable quantity with best guesses for average impact velocity, target sound velocity, and density ratio for different planets with different gravitational fields (Fig. 2). Such a strategy reveals that a. normalized crater diameter approximately scales as $r_0^{-1/6}$ consistent with expectations; b) central peaks and peak rings for different planets collapse into a single relation for reasonable values of impactor velocity and target properties (excluding highly oblique impacts and multi-ring basins); c) peaks and peak rings for a given planet are part of progression; d) the onset diameter for peaks and peak rings for different planets depends on both target $(g)$ and impactor $(v/v_r)$ properties; and e) the ubiquitous occurrence of central pits on Mars are consistent with lower impactor velocities (<14 km/s) comprising 2/3 of its population.


![Fig. 1](image1.png)

**Fig. 1.** Central penetration pit ($d_p$) normalized to impactor ($D_i$) diameter produced by impacts into solid aluminum (A0) and copper (Cu) targets as a function of impact velocity ($v_i$) and target sound velocity ($v_s$). The pit diameter is independent of impact angle provided that the vertical velocity component is greater than the sound speed of the target. Hence, size of the penetration zone may provide an indicator of the impactor dimensions.

![Fig. 2](image2.png)

**Fig. 2.** Crater diameter ($D$) normalized to estimated impactor diameter ($D_i$) as a function of the gravity-scaling parameter $v_i/v_s$; Central peak diameter is based on the assumption that the central peak and peak rings diameters represent connecting target responses to impactor penetration zone. For central peaks, assumed impact velocities are 16 km/s and 40 km/s for the Moon and Mercury, respectively; for peak rings, impact velocities are 14, 16 and 32 km/s for Mars, Moon, and Mercury, respectively. Vertical offset of peaks and peak rings probably indicate additional processes, e.g., collapse.