IMPACT DECAPITATION FROM LABORATORY TO BASIN SCALES; P.H. Schultz,
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Although vertical hypervelocity impacts result in the annihilation (melting/vaporization) of the
projectile, oblique impacts (<15°) fundamentally change the partitioning of energy with fragments
as large as 10% of the original projectile surviving (1, 2, 3). Laboratory experiments reveal that
both ductile and brittle projectiles produce very similar results where limiting disruption depends
on stresses (σ) proportional to the vertical velocity component, i.e., v²sin²θ. The failure process
occurs in two ways. First, shock pressures generated at first contact spall the top of the projectile.
The resulting decapitated projectile fragments impact downrange due to the added upward velocity
component. The size of the largest fragment depends on the rise time of the shock wave, which
depends on both depth of penetration before the shock reaches the back surface (related to impact
velocity and material properties) and a dimensionless penetration time, τ, expressed as projectile
diameter (2r) divided by the horizontal impact velocity component (vcosθ). As previously reported
(3), the impactor fragments form craters downrange that are distinct from secondaries (defined as
impacting target debris); hence, they have been termed "sibling" impacts. The distance from the
uprange crater rim, x, is approximately given as 2r/vtanθ where θ' reflects the altered trajectory
(from horizontal) due to the upward spall velocity component. Experiments reveal that θ' can be
significantly modified by entrainment in impact-generated vapor. Specifically, vapor produced
during impacts into water, plasticene, and carbonate targets disperse the sibling fragments and
extend the impact distance.

The second failure mode is expressed by pits overlapping the downrange rim of the oblong
primary craters formed in strength-controlled aluminum at (15°). This mode may reflect simple
shear as the projectile penetrates farther into the target with time and as strain rates decrease. This
layer-cake failure style is most suggestive for ductile aluminum projectiles at lower impact
velocities (3 km/s) or low angles and for projectiles with low yield strengths (e.g., pure aluminum).
Downrange witness plates in such cases record a vertical chain of sibling impacts with reduced lateral dispersion. Paired downrange pits to either side of the trajectory axis commonly occur for hard (2024) aluminum spheres impacting aluminum and may indicate conjugate shear sets.

For strength-controlled cratering, the resulting profile of the primary crater along the trajectory
exhibits deepest penetration uprange (reflecting energy partitioned at first contact) and a distinctive
shelf-like region downrange (sibling impacts by the sheared projectile) at relatively modest impact
angles (15°). As impact velocity or projectile-target density ratio decreases, however, the primary
 crater takes on a distinctive arrowhead shape with deeper penetration downrange. Clustered
impacts provide an extreme example of this morphology (4). For gravity-controlled craters, such
profiles also occur, but require much lower impact angles (<5°). Even though the profile and
outline for craters in loose particulates are not dramatically changed at 15°, impacts by sibling
 fragments nevertheless emerge downrange from beneath the ejecta.

Failure of the projectile at laboratory impact velocities (6 km/s) is largely controlled by stresses
established before the projectile has penetrated a significant distance into the target. This can be
demonstrated by comparing the ricochet pattern and size distribution for an oblique (15°) impact
into a thick plasticene block with an impact into a thin plasticene layer (equal to r) coating an
aluminum block. The resulting siblings impacted downrange at identical distances; hence, the spall
velocity was established by the plasticene, not the aluminum. Moreover, the underlying aluminum
block showed only a subtle dent. Use of a thin water layer over aluminum gave the same results.

The planetary surface record exhibits numerous examples of oblique impacts with evidence for
projectile failure and downrange sibling collisions. Selected examples were present previously (3)
but a further survey has allowed quantifying the results. Figure 1 presents data for Mars where the
downrange distance to the smaller sibling scaled to primary crater width is compared with the
primary crater shape in plan. If crater width is controlled by strength scaling while crater length is
controlled by the work expended during penetration, then crater length/width should be
proportional to cotθ. Similarly, the downrange sibling impact distance scaled to crater width

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should scale as $\cot \theta/v^{2/3}$ for $\theta' \sim \theta$. The assumption of strength control in Figure 1 on the extreme reduction in peak stress expected for extremely low-angle impacts (0.8% vertical). Oblique impacts without downrange companions could indicate ejection off the planet. The crater Hale can be linked with downrange oblique sibling craters with arrowhead shapes extending completely around the planet.

The Crisium Basin on the Moon provides a specific example that bears remarkable similarities to strength-controlled craters in the laboratory. Figure 2 shows a sketch map identifying the basin massifs, mare units, and outer scarp. In addition to its oblong shape the western end exhibits the characteristic pinched morphology, whereas the eastern end exhibits a shelf and breach in the massif ring. Both elements are consistent with an east-west impact direction. The interior ring is more circular and offset to the west, analogous to the deeper penetration uprange observed in the laboratory. The striking similarity between the laboratory impacts and Crisium raises several intriguing questions. First, could Mare Marginis indicate downrange sibling collisions? If created by simple shear and allowing for surface curvature, such a scenario would lead to a projectile 360 km in diameter with an impact angle of 25°. If, instead, the eastern shelf marks impacts by this failure mode, then the projectile approaches 120 km in diameter with an impact angle of 15°. Mare Marginis would then represent decapitated sibling impacts. Second, could Mare Angus and Mare Undarum also indicate sibling fragments created by conjugate shear failure of the middle portion of the projectile? And third, what other impactor signatures exist on the planets and can the different modes of failure (e.g., Orcus Patera vs Crisium) provide new clues about basin-scale collisional processes and scaling?


Figure 1. Distance from uprange crater rim (first contact) to downrange decapitation impact separated from crater (dots) or overlapping the crater (open circle) as a function of crater shape in plan. Lines correspond to two different relative velocities ($v$) predicted from strength scaling.

Figure 2. Terrain map of the Crisium Basin showing massifs (stipple) and mare regions. Eastern mare shelf may indicate consequence of projectile shear failure while Mare Marginis may indicate decapitation impacts.