RELATING CRATER PEAKS, PITS, AND PEAK RINGS ON ICY AND SILICATE BODIES.

P. H. Schultz, Department of Earth, Environmental, and Planetary Sciences, Box 1846, Brown University, Providence, RI 02912-1846, peter_schultz@brown.edu

Introduction: Impact craters with central pits are prominent features on Mars and the icy satellites of the outer planets. Because of the assumption that such bodies have a thick cryosphere, various studies implicate the controlling role of ice in their formation or expression [e.g., 1-5], even though central pit craters also occur on the Moon, Mercury, and Venus but with different onset diameters [5, 6]. A common model involves the collapse of the central uplift, as part of a continuum from peaks to pits to rings in response to gravity collapse [e.g., 2]. A contrasting model proposes that central structures represent "footprints" of the impactor [6-8]. In this case, pits in craters respond to a combination of variables related to crater scaling relations and impactor size.

Background: In the "footprint model," central structures follow a scaling relation different from the gravity-controlled crater diameter. It is based on several key observations: (a) the diameter (x) of the central structure increases relative to the crater diameter (D) on a given planet for oblique impacts; (b) the onset of different morphologies depends on both gravity and the impact speed [6,7,9]; (c) the shape of the inner structure (pits or inner ring) becomes increasingly oblong along the trajectory with decreasing impact angle (from the horizontal) and may be breached downrange; (d) impactor flow field can be preserved on the crater floor (i.e., not always erased during rim collapse or uplift); and (e) the central peak or peak-ring is offset uprange, after corrections for enhanced uprange rim collapse. The footprint model proposes that central pits and peak rings are proportional to the size of impactor for both silicate (Fig. 1a) and icy (Fig. 1b) bodies. Different scaling relations between the interior structures and crater diameter yield a simple analytical formulation that allow relating peak rings and pits to crater diameter on different planetary bodies.

Constraining Estimates for Impactor Size: Oblique impacts (impact angles < 20°) may result in sheared and spalled fragments from the impactor that form distinct grooves or highly elongate craters (prior to ejecta emplacement), a process documented in laboratory/hydrocode experiments and recorded on the planets [10]. Decapitated impactor fragments traveling downrange produce oblong sibling craters (distinct from ejecta from the primary crater) that can be traced back to the region of impact (offset uprange in oblique impacts). Their mapped trends can be used to constrain the maximum impactor, as illustrated by selected craters (well-expressed siblings) on the Moon, Mercury, Mars, and Ceres (**Fig. 2**) independent of any scaling relation. The derived impactor sizes are larger than in 2D computational models (e.g., Orientale [11]), but are consistent with gravity-scaling relations corrected for impact angle in 3D models [10]. Although this strategy can only apply to oblique impacts, scaling relations allow corrections for higher impact angles. Figure 2 reveals that the derived impactor sizes for central crater pits and peak rings on different bodies are significantly offset, mirroring the offsets for central structure diameters (Fig. 1). The goal is to reconcile the different ring or pit diameters on different bodies.

Working Model: The working hypothesis proposes that central structure diameters scale (d) with impactor diameter ($2r$), i.e., impactor footprint. This perspective explicitly assumes that central structures express and preserve dimensions of the initial coupling by impacts (not lost during collapse or uplift). The strategy is to compare the relative diameters of impactor pits and rings on different bodies through gravity-scaling relations for the same crater diameter [e.g., 12,13], which must include an assumption that the amount of rim collapse on different bodies is the same for the same crater diameter.

It is proposed that central structures is proportional to a footprint zone with a diameter (x) where the peak-pressure (P) lateral to the impactor decays to a certain level. Peak pressure decay can be expressed as $P/\delta c^2 \sim [(x/r)\,(c/v)^2]^{-2/\mu}$ where c is the pre-shock sound speed in the target and δ = target density [13]. In this model, the central pit or ring diameter (d) corresponds to a distance where the scaled pressure approaches a common scaled strength level ($Y_o/\delta_o c_o^2$). This value will be approximately the same on silicate bodies. Exceptions, however, can occur: at small scales where different strengths (rock vs. weak porous materials vs. ice) play a greater role; or at very large scales where crater depth exceeds the brittle-ductile transition. The strength-limit term is used to adjust the impactor diameter ($2r$) derived from the central structure diameter (d) which is proportional to $\delta^{-0.275}\,(\delta/\rho)^{0.454}\,v^{-0.825}\,g^{0.276}\,(Y_o)^{-0.275}$ for the same crater diameter on a body with gravity (g). Consequently, the impactor footprint on different bodies can be simply expressed in terms of impactor (speed, impact angle, density) and target (sound speed, density, and strength) properties.

Results: Ratios of published values characterizing each planet and its impactor population were used to correct observed offsets of central pit diameters on different bodies (Fig. 3) for low-speed impacts: Mars (~ 8 km/s); Mercury (10 km/s); and the Moon (8 km/s). Higher speed impacts (> 15 km/s) produce much smaller footprints resulting in central uplift expressed as central peaks. Transitional types of central structures reflect intermediate speed impacts, e.g., pit-peaks (central peaks with summit pits) or proto-basins. On Ganymede and Callisto, however, the lower density impactors (0.5 g/cc) and higher expected speeds (20 km/s) result in dimensions that merge with the silicate-body data sets for craters < 70 km for an assumed rock-to-ice target strength ratio of 4:1. Larger craters, however, gradually increase until merging with a level characterized by "anomalous pit craters" [1] and peak-ring basins. This can be reconciled by either a gradual reduction in target strength with depth for craters with D > 50 km or a population of lower speed bodies. For Ganymede, anomalous pit craters have been noted to be old and degraded and could fit either model. For other craters on the Moon, however, the most likely explanation is a temperature-related strength gradient, consistent with earlier proposed effects of crustal thickness [e.g., 14]. Based on these same scaling relations, central peaks should dominate small bodies (Ceres, Vesta, Tethys, etc.), regardless of the presence of volatiles. At very low impact angles (e.g., Dantu, Urvara, and Yalode on Ceres) the reduced crater diameter requires an additional correction (Fig. 3). At very large sizes (e.g., Odysseus on Tethys), the oblique impacts decouple large portions of the projectile from the cratering process [15,16].

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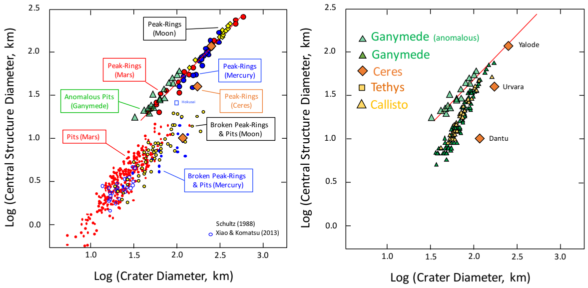

Fig. 1: Dimensions of central structure (pits, peak rings) as a function of diameter on silicate bodies (Moon, Mercury, Mars) in comparison to anomalous pits on Ganymede (**Fig. 1a**, left) and icy bodies (**Fig. 1b**, right) on Ganymede, Callisto, Ceres, and Tethys.

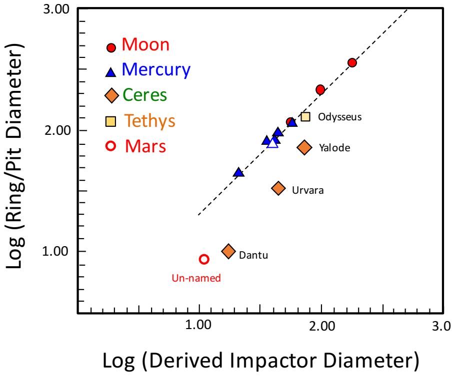

Fig. 2: Dimensions of central structure (pits, peak rings) as a function of the diameter of the impactor derived from convergence of downrange grooves caused by impactor disruption at impact (see [8]) mapped on different silicate and icy bodies.

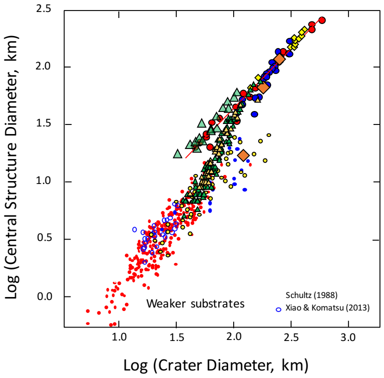

Fig. 3: Dimensions of central structure (pits, peak rings) corrected by the relative roles of impact speed, angle, and target strength for a given crater diameter. Convergence at large scales along a parallel trend likely represents reduced strengths at depth at early times. Departure at small sizes indicates insufficient correction for weaker targets at shallower depths on Mars.