THE MECHANICS OF COMPLEX CRATER AND RINGED BASIN FORMATION: CONSTRAINTS FROM 30 YEARS OF PLANETARY OBSERVATIONS. William B. McKinnon, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, Saint Louis, MO 63130 (mckinnon@wustl.edu).

Introduction: Thirty years ago "bridging the gap" meant bringing the impact and explosion cratering communities together. That highly successful enterprise ushered in many fruitful lines of inquiry, from crater scaling and centrifuge studies [1], to observations of impactor populations [2], to the first model of the *mechanics of complex crater formation* [3]. Complex craters, of course, are seen in a variety of morphological forms across the solar system today, but in the mid-70s the touchstone was the Moon, and the key observations concerned lunar craters with central peaks and rim terraces and those without (complex vs. simple) [4]. Some concepts of the time, such as "elastic" rebound [5] and shallow excavation at large scales (due to target layering or non-proportional growth [e.g., 6]) did not gain acceptance. The concepts that the mechanical properties of the "target" governed the response to impact, and specifically that impacted rock was much weaker than even static rubble [3,7], were not immediately embraced either, but these concepts have proven remarkably durable [8,9]. In elaborated and extended form, the hypothesis of weakening by shock and high bulk strain-rate flow has been adapted to the formation of central peak craters, peak-ring craters (or basins) and multi-ringed basins on the terrestrial planets (including the Moon), and to central peak and pit craters, peak-ring basins, and multiringed basins on the icy satellites of the giant planets [8–11]. Studies of impact morphology in such radically different geological settings (different gravities, different lithologies, ice vs. rock) have proven enlightening.

We now view the "modification stage," as defined by Don Gault, as a continuing part (albeit terminal) of the *late stage* of crater excavation, in which the inertial motion of the crater flow field increasingly responds to some combination of gravity, internal friction, and material viscosity [8–10]. We do not understand precisely how rock (and ice) is weakened during impact, and the major models advanced, acoustic fluidization [12], block oscillation [13], and thermal degradation [14], may or may not embrace the same physics [9].

In the 1970s, observations of lunar crater and basin morphology were augmented by similar data from *Mariner 10* images of Mercury, *Viking Orbiter* images of Mars (late 70s), and a field studies of the few well-preserved terrestrial complex craters [e.g., 15]. Mercury data, though extensively "mined," was limited [16], and measurements and interpretation of martian images are compromised by the active geology of that body [17]. Since that decade major advances have come from 1) the *Voyager* observations of the icy satellites [10], 2) *Magellan* radar images of Venus (especially revealing in terms of peak ring and multiringed basin formation) [18,19], 3) *Galileo* images of impact features on Europa, Ganymede, and Callisto [11], and 4) a resurgence in discovery and geological characterization of complex terrestrial craters and basins (e.g., Chesapeake Bay [20] and Chicxulub [see 21]). Highly capable spacecraft are now operating in martian orbit and on the martian surface (although impact studies are not their focus), and *Cassini* continues its multiyear tour of the Saturn system. High quality images of the midsized icy satellites of Saturn are revealing central peak and peak ring craters there in unprecedented detail (although the dearth of pristine impacts on Titan is disappointing).

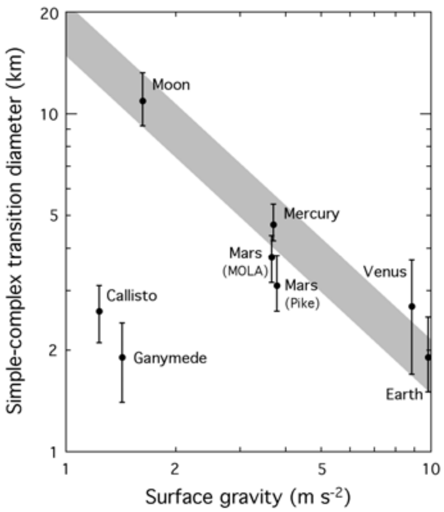
In this review I will highlight the advances that have come from 30 years of planetary exploration (including the Earth), and how these have influenced and constrained the development of theories of crater modification. I will also look forward to data to come, from the *Messenger* mission to Mercury, from (proposed) high quality lunar gravity and topography, and from terrestrial field studies of rock that has actually participated in impact flow, where "bridging the gap" between theory and observation may finally occur. The rest of this abstract focuses on fundamentals.

Simple-to-complex transition: Of all the morphological indices that characterize this transition, depth over diameter (*d/D*) is arguably the most quantifiable and the most significant. Measurements usually follow a power-law form:

$$d = aD^b \quad . \qquad (1)$$

For morphologically fresh, simple lunar and mercurian craters, $a = 0.20$ and $b = 1.0$, reflecting their geometric similarity; for lunar complex craters ($d > 15$ km), $b = 0.30$ [4,16]. It was the recognition that complex lunar craters "collapse" (a combination of slumping and uplift) to some limiting depth that led Melosh to argue that a material strength (*c*) threshold had been exceeded [3]. Fundamental soil mechanics principles then lead to a dimensionless parameter ρ *d/c*, which must exceed ≈5–7 for uplift or terrace failure to occur in a parabolic crater in rock of density ρ and subject to local gravity *g*. As is now well known, the value of *c* implied by a limiting depth of 3 km on the Moon is

~2–3 MPa (extraordinarily low); internal friction must also be very low [8].



The figure above shows the intersection (including errors) of the *d/D* power-laws for "fresh" simple and complex craters on planets and satellites. Lunar, terrestrial, martian, and mercurian data are from [16]; abundant Mars laser altimeter (MOLA) data confirm the general trends measured by Pike [16,17], but also reveal the morphometry of the most pristine of fresh craters [22] and clear examples of simple craters with *d/D* = 0.2 in specific regions [23], to which the complex crater power-laws in [22] are extended. The terrestrial point should be viewed with caution, as all terrestrial crater rims are eroded to a degree, whereas Venus depths (from floor–rim-crest radar offsets) are only for the freshest, parabola-deposit-bearing craters [24]. There are no simple, bowl-shaped craters on Venus, due to its thick atmosphere [19], so the complex crater power-law is extended to *d/D* = 0.2, and an error of ± 1 km is assumed.

The inverse gravity trend for simple-to-complex transition diameters on the terrestrial planets (gray bar centered on the lunar point) is now much clearer than in the past: the strength measure (*c*) during modification is nearly constant for all five bodies, subject to terrain effects. Mars shows clear morphometric variations for different regions [17,22,23], and has (a) comparatively lower gravity-scaled transition diameter(s) (lower *c*), the simple-complex transition has long been known to occur at smaller diameters for craters formed in sedimentary, as opposed to crystalline, targets on Earth [25], and even the Moon shows a subtle mare/highlands influence on complex crater *d/D* [17].

The nature of Modification-stage strength: No laboratory measurements predict the strength and internal friction required for crater collapse [9]. Even the intuitive dependence of *c* with composition, weaker for sedimentary targets and especially weak for ice-dominated ones, has no obvious basis in rock mechanics (the Ganymede and Callisto points in the figure are based on *Galileo* imagery, and supercede all previous work [11], although details are not yet published).

Thermal weakening [14] would be material dependent, but the influence of temperature at the scales in question does not seem plausible [9]. Code calculations using acoustic fluidization or block oscillation (or simplified versions thereof) have had some success [9,26], but relating these models to geological ground truth remains a major challenge. Post-impact cohesion (*c*) does not depend *explicitly* on impactor properties such as velocity or size, for otherwise there would not be such well-defined *d/D* power laws for complex craters on the Moon and Mercury. Rather, on a given body it depends on crater diameter (or equivalently, the point-source measure of the impactor, the coupling parameter [27]); that is, $b > 0$ for complex craters, often markedly so. This dependence should be degenerate for bodies of similar geology if all lengths gravity-scale. High quality data from *Messenger* will be a test.

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