THE TRANSITION FROM COMPLEX CRATERS TO MULTI-RINGED BASINS ON TERRESTRIAL PLANETARY BODIES: THE SCALE-DEPENDENT ROLE OF THE EXPANDING MELT CAVITY AND PROGRESSIVE INTERACTION WITH THE DISPLACED ZONE.

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Introduction: The morphological transition from complex craters to two-ringed basins (peak-ring basins; PRB) and the origin of multiple rings in planetary impact basins has been of fundamental interest for decades. Two developments in the understanding of impact cratering processes have provided new insights into the formation of craters and basins. First, as summarized in [1,2], the realization of the importance of the "displaced zone", the area below the growing transient cavity that compresses and moves downward and radially away from the sub-impact point (Fig. 1a), was a major factor in understanding the importance of the depth of excavation, the shape of the transient cavity, the nature of cavity growth and collapse, and implications for the depth of sampling. The formation of the displaced zone also explained the nature and source of the structural uplift of the crater rim (hinge-like uplift out to as much as ~1.5 of the crater radius from the rim [3]). These developments resulted in a significantly better understanding of the crater and basin-forming process (see summaries [1,2]). Remaining uncertain, however, were processes involved in the formation of rings and the cause of the observed transitions.

Following these fundamental syntheses, additional developments have occurred that provide new insight into impact cratering at large scales. Among the most important for understanding the complex crater to basin transition was a series of papers by R. A. F. Grieve and M. J. Cintala [4-7]. These contributions used data from hypervelocity experiments, theory, modeling and terrestrial craters to assess the role of projectile kinetic energy partitioning as a function of increasing energy and scale of the cratering event. They [4] used the fact that the volume of impact melt, relative to that of the transient cavity, increases with the magnitude of the impact event to investigate the influence of this factor on the nature of terrestrial impact craters. They found that with increasing impact event size, the depth of melting approaches the depth of the transient cavity; a consequence of this trend is that the sub-impact point, destined to become the rebound-induced uplifted central structure in a complex crater, will instead be subject to shock stresses sufficient to cause melting. As the depth of melting approaches the depth attained by the transient cavity, the floor of the transient cavity has progressively less strength, and thus central peaks will not be produced during cavity modification and uplift. They [4] proposed that differential scaling between crater dimensions and melt volumes could thus be a possible mechanism for the transition from central peaks in complex craters to peak rings. Cintala and Grieve [7] applied the consequences of differential scaling to lunar craters, exploring size-dependent changes in the dynamics of simple to complex crater formation, and accounting for the major observed changes in morphology and impact melt distribution and purity.

Application to Basin Formation: Combined with the concept of the damaged zone, the Cintala and Grieve model has significant consequences and predictions for large crater and basin processes and the major trends in the crater to basin transition. What accounts for the transition from complex crater to protobasin and to PRB? With increasing event size, proportionally more impact melt is produced and a new phase emerges. The central cavity of melted material grows parabolically along the axis of penetration, becomes proportionally deeper and more voluminous, and forms a second, melt-filled crater-like feature inside the growing transient cavity (Fig. 1b). The outer edge of this second "melt-cavity" crater is the boundary between the melted zone and the unmelted zone (the solid material that experiences peak shock stresses just short of melting). With increasing size, the depth of melting eventually overtakes the depth of excavation [7], penetrating down into the displaced zone, and melting deeper target material not sampled by ejecta from the transient cavity (Fig. 1b).

As the transient cavity rebound vectors reverse the outward paths followed during the compression phase (compare Fig. 1a,c), the consequences are predicted to be much different than in the case of central peak rebound in complex craters. Instead of dynamic rebound of highly shocked central peaks, the peak shock pressures in solids occur at the edge of the melt cavity [7], and this zone moves inward and upward to form an annulus of peaks, or a peak ring. Instead of solid rock rebound-dominated uplift and faulting (typical of complex crater central peaks), melt in the central cavity is displaced inward and upward as the cavity collapses, coating the collapsing cavity floor and ponding in the modified central crater. The differential melt-scaling model predicts that the larger the peak ring basin, the larger the size of the peak ring should be relative to the basin diameter, a trend observed for both the Moon [8] and Mercury [9].

What then might account for the addition of an outer and inner ring, as observed in Orientale [10-11]? The onset of the main outer ring in multi-ring basins is interpreted here to be related to the same process of nested melt-cavity expansion. Outer ring formation begins to occur at larger basin diameters: As the melt cavity becomes relatively larger with increasing event size, it eventually expands downward to intersect and penetrate the base of the displaced zone. This creates a strength discontinuity at the base of the highly deformed rocks of the displaced zone and the inner, much weaker fluid-filled melt cavity wall (Fig. 1d). This favors lateral movement into the cavity along the base of the displaced zone (Fig. 1e). Inward and upward translation of the inner peak rings is then accompanied by deep-seated inward listric faulting along the base of the displaced zone. This listric fault propagates outward and upward to the surface, intersecting the surface at the hinge-like edge of structural uplift outside the transient cavity rim (at ~1.5 crater radii). This listric fault forms an additional outer ring (an inward-facing fault scarp); collapse of the rim forms a megaterrace, modifying the innermost radial ejecta on the basin rim to the observed domical facies. Deep inside the basin, the innermost ring/depression represents the residual rebounded melt cavity, subsequently further deepened by post-impact thermal equilibration. At these large multi-ring basin scales, significantly deeper penetration occurs in the expanding melt cavity than in the excavation zone (Fig. 1d,e), thus accounting for the fact that the maximum crustal thickness decrease occurs inside the peak ring in the final basin.

Conclusions: The "nested melt-cavity" model combines three main components of the cratering process (transient cavity, displaced zone and melt cavity) and provides a basis for understanding the characteristics of the transition from complex craters to multi-ringed basins: Differential melt scaling [7] creates an increasingly larger and deeper melt cavity in the sub-impact region as a function of increasing scale (Fig. 1). The progressively more significant penetration of the expanding melt cavity and its intersection with the displaced zone with increasing size leads to stepwise phases in basin collapse, from complex crater to peak ring (Fig. 1b,c), and then from peak ring to multi-ringed basin (Fig. 1d,e). This mechanism provides plausible explanations for the observed morphology, morphometry, facies and crustal thickness trends. The unusual characteristics of peak-ring basins on Mercury (lower transition diameter and larger population density) can also be accounted for by higher mean impact velocity: impactors creating complex craters on other bodies are accelerated in the Mercury environment to higher velocities so that their resulting kinetic energy is sufficient to create sub-impact point melting rather than elastic rebound, and thus a peak-ring basin; the transition shifts to smaller sizes where more projectiles are available. The "nested melt-cavity" model of complex crater to multi-ringed basin transitions is primarily linked to natural transitions in the cratering process with increasing size, rather than fundamental properties of the substrate or individual planet; more detailed interplanetary morphometric relationships are influenced by gravity [e.g., 7] and other parameters such as impact angle.

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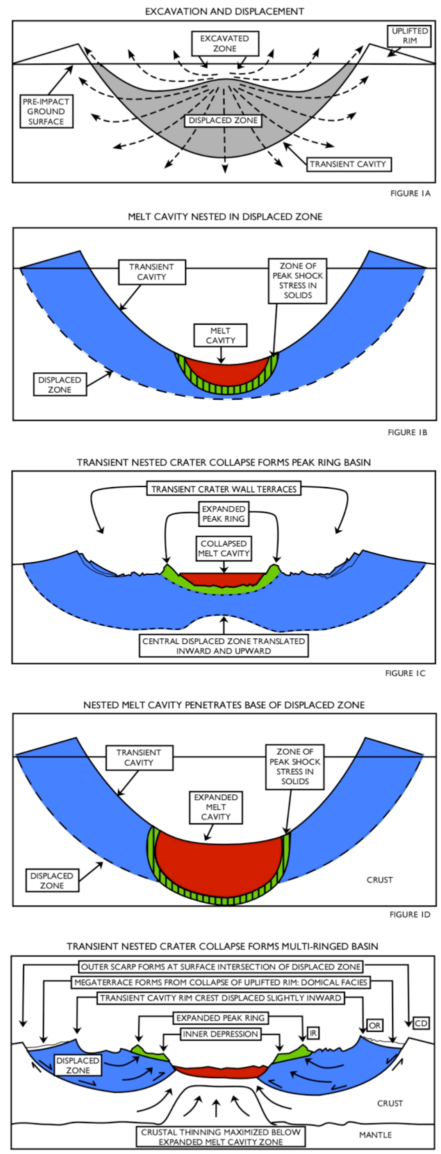

Figure 1. Nested melt-cavity model of crater to MRB transition. a. A hypervelocity complex impact cratering event produces excavated and displaced zones, comprising the transient cavity [after 4]. b. Larger events produce melt cavities nested in the displaced zone due to differential melt scaling; cavity collapse produces peak ring basins (c). d. With increasing size, the melt cavity expands and penetrates to below the base of the displaced zone (inner portions of the melt cavity area, red, are vaporized); collapse of the expanded melt cavity along listric faults at the base of the displaced zone forms a multi-ring basin (e).