PEAK-RING CRATERS AND MULTIRING BASINS. H. J. Melosh[1] [1]Earth Atmosphere and Planetary Sciences, Purdue University, West Lafayette IN 47907. jmelosh@purdue.edu

The Impact Crater Size-Morphology Progression: The smallest impact craters on any planetary body are bowl-shaped with approximately parabolic topographic profiles and a ratio of depth to diameter of about 1:5. In some cases this basic shape may be modified due to layers of different strength or structure in the target, or for highly oblique impact angles. Larger "complex" craters exhibit flat floors, terraced walls and central peaks. The transition from simple to complex is inversely correlated with planetary surface gravity: On the Moon this transition occurs at about 15 km diameter, whereas on the Earth it begins at about 3 km. Complex crater collapse requires a substantial degradation of strength in the rock surrounding the just-excavated crater [1]. Terrace collapse implies yield strengths on the order of 1 MPa and central peak formation implies effective viscosities on the order of 10^9 Pa-sec, suggesting that a Bingham-type rheology develops in the rock surrounding the crater for a short time after the impact[2].

Still larger craters transition from a central-peak morphology to a peak-plus-ring intermediate phase, then to a central peak-ring pattern in which the diameter of the peak ring is about half of the rim diameter. This transition takes place at about 140 km diameter on the Moon and like the simple-to-complex transition is inversely proportional to surface gravity. Peak ring craters are observed on every body on which sufficiently large craters occur. They are particularly common and well developed on Venus [3] and Mercury [4], but are also frequent on Mars. The Ries Crater (22 km diameter) and West Clearwater Lake (36 km diameter) are terrestrial examples.

Impact craters at the very largest sizes are encircled by one or asymmetric scarps, typically steeper on the side facing the crater center. This morphology does not seem to be universal: While the Moon has a dozen or so such multi-ring basins, Mercury and Mars arguably have none, while on the icy satellites such as Europa, Ganymede and Callisto large craters are surrounded by dozens of concentric rings. The Chicxulub crater is the only well-documented example on the Earth [5].

Mechanics of Ring Formation: Peak ring craters have long been described as the further development of central peaks. Central peaks are now believed to originate from hydrodynamic flow of material lifted by inward-collapsing crater walls, while the impact-shattered rock debris is briefly fluidized by strong vibrations that develop during crater excavation [6].

This picture was refined by Collins et al.[7], who demonstrated that the peak-ring structure at the seismically imaged Chicxulub crater probably formed as the inward-collapsing rim material collided with a collapsing, over-steepened central peak to create a hydraulic jump at the location of the peak ring.

Several theories of multiring crater formation have been proposed, as reviewed in Melosh [8]. Most current theories regard the asymmetric ring scarps as deep-seated normal faults initiated by inward collapse of the rock surrounding the transient cavity excavated by the impact.

The Impact of GRAIL: Progress on understanding of large craters and basins had been slow up until 2012, with the advent of NASA's highly successful GRAIL mission to map the Moon's gravity field at high precision [9]. GRAIL data permitted us, for the first time, to "look" deep below the Moon's surface in the vicinity of the large craters and basins and to map the subsurface density variations that create the distinctive gravity signatures of large impact structures on the Moon. This data, in turn, led to a spurt of modeling activity using modern hydrocodes (mainly iSALE) that has very rapidly advanced our understanding of large impact basins, at least those on the Moon.

The Free-Air or Bouguer gravity signature of large lunar craters is quite distinctive: A central high is surrounded by an annular low, which is itself surrounded by a more muted high[10]. This bulls-eye structure is apparent in all craters larger than about 200 km in diameter and, where the crater morphology is visible, the edge of the central gravity high nearly coincides with the peak ring. This observation allows us, for the first time, to estimate the diameter of the final crater as roughly equal to twice the diameter of the central Bouguer gravity high (and as approximately equal to the transient crater diameter). In the case of craters flooded by lava, the gravitational attraction of the lava flows adds to the pre-existing field to create the classic strong nearside mascons.

A combination of hydrocode modeling of the impact event and finite element modeling of its subsequent geodynamical evolution, all constrained by GRAIL data, has now revealed the crater formation process in some detail [11]. The final crater size depends on the thermal gradient (hence strength) in the underlying mantle and crust [12]. The gravity high in the center of large lunar craters is due to uplift of the underlying denser mantle, while the low-gravity collar is created by the frozen-in deformation of the surrounding cool (but shattered) crust which bends downwards as it slides toward the excavation cavity during crater collapse. Vibrational fluidization plays little role in the deep-seated motions during collapse, although it may play more of a role in near-surface topographic construction [13]. A thick ejecta deposit that loads the surrounding cool, strong crust createing the outer gravity high.

The last phase of the GRAIL mission included many very low passes over the young Orientale multi-ring basin [14]. Although the data collected by this "end-game" of the mission is still being analyzed, detailed iSALE models of the excavation of Orientale by Johnson et al. [15] now reproduce most of the current observations and provide a picture of how the ring fault scarps form. The collapse process of such a large basin is surprisingly dynamic. While the rings do seem to form during inward motion as suggested by the ring tectonic model [16], the faults develop during a time when the crust is moving inward and *upward* as a large central rebound briefly lifts the crust high above its original level, before it collapses downward to eventually create a shallow depression over the site of the impact. This depression in the simulations is generally much deeper than the basin today, but given the high temperature of the underlying melt and surrounding mantle, a great deal of subsequent isostatic uplift is expected to raise the basin floor. This analysis is still a work in progress, but ongoing simulations in conjunction with further analysis of GRAIL data can be expected to add many more details to this picture of the formation of very large impact basins.

Beyond GRAIL: The current spate of analysis of large basins is very strongly focused on lunar impacts. This is a very large step forward, but this obscures the fact that some processes may be specific to the Moon. For example, the thermal gradients assumed in the current round of models are appropriate for the ancient Moon, at the time when the currently observed basins were forming. Basin formation is quite different on a cold (modern) Moon [11], as it would be on a much hotter Moon. The coincidence between the peak ring and the outer edge of the mantle uplift seems to hold quite generally on the Moon, but does not hold for Chicxulub crater on the Earth, which has only a tiny mantle uplift [17]. Large impact basins on the icy satellites have very different morphologies, which are not yet addressed by the current models. We also have yet to fully understand the Caloris Basin on Mercury, whose formation may have been influenced by the presence of Mercury's large core. There is thus much yet to be done in the continuing dialog between modeling and observation before we can feel confident that we really understand the formation of large impact basins in our solar system.

References:

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