MULTIRING BASIN FORMATION: CONTROLS ON RING LOCATION AND SPACING. B. C. Johnson[1], J. C. Andrews-Hanna[2], G. S. Collins[3], A. M. Freed[4], H. J. Melosh[4], M. T. Zuber[5] [1]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912, USA (Brandon_Johnson@Brown.edu). [2]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA. [3]Impacts and Astromaterials Research Centre, Department of Earth Science and Engineering, Imperial College London, London SW7 2AZ, UK. [4]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, IN 47907, USA. [5]Massachusetts Institute of Technology Haystack Observatory, Route 40, Westford, MA 01886, USA

Introduction: Multi-ring basins, large impact craters characterized by multiple concentric topographic rings, dominate the stratigraphy, tectonics, and crustal structure of the Moon [1-4]. Recent modeling of the formation of Orientale clearly resolves the formation of basin rings and matches crustal thickness estimates based on GRAIL gravity and LOLA topography [5]. Orientale's innermost ring, the Inner Rook, forms by collapse of a central uplift similar to the formation of peak rings in smaller basins [5-7]. The Outer Rook and Cordillera, the outer rings of Orientale, are large normal faults that form during crater collapse as the result of inward flow of warm, weak mantle material during collapse of the transient cavity [5]. This flow of weaker underlying material pulls the cooler crust along with it, ultimately causing extensional faulting with large offsets far from the transient cavity rim. The importance of the weak underlying mantle material is consistent with ring tectonic theory of multi-ring basin formation [8]. These faults offset the crust-mantle interface and locally thin the crust.

Along with recent advances in modeling, the high-resolution lunar gravity field provided by GRAIL mission [3] and lunar topography from the LOLA instrument on the LRO spacecraft [9] offer an exceptional opportunity to investigate lunar basins and their rings to gain valuable insight into the process of multi-ring basin formation and modification and the factors that control the nature of basin rings**.** Detailed comparison of modeled basin structures to observed gravity and topography may shed light on temporal and spatial variations in lithospheric thickness during the epoch of basin formation. Here we present initial modeling efforts to determine the effects that pre-impact thermal structure, impactor size, and crustal thickness have on the formation of basins and their rings.

Methods: Following Johnson *et al.* [5], we model basin formation using iSALE, a multi-material, multi-rheology, finite difference, shock physics code [10-12]. We simulate dunite impactors striking spherical Moon-like targets at 15 km/s. We include two more improvements from the models of Johnson et al. [5]. We include a stress dependent visco-elastic-plastic rheology for mantle material, which was recently added to iSALE [Elbeshausen priv. comm.]. We also include tensile failure, which is neglected by default to reduce computational expense. Our preliminary results (fig. 1) suggest these changes produce relatively minor differences from [5]. However, in most cases the outermost ring becomes more apparent than in previous models.

Results: To test the effect of impactor diameter we simulate impacts by bodies 50-80 km in diameter while keeping the thermal gradient (13 K/km) and crustal thickness (52 km) constant at values similar to those found to be a best fit for Orientale [5]. Our results are generally as expected, rings move outward and ring spacing increases with increasing impactor size. The offsets along faults for the outer rings also become larger.

We determine the effect of pre-impact crustal thickness by varying crustal thickness from 20-60 km while keeping thermal gradient and impactor size constant at values similar to those found to be a best fit for Orientale [5]. We find that as crustal thickness increases ring spacing tends to increase. This is in contrast to previous work that explored a smaller range of pre-impact crustal thickness, which concluded that ring location and spacing was insensitive to pre-impact crustal thickness [5].

To test the effect of thermal structure and lithospheric thickness, we vary the conductive thermal gradient from the surface from 10-20 K/km corresponding to lithospheric thicknesses from ~50-100 km while keeping the impactor size (64 km diameter) and crustal thickness (52 km) constant at values similar to those found to be a best fit for Orientale [5]. Fig. 1 shows that ring location and spacing is very sensitive to lithospheric thickness.

For a lithospheric thickness, t_{litho}= 103 km, (fig. 1 top), material at depth is relatively strong and the inward collapse of deep material far from the basin center is limited. This causes the final basin to be very deep and the outermost fault or 'Cordillera' is closer to the basin's center than in the other models. Hereafter we will refer to rings as their closest equivalent ring observed in Orientale even though some models are not a good fit for Orientale. In this model there is no obvious Inner Rook ring.

For t_{litho}= 79 km (fig. 1 middle) there is significantly more inward collapse of material far from the basin center. Figure 1 (middle) corresponds to nearly the same conditions for the best fit of Orientale

[5].This produces a decent fit for Orientale with a large offset at the Cordillera as compared to the Outer Rook. However, a better fit would have the Inner Rook and Cordillera further from the basin center. This suggests a slightly larger impactor may produce a better fit for Orientale.

For t_{litho}= 51 km (fig. 1 bottom), the deep material far from the basin center is very weak and readily collapses moving the rings outward. The higher thermal gradient leads to more ductile deformation and offsets along faults are subdued. Although detailed conclusions cannot be drawn from only three models, this preliminary work shows that the locations, spacing, and morphology of basin rings is clearly dependent on the assumed pre-impact thermal structure and lithospheric thickness.

Our initial work demonstrates that pre-impact crustal thickness, thermal gradient, and impactor size are all important controls on the formation of multitring basins. Ongoing exploration of this parameter space (i.e. impactor size, thermal structure, and crustal thickness) will encompass nearly the entire range of lunar basin formation conditions and provide valuable insight into the process of basin formation.

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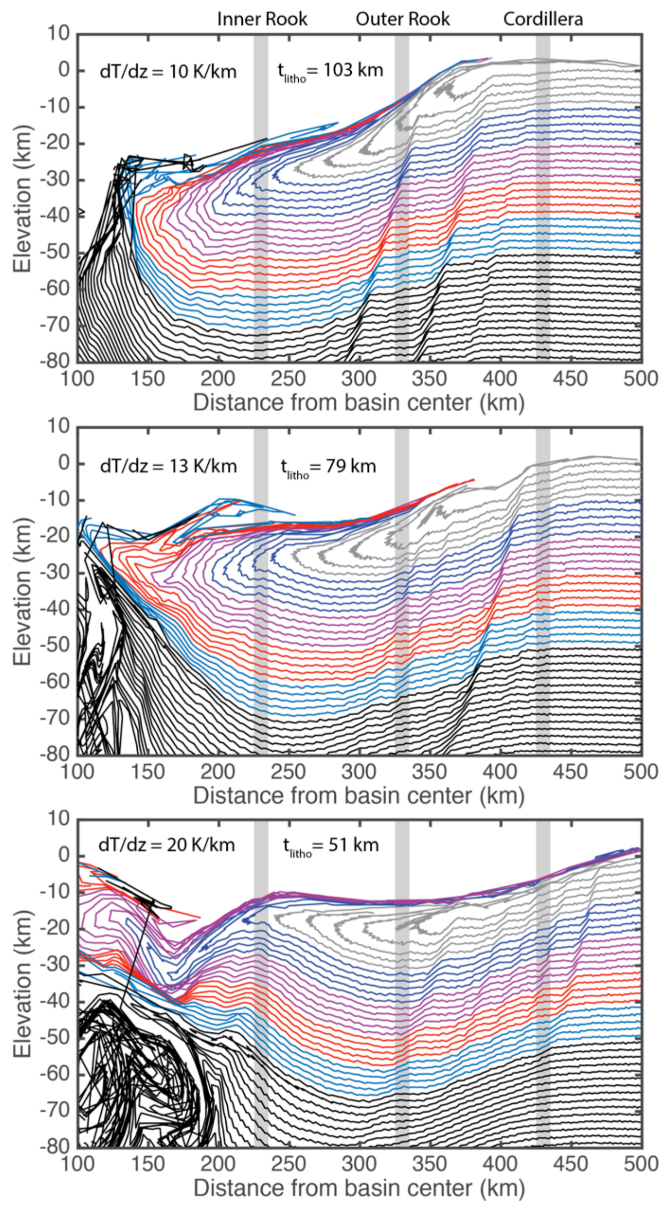

Figure 1: Plot illustrating the effect that lithospheric thickness has on ring locations, spacing, and morphology. All three models are of a 64 km diameter impactor striking a moonlike target with pre-impact crustal thickness of 52 km at 15 km/s. The models assume a thermal gradient of 10, 13, and 20 K/km (Top, Middle, Bottom), from a surface temperature of 300 K with temperatures at the base of the lithosphere of 1300 K which is defined by the temperature at which the conductive thermal profile turns to a relatively constant convective adiabat. With this definition of lithospheric thickness, the lithosphere is 103, 79, and 51 km thick for the top, middle, and bottom plots, respectively. All plots are from 50 minutes after impact, after formation of the ring corresponding to the Inner Rook (i.e. the last ring to form). Thin lines connect Lagrangian tracers that were initially at equal depths. Before the impact, these lines are parallel with a constant spacing of 2 km. In the crust, the color of tracer lines changes every 10 km in pre-impact depth. The thick gray lines are guides to the eye, marking the distance from basin center where Orientale's rings are observed at the surface.