New Estimates of the Orientale Basin Impactor Size from Modeling of the Ejecta Thickness Distribution. M. -H. Zhu[1], K. Wünnemann[2], and R. W. K. Potter[3], [1]Space Science Institute, Macau University of Science and Technology, Taipa, Macau (mhzhu@must.edu.mo), [2]Museum für Naturkunde, Leibniz Institute for Research on Evolution and Biodiversity, Berlin, Germany (Kai.Wuennemann@mfn-berlin.de), [3]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, USA (ross_potter@brown.edu).

Introduction: The Orientale basin is the youngest multi-ring impact structure on the Moon. It has four approximately concentric topographic rings: the Cordillera Ring (CR, D ~ 930 km), the Outer Rook Ring (ORR, D ~ 620 km), the Inner Rook Ring (IRR, D ~ 480 km), and the Inner Ring (IR, D ~ 320 km) [1]. The formation of the Orientale basin has been reconstructed by different numerical modeling studies [e.g., 2, 3] using its surface expression and dimensions as constraints. *Potter et al.* [2] proposed an impactor of 50 – 80 km in diameter assuming an impact velocity of ~ 15 km/s which corresponds to a kinetic energy of 2 – 9 × 10^{25} J. *Stewart* [3] suggested a 100-km-diameter projectile impacting the lunar surface at 10.6 km/s, which corresponds to an impact energy of ~ 15 ×10^{25} J for the formation of the Orientale basin. We attribute this difference in impact energy to insufficient observational constraints as there are only a few features that can be used to constrain the magnitude of the impact. Besides morphological and morphometric data, only low resolution gravity data were available that did not allow for more accurate modeling of subsurface deformation [4].

Recent high-spatial resolution maps of the crustal thickness, derived from GRAIL data [5], and topography obtained from LOLA [6], give new insights into the crustal structure and ejecta thickness distribution of the Orientale basin, and provide an opportunity to further constrain modeling by the higher resolution observations. In this work we reinvestigate the basin-forming process of Orientale basin with numerical modeling and focus on the ejecta thickness distribution. We fit our models to the calculated ejecta thickness and crustal structure based on recent observations from LOLA and GRAIL in an attempt to further constrain the Orientale basin impact scenario and improve our understanding of the formation of this youngest multi-ringed basin on the Moon.

Orientale Crust Thickness and Ejecta Distribution: The crustal thickness model derived from GRAIL data [5] suggests an ~ 11 km thick crust at the center of Orientale basin. The thickness increases abruptly at a radial distance of ~ 120 km from the basin center and reaches a maximum value at a radial distance of 270 km in the western sector and 290 km in the eastern sector, respectively, forming an annular bulge [2]. Outside the bulge the crustal thickness remains relatively uniform representing the pre-impact condition. The Orientale basin is located at the transition to the lunar highlands explaining the somewhat thicker crust of ~ 60 km in west and only ~ 40 km in the east (see Fig. 1).

Fassett et al. [6] used LOLA data to estimate the ejecta thickness by measuring the smallest crater that survived the Orientale basin-forming impact. The ejecta thickness deposited within one basin diameter is estimated to be $t = 2.9 \pm 0.3$ km at the crater rim (CR) with the radius R_{CR} and decreases as a function of distance r with a power law $t = 2.9(r/R_{CR})^{-b}$ with an exponent b of 2.8 ± 0.5. The exponent b is consistent with the estimated value of 3.0 from *McGetchin et al.* [7] and the value of 2.6 determined empirically by scaling law in *Petro and Pieters* [8] (see Fig. 2).

Numerical Modeling: In this work we use the 2D iSALE shock physics code [9, 10] to simulate the formation of the Orientale basin. We adopt a target setup suggested by *Potter et al.* [2] in which two-layers consisting of gabbroic anorthosite (Tillotson equation of state) and dunite (ANEOS [11]) represent the crust and the mantle, respectively. For simplicity we assume that the impactor was also composed of dunite. For the material models describing the mechanical resistance against deformation (including strength deformation history, thermal softening, and acoustic fluidization), we chose the same parameters as suggested previously by *Potter et al.* [2].

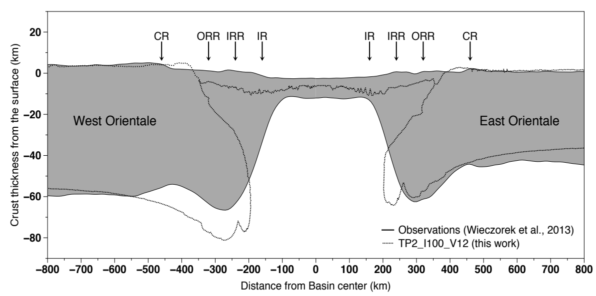

Fig. 1 The modeled and observed crustal profile for the west and east Orientale basin.

According to *Potter et al.* [2] and *Ivanov et al.* [12] the thermal gradient in the target is very important for determining the final structure of the basin. Two possible thermal gradients were used in our simulations as in *Potter et al.* [2]. Thermal profile 1 (TP1) represents a warm Moon with a crust and upper mantle temperature gradient of 10 K/km, temperatures at the mantle solidus at a depth of 150-350 km and a deep mantle temperature of 1670 K below 800 km [2]. Thermal profile 2 (TP2) representing a cooler Moon with a crustal temperature gradient of 10 K/km, mantle temperatures that approach, but do not reach, the solidus between depths of 300-500 km, and a deep mantle temperature of 1770 K [13].

We conducted a series of models with the projectile ranging from 50 to 100 km in diameter impacting the lunar surface vertically. The velocity varies from 10 to 20 km/s. The iSALE model domain extends to 1200 km in the lateral and vertical direction with a cell size of 1 km × 1 km in the high-resolution zone. All simulations were stopped at 2.5 hours after initial impact because the dynamic basin processes have ceased by that time. To account for the variation in pre-impact crustal thickness we conducted each model with pre-impact crustal thickness of 60 km (for the west side) and 40 km (for the east side), respectively.

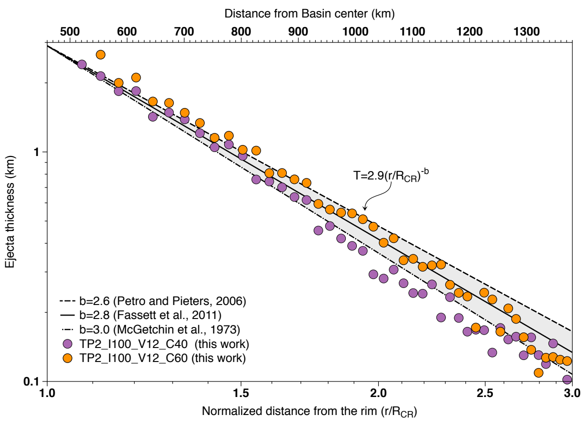

Fig. 2 The modeled and observed ejecta thickness distribution along with the normalized distance from the rim of the Orientale basin.

Ejecta Thickness Estimation: We use tracer particles that are initially placed at the center of each computational cell to record the launch angle and velocity at the time of ejection. Assuming pure ballistic flight of the ejecta, we reconstructed the parabolic trajectory of each tracer to calculate its velocity and deposition distance. We assume that each tracer is representative for the mass of the cell it was initially located in. The surrounding surface of the crater was subdivided into discrete concentric rings. The ejecta thickness was then calculated from the number of tracers that land in each ring. Note, we do not account for the formation of an ejecta plume in our models and assume that the effect of vaporized material on the distribution of ejecta is negligible in the calculation of ejecta distribution. We also do no take secondary mass wasting into account.

The Best-fit Model for Orientale Basin: We compared the modeled ejecta distribution with the estimated thickness from observations (see Fig. 2). Those models with a reasonable agreement were then compared with the subsurface structural models derived from GRAIL data. The model matching both observational constraints, the ejecta thickness distribution and crustal structure, is considered as the best-fit model.

For the warm Moon (TP1) we find a good agreement with the ejecta thickness distribution for projectile diameters of L = 80 - 100 km with an impact velocity of v = 10 - 14 km/s. The projectile size in our models is significantly bigger than the one proposed by *Potter et al.* [2] (L = 50 km and v = 15 km/s). However, all our models have an annular bulge larger than the value proposed from gravity modeling [5]. Therefore, we conclude that a warm Moon according to TP1 is an unlikely scenario for the thermal condition at the time of impact when the Orientale basin was formed.

For a cold Moon (TP2), we find that a 100-km-diameter projectile impacting at a velocity of 12 km/s matches well with both observations, the ejecta thickness and crustal structure. The models agree inside estimated uncertainties resulting from the post-impact long-term geologic activities of the Orientale basin. Fig. 2 displays the ejecta thickness distribution as a function of radial distance. The ejecta layer is 3.9 km thick at the CR. The thickness decreases with distance according to a power-law with an exponent b = -3.2 for 60-km-thick pre-impact crust. For the 40-km-thick pre-impact crust the thickness of the ejecta layer is 3.3 km at CR and the exponent b = -3.2. In Fig. 1 we compare the crustal structure underneath the basin of the best-fit model with the one derived from the gravity data [5]. The crustal annular bulge occurs at a radial distance of about 270 km in both best-fit models (40- and 60-km-thick crust) which agrees well with the models derived from GRAIL data [5].

In conclusion, our modeling indicates that Orientale basin was most likely formed by a 100-km-diameter projectile impacting on a relatively cold lunar crust and mantle with a velocity of 12 km/s. The best-fit model suggests a larger impactor than previous models have suggested [2] when the ejecta thickness distribution was used as an additional constraint.

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