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Estimates of primary ejecta and local material for the Orientale basin: Implications for the formation and ballistic sedimentation of multi-ring basins

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A B S T R A C T

A clear understanding of thickness distributions of primary ejecta and local material is critical to interpreting the process of ballistic sedimentation, provenances of lunar samples, the evolution of the lunar surface, and the origin of multi-ring basins. The youngest lunar multi-ring basin, Orientale, provides the best preserved structure for determining the thicknesses of primary ejecta and local material. In general, the primary ejecta thickness was often estimated using crater morphometry. However, previous methods ignored either crater erosion, the crater interior geometry, or both. In addition, ejecta deposits were taken as mostly primary ejecta. And, as far as we know, the local material thickness had not been determined for the Orientale. In this work, we proposed a model based on matching measurements of partially filled pre-Orientale craters (PFPOCs) with the simulations of crater erosion to determine their thicknesses. We provided estimates of primary ejecta thickness distribution with the thickness of 0.85 km at Cordillera ring and a decay power law exponent of $b = 2.8$, the transient crater radius of 200 km, excavation volume of 2.3×10^6 km^3, primary ejecta volume of 2.8×10^6 km^3. These results suggest that previous works (e.g., Fassett et al., 2011; Moore et al., 1974) might overestimate the primary ejecta thicknesses of Orientale, and the primary ejecta thickness model of Pike (1974a) for multi-ring basins may give better estimates than the widely cited model of McGetchin et al. (1973) and the scaling law for impacts into Ottawa Sand (Housen et al., 1983). Structural uplift decays slower than previously thought, and rim relief is mostly rim uplift for Orientale. The main reason for rim uplift may be the fracturing and squeezing upward of the surrounding rocks. The proportion of local material to ejecta deposits increases with increasing radial distance from basin center, and the thickness of local material is larger than that of primary ejecta at distance larger than certain distance (~1.5 basin radius for Orientale). These results suggest ballistic sedimentation is important for multi-ring basins, and ejecta deposits can't be considered as mostly primary ejecta everywhere.

1. Introduction

The Orientale basin is assumed to have formed ~3.8 billion years ago (Greeley et al., 1993) and is the youngest multi-ring basin on the Moon. Due to the relatively young age, the Orientale basin suffered minor geological modification since its formation (Spudis, 1993; Kreslavsky and Head, 2012), and its well-preserved morphology, therefore, provides the best choice to study the thicknesses of primary ejecta and local material for large-scale impact basins on the Moon. In this paper, primary ejecta always refers to the ejecta of the Orientale basin; local material is used to represent the preexisting surface material that was excavated and incorporated by the primary ejecta when they impacted the lunar surface; and ejecta deposits refer to the mixture of primary ejecta and local material.

The thickness of primary ejecta was often estimated indirectly from the measurements of partially filled pre-Orientale craters (PFPOCs) using crater morphometry (e.g., Moore et al., 1974; Fassett et al., 2011). However, previous works did not consider either crater erosion, the crater interior geometry (e.g., the shallowing of crater near crater rim and the existence of central peak), or both. In addition, ejecta deposits were taken as mostly primary ejecta everywhere. As a result, they might overestimate the primary ejecta thickness, and other related characteristics of Orientale, such as the size of transient crater cavity. In this work,

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we considered all these factors and gave estimates of the thicknesses of primary ejecta and local material. The primary ejecta directly relates to the formation condition and the size of excavation cavity, from which the formation of the Orientale basin can be better understood, and it provides new insights on the formation of multi-ring basins. Since the proportion of local material to ejecta deposits is not well known for lunar craters (Oberbeck et al., 1975), estimates of the local material thickness could help us understand the process of ballistic sedimentation and the evolution of the lunar surface (Oberbeck et al., 1975), and reveal provenances of lunar samples (McGetchin et al., 1973; Oberbeck, 1975; Haskin et al., 2003; Petro and Pieters, 2006).

In this paper, we propose a model that considers the erosion of PFPOCs to re-investigate the primary ejecta and local material. The high resolution digital elevation model (DEM) with a spatial resolution of 256 pixels/degree derived from Lunar Orbiter Laser Altimeter (LOLA) (Smith et al., 2010) was used for all measurements of elevations.

2. Methods

Craters undergo some degree of degradation since its formation because of topographic diffusion due to the formation of small impact craters (Soderblom, 1970), and seismic shaking (Schultz and Gault, 1975; Richardson et al., 2004, 2005). During the modification stage of complex crater formation, advective process (e.g., landslide) play an important role in forming terrace zone. And after crater formation, it may also have effect on initial stage of crater degradation. However, after the initial stage of degradation, it may be neglected because it requires steeper gradient (Craddock and Howard, 2000). Therefore, we assume that topographic diffusion is the main reason accounting for complex crater degradation.

In order to accurately estimate the primary ejecta thickness (T_{PE}), and to give a first order estimate of the local material thickness (T_{LM}) (parameters used in this work were illustrated in Fig. 1), we have to consider the erosion of PFPOCs and the crater interior geometry. But the exact crater profile was unknown due to the burial by ejecta deposits, and it meant there was another unknown. Fortunately, PFPOCs have two attributes, the exposed rim height (H_{ER}) and average exposed rim-floor depth (D_{AERF}), which can be determined by measurements (see section 2.1) and are both related to the two unknowns. And we could derive numerical relations of $[T_{PE}, T_{LM}] = F\ (H_{ER}, D_{AERF})$ by using simulations of crater erosion, where F represents a relation that each pair of inputs (H_{ER} and D_{AERF}) is related to exactly one pair of outputs (T_{PE} and T_{LM}) (see section 2.2). Therefore, measurements and simulations had two parameters in common for each measured PFPOC. A best fit model was used to match H_{ER} and D_{AERF} of measurements with those of simulations, then T_{PE} and T_{LM} could be determined from the numerical relations (see section 2.3).

2.1. Measurements of PFPOCs

There were 186 PFPOCs identified by Fassett et al. (2011). We used a minimum crater diameter of 25 km to exclude simple craters due to the fact that a measured PFPOC is degraded from a relatively small fresh crater (Fassett and Thomson, 2014), and a maximum crater diameter of 175 km to exclude peak ring craters. In order to simulate the process of crater erosion, a PFPOC should form on a near flat surface, and have not been modified severely. In addition, in the region of a measured PFPOC, the crater density should be relatively low to avoid being blanketed by adjacent craters. Therefore, there were 27 PFPOCs left for measurements (see Fig. 2). Note, all maps in this paper are given in an equidistant cylindrical projection, and all results are calculated in a local map projection.

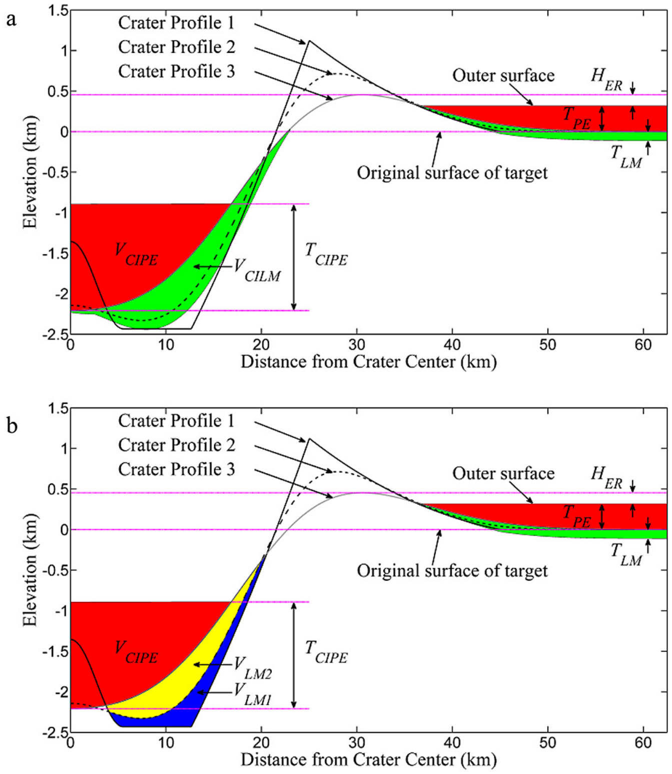

Fig. 1. Morphometric parameters used for our model. Note that the red and green regions are both ejecta deposits. Crater Profile 1 represents the initial crater profile, Crater Profile 2 represents the crater profile just before the Orientale impact event, Crater Profile 3 represents the crater profile after the Orientale impact event. T_{PE} is the thickness of primary ejecta, H_{ER} is the exposed rim height, V_{CIPE} is the volume of crater interior primary ejecta, and T_{CIPE} is equal to the maximum thickness of crater interior primary ejecta. (a) V_{CILM} is the volume of excavated local material within crater rim. (b) V_{LM1} and V_{LM2} are approximately equal to the volume of infilling material when Crater Profile 1 degraded into Crater Profile 2 and Crater Profile 2 degraded into Crater Profile 3, respectively. And the sum of V_{LM1} and V_{LM2} are considered to be approximately equal to V_{CILM}. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

We used polylines to outline crater rim and outer surface (see Fig. 3a). All measurements were within circular sectors, and a circular sector (e.g., CS1 in Fig. 3a) was excluded from measurements either because of topographic irregularities (e.g., other craters and highland topography) or destruction of crater rim. The rim elevation and outer surface elevation were both calculated by equation (1), and their uncertainties were both determined by equation (2) (see Fig. 3b).

$$h_{mean} = \sum_{i=1}^{N} h_i \varphi_i \Big/ \sum_{i=1}^{N} \varphi_i \tag{1}$$

$$h_{uncertainty} = \sqrt{\sum_{i=1}^{N} \varphi_i (h_i - h_{mean})^2 \Big/ \sum_{i=1}^{N} \varphi_i} \tag{2}$$

where h_i is the mean elevation at the locations of a small segment (the red line between locations P_1 and P_2), N is the number of segments, and φ_i is the central angle in radians. Because measurements of crater rim and outer surface were not exactly perpendicular to radial direction, elevations were multiplied by their corresponding central angles to make sure that the measurements are equally-weighted.

In this paper, we used the Crater Helper Tools toolkit extension to ArcGIS (Nava, 2011) to measure crater diameters from the Lunar