Thickness of proximal ejecta from the Orientale Basin from Lunar Orbiter Laser Altimeter (LOLA) data: Implications for multi-ring basin formation

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1. Introduction

Early in the history of the Moon, basin-scale impact events modified millions of square kilometers in a geological instant, excavating deep into the lunar crust and perhaps mantle, and spreading ejecta radially over areas often approaching a lunar hemisphere [Moore et al., 1974; Head, 1974; Melosh, 1989; Head et al., 1993; Spudis, 1993]. Despite the significance of basins in planetary history, key questions remain about the volume of basin ejecta, the origin of basin rings, the size and geometry of the transient cavity, and the depth of excavation and sampling.

The Orientale impact basin (D = 930 km) is the most recent large multi-tinged lunar impact basin, and for this reason, it has long provided a type-example for basin formation processes [Moore et al., 1974; Head, 1974; Spudis, 1993, and references therein]. The lack of measurements of lunar topography at high spatial resolution and precision has complicated prior attempts [e.g., McGetchin et al., 1973; Moore et al., 1974; Head et al., 1975] to characterize the thickness of Orientale ejecta and its radial decay away from the basin. The high-resolution altimetric data recently acquired by the Lunar Orbiter Laser Altimeter (LOLA) instrument onboard the Lunar Reconnaissance Orbiter (LRO) [Smith et al., 2010] now makes it possible to provide a more refined and accurate ejecta-thickness estimate. We use a digital terrain model (DTM) of LOLA data for the Orientale region gridded to 128 pixels per degree (237 m/pixel; interpolation of LOLA point observations) for all measurements.

2. Methods

The first of the techniques used to estimate the thickness of Orientale ejecta relies on LOLA to measure the amount of material in partially filled, pre-Orientale craters, many of which are clearly recognizable in Figure 1a. There are 154 such pre-Orientale craters with D = 20 to 100 km, and we have measured their observed rim crest-to-floor relief. The difference between the observed relief in these craters and the expected relief in a fresh crater of the same size represents a firm upper limit on the amount of ejecta (or, strictly, degradation of relief) contributed by Orientale to the crater’s morphometry [e.g., Moore et al., 1974] (Figure 2a; see also Text S1 of the auxiliary material). In general, we would expect this to be an overestimate of the ejecta thickness, since most craters on the lunar surface have experienced some amount of mass wasting, weathering, or infill that would have reduced the relief of the pre-Orientale crater population before the basin-forming impact. We use the empirical morphometric relationships derived by Pike [1977] for the expected relief of fresh lunar craters.

A second technique we apply to assess the thickness of ejecta is to find the smallest crater which survived the Orientale basin-forming impact at a given radial range (Figure 2b and Text S1 of the auxiliary material). Since small craters are far more common on planetary surfaces than larger craters, we can be confident that numerous smaller craters must have existed prior to the Orientale event and been erased, and the smallest surviving crater provides information about the scale below which all pre-existing craters were erased, again applying Pike’s [1977] relationships. We divide the area...
models described below. The distribution of locations where we have measured Orientale ejecta thicknesses is shown in Figure 1b, and thickness derived are shown in Figure 2a. Following McGetchin et al. [1987], we assume that the radial variation in ejecta thickness, \( t \), away from the Cordillera ring (which has thickness \( T_{CR} \)) can be expressed by a power function of the range \( r \) (measured from the center of Orientale), scaled by the radius \( R_{CR} = 465 \) km:

\[
t = T_{CR}(r/R_{CR})^B
\]  

[1] From this equation, we treat both \( T_{CR} \) and \( B \) as independent unknowns and compute a nonlinear least squares fit to the lower envelope of the data in Figure 2a and thickness estimates from crater survival in Figure 2b. The resulting thickness at the Cordillera ring is \( T_{CR} = 2900 \pm 300 \) m, decaying with a power law exponent of \( B = 2.8 \pm 0.5 \) (the quoted uncertainties are 95% confidence intervals from the non-linear least square fit). This ejecta-thickness profile should be understood as an average and local variations are common. Since this estimate is derived from burial and relief degradation, it excludes structural uplift that is known to occur close to crater rim crests, but includes an unknown component of locally derived material incorporated in the ejecta deposit that increases as a function of increasing radial range [e.g., Oberbeck, 1975].

[2] It has been argued that Orientale formed by an oblique impact on the basin of other morphological and morphometric characteristics, such as asymmetry in the far-field ejecta (secondary crater chains) [Scott et al., 1977; Wilhelms, 1987; Schultz, 1996; Schultz and Papanastassiou, 2010]. Although we do not see a major asymmetry in near-field ejecta thickness, the scale of variation in near-field ejecta thickness may simply be unresolvable using our techniques.

[3] To assess how directly this ejecta decay profile affected nearby topography and how it might contribute to the elevation of the basin rim, we can measure the topography at the Cordillera ring and compare it to topography at some distance away. From the ejecta profiles, we expect \(~2\) km more ejecta deposited at the Cordillera ring than at \( r/R_{CR} = 1.5 \) (half of a basin radius from the Cordillera). Comparing the average elevation of the Cordillera rim (\( \mu = 3.7 \) km from the LOLA DTM; \( \sigma = 2.6 \) km) and the average elevation of terrain at \( r/R_{CR} = 1.5 \) (\( \mu = 1.3 \) km; \( \sigma = 3 \) km), we find a \(~2400\) m difference (note that the \( 1 - \sigma \) values given here reflect azimuthal variability in elevations, not errors in altimetric measurements, which are negligible). The similarity of the \(~2000\) m expected change (from the ejecta profile alone) and \(~2400\) m difference (in observed, average elevation difference) suggest that much of the elevation change between \( r/R_{CR} = 1 \) and \( r/R_{CR} = 1.5 \) is a result of the decay in ejecta thickness; some of the additional \(~400\) m may be the result of structural uplift.

4. Discussion

[4] In this section, we compare our measurements to earlier estimates for the ejecta thickness and its decay. We also use the derived ejecta-thickness function to calculate

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**Figure 1.** (a) A portrayal of the LOLA DTM of Orientale, with regional trends removed to help emphasize the alteration of topography surrounding the basin by ejecta. Note that pre-Orientale craters are visible in its surroundings, but most have been significantly altered by ejecta. Major rings of the basin are labelled; CR: Cordillera Mountain ring, \( R = 465 \) km; OR: Outer Rook ring, \( R = 310 \) km; IR: Inner Rook ring, \( R = 240 \) km; ID: Inner Depression, \( R = 160 \) km. (b) Locations where measurements were obtained that constrain the ejecta thickness (dots, fill measurements, Figure 2a; triangles, direct measurements, Figure 2b; triangles, direct measurements of lobes, see Text S1 of the auxiliary material). Base map is a LOLA DTM superposed on a LOLA hillshade.
Figure 2. (a) Distribution of fill material within craters near Orientale based on their reduced relief when compared to fresh craters of the same size. Since this reduction in relief reflects the sum of pre-Orientale infill and Orientale ejecta, it is generally an overestimate of ejecta thickness. For this reason, the lower envelope on the data is relied upon for fitting. (b) Estimates for the thickness of ejecta required to erase the small crater population below the size of the smallest surviving craters at various ranges. The dashed thickness line reflects uncertainty in our assumptions about the degradation state of the fresh craters that were erased and the size below which all craters were erased (see Text S1 of the auxiliary material); the thin solid line in range is the 100 km range over which we binned our measurements. In Figures 2a and 2b the primary x-axis is normalized to the Cordillera radius (RCR = 465 km), and the black line is the ejecta-thickness model, T = 2900(r/RCR)^{2.8}.

the ejecta volume outside the Cordillera ring and extrapolate this function inward to assess the volumes of ejecta implied as a function of the location of the transient cavity rim crest.

4.1. Comparisons of Past Estimates of Ejecta Thickness and Decay

[12] A wide range of estimates have been made for the thickness of ejecta at the rim crest of the transient cavity, and for the ejecta-thickness decay function. McGetchin et al. [1973] suggested a function for the thickness of ejecta at the transient cavity rim crest T_{TR} = 0.14 R_{TR}^{0.75}, with R_{TR} and T_{TR} in meters, on the basis of nuclear craters, Meteor Crater, and observations of lunar craters. The McGetchin et al. function, assuming the Cordillera ring as the location of the transient crater rim crest, implies ejecta thicknesses at this location of 2190 m, a value smaller than our measured ejecta thicknesses. This function implies even smaller thickness estimates if the transient cavity is significantly smaller than the Cordillera Ring, as seems likely. Pike [1974] suggested a wide range of models for T_{TR}, his equation (11), T_{TR} = 0.033 R_{TR}, would imply a thickness of ejecta at the Cordillera ring of ~15 km (assuming that the Cordillera ring was the transient cavity rim crest), at least factor of 5 larger than our measurements. If, however, the transient crater was well within the Cordillera ring, as discussed below, the thickness at the rim of the transient cavity implied by this equation is potentially consistent with our results. Petro and Pieters [2006] applied the Housen et al. [1983] scaling [see also Haskin et al., 2003] to suggest T_{TR} = 0.0078 R_{TR}, which would imply a thickness of 3600 m if the Cordillera rim is the appropriate radius for the transient crater.

[13] Our ejecta-thickness measurements also allow derivation of a new power law for the decay of ejecta, with an exponent of B = 2.8 (±0.5); this is shallower than that estimated by McGetchin et al. [1973] (B = 3) and steeper than that determined by Petro and Pieters [2006] (B = 2.61), who applied the model of Housen et al. [1983], although it is formally consistent with both. Our measurements and inferred decay law differ significantly from the monotonic linear decay suggested by Short and Forman [1972] and the concave down profile of Cordell [1978]. Both of these profiles have thicknesses of ejecta of >2 km at r/RCR ~ 1.5, which is inconsistent with our observations and the preservation of several 7 to 10 km pre-Orientale craters at this range. When fresh, such craters would be expected to have relief of only 1.5 to 2 km, which would have been destroyed by deposition of >2 km of ejecta.

4.2. Ejecta Volumes and Comparisons to Estimated Transient Rim Crest Positions

[14] Using our power law description of the radial decay of ejecta, we can now integrate this function to calculate the volumes of ejecta deposited in various regions, and evaluate the results in light of proposed locations of the transient cavity’s rim crest for Orientale. Some ejecta was undoubtedly deposited at larger radial ranges than we measure [e.g., Spudis, 1993; Ghent et al., 2008], but it is likely to be a small percentage of the total ejecta volume because it commonly occurs in radial chains and is discontinuous.

[15] The Orientale basin consists of the Cordillera ring, which defines the topographic basin rim, the Outer Rook, a ring of continuous inward facing massifs, the Inner Rook, a ring of peaks, and an inner depression that contains Mare Orientale (Figure 1a). A variety of these rings have been suggested to approximate the location of the transient cavity’s rim crest (see discussion in the work of Spudis [1993]), and our new thickness, volume, and decay law estimates permit us to assess the plausibility of these assignments (Table 1). From the Cordillera ring to one basin diameter from this topographic rim crest (r/RCR = 3), we calculate an ejecta volume of 2.9 × 10^6 km^3 (+1.2, -0.8).

[16] Assuming a paraboloidal shape for the excavation cavity, its volume is V_E = 0.5πd(R_{TR})^2 for radius of the transient and excavation cavity, R_{TR}, and for depth of excavation d, which we assume to be 50 km. This assumed depth is supported by spectroscopic observations that suggest that the ejecta and ring massifs of Orientale are predominantly
felspathic and lack obvious signatures of lunar mantle material [Pieters et al., 2009; Yamamoto et al., 2010] as well as by geophysical modelling [Wieczorek and Phillips, 1999; Hikida and Wieczorek, 2007]. If the Cordillera ring radius approximates the radius of the excavation, this would imply an excavation volume of $17.0 \times 10^6$ km$^3$, substantially greater than the $\sim 2.9 \times 10^6$ km$^3$ of ejecta observed within one basin diameter of the Cordillera ring.

[17] Extrapolating the power law description of ejecta inward to the current position of rings inside the Cordillera by varying radius $R_{TR}$, we can estimate the thickness of ejecta at the transient cavity’s rim crest and the additional ejecta volume expected between $R_{TR}$ and $R_C$. If the transient radius is expressed as a fraction of the Cordillera radius, $\rho = R_{TR}/R_C$, then the thickness expected at the transient crater rim is:

$$T_{TR} = T_C \rho^{-6/3}$$  \hspace{1cm} (2)

[18] If the next innermost ring, the Outer Rook Mountains approximates the size of the transient cavity [Head, 1974], then $\rho \approx 2/3$. Thus, given $B = 2.8$, we would expect 3.1 times as thick an ejecta deposit at the Outer Rook ($\sim 9000$ m) than at the Cordillera ring, and $\sim 1.9 \times 10^6$ km$^3$ of additional ejecta would have been emplaced between the Cordillera ring and Outer Rook ring. This ejecta would have ended up within the final topographic depression of the basin defined by the Cordillera ring, with an average thickness of ejecta of $\sim 5$ km in this region, known as the Montes Rook Formation [Scott et al., 1977]]. The deposition of this volume of ejecta would have provided a significant load that may have influenced the modification stage of basin formation by facilitating the collapse of the transient cavity’s rim [e.g., Head, 2010]. If we were to include this inferred volume of ejecta between the Cordillera ring and Outer Rook, a total ejected volume of $\sim 4.8 \times 10^6$ km$^3$ would be implied (Table 1).

[19] The Inner Rook Mountain ring has also been proposed to represent the approximate position of the transient cavity rim crest [Florian and Dence, 1976]. This smaller transient cavity would have an ejecta thickness of $\sim 18.5$ km at the rim crest, a volume inside the Cordillera ring of $\sim 3.4 \times 10^6$ km$^3$, and a total volume of $\sim 6.3 \times 10^6$ km$^3$. The inner depression could also represent the transient cavity rim crest. Extrapolating our ejecta decay function to this much smaller transient cavity would imply an ejecta thickness at the rim crest of $\sim 50$ km, a volume inside the Cordillera ring of $\sim 6.6 \times 10^6$ km$^3$, and a total volume of $\sim 9.5 \times 10^6$ km$^3$. The extremely large volume of ejecta for such a small transient cavity rules out this ring as a realistic candidate for the transient cavity’s rim crest. Similarly, the extremely small volume of ejecta, relative to the excavation cavity of volume for a Cordillera ring–sized excavation cavity also suggests that it is unlikely to have been the location of the transient crater rim.

[20] These ejecta volumes can also be compared to the volume estimates for the Orientale transient cavity derived on the basis of alternative approaches. On the basis of gravity data, Wieczorek and Phillips [1999] determined a volume of $3.1 \pm 0.4 \times 10^6$ km$^3$ for the transient cavity, with a maximum excavation depth of $\sim 50$ km and radius of excavation of $R_{TR} \sim 200$ km (midway between the Inner Rook ring and the inner depression). More recently, Hikida and Wieczorek [2007] derived similar values for the radius of the excavation cavity and slightly smaller depths using different gravity–inversion techniques.

[21] The ejecta volume we infer outside the Orientale topographic basin (outside the Cordillera ring), but within one basin diameter, is $\sim 2.9 \times 10^6$ km$^3$. This rises to $\sim 4.8 \times 10^6$ km$^3$ if the ejecta profile is extrapolated back inside the basin to the Outer Rook ring ($R = 310$ km). Estimates for the transient cavity volume derived from lunar gravity analyses ($\sim 3.1 \pm 0.4 \times 10^6$ km$^3$) [Wieczorek and Phillips, 1999; Hikida and Wieczorek, 2007] are more comparable to the value we observe outside the Cordillera ring ($R = 465$ km), but the Cordillera ring radius is considerably greater than their estimated $R_{TR}$ of $\sim 200$ km. One possibility is that the radius of the transient cavity is simply larger than inferred in these gravity models. For example, if the current Outer Rook approximates the size of the transient cavity, then a 50 km depth of excavation would imply a volume of $\sim 7.5 \times 10^6$ km$^3$, and a 40 km depth of excavation would yield a volume of $\sim 6 \times 10^6$ km$^3$, consistent with predicted ejecta volumes.

[22] Four other factors may contribute to this difference: (1) the excavation cavity volume of a large basin is greater than the total ejecta volume deposited outside the crater [e.g., Schultz et al., 1981]; (2) the shape of the excavation cavity may be more realistically estimated by a nested cavity configuration than by assuming a paraboloidal geometry [Cintala and Grieve, 1998; Head, 2010; Baker et al., 2011]; (3) the ejecta–thickness model assumes no ‘bulking’ or net change in density or porosity of the ejecta, and does not include incorporation of local material into the ejecta; and (4) extrapolating the ejecta profile from outside the basin into its interior may not adequately reflect what would be deposited within the rim of the basin as it formed.

[23] In summary, our new ejecta measurements and inferred ejecta decay profile are consistent with a transient cavity radius approximated by the current location of the Outer Rook.

<table>
<thead>
<tr>
<th>Mapped Ring</th>
<th>Transient Crater Radius, $R_{TR}$</th>
<th>Volume of Excavation, $V_{EX}$</th>
<th>Volume of Ejecta, $V_{EJ}$</th>
<th>Volume of Ejecta From $R_{TR}$ to $R_C$</th>
<th>Volume of Ejecta From $R_C$ to 3 $R_C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Dep.</td>
<td>160 km</td>
<td>$2.0 \times 10^6$ km$^3$</td>
<td>$57.5$ km ($50.7$ to $27.2$)</td>
<td>$6.6 \times 10^6$ km$^3$ ($3.4$ to $1.1$)</td>
<td>$2.9 \times 10^6$ km$^3$ ($1.2$ to $0.8$)</td>
</tr>
<tr>
<td>Inner Rook</td>
<td>240 km</td>
<td>$4.5 \times 10^6$ km$^3$</td>
<td>$18.5$ km ($9.9$ to $6.6$)</td>
<td>$3.4 \times 10^6$ km$^3$ ($1.1$ to $0.9$)</td>
<td>$2.9 \times 10^6$ km$^3$ ($1.2$ to $0.8$)</td>
</tr>
<tr>
<td>Outer Rook</td>
<td>310 km</td>
<td>$7.5 \times 10^6$ km$^3$</td>
<td>$9.0$ km ($3.2$ to $2.4$)</td>
<td>$1.9 \times 10^6$ km$^3$ ($0.4$ to $0.4$)</td>
<td>$2.9 \times 10^6$ km$^3$ ($1.2$ to $0.8$)</td>
</tr>
<tr>
<td>Cordillera</td>
<td>465 km</td>
<td>$17.0 \times 10^6$ km$^3$</td>
<td>$2.9$ km ($0.3$)</td>
<td>0 km</td>
<td>$2.9 \times 10^6$ km$^3$ ($1.2$ to $0.8$)</td>
</tr>
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</table>

*This table gives the volume of excavation assuming a paraboloidal cavity with depth of 50 km, the ejecta thickness at the transient crater rim found by extrapolating the derived ejecta–thickness model to that location, the volume of ejecta between the transient crater rim and Cordillera, and the volume measured between the Cordillera rim and one basin diameter away.
ring and are inconsistent with a much larger ($R_{TR} > 400$ km) or smaller ($R_{TR} < 200$ km) transient cavity.

5. Conclusions

We have used new LOLA altimetry data and a variety of techniques to estimate the ejecta thickness deposited within one basin diameter of Orientale. We use this estimate to find its volume, and calculate a new ejecta-thickness decay law. We find that the thickness of ejecta is $2900 \pm 300$ m at the Cordillera ring, the main topographic rim of Orientale. The thickness of ejecta decays with a best-fit power law exponent of $B = 2.8 \pm 0.5$. The total volume of ejecta outside the basin (Cordillera ring) and within one basin diameter of its rim is $2.9 \times 10^6$ $\text{km}^3$. Extrapolation of the ejecta thickness profile inward to the next ring, the Outer Rook Mountains, would imply that an additional $1.8 \times 10^6$ $\text{km}^3$ of ejecta was excavated and deposited between the Outer Rook and Cordillera ring with average thickness of 5 km. Candidate locations of the transient cavity’s rim crest either inside the Outer Rook Ring (Inner Rook Mountains and the inner depression) or beyond it (the Cordillera ring) are less consistent with our ejecta-thickness profiles than the Outer Rook ring. The total volume of Orientale ejecta we infer is comparable to, but somewhat larger than, geophysical estimates for the volume of the Orientale excavation cavity volume. Upcoming higher-resolution measurements of the lunar gravity field [Zuber et al., 2008] and improved numerical modeling of the basin formation process [e.g., Stewart, 2011] may further address this discrepancy.

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References


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