Gravity field of the Orientale basin from the Gravity Recovery and Interior Laboratory Mission


The Orientale basin is the youngest and best-preserved major impact structure on the Moon. We used the Gravity Recovery and Interior Laboratory (GRAIL) spacecraft to investigate the gravitational field of Orientale at 3- to 5-kilometer (km) horizontal resolution. A volume of at least \( (3.4 \pm 0.2) \times 10^6 \) km\(^3\) of crustal material was removed and redistributed during basin formation. There is no preserved evidence of the transient crater that would reveal the basin structure of Orientale provides constraints on the formation of multiring basins.

Gravity field

The gravity field resolves distinctive structures of Orientale’s three rings and suggests the presence of faults associated with the outer two that penetrate to the mantle. The crustal structure of Orientale provides constraints on the formation of multiring basins.

Energy and its corresponding geological and environmental effects early in planetary history. Surface signatures of impact basins on solid planets have been extensively documented (1, 2), but their subsurface structure has, to date, been poorly characterized. We present a high-resolution orbital gravity field model of the Orientale basin on the Moon as mapped by the Gravity Recovery and Interior Laboratory (GRAIL) mission (3).

Orientale, located on the southwestern limb of the lunar nearside, is the youngest (~3.8 billion years old) (1, 4), large (~930-km diameter) impact basin on the Moon. As a consequence of its good state of preservation (1, 5), with relatively few superposed large craters (6), it is often considered the standard example of a well-preserved, multiring basin in comparative studies of large impacts on terrestrial planetary bodies (2, 7). Because of the basin’s importance, the GRAIL Extended Mission (see the supplementary text) featured a low-altitude mapping campaign during the mission’s Endgame phase (8), in which the dual spacecraft orbited the Moon at an average altitude of 6 km and acquired observations less than 2 km above the basin’s eastern rings (figs. S1 and S2).

To produce the highest-resolution gravity map achievable from the data and to ensure that small-scale features resolved were robust, we developed two maps that used the same data but independent methodologies (9). The first is derived from a global spherical harmonic expansion of GRAIL’s Ka-band (32 GHz) range-rate (KBRR) tracking data to degree and order 1200 (spatial block size = 4.5 km). The second is from a local model that implemented a short-arc analysis (10) of the tracking data and used a gravitational field model to degree and order 900 (11) as the a priori field. Local gravitational anomalies were estimated with respect to the spherical harmonic model at the center coordinates of a set of grid points. The final model has a mixed-grid resolution of 0.1° by 0.1° and 0.166° by 0.166°, corresponding to a maximum spatial resolution varying between 3 and 5 km.

These independent analyses produced gravitational models of Orientale that are essentially indistinguishable (see fig. S4). The maps are shown in Fig. 1; they resolve the shallow subsurface structure of Orientale at a spatial resolution comparable to that of many geological structures at the surface, including simple and secondary craters.

The topography of the Orientale basin (12) from the Lunar Orbiter Laser Altimeter (13) and the free-air gravity anomaly field of the region are shown in Fig. 1A and B. The maps show similar detail at small spatial scales because above degree and order 80 (spatial block size <86 km), more than 98% of the lunar gravity field is attributable to topography (14). The high correlation of topography and gravity at short horizontal scales is due to the large magnitude of the gravity anomalies arising from topography relative to the weaker anomalies attributable to density anomalies in the shallow subsurface (14).

Both topography and free-air gravity anomaly resolve Orientale’s Inner Depression, as well as the Inner Rook ring, Outer Rook ring, and Cordillera ring (see Fig. 1). The rings, which were only partially resolved in pre-GRAIL gravitational models (15), formed in the process of cavity collapse during the modification stage of the impact event, within an hour of the initiation of basin formation (16). The mechanism for ring formation, however, has been controversial (2, 5, 17–19), in large part because of a lack of understanding of subsurface structure needed to provide constraints on impact basin formation models.

Variations in subsurface mass are best revealed in the Bouguer gravity anomaly field (Fig. 1C), a representation of the gravitational field after the attraction of surface topography has been removed. Determination of crustal structure requires careful consideration of likely crustal and mantle composition (supplementary text). For uniformly dense crust and mantle (2550 and 3220 kg m\(^{-3}\), respectively (20), the Bouguer gravity anomaly can be used to map the crust-mantle boundary and thus crustal thickness (Fig. 1D and fig. S5). Although the assumption of uniform density is an approximation, its application to the regional crustal structure is supported by crustal density inferred from GRAIL (20), as well as from orbital remote sensing data (supplementary text and fig. S6). Some models for the crust invoke a mixed feldspathic layer that overlies a layer of pure anorthosite (21), but the density contrast between these rock types is small in comparison with that across the crust-mantle interface. In the mantle, there is likely a pronounced

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Fig. 1. High-resolution maps. (A) Topography, (B) free-air anomaly (1 mGal = 1 milliGalileo = $10^{-9}$ m s$^{-2}$), (C) Bouguer anomaly, (D) crustal thickness over shaded-relief topography, and (E) Bouguer gravity gradient (1 Edtős = $10^{-4}$ mGal m$^{-1}$ = $10^{-6}$ m s$^{-2}$) of the Orientale basin and surroundings. Dashed lines in (A) from innermost to outermost correspond to the Inner Depression, Inner Rook Ring, Outer Rook Ring, and Cordillera Ring (ID, IRR, ORR, and CR, respectively). The solid white line in (D) shows the location of the cross-sectional profile A–A’ in Fig. 2A. Blue lines show the locations of the azimuthally averaged cross sections in Fig. 2B. Topography is updated from Lunar Orbiter Laser Altimeter (LOLA) (L2) map LDEM_64, 0.015625° spatial resolution. To highlight short-wavelength structure, we have subtracted spherical harmonic degrees and orders less than 6 from the Bouguer gravity field. Calculation of crustal thickness and Bouguer gravity gradient is discussed in the supplementary materials (9).
thickness profile (fig. S5), the transient crater diameter is between 320 and 460 km, placing it between the diameters of Orientale’s Inner Depression and Inner Rook ring. The transient crater thus does not correspond to a specific ring; indeed, hydrocode modeling constrained by this crustal structure model (16) indicates that rings form subsequent to the transient crater, during the collapse phase.

The transition between the basin excavation cavity and the surrounding crust is well illustrated in Fig. 2. At the outer edges of the zone of mantle uplift, the crust-mantle boundary slopes outward and downward by at least 20° to 25°. The spatial correspondence of this plug of uplifted mantle with the Inner Depression is similar to the pattern seen in other multiring basins (37), but it is in contrast to peak-ring basins, where the zone of uplifted mantle is limited to the area within the peak ring.

The model also shows, beyond the basin depression, an annulus of thickened crust (Fig. 1D and fig. S8D), as well as radial structure in gravity gradients (Fig. 1E and fig. S8E) that locally correlates with observed ejecta structures (e.g., secondary crater chains) (23).

Aspects of Orientale’s asymmetry in surface structure extend to the subsurface, as indicated in Figs. 1 and 2. For instance, the basin exhibits an east-west variation in regional crustal structure that predated formation of the basin.

There are also radial variations in crustal thickness, some of which are distinctly associated with Orientale’s outer two basin rings. The simplest interpretation of the azimuthally averaged models is that they could correspond to displacements associated with normal faults that penetrate the crust. The crust-mantle boundary relief in Fig. 2B suggests that there could be multiple faults dipping inward from the Outer Rook and Cordillera rings. The crust thickness model also suggests the presence of other crustal faults that lack a visible surface expression. Although these faults may be listric—i.e., the dip angle may decrease with depth—a dip of 50°, indicated by hydrocode simulations (16), is consistent with prominent changes in crust-mantle boundary depth. These simulations also support crustal faulting not associated with rings.

Insight into the distinctive nature of each ring can be gained from scrutiny of Figs. 1 and 2 and fig. S8. The Inner Depression has the most axisymmetric and the largest variation in crustal thickness; a change in the sign of the gravity gradient (9) marks the depression’s edge. The topography of the Inner Rook ring is morphologically similar to that of peak rings in small basins (16). Individual peaks within the Inner Rook are associated with positive free-air and Bouger anomalies embedded within an annulus of negative free-air and Bouger anomalies. The Inner Rook also appears associated with a near–circularly continuous change in the sign of the gravity gradient (Fig. 1E) and a flattening in relief along the crust-mantle boundary.

The Outer Rook ring also displays well-developed topography consistent with the surface expression of a normal fault scarp (38). Ring topography has associated positive free-air anomalies embedded within the same annulus of negative free-air and Bouger anomalies. The most negative Bouger gravity in the region appears within the Outer Rook and may reflect a combination of thickening of the crust by ejecta and extensive fracturing in the crustal column. The Outer Rook displays a sign change in the gravity gradient and a mild shoaling of the crust-mantle boundary. The collective characteristics of the Outer Rook ring are consistent with local thinning of the crust by faulting.

The topography of the Cordillera ring deviates markedly from axisymmetry; it is less developed than the Inner and Outer Rook rings and has little expression in part of the basin’s southwestern quadrant. This asymmetric structure may be a consequence of the northeast-to-southwest-directed oblique impact that formed the basin (39) of preexisting heterogeneity of crustal or lithospheric structure (2, 38), with a clear west-to-east gradient of decreasing crustal thickness still preserved (Fig. 1D). The topography of this ring is also consistent with the surface expression of a normal fault scarp (16). The ring is characterized by positive free-air and Bouger anomalies, a gradient in crustal thickness, and a circumferentially discontinuous sign change in the gravity gradient. The variation of relief along the crust-mantle boundary strongly suggests fault penetration to the lower crust and possibly upper mantle. The gravitational signature could alternatively reflect contributions from magmatic intrusions along the irregularly developed ring fault, but regional seismic reflection profiles of a portion of the terrestrial Chicxulub impact structure, 20 to 25% of the size of Orientale, show ring faults that extend well into the lower crust (40).

Our observations, combined with the accompanying simulations (16), elucidate the planet-shaping thermal, tectonic, and geological consequences of Orientale and, by extension, other large impacts that dominated the early evolution of the Moon and other solid planets.

REFERENCES AND NOTES
**Formation of the Orientale lunar multiring basin**

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Multiring basins, large impact cratering characterized by multiple concentric topographic rings, dominate the stratigraphy, tectonics, and crustal structure of the Moon. Using a hydrocode, we simulated the formation of the Orientale multiring basin, producing a subsurface structure consistent with high-resolution gravity data from the Gravity Recovery and Interior Laboratory (GRAIL) spacecraft. The simulated impact produced a transient crater, ~390 kilometers in diameter, that was not maintained because of subsequent gravitational collapse. Our simulations indicate that the flow of warm weak material at depth was crucial to the formation of the basin’s outer rings, which are large normal faults that formed at different times during the collapse stage. The key parameters controlling ring location and spacing are impactor diameter and lunar thermal gradients.

Orientale, the youngest and best-preserved lunar multiring basin, exhibits three concentric topographic rings and an Inner Depression (I). The Inner Depression is a central topographic low associated with the zone of excavated crust that extends to a radial distance $R = 160$ km from the basin center and is bounded by a scarp (2, 3). The Outer Rook ($R = 330$ km) and Cordillera ($R = 430$ km) rings are topographically consistent with fault scarps (3, 4). High-resolution gravity data from the Gravity Recovery and Interior Laboratory (GRAIL) spacecraft reveal that the Outer Rook and Cordillera rings are associated with offsets at the crust-mantle interface and localized zones of crustal thinning (2). The Inner Rook ($R = 230$ km) is distinct, with a topographic signature similar to those of the peak rings of smaller basins (3, 5) and is associated with a flattening of relief at the crust-mantle boundary (2).

To understand the processes that produced the subsurface structure inferred from gravity (2), we modeled the formation of Orientale using the two-dimensional version of iSALE, a multi-material, multiphysics code (6–8). Because iSALE is a continuum model, faults are manifest as localized regions of high strain rather than as discrete slip planes. Previous models of Orientale-scale impacts (9, 10) showed subtle strain localization in the crust around the crater, hinting at ring fault formation during crater collapse, but were unable to resolve fault offsets (i.e., the amount of slip along the fault) and topographic expression. Below, we describe several model improvements that allowed us to directly resolve the formation of Orientale’s rings and faults with kilometers of offset, in a manner not achievable with previous basin formation models (9–13). We include a dilatancy model (14), which describes how deformation increases the porosity of geological materials and contributes to shear localization (15). We use a damage model with an exponential dependence on strain (15), which results in more localized deformation in rocks that are already heavily fractured. For structures the size of Orientale, the curvature of the Moon’s surface is important (16), so we model impacts into a spherical Moon-like target with a realistic gravity field (17).

We assume a vertical impact of an asteroid made of dunite at a typical lunar impact velocity of 15 km/s (18). Our axisymmetric models have a spatial resolution of 1 km. We vary the impactor diameter, pre-impact crustal thickness, and thermal structure while attempting to match ring locations as well as the crustal thickness, which is derived from GRAIL gravity measurements and topography from the Lunar Orbiter Laser Altimeter (LOLA) on the Lunar Reconnaissance Orbiter (19, 20). Because rock strength decreases as the melting temperature is approached (7), the assumed pre-impact thermal structure of the target body has the most
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Editor's Summary

On the origin of Orientale basin

Orientale basin is a major impact crater on the Moon, which is hard to see from Earth because it is right on the western edge of the lunar nearside. Relatively undisturbed by later events, Orientale serves as a prototype for understanding large impact craters throughout the solar system. Zuber et al. used the Gravity Recovery and Interior Laboratory (GRAIL) mission to map the gravitational field around the crater in great detail by flying the twin spacecraft as little as 2 km above the surface. Johnson et al. performed a sophisticated computer simulation of the impact and its subsequent evolution, designed to match the data from GRAIL. Together, these studies reveal how major impacts affect the lunar surface and will aid our understanding of other impacts on rocky planets and moons.

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