ABSTRACT

COLLINS, MATTHEW SCOTT. Thrust Faults Bound an Elevated Mantle Plug Beneath Several Lunar Basins. (Under the direction of Dr. Paul Byrne)

The lunar maria are large, volcanically infilled impact basins which host vast basaltic deposits. Several of these basins show a distinct free-air gravity signature, with a central positive gravity anomaly representing elevated, superisostatic mantle material; this mass concentration is called a “mascon.” At Mare Crisium, basin-concentric, high-standing topography, which is demarcated by landforms called “wrinkle ridges,” is collocated with the boundary of the peak positive gravity anomaly values. Previous work demonstrated that outward-dipping thrust faults create a ring-fault system that is responsible for this topographic pattern, and these faults geometrically bound the elevated mantle plug beneath the basin. Finite-element modeling of the differential stress produced by the subsidence of a superisostatic mantle plug and uplift of a subisostatic crustal collar in Crisium suggests that thrust faults should form preferentially along the inner perimeter of the basin and parallel to the crust–mantle interface. This pattern of basin-concentric shortening structures is evident in several other mascon basins—Maria Serenitatis, Nectaris, Humorum, Imbrium, and Moscoviense. Within each of these basins, wrinkle ridges and the associated elevated topography, where evident, outline the boundary of the maximum positive gravity anomaly. Here, a forward modeling approach using elastic dislocation modeling software, Coulomb, was applied to investigate the fault geometry responsible for generating these landforms and how those modeled fault solutions relate to the crust–mantle boundary beneath each basin. Modeled fault solutions for shortening structures within the lunar mare basins exhibit a range of penetration depths and dip angles. For the best-fit model solutions across all five of the study basins, the average faulting depth is 21.8 ± 3.0 km, and the average fault dip angle is 25.0 ± 2.3°. These results show that the mare ridges are produced by deep-
seated thrust faults that penetrate beyond the base of the mare infill. In the case of Maria Serenitatis, Nectaris, Moscovienne, and, to some degree, Humorum and Imbrium, outward-dipping thrust faults are sub-parallel to the elevated mantle plug at depth. This fault architecture implies that, as for Mare Crisium, the attempted isostatic adjustment of the heterogeneous lunar lithosphere results in the formation of a (partial) mascon-bounding ring-fault system; this geometric arrangement is evident for both near- and far-side basins. However, the topographic expression of mascon-bounding thrust ring faults is limited for Imbrium and Humorum, suggesting that some combination of variables restricted their formation, i.e., timing of basin formation, basin size, or basin location. Numerous mascon basins exists on Mars and Mercury, but no basins on either world clearly exhibit the arcuate, elevated topography expressed within the lunar maria. Whether the structural architecture reported for basins on the Moon is representative of large mascon-bearing basins on rocky planets in general therefore remains an open question.
Thrust Faults Bound an Elevated Mantle Plug Beneath Several Lunar Basins.

by
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DEDICATION

This thesis is dedicated to my friends and family. You all are the reason I have been able to make it this far in my young career. In the age of COVID-19, I would not have been able to finish this thesis without your love and support. In particular, I want to thank AJ Schalk and Andrew Stevenson for being the best friends that any person could possibly have. To my mother and father, thank you for instilling in me the values I hold most dear—curiosity, integrity, kindness, and authenticity. I love you all, very much.
BIOGRAPHY

After spending my time trying to decide what to do with my life and frequenting punk rock shows, I returned to college in January of 2015. I graduated *Magna Cum Laude* with my B.Sc. in Geology from Grand Valley State University (GVSU) in Allendale, Michigan in 2017. During my time at GVSU, I had the chance to actively participate in oceanographic and paleoclimatological research with Dr. Figen Mekik and presented my undergraduate research at the American Geophysical Union (AGU) Fall Meeting in 2017. After receiving my B.S. in Geology, I relocated to Raleigh, North Carolina to work with Dr. Paul Byrne. When I’m not teaching or conducting research, I enjoy playing ice hockey, attending live music, hiking, and spending time with my canine companions.

Funded by a NASA Lunar Data Analysis Program (LDAP) grant, I have spent the last two years engaged in research on the tectonic evolution of large, basalt-filled impact basins on the Moon. Many of these basins host a distinct positive gravity anomaly pattern thought to be indicative of an elevated crust–mantle boundary. The subsidence of this elevated mantle plug may be responsible for helping drive brittle failure and displacement along deep-seated thrust faults that delineate the boundaries of the mantle plug itself. The geometry of these faults are investigated using a number of techniques, including a mapping effort, forward modeling, statistical analysis, and 3-D modeling. My interests in the geological sciences incorporate a large number of sub-disciplines but all focus on the same question—how do tectonic processes drive landscape change on planetary surfaces? I will be continuing by academic pursuits at the University of Massachusetts – Amherst in Fall 2020.
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1. Introduction

The lunar mare basins host vast deposits of tholeiitic basalt, which is compositionally comparable to mid-ocean ridge basalts (MORBs) on Earth (Wedepohl, 1981). Since their formation during the infancy of the Solar System ca. 4.2–3.8 Ga (Stöffler et al., 2006; Fassett et al., 2012) and subsequent infilling by effusive volcanism over the next 2.7 Gyr (Hiesinger et al., 2000; Hiesinger et al., 2010; Hiesinger et al., 2011), these mare-hosting basins show evidence for post-emplacement deformation by tectonic processes (Bryan, 1973; Maxwell et al., 1975; Solomon and Head, 1980). This observation suggests that tectonic activity persisted well beyond the period of initial basin formation. However, the process(es) acting to deform these ponded basalt deposits, and the stresses driving that deformation, have not yet been fully characterized.

1.1 Formation of Mascon Basins and Subsequent Deformation

The lunar mare basins are characterized by a relatively low spectral reflectance and spatial crater density. In numerous such basins, the free-air gravity anomaly signature resembles a bulls-eye pattern, with a broad central positive anomaly peak surrounded by an annulus of negative values with another ring of positive values farther out again (Figure 1) (Melosh et al., 2013). Recent modeling efforts have proposed that this pattern is a relict of basin formation, with the central positive gravity anomaly representing elevated, superisostatic mantle material (“mantle plug”) (Melosh et al., 2013; Freed et al., 2014). Under this interpretation, the superisostatic state of the mantle is explained by the mechanical coupling of the melt sheet and uppermost mantle with a subisostatic crustal collar immediately after impact. As this crustal collar slowly rises toward isostatic equilibrium, the coupled mantle material achieved and maintained a superisostatic state (Freed et al., 2014).
This positive gravity anomaly pattern, associated with a concentration of uplifted mantle mass and thus termed a “mascon” (for “mass concentration”), is characteristic of several lunar basins (Muller and Sjogren, 1968). These basins also show signs of extensive tectonic deformation (Bryan, 1973), which has been attributed to the subsidence of the mare deposits (Maxwell et al., 1975) that likely occurred throughout mare emplacement (Solomon and Head, 1980). This subsidence is manifested as sets of shortening structures termed “wrinkle ridges,” which are interpreted as folds over blind or surface-breaking thrust faults (e.g., Golombek, 1985; Golombek et al., 1991; Schultz, 2000). Wrinkle ridges are often concentrated around the perimeter of the mare basins, although many individual ridges occur throughout the mare. The exact geometry of the faults responsible for generating these landforms has, historically, been the
subject of a debate as to whether they are thin- or thick-tectonic structures (Watters, 1991; Zuber, 1995; Mangold et al., 1998; Golombek et al., 2001; Montési and Zuber, 2003; Byrne et al., 2015).

![Figure 2](image_url)

**Figure 2.** Robinson projection, centered at 0°E, of the lunar surface showing the location of each basin detailed in this study: Maria Crisium, Serenitatis, Nectaris, Humorum, Imbrium, and Moscoviense. Dashed white lines of longitude demarcate the approximate boundary between the near- and far-side hemispheres.

Mare Crisium, located within the inner ring of a Nectarian-aged basin (Stöffler et al., 2006; Fassett et al., 2012) on the lunar near side (**Figure 2**), hosts a circumferential set of wrinkle ridges demarcating the inner edge of an annulus of elevated topography (Byrne et al., 2015) that was first reported by Zisk et al. (1978). The relief across these structures is as much as 500 m in places; wrinkle ridges occur along nearly the entire inner perimeter (**Figure 3; Figure 4; Figure 5a**). Notably, these concentric ridges delineate the boundary of the maximum positive
gravity anomaly within the basin (Figure 5b) (Byrne et al., 2015). Whether or not these landforms can be wholly attributed to subsidence of the mare basalts remains an open question.

Figure 3. Distribution of wrinkle ridges (thin black lines) within Mare Crisium. Basin-concentric landforms mark the inner edge of an elevated topographic bench. The basemap is SLDEM2015 topography (Barker et al., 2016) overlain on the Lunar Reconnaissance Orbiter Camera Wide-Angle Camera (LROC WAC) global mosaic (Speyerer et al., 2011). The thick black line is a line of section across one such structure. The topographic profile in the lower inset demonstrates the typical broad, low-relief, asymmetric morphology of these landforms, where the forelimb (~3°) is more steeply dipping than the backlimb (<1°).

1.2 Formation of Shortening Structures within Mare Crisium

A study by Byrne et al. (2015) investigating the nature of the bench-bounding shortening structures within Mare Crisium serves as the motivation for this investigation of similar structures within several other lunar mascon basins. Finite-element modeling has demonstrated
that the subsidence of a superisostatic mantle plug, coupled with the uplift of a subisostatic crustal collar, will concentrate stresses in such a way to induce slip along outward-dipping thrust faults within the basin that are sub-parallel to the crust–mantle interface at depth (Figure 4) (Byrne et al., 2015).

The sub-surface geometry of the thrust faults responsible for producing these basin-concentric landforms was evaluated through the use of forward modeling with the open-source elastic dislocation program Coulomb (Okada, 1992; Lin and Stein, 2004). Byrne et al. (2015) demonstrated that a network of outward-dipping thrust faults accommodates upwards of 1000 m

Figure 4. Schematic block diagram (left) of the geometric relationship between outward-dipping thrust faults and an elevated mantle plug beneath Mare Crisium. Orthographic projection of Mare Crisium (right) with LROC Wide-Angle Camera Global Mosaic is provided for spatial context. Wrinkle ridges (black lines) demarcate the inner edge of an elevated topographic bench. This illustration is not drawn to scale.
of displacement. These faults together comprise a ring-fault system that penetrates some 20 km into the lunar lithosphere and bounds the superisostatic mantle plug. A similar topographic signature has been observed for the Orientale basin and has been attributed to thermal contraction of the post-impact melt pool (Wilson and Head, 2011; Vaughan et al., 2013). In Mare Crisium, at least, this morphology suggests that crustal shortening along the perimeter of the basin also reflects the isostatic adjustment of the mantle plug and crustal collar, as opposed to solely the cooling and subsidence of the mare basalts. This study expands on the work by Byrne et al. (2015) to gain insight into the sub-surface relationship between, and evolution of, thrust faults and the elevated mantle plug beneath several other mascon basins.

1.3 Application to Lunar Mascon Basins

Mare Crisium is not the only lunar mascon basin to host a basin-concentric network of wrinkle ridges or an annulus of elevated terrain. Basins were identified for study based on the presence of at least portions of a topographic “bench” delimited on its inner edge by wrinkle ridges. These basins—Maria Serenitatis, Nectaris, Humorum, Imbrium, and Moscoviense—are
predominantly situated on the lunar near side, although Mare Moscoviense is located on the lunar far side (Figure 2).

The 674-km-diameter Mare Serenitatis is adjacent to the southeastern margin of Mare Imbrium (Figure 2). An elevated bench delineates the inner basin at azimuths of 180°–240°. Serenitatis is thought to have formed during the Nectarian period at ca. 3.9 Ga (Stöffler and Ryder, 2001; Stöffler et al., 2006), although a Pre-Nectarian (>3.9 Ga) formation age has been proposed (Fassett et al., 2012); the exact age of Serenitatis remains an open question. Estimates of the basaltic infill within Serenitatis suggest a maximum mare thicknesses of up to 4.3 km (Williams and Zuber, 1998), although previous estimates have indicated thicknesses up to 10 km (Solomon and Head, 1980). Most of these basalts were erupted during the Upper Imbrian period at approximately 3.8–3.4 Ga (Hiesinger et al., 2000; Hiesinger et al., 2011).

Mare Nectaris (Figure 2) is 340 km across and marks the beginning of the Nectarian period (Fassett et al., 2012). As for Serenitatis, Nectaris hosts a partial elevated topographic bench, which is most pronounced in the eastern and western parts of the basin. The crater model production function of Neukum and Ivanov (1994) suggests that Nectaris formed at 4.1 ± 0.1 Ga. However, basin formation age estimates are as young as 3.92 Ga (Stöffler and Ryder, 2001; Stöffler et al., 2006). The basaltic infill of Nectaris is younger than the basin itself, with radiometric dating of Apollo 16 samples suggesting that at least some of mare basalts are as old as 3.8 Ga (Maurer et al., 1978). Previous estimates of the mare thickness within Mare Nectaris (0.8 km) are substantially less than those for the other near side basins detailed in this study, as well as for Mare Crisium (Williams and Zuber, 1998).

Mare Humorum (Figure 2) is the southernmost case-study basin and, at 420 km in diameter, is comparable in size to Mare Nectaris. An elevated section of the mare floor,
measured clockwise from north, is located at 90°–170° azimuth. To the northwest of Humorum, a set of graben indicates that extensional tectonics prevailed outside of the basin perimeter (Melosh, 1978; Solomon and Head, 1980). Humorum is intermediate in age between Maria Nectaris and Imbrium (Fassett et al., 2012). In contrast to the other southern hemisphere basin detailed herein (Mare Nectaris; 0.8 km), the mare basalts in Humorum are considerably thicker at 3.6 km (Williams and Zuber, 1998), implying thermal heterogeneities within the lunar crust as suggested by Solomon and Head (1980).

Mare Imbrium (Figure 2) is the largest lunar mascon basin, with a diameter of 1,145 km. In addition to its large areal extent, Imbrium appears to have a regional slope, with elevations in the south that are higher than those in the north. The most pronounced shortening structures within Imbrium are found at azimuths of 90°–180° and 270°–360°. The basin floor outward of these structures (i.e., toward the basin perimeter) sits at elevations above the corresponding portion in the north; however, a prominent annular bench is lacking at nearly all azimuths. The geologically youngest of our study basins, the formation of Mare Imbrium marks the start of the Lower Imbrian period at ca. 3.85 Ga (Stöffler et al., 2006; Fassett et al., 2012). Williams and Zuber (1998) demonstrated that the mare thickness within Imbrium is as much as 5.3 km. Data from the Apollo and Lunar Prospector missions show that Imbrium hosts a higher abundance of KREEP-enhanced rocks, i.e., enriched in potassium (K), rare-earth elements (REE), and phosphorous (P), than the other near side lunar basins (Lawrence et al., 1998; Wieczorek and Phillips, 2000). This abnormally high abundance of radiogenic elements likely affected the early thermal and tectonic evolution of Imbrium (Wieczorek and Phillips, 2000).

Mare Moscoviense (Figure 2) is the only case-study basin located on the lunar far side. Moscoviense is highly asymmetric and much narrower when measured parallel to latitudinal
small circles (Diameter (D) = 275 km) than in its southwest–northeast extent (D = 445 km). Therefore, to analyze the effect of basin size on the geometric properties of ridge-producing thrust faults, Nectaris is considered the smallest case-study basin (D = 340 km). Relative age chronology of the lunar mare basins suggests that Moscoviense formed after the Nectaris basin but before Crisium (Fossett et al., 2012).

This basin is an essential addition to the study because of the substantial difference in crustal and mare thickness between the Moon’s near- and far-side hemispheres. That is, average crustal thickness values are about 15 km greater and mare thicknesses 100–200 m less on the lunar far side than on the near side, although isolated far-side deposits do exceed 1 km in thickness (Yingst and Head, 1997, 1998, 1999; Gillis and Spudis, 2000; Wieczorek et al., 2006). If our findings for Moscoviense are similar to those for the near-side basins, we will have determined that the process(es) that drive deep-seated thrust faulting are not restricted to the lunar near side. However, the possibility exists that the Moscoviense structures are not geometrically similar to those in other basins. If so, then it is likely that the tectonic modification of Mare Moscoviense may have been influenced by having formed within the thicker crust (Wieczorek et al., 2013) that underlies basins on the lunar far side.

Each of the basins described above shows evidence for crustal shortening, and so determining the penetration depth of the bench-bounding ridge faults in these basins may provide insight into the nature and development of those structures. If the fault penetration depths within and between these case-study basins vary considerably in otherwise similar structural settings, then the debate of whether wrinkle ridges are thin- or thick-tectonic structures (Watters, 1991; Zuber, 1995; Mangold et al., 1998; Golombek et al., 2001; Montési and Zuber, 2003) may need to be revised into a continuum of faulting depths. In addition to their penetration depths,
determining the spatial relationship between these faults and the elevated crust–mantle interface beneath each basin will provide further insight into the evolution of these basins. If the bench-bounding faults within other basins partially or wholly encircle, and are sub-parallel to, the mascon boundary at depth, then their formation may be typical of the evolution of lunar mascons in general. Conversely, if the fault architecture does not coincide with the crust–mantle interface beneath any or all of these basins, then the formation of these structures is likely affected by several interrelated factors.

2. Methods

The workflow established for Mare Crisium (Byrne et al. 2015) was refined and expanded to several other mascon basins that feature a partial annulus of elevated terrain—Maria Imbrium, Serenitatis, Humorum, Nectaris, and Moscoviense. Prominent geological features were mapped within each basin, placing particular emphasis on tectonic structures. A forward modeling approach was used to investigate the fault geometry responsible for accommodating shortening strain and thus producing wrinkle ridges within the basins. Finite-element modeling of the differential stress produced by the subsidence of a superisostatic mantle plug and uplift of a subisostatic crustal collar in Mare Crisium suggests that thrust faults should preferentially form along the inner annulus of the basin and parallel to the crust–mantle interface (Byrne et al., 2015). Fault solutions were superposed on a model of the crust–mantle boundary beneath each basin to assess the validity of this model for these five mascon basins.

2.1 Mapping

Structural mapping was performed in an ArcGIS® environment at a minimum visual scale of 1:200,000. This scale was deemed sufficient to identify the primary circumferential shortening structures. Wrinkle ridges were identified using the Lunar Reconnaissance Orbiter
Camera Wide-Angle Camera (LROC WAC) global mosaic, which has an equatorial resolution of 100 meters per pixel (m/px) (Speyerer et al., 2011). For structures not readily resolvable with LROC WAC imagery, the Lunar Orbiter Laser Altimeter (LOLA) and Kaguya Terrain Camera Merge digital elevation model (DEM) (SLDEM2015; Barker et al., 2016), with an equatorial resolution of 59 m/px, was used in conjunction with artificially illuminated shaded relief maps. Illumination azimuths of 0° and 180° were used to identify east–west-oriented structures, whereas azimuths of 90° and 270° were used to identify north–south-oriented structures.

Shortening structures were identified based on a morphology generally characterized in cross-section by a steeply dipping forelimb (~3°) and tapered backlimb (<1°) (Schultz, 2000), and not related to cratering, ejecta blanketing, or normal faulting. The cross-sectional asymmetry of these structures, however, is variable and likely related to along-strike changes in the geometry of underlying faults; no one single morphology consistently characterizes these landforms. Each of the investigated basins hosts a bench of elevated terrain that encircles at least a portion of the basin. In most cases, the inner edge of this annulus is marked by arcuate wrinkle ridges. These shortening structures are of interest given their approximate collocation with the boundary of the peak free-air and Bouguer gravity anomaly values within each basin; gravity data are from the Gravity Recovery and Interior Laboratory (GRAIL) (Zuber et al., 2013).

2.2 Fault Modeling

A minimum of three ridges was selected in each basin for further modeling based on a relatively preserved morphology with minimal degradation by cratering, subsequent faulting, or ejecta blanketing. Circumferential, bench-bounding structures resembling those in Mare Crisium (Byrne et al., 2015) were preferentially selected. Topographic profiles were extracted perpendicular to the strike of these structures for comparison to model outputs. In the case of a
regional slope, these topographic data were detrended. Several profiles were clipped to exclude anomalous topography that was unrelated to the primary fault. An elastic dislocation model, Coulomb v3.3 (Lin and Stein, 2004; available online at https://earthquake.usgs.gov/research/software/coulomb), was used to generate surface displacement profiles for a variety of fault configurations.

Input files were generated for over 600,000 unique fault configurations, with fault dip angle (\(\delta\)), depth of burial (\(d_{\text{top}}\)), penetration depth (\(d_{\text{bottom}}\)), and maximum fault displacement (\(D_{\text{max}}\)) varied for each iteration (Figure 6). The fault dip angle was varied in 1° increments, the fault penetration and fault burial depths in 1 km increments, and the maximum fault displacement in 50 m increments (Table 1). Fault displacement was tapered at the upper and lower fault tips to avoid model edge effects. We considered faults with both constant and variable dip angles. However, faults were preferentially tested with a homoclinal (i.e., constant dip angle with depth) geometry to avoid adding complexity to the models. Due to the added

![Figure 6](image)

**Figure 6.** Schematic diagram (not to scale) of each fault parameter considered for elastic dislocation modeling, with fault dip angle (\(\delta\)), depth of burial (\(d_{\text{top}}\)), penetration depth (\(d_{\text{bottom}}\)), and maximum fault displacement (\(D_{\text{max}}\)) being varied for each model iteration.
complexity and computational demands of listric fault models, the maximum fault dip angle and fault penetration were varied in 3° and 3 km increments, respectively. Each model featured a fixed fault length of 60 km; this fault length was sufficient to avoid edge effects when extracting cross-sections through the center of the resultant model surface displacement. The modeled fault length did not affect the overall morphology of the simulated surface displacement when extracting a cross-section at half of the fault length to capture the maximum vertical surface displacement. However, modeled fault length did alter the maximum fault displacement \( (D_{\text{max}}) \) required to produce a landform with the same maximum topographic relief (Nahm and Peterson, 2016).

Table 1. Summary table of fault parameters used for forward modeling of lunar shortening structures. A total of 600,120 fault configuration files were generated for both homoclinal and listric faults. Fault dip angle, penetration depth, burial depth, and maximum fault displacement was varied for each model iteration. To simulate listric fault geometries, the maximum dip angle was set at the upper fault tip and decreased linearly at five equal depth intervals to a minimum dip angle at the lower fault tip (0–20°). For each model iteration, all but one parameter was held constant.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( \delta )</th>
<th>( d_{\text{bottom}} )</th>
<th>( d_{\text{top}} )</th>
<th>( D_{\text{max}} )</th>
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</thead>
<tbody>
<tr>
<td><strong>Planar Faults</strong></td>
<td>Degrees</td>
<td>Kilometers</td>
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<td>Meters</td>
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<tr>
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<tr>
<td><strong>Range</strong></td>
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<td>6-60</td>
<td>0-5</td>
<td>50-2000</td>
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<tr>
<td><strong>Increment</strong></td>
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<table>
<thead>
<tr>
<th><strong>Listric Faults</strong></th>
<th><strong>Units</strong></th>
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<td><strong>Units</strong></td>
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<td><strong>Increment</strong></td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>50</td>
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</table>
Each fault parameter has a characteristic effect on the morphology of the resultant landform (Figure A1). Here, the primary focus is placed on the penetration depth and dip angle of each fault. There is a trade-off in these two parameters, where a broad structure at the surface can be produced both by a shallowly dipping fault with a shallow penetration depth and by a more steeply dipping fault that penetrates to much greater depths. The fault burial depth primarily controls the asymmetry of the resultant topography, where the degree of asymmetry is inversely related to the burial depth (Figure A1). The maximum displacement determines the total relief across the landform, as well as the amplitude of the trailing syncline.

Surface displacement profiles were compared with the observed topography across each of the selected ridges. Vertical scaling discrepancies between the modeled and observed topography were corrected by setting the origin of the datum at the inflection point along the crest of each ridge. Signal cross-correlation, which quantified the horizontal offset between the shape of the observed topography and modeled vertical displacement, was used to align the model-generated profiles with the extracted topographic profile horizontally. The root-mean-squared error (RMSE) was calculated to quantify the mismatch between the two profiles. Error calculations were performed across a domain that encompassed the entire morphology of the structure at a sampling interval of 0.5 km; this analysis domain varied as a function of the breadth, or total horizontal extent, of the structure being analyzed. The model solution with the minimum RMSE value was accepted as representative of the fault geometry responsible for producing the observed structure. To address the non-uniqueness of the fault solutions, contour maps were generated with each node representing the minimum RMSE for each combination of fault dip angle and fault penetration depth (see examples in Figure 11, 14, 17, 20, 23). The
region of this parameter space where the RMSE values converge on a minimum value was considered representative of the geometry of the fault under consideration.

2.3 Crust–Mantle Interface

Elevation values were extracted from the SLDEM2015 digital elevation model (Barker et al., 2016) along radial cross-sections constructed from the center of each basin. Each cross-section passed through a landform with a modeled fault solution. Crustal thickness values from the model by Wieczorek et al. (2013) were extracted along this same line of section. The approximate depth to the crust–mantle interface beneath each basin was determined by subtracting crustal thickness values from the elevation values. The best-fit modeled fault solutions were superposed on the crust–mantle interface model to assess the geometric and spatial relationship between these faults at depth and the elevated mantle plug beneath each basin.
3. Results

Figure 7. The distribution of mapped wrinkle ridges (black lines) relative to topography (left) and GRAIL-derived Bouguer gravity anomaly (right) for Maria Crisium (a,b), Serenitatis (c,d), and Nectaris (e,f).
Figure 8. The distribution of mapped wrinkle ridges (black lines) relative to topography (left) and GRAIL-derived Bouguer gravity anomaly (right) for Maria Humorum (a,b), Imbrium (c,d), and Moscoviense (e,f).
3.1. Mare Serenitatis

3.1.1. Structural Mapping and Gravity Signature

Mare Serenitatis (Figure 7c) hosts a nearly complete set of wrinkle ridges arranged in an en échelon, basin-circumferential manner. The vertical offset, which is assumed to be directly manifest as the topographic relief, and breadth of these structures vary along strike, but generally, they have 200–400 m of relief. Broader structures, located at azimuths of 80°–100° and 170°–240°, mark the inner edge of an annular bench of elevated topography. Another set of landforms parallel to this elevated bench in the eastern portion of Serenitatis is situated about 100 km toward the basin interior and consists of a belt of ridges stretching nearly 300 km from north to south. Several north–south-oriented structures with <200 m relief extend across the center of the basin.

Typically, wrinkle ridges within Mare Serenitatis are asymmetric in cross-section. The vergence (or the direction of tectonic transport) of these structures, however, does vary along strike. No one single specific morphology characterizes shortening structures within Serenitatis, or any of the investigated basins. At azimuths of 270°–350°, ridges are either limited in their topographic expression or completely absent.

Importantly, inward-verging structures within Mare Serenitatis approximately delineate the boundary of the maximum positive gravity anomaly (Figure 7d). Much like Mare Crisium (Byrne et al., 2015), these ridges tend to be sub-parallel to this boundary and are slightly offset from the maximum gravity gradient toward the basin interior. The morphological similarities between Maria Crisium and Serenitatis strongly suggest that a comparable geometric and genetic arrangement between thrust faults and the elevated mantle plug exists in this basin, too.
3.1.2. Modeling Results and Sub-Surface Geometry

The Coulomb elastic dislocation modeling approach was applied to seven basin-circumferential ridges within Mare Serenitatis (Table A1). Four of those structures are presented here (Table 2; Figure 9–10), as they are representative of many of the structures seen in Serenitatis (albeit are better preserved than many of the landforms in the basin). This subset of wrinkle ridges is indicative of outward-dipping faults (Figure 10) that collocate with the boundary of the maximum positive gravity anomaly (Figure 7d).

**Figure 9.** Solid black lines (a–d) in Figure 9a are lines of section along which elevation values were extracted for use in modeling landforms (Figure 10a–d). Dashed black lines (e–h) in Figure 9b are lines of section along which elevation data and crustal thickness values (Wieczorek et al., 2013) were extracted to visualize the relationship between our modeled fault solutions and the crust–mantle interface (Figure 10e–h). Orthographic projection of Mare Serenitatis. The basemap is SLDEM2015 topography (Barker et al., 2016) overlain on the Lunar Reconnaissance Orbiter Camera Wide-Angle Camera (LROC WAC) global mosaic (Speyerer et al., 2011).
Each of these ridges has variable breadth and relief, but the best-fit model solutions suggest that in each case the thrust faults responsible for these landforms penetrate to depths >14 km (Figure 10a–d) (Table 2). These faults are shallowly (<4 km) buried beneath the lunar surface and penetrate to depths of 14 km to 28 km. The dip angle of these faults is never more than 21°. However, the RMSE mismatch between the observed topography and the best-fit model solutions shows that a satisfactory fit can be produced with dip angles that vary by as much as 10° from the best-fit solution (Figure 11). Despite uncertainty in the exact geometric attributes of these faults, this elastic dislocation modeling approach reliably reproduces the landforms observed in Serenitatis and shows that these thrust faults penetrate substantially beyond the base of the mare infill (4.3 km; Williams and Zuber, 1998).

Radial cross-sections extracted across the landforms for which model solutions were obtained allowed us to visualize the sub-surface geometric relationship between these faults and the elevated crust–mantle interface beneath the basin (Figure 10e–h). These results show that an outward-dipping thrust ring-fault system bounds the superisostatic mantle plug at Mare Serenitatis, at least at azimuths of 0°–260° (Figure 9; Figure 10e–h). This fault architecture indicates that, as for Mare Crisium (Byrne et al., 2015), the isostatic adjustment of this superisostatic mantle material localized stresses along the crust–mantle boundary during and after basin formation.
Figure 10. Model solutions are shown for four landforms within Mare Serenitatis (a–d; Figure 9a), along with the corresponding crust–mantle model depicting the geometric relationship between the “best-fit” fault solution and the elevated mantle plug (e–h; Figure 9b). RMSE values were calculated for the domain represented by the black (start) and white (finish) circles along each cross-section (a–d).
Figure 11. Model solution contour maps for Mare Serenitatis. Fault dip angle (in degrees) is plotted against fault penetration depth (km) with Z-values representing the root-mean-squared error (RMSE) mismatch between each model iteration and the observed landform. Each inset (a–d) corresponds to the model solutions presented in Figure 10. Cool colors represent zones of low RMSE values, and warm colors depict higher RMSE values. The “best-fit” model solution presented in Figure 10 is represented by the magenta “X.” Dark blue zones are indicative of parameter combinations with RMSE values less than 7.5% of the maximum RMSE value; this region is outlined in white.
3.2. Mare Nectaris

3.2.1. Structural Mapping and Gravity Signature

Of the basins investigated, ridges within Mare Nectaris are the least pronounced. The ejecta from several adjacent 100-km-diameter craters, including Theophilus, Cyrillus, and Catharina, have locally obscured tectonic structures and the deformed mare infill (Figure 7e). This tempering of morphology is most evident along the northwestern perimeter of Nectaris, where shortening structures are not expressed at the surface, although they are possibly covered by ejecta. If crustal shortening did occur along this boundary, any evidence of such is masked by the Moon’s long impact history; this ejecta material does not show any sign of being deformed by shortening or extensional structures.

A partial bench of elevated terrain is apparent at azimuths of 0°–160° and 200°–290°. Along the eastern perimeter of the basin, as observed for Maria Crisium and Serenitatis, this arcuate bench is marked by wrinkle ridges along its inner edge (Figure 7e). In the west–southwest of the basin, however, ridges are less pronounced and are frequently veiled by ejecta deposits.

At azimuths of 080°–170° and 200°–280°, the maximum positive gravity anomaly within Nectaris is well constrained by wrinkle ridges (Figure 7f). These ridges are typically situated 20–30 km inward from the boundary of this positive gravity anomaly. This spatial pattern is similar to those observed for Crisium and Serenitatis, and, as such, provides qualitative evidence for a similar geometry of outward-dipping thrust faults bounding the elevated mantle plug beneath the basin.
3.2.2. Modeling Results and Sub-Surface Geometry

The proximity of several large, adjacent craters impeded our forward modeling approach by limiting the number of ridges with a sufficiently pristine morphology for this analysis. Thus, structures were selected regardless of their degradation state, at a wide range of azimuths to visualize the relationship between underlying faults and the elevated mantle plug along the entire circumference of Nectaris (Figure 12–13). This limitation introduced substantial error to model solutions, as a satisfactory fit was possible for a broad spectrum of parameters, and particularly fault dip angle and penetration depth (Figure 14).

**Figure 12.** Solid black lines (a–c) in Figure 12a are lines of section along which elevation values were extracted for use in modeling landforms (Figure 13a–c). Dashed black lines (d–f) in Figure 12b are lines of section along which elevation data and crustal thickness values (Wieczorek et al., 2013) were extracted to visualize the relationship between our modeled fault solutions and the crust–mantle interface (Figure 13d–f). Orthographic projection of Mare Nectaris. The basemap is SLDEM2015 topography (Barker et al., 2016) overlain on the Lunar Reconnaissance Orbiter Camera Wide-Angle Camera (LROC WAC) global mosaic (Speyerer et al., 2011).
Three ridges along the perimeter of Mare Nectaris were selected for modeling at azimuths of 060°, 130°, and 270° (Figure 12; Figure 13a–c). Each of these landforms marks the inner edge of an arcuate portion of elevated terrain. The cross-sectional relief (250–500 m) and general morphology of these structures is variable. Despite the inconsistent surficial characteristics of resultant landforms, the geometric attributes of the underlying thrust faults are

Figure 13. Model solutions are shown for four landforms within Mare Nectaris (a–c; Figure 12a), along with the corresponding crust–mantle model depicting the geometric relationship between the “best-fit” fault solution and the elevated mantle plug (d–f; Figure 12b). RMSE values were calculated for the domain represented by the black (start) and white (finish) circles along each cross-section (a–d).
relatively uniform (Figure 13). The fault dip angles suggested by model solutions range from 12° to 28°; the implied penetration depths are 21–29 km. The average burial depth of faults within Nectaris (4–5 km) is greater than the <1 km found for Crisium (Byrne et al., 2015) and the <2 km for Serenitatis (Table 2).

These modeled fault solutions demonstrate that radially outward dipping thrust faults along the perimeter of Mare Nectaris, at least along its eastern and western boundary, are sub-parallel to the crust–mantle interface at depth (Figure 12; Figure 13d–f). The structure located at an azimuth of 270° dips more shallowly (12°) than the boundary of the elevated mantle plug; this finding may be the result of the degraded nature of this landform, as acceptable fits are obtainable with fault dip angles of 10°–27° (Figure 14). Regardless of the modeling limitations, the results show that, as for Crisium and Serenitatis, an outward-dipping thrust ring-fault system bounds at least a portion of the elevated mantle plug beneath Nectaris.
Figure 14. Model solution contour maps for Mare Nectaris. Fault dip angle (in degrees) is plotted against fault penetration depth (km) with $Z$-values representing the root-mean-squared error (RMSE) mismatch between each model iteration and the observed landform. Each inset (a–c) corresponds to the model solutions presented in Figure 13. Cool colors represent zones of low RMSE values, and warm colors depict higher RMSE values. The “best-fit” model solution presented in Figure 13 is represented by the magenta “X.” Dark blue zones are indicative of parameter combinations with RMSE values less than 7.5% of the maximum RMSE value; this region is outlined in white.
3.3 Mare Humorum

3.3.1. Structural Mapping and Gravity Signature

Mare Humorum, adjacent to the southern extent of Oceanus Procellarum (Figure 2), hosts an arcuate portion of elevated topography that is apparent at azimuths of 90°–170° and is generally delimited by wrinkle ridges (Figure 8a). These structures typically have <300 m of relief and their morphology suggests that underlying thrust faults dip away from the basin interior. Similar to findings for Mare Nectaris (Figure 7e), landforms indicative of crustal shortening are absent along the western–northwestern boundary of Humorum (Figure 8a). Instead, a series of rilles, or graben, has formed in the adjacent highlands as a result of crustal tension (Solomon and Head, 1980).

In the eastern portion of Humorum, three distinct belts of shortening structures are evident and each is sub-parallel to the basin boundary. The innermost of these lineaments is offset by 50–70 km from the outermost, bench-bounding ridges. Ridges located at azimuths of 0°–170° are more pronounced than those along the southwestern perimeter of Humorum, where the tectonic regime appears to transition from compressional to extensional. As for the other basins on the lunar near side, scattered wrinkle ridges within the interior of Mare Humorum have a preferential north–south orientation (Figure 8a).

The positive gravity anomaly signature within Mare Humorum mirrors the geometry of the basin itself and, where such structures are present, is delimited by wrinkle ridges (Figure 8b). As before, these ridges are typically located several tens of km from the boundary of this maximum positive gravity anomaly toward the basin interior. Curiously, this gravity signature also parallels the basin boundary along the northwestern perimeter of Humorum where the only tectonic structures present are extensional (Figure 8b). Wrinkle ridges parallel to the eastern
boundary of the basin are situated inward of the outer edge of the maximum gravity anomaly values by up to 100 km.

3.3.2. Modeling Results and Sub-Surface Geometry

Four shortening landforms (Table 2) at azimuths of 010°–160° and 350° were selected for modeling (Figure 15). These structures were chosen based on their approximate collocation with the boundary of the maximum positive gravity anomaly within Mare Humorum (Figure 8b; Figure 15). One such ridge (Figure 15; Figure 16c), situated along an isolated belt of similar structures, is found about 50 km from the elevated bench to the west (Figure 8a; see Section 3.3.1). This structure was selected to characterize further the relationship between these lineaments which, in plan view, are sub-parallel to the basin boundary and the underlying mantle plug.

Three of the landforms have similar geometric attributes, although one structure requires a listric model fault geometry to achieve a satisfactory model fit (Table 2). The homoclinal fault solutions at azimuths of 160° and 350° are nearly identical, having dip angles of 18°–21° and penetrating the lunar lithosphere to depths of 10–13 km (Table 2; Figure 16a,b). The ridge located at an azimuth of 010° requires a listric model fault geometry with a maximum dip angle of 40° as it nears the surface and a minimum dip angle of 5° at the lower fault tip; the modeled fault solution suggests a fault penetration depth of 9 km (Figure 16d). All of these faults dip toward the exterior of Humorum.

As for the fault underlying the Humorum ridge at 010° azimuth, a listric model fault geometry provides a satisfactory fit to the structure observed at a bearing 060° (Table 2; Figure 16c). The modeled fault solution indicates that this listric thrust fault has a maximum dip angle of 20° at the upper fault tip and terminates sub-horizontally at a depth of 6 km (Figure 16c),
approximately 2 km below the estimated base of the mare infill (Williams and Zuber, 1998). In contrast to every other structure detailed in this study, this fault appears to dip toward the basin interior.

**Figure 15.** Solid black lines (a–d) in Figure 15a are lines of section along which elevation values were extracted for use in modeling landforms (Figure 16a–d). Dashed black lines (e–h) in Figure 15b are lines of section along which elevation data and crustal thickness values (Wieczorek et al., 2013) were extracted to visualize the relationship between our modeled fault solutions and the crust–mantle interface (Figure 16e–h). Orthographic projection of Mare Humorum. The basemap is SLDEM2015 topography (Barker et al., 2016) overlain on the Lunar Reconnaissance Orbiter Camera Wide-Angle Camera (LROC WAC) global mosaic (Speyerer et al., 2011).

The outward-dipping thrust faults within Mare Humorum (Figure 16a–b,d) are all sub-parallel to the boundary of the elevated mantle plug beneath the basin (Figure 16e–f,h). However, these faults, unlike for Maria Crisium, Serenitatis, and Nectaris, penetrate no deeper than about 13 km. Although it appears that a partial thrust ring-fault system does approximately
bound the crust–mantle interface beneath Humorum, this arrangement is only evident at azimuths of 010°–170° and 350° (Figure 15). The exact down-dip geometry of this network of faults varies along strike.

Figure 16. Model solutions are shown for four landforms within Mare Humorum (a–d; Figure 15a), along with the corresponding crust–mantle model depicting the geometric relationship between the “best-fit” fault solution and the elevated mantle plug (e–h; Figure 15b). RMSE values were calculated for the domain represented by the black (start) and white (finish) circles along each cross-section (a–d).
Figure 17. Model solution contour maps for Mare Humorum. Fault dip angle (in degrees) is plotted against fault penetration depth (km) with $Z$-values representing the root-mean-squared error (RMSE) mismatch between each model iteration and the observed landform. Each inset (a–d) corresponds to the model solutions presented in Figure 16. Cool colors represent zones of low RMSE values, and warm colors depict higher RMSE values. The “best-fit” model solution presented in Figure 16 is represented by the magenta “X.” Dark blue zones are indicative of parameter combinations with RMSE values less than 7.5% of the maximum RMSE value; this region is outlined in white.
3.4. Mare Imbrium

3.4.1. Structural Mapping and Gravity Signature

Similar to results for Mare Crisium and Mare Serenitatis, a near-circumferential set of shortening structures is observable inbound of the perimeter of Mare Imbrium. Wrinkle ridges are found at all azimuths along the basin perimeter and compose a network of landforms that stretches over 5,000 km in length (Figure 8c). These structures do not appear to form with any preferential orientation, nor do they have a consistent morphology. Ridges mapped along a north–south transect typically have a higher degree of asymmetry than the more narrow structures found along an east–west transect.

In contrast to several of the other near-side basins detailed above, Imbrium does not host a complete, elevated topographic bench. Also of note is the absence of tectonic structures within the interior of the basin (Figure 8c), which contrasts with the other study basins, as well as Mare Crisium, all of which exhibit some degree of interior crustal shortening. In addition to its vast size (>1,000 km diameter), the regional slope across the north–south extent of Imbrium is higher than any other mare basin (Figure 8c).

Basin-circumferential structures within Imbrium typically outline the boundary of the maximum positive gravity anomaly (Figure 8d). This collocation is evident even in the absence of an elevated topographic bench. As shown for several other mare basins, these ridges are typically situated tens of kilometers from the boundary of the maximum positive gravity signature within Imbrium. However, in places, these structures closely follow or are located outboard of the maximum gravity gradient.
3.4.2. Modeling Results and Sub-Surface Geometry

Five ridges with variable relief, breadth, and degrees of asymmetry were selected for modeling based on their approximate collocation with the maximum gravity gradient within Mare Imbrium (Table A1). Four of those landforms are shown here (Table 2; Figure 18). The morphology of these structures varies by azimuth, where broader, more cross-sectionally asymmetric structures are seen along an east–west transect and narrow, approximately symmetric structures are in the north and south of Imbrium. As discussed above, the morphology of these

**Figure 18.** Solid black lines (a–d) in Figure 18a are lines of section along which elevation values were extracted for use in modeling landforms (Figure 19a–d). Dashed black lines (e–h) in Figure 18b are lines of section along which elevation data and crustal thickness values (Wieczorek et al., 2013) were extracted to visualize the relationship between our modeled fault solutions and the crust–mantle interface (Figure 19e–h). Orthographic projection of Mare Imbrium. The basemap is SLDEM2015 topography (Barker et al., 2016) overlain on the Lunar Reconnaissance Orbiter Camera Wide-Angle Camera (LROC WAC) global mosaic (Speyerer et al., 2011).
landforms is a function of several variables, namely the fault dip angle, penetration depth, and burial depth (Figure A1).

As expected, the narrow, relatively high-relief (400–500 m) structures along an east–west transect are the function of more steeply dipping faults that are buried several km beneath the lunar surface (Figure 19a,d). The broader, bench-bounding structures along the eastern and western perimeter of Imbrium result from shallowly dipping thrust faults (Figure 19b–c). The structure shown in Figure 19b penetrates to a far greater depth (30–55 km; Figure 20) than any of the faults detailed for Imbrium, or any of the other near-side lunar basins; the best-fit model solution suggests a fault penetration depth of 47 km.

With the exception of the outward-dipping thrusts at an azimuth of 150°, the faults responsible for generating circumferential wrinkle ridges within Mare Imbrium do not closely parallel the crust–mantle boundary at depth (Figure 19e–h). Thrust faults underlying the broad, bench-bounding structures along a north–south transect do tend to more closely follow this interface at depth (Figure 19f–g). However, modeled fault solutions for landforms along the eastern and western boundary of Imbrium do not appear to match the geometry found for thrusts and uplifted mantle plugs in the other basins considered here (Figure 19e–h).
Figure 19. Model solutions are shown for four landforms within Mare Imbrium (a–d; Figure 18a), along with the corresponding crust–mantle model depicting the geometric relationship between the “best-fit” fault solution and the elevated mantle plug (e–h; Figure 18b). RMSE values were calculated for the domain represented by the black (start) and white (finish) circles along each cross-section (a–d).
Figure 20. Model solution contour maps for Mare Imbrium. Fault dip angle (in degrees) is plotted against fault penetration depth (km) with Z-values representing the root-mean-squared error (RMSE) mismatch between each model iteration and the observed landform. Each inset (a–d) corresponds to the model solutions presented in Figure 19. Cool colors represent zones of low RMSE values, and warm colors depict higher RMSE values. The “best-fit” model solution presented in Figure 19 is represented by the magenta “X.” Dark blue zones are indicative of parameter combinations with RMSE values less than 7.5% of the maximum RMSE value; this region is outlined in white.
3.5. Mare Moscoviense

3.5.1. Structural Mapping and Gravity Signature

Mare Moscoviense, the only far-side, mascon-bearing basin included in this study, hosts structures with morphologies that resemble those within near-side basins in that they typically mark the inner edge of a topographic bench. The backlimbs of these ridges are frequently terminated by inward-dipping normal faults that define the basin perimeter (Figure 8e). Basin-concentric elevated terrain, and the associated wrinkle ridges, is evident at nearly all azimuths. The basin itself is highly asymmetric. In the northeast, the topographic bench is situated approximately 100 km from the central basin, whereas the elevated terrain at azimuths of 130°–360° defines the inner ring of central Moscoviense (Figure 8e). The gravity anomaly signature for Moscoviense mirrors this topographic pattern (Figure 8f).

Ridges within Moscoviense are relatively continuous along the basin perimeter, and the interior of the basin, much like those on the lunar near side, and record limited signs of tectonic shortening (Figure 8e). The relief across these shortening structures is variable but, in isolated cases, can be upwards of 700 m. Landforms with this degree of relief are not found within any of the near-side mare basins. As is shown for each of the basins detailed above, wrinkle ridges, which in Moscoviense are nearly ubiquitously bench-bounding, are approximately collocated with the boundary of the maximum positive gravity anomaly (Figure 8f). As such, structural mapping of the basin supports the proposition that the faults responsible for these shortening landforms may, indeed, bound the mascon at depth.

3.5.2. Modeling Results and Sub-Surface Geometry

Four tectonic landforms were selected for Coulomb modeling, three of which demarcate the inner edge of elevated terrain (Figure 21). One structure, located within the interior of
Moscoviense, was selected due to its collocation with the boundary of the peak gravity anomaly values within the basin (Figure 21; Figure 8f). The positive gravity anomaly, however, continues outboard of this structure to the northeast, albeit with lower values (Figure 8f).

Figure 21. Solid black lines (a–d) in Figure 21a are lines of section along which elevation values were extracted for use in modeling landforms (Figure 22a–d). Dashed black lines (e–h) in Figure 21b are lines of section along which elevation data and crustal thickness values (Wieczorek et al., 2013) were extracted to visualize the relationship between our modeled fault solutions and the crust–mantle interface (Figure 22e–h). Orthographic projection of Mare Moscoviense. The basemap is SLDEM2015 topography (Barker et al., 2016) overlain on the Lunar Reconnaissance Orbiter Camera Wide-Angle Camera (LROC WAC) global mosaic (Speyerer et al., 2011).

Modeled fault solutions indicate that the thrust faults responsible for producing bench-bounding ridges within Moscoviense typically penetrate to depths >15 km (Figure 22a–b,d). One such structure, with nearly 800 m of relief, resulted in a modeled fault solution penetrating to substantially greater depths (51 km; Figure 22a). The best-fit model solution for the
shortening landform within the interior of the basin shows that this thrust is much shallower, only penetrating to a depth of 7 km (Figure 22c). Although this structure was able to be reproduced with a homoclinal model fault geometry, this model fault penetration depth value is comparable to that of the structure depicted in Figure 16c and located within the interior of Mare Humorum.

As for several near-side mascon basins, i.e., Maria Crisium, Serenitatis (Figure 10), Nectaris (Figure 13), and, to some degree, Humorum (Figure 16), the thrust faults responsible for wrinkle ridges within Mare Moscoviense penetrate to substantially greater depths than the base of the mare infill (Williams and Zuber, 1998) and tend to coincide with the boundary of the elevated mantle plug (Figure 22e–f,h). The exception to this geometric arrangement is in the case of the shallowly penetrating model fault responsible for the interior ridge mentioned above (Figure 22g). Generally speaking, there does not seem to be any difference between the fault architecture shown for Moscoviense and the near-side basins considered herein.
Figure 22. Model solutions are shown for four landforms within Mare Moscoviense (a–d; Figure 21a), along with the corresponding crust–mantle model depicting the geometric relationship between the “best-fit” fault solution and the elevated mantle plug (e–h; Figure 21b). RMSE values were calculated for the domain represented by the black (start) and white (finish) circles along each cross-section (a–d).
Figure 23. Model solution contour maps for Mare Moscoviense. Fault dip angle (in degrees) is plotted against fault penetration depth (km) with Z-values representing the root-mean-squared error (RMSE) mismatch between each model iteration and the observed landform. Each inset (a–d) corresponds to the model solutions presented in Figure 22. Cool colors represent zones of low RMSE values, and warm colors depict higher RMSE values. The “best-fit” model solution presented in Figure 22 is represented by the magenta “X.” Dark blue zones are indicative of parameter combinations with RMSE values less than 7.5% of the maximum RMSE value; this region is outlined in white.
Table 2. Summary table of modeled fault solutions for each mascon basin—Maria Serenitatis, Nectaris, Humorum, Imbrium, and Moscoviense. A minimum of three model solutions is shown for each basin. Visual representations of the model solutions are shown in Figures 10–23. The “→” symbol indicates a listric fault geometry where the fault dip angle decreases from a maximum value at the upper fault tip to a minimum value at the lower fault tip.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Fault Type</th>
<th>Dip Angle</th>
<th>Penetration Depth</th>
<th>Burial Depth</th>
<th>Maximum Fault Displacement</th>
<th>RMSE</th>
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<td>Planar</td>
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<td>&lt;1 km</td>
<td>300 m</td>
<td>15.2 m</td>
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<tr>
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<tr>
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</tr>
<tr>
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<td>500 m</td>
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</tr>
<tr>
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<tr>
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<td>17.7 m</td>
</tr>
<tr>
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<tr>
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<tr>
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<td>200 m</td>
<td>15.4 m</td>
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</table>
4. DISCUSSION

All of the analyzed basins host a topographic bench, although this elevated terrain is typically discontinuous and only encircles a portion of each basin. The inner edge of this elevated bench, where present, is typically demarcated by wrinkle ridges (Figure 7–8). Basin-concentric wrinkle ridges are present even where such elevated, arcuate portions of topography are absent. These ridges are collocated with the boundary of the maximum positive gravity anomaly in each basin, albeit to varying degrees; wrinkle ridges and the associated bench, where present, are typically situated <50 km from this boundary toward the basin interior (Figure 7–8).

Faults within the lunar mare basins exhibit a range of penetration depths with variable dip angles and dip directions (Table 2). These low-angle thrust faults typically penetrate to depths greater than 15 km and dip radially outward, i.e., away from the basin interior. The results of the

![Probability distribution function (PDF) histogram for bootstrapped mean values (n = 5,000) of best-fit modeled fault penetration depths in km (left) and fault dip angles in degrees (right). The best-fit modeled fault solutions suggest that the mean fault penetration depth is 21.8 km ± 3.0 km, and the mean fault dip angle is 25.0° ± 2.3°. The solid black line in each histogram represents the bootstrapped mean value for each parameter, while the dashed black lines represent the 68% confidence interval. These results are for all of the analyzed basins.](image)
bootstrapping method \((n = 5,000)\) used to determine the mean fault penetration depth and dip angle for best-fit modeled faults indicate that the average faulting depth across all of the case-study basins is \(21.8 \pm 3.0\) km with a dip angle of \(25.0 \pm 2.3^\circ\) (Figure 24). In general, the faults responsible for basin-circumferential wrinkle ridges within the lunar mascon basins are deep-seated structures that penetrate beyond the base of the mare basalts.

In the case of Maria Serenitatis (Figure 10), Nectaris (Figure 13), Moscoviense (Figure 22), and, to some degree, Humorum (Figure 16) and Imbrium (Figure 19), outward-dipping thrust faults are sub-parallel to the crust–mantle boundary at depth. As shown by Byrne et al. (2015) for Mare Crisium, compressional stresses are concentrated at this interface as a consequence of the subsidence of the superisostatic mantle plug and uplift of the subisostatic crustal collar encircling the basins. The attempted isostatic adjustment of the heterogeneous lunar lithosphere results in the formation of a (partial) mascon-bounding ring-fault system. It is intriguing that, despite the substantial difference in crustal (Wieczorek et al., 2013) and mare thicknesses (Wieczorek et al., 2006) between the lunar near and far sides, mascon-bounding thrust ring-fault systems are found for basins in both hemispheres. However, this geometric arrangement is absent in the northwestern quadrant of the Maria Nectaris and Humorum, as well as for most of Mare Imbrium, suggesting that some combination of variables, i.e., timing of basin formation, local heat flux, and effective elastic thickness, likely impeded strain localization along the crust–mantle interface.

4.1 Ring-Faults on the Earth and Moon

Geometrically comparable structures, albeit on a considerably smaller scale and with substantially steeper dip angles, have been the subject of studies focused on the dynamics of caldera collapses (Acocella, 2006; Acocella et al., 2007; Burchardt and Walter, 2010; Geyer and
Martí, 2014; Levy et al., 2018) (Figure A2). The formation of outward-dipping reverse ring faults is a kinematic consequence of caldera subsidence and collapse. It has been found that, if these ring faults are upward-propagating, i.e., they nucleate near the magma chamber and propagate toward the surface, then magma transport is possible very early in caldera subsidence (Burchardt and Walter, 2010). Despite the difference in scale, the dynamics allowing for the initiation of reverse slip along radially outward-dipping ring faults is analogous to what was found for Mare Crisium (Byrne et al., 2015). It is possible, then, that these faults acted as a magma conduit and helped facilitate the emplacement of the mare basalts; magma transport along these ring faults would vary temporally due to their closure (Burchardt and Walter, 2010).

Although not included in the study basins presented herein, ring-fault systems have been proposed for Orientale Basin (Figure 25), with shallowly outward-dipping faults (13°–22°), as well as steeply inward-dipping normal faults (60°–71°) that define the outer crater rings, that extend to, or into, the mantle (Andrews-Hanna et al., 2018). These high-angle faults typically accommodate normal slip, although the shallowly outward-dipping faults responsible for Orientale’s innermost ring geometrically resemble those identified for Mare Crisium (Andrews-Hanna et al., 2018; Byrne et al., 2015), as well as those presented above (see Section 3), and possibly accommodate reverse slip. The localization of shear along structures resembling ring faults has been predicted by hydrocode modeling, with faults penetrating well into the mantle (Potter et al., 2013; Potter, 2015; Johnson et al., 2016). In the case of the Orientale ring faults, these structures likely formed within several minutes after basin excavation (Nahm et al., 2013; Johnson et al., 2016). Previous studies on Orientale basin focused on the formation of the outer basin rings and inward-dipping normal faults. Our results for several large impact basins, namely Maria Serenitatis, Nectaris, Moscoviense, and, to a lesser extent Humorum and Imbrium,
demonstrate that thrust ring faults are topographically expressed as basin-concentric wrinkle ridges that frequently demarcate an elevated topographic bench, with slip taking place either continuously or intermittently throughout and after mare emplacement.

That this fault architecture is found within several lunar basins implies that this structural outcome is characteristic of the evolution of large, volcanically infilled mascon basins in general. This outcome is particularly evident for Mare Serenitatis (Figure 10) and Mare Nectaris (Figure 13), where outward-dipping thrust faults penetrate to depths of >20 km and bound the elevated mantle plug beneath each basin, just as was found for Mare Crisium (Byrne et al., 2015). Under the assumption that this fault architecture develops as has been proposed for Crisium, then the

Figure 25. Illustration of a proposed geological cross-section for Orientale Basin. Credit: LPI (after Head et al., 1993).
differential vertical motion of a subisostatic crustal collar and superisostatic mantle plug
concentrated stress along the crust–mantle interface, driving the formation of these deep-seated faults and the portions of arcuate, elevated, and ridge-bounded topography within each basin.

4.2 Factors Controlling the Formation of Mascon-Bounding Ring Faults

The expression of this arcuate topographic bench is manifest in all of the study basins presented herein, but the extent to which this topography is present varies. In the case of both Mare Imbrium (Figure 8c) and Mare Humorum (Figure 8a), basin-circumferential shortening landforms are not typically associated with an annulus of elevated terrain. These landforms do, however, collocate with the boundary of the maximum positive gravity anomaly (Figure 8b,d). Model solutions show that the faults responsible for these landforms generally penetrate to depths <20 km and do not fully bound the elevated mantle plug beneath these basins (Table 2; Figure 16; Figure 19). The absence of mascon-bounding thrust faults at some azimuths suggests that, for these basins at least, only a portion of the uplifted mantle is bounded by an outward-dipping thrust ring-fault system. The mechanism responsible for this fault architecture (Byrne et al., 2015) likely operated in Imbrium and Humorum. However, other local- or regional-scale factors impeded the ability of the faults to propagate fully around the mantle plug or to reach depths of tens of kilometers.

These thrust fault systems require a mechanical coupling of the crustal collar surrounding large impact basins and their impact melt sheets, in addition to upwelled mantle material (Melosh et al., 2013; Dombard et al., 2013; Freed et al., 2014; Byrne et al., 2015). Since the entirety of a large basin is in a subisostatic state immediately after impact, excavation, and collapse (Melosh et al., 2013; Dombard et al., 2013; Freed et al., 2014), cooling rates must be sufficiently rapid to prevent the mantle from undergoing viscoelastic relaxation and subsidence
for such mascon–bounding faults to form. This process allows the solidified melt sheet and the underlying portion of the mantle to achieve a superisostatic state. In the case of Mare Imbrium, a locally high abundance of KREEP-rich rocks (Lawrence et al., 1998; Wieczorek et al., 2006) may have limited the cooling rate and, in turn, the degree to which this mechanical coupling occurred.

Mascon formation and preservation are likely affected by a balance between the rates of cooling of impacted material and mantle relaxation rates. Thus, an increased heat flux locally (i.e., at the impact site) or even globally at the time of impact (for, say, an earlier point in lunar history) might have sufficiently decreased the Maxwell time of the uplifted mantle to allow for a sufficiently rapid relaxation such that a thrust ring fault could only partially form. It is likely, then, that some combination of the location, size, and timing of a given basin-forming impact event contributes to the nature and behavior of post-impact modification. For Imbrium and Humorum, as well as the northwestern boundary of the Nectaris basin, the proximity to Oceanus Procellarum (Figure 2)—the region with the highest heat flux (Wieczorek et al., 2006) and most recent mare volcanism (Hiesinger et al., 2000; Hiesinger et al., 2011)—may have impeded the formation of these structures.

Where faults do not penetrate to depths of tens of kilometers, but do extend below the base of the mare infill, some local mechanical or stratigraphic impediment may hinder or arrest further downward propagation (cf. Nicol et al., 1996; Gross et al., 1997; Cooke and Underwood, 2001; Schultz et al., 2006). This outcome may be the case in Mare Humorum, where relatively shallow, listric faults shoal into a sub-horizontal detachment at depths of <10 km (Figure 16). This detachment could represent the upper boundary of a more competent rock layer with lower fracture density. It is possible, too, that the depth of these listric faults represents some thermal or
rheological discontinuity at the time of their formation. Estimates of present lunar lithospheric thickness are variable but typically suggest an elastic thickness of <100 km (Kuckes, 1977; Comer et al., 1979; Solomon and Head, 1980; Williams et al., 1995; Crosby and McKenzie, 2005). The thick, elastic lithosphere should allow for continued downward fault propagation, assuming that tectonic forcing is sufficient to exceed the confining stress and yield strength of the lower lithosphere and induce slip. However, under the assumption that the effective elastic thickness early in the Moon’s history was inversely proportional to heat flux, and that isostatic adjustment has mostly ended, then the maximum penetration depth of these faults would be correspondingly less than is possible today.

Indeed, the finding that faults within these lunar mare basins generally penetrate to depths of less than 30 km can, in part, be explained by an elastic lithosphere that was meaningfully less thick when these basins formed. It is also likely that, as the Moon progressively cooled and, therefore, impeded the lunar mantle’s ability to deform viscoelastically, the elevated superisostatic mantle plug, as well as the coupled subisostatic crustal collar, became immobilized. Impairment of the basin’s ability to adjust isostatically would thus limit the ability of faults to continue propagating, especially as the differential stress required would increase proportionally to depth. Presumably, then, at some point the magnitude of the differential stress was insufficient to overcome the strength of the mechanical lithosphere at depths greater than about 30 km.

4.3 Deep-Seated Structures on the Moon and Beyond

These results, above, demonstrate that the faults responsible for producing circumferential landforms within several of the lunar mare basins penetrate to greater depths than the base of the volcanic infill (Williams and Zuber, 1998) (Figures 10–23). Further, the average
penetration depth of faults detailed in this study is $21.8 \pm 3.0$ km (Figure 24). Downward fault propagation and brittle deformation, instead, continues into the lower lunar crust and, in some cases, the upper mantle (Figures 10–23).

Not only do outward-dipping thrust faults typically penetrate to depths $>$10 km, but they are generally sub-parallel to the crust–mantle interface beneath the study basins. These results, therefore, indicate that the mechanical coupling of a subisostatic crustal collar and superisostatic mantle plug, and the resulting partial or near-encircling thrust ring-fault system, is characteristic of large, i.e., greater than or equal to the smallest case-study basin (Mare Nectaris; Diameter = 340 km), impact basins on the Moon in general.

Despite the ubiquitous nature of mascons within the lunar mare basins, the preservation of these gravity signatures appears uncommon on other terrestrial planets. Large impact basins subsequently deformed by tectonic activity are evident on Mars (e.g., Hellas, Argyre, Isidis, and Utopia) and Mercury (e.g., Caloris and Rembrandt). However, of the largest Martian impact basins, Isidis is the only such feature characterized by a mascon similar to that observed on the Moon (Yuan et al., 2001; Arkani-Hamed, 2009). The absence of crust–mantle boundary uplift for Martian basins greater than 200 km in diameter is likely a byproduct of viscous flow in the lower crust due to elevated heat flow (Mohit and Phillips, 2007; Karimi et al., 2016).

In the case of Mercury, Caloris Basin is the only large impact basin with a positive free-air gravity anomaly (Smith et al., 2012). The nature of the positive gravity signature for Caloris Basin is currently unknown and may be the product of elevated topography within the basin (Smith et al., 2012; Dombard et al., 2013). The apparent lack of mascon basins on Mercury may reflect the relatively low-resolution gravity field data available from the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft, which had an orbital
periapsis situated in the northern hemisphere (Genova et al., 2019). Thus, further investigation of
the Mercurian gravity field by BepiColombo upon its expected arrival in 2025 (Hussmann and
Stark, 2020) may provide further insight into basin formation and evolution on the innermost
planet.

The seeming relative scarcity of mascon-bearing impact basins on Mars and Mercury
suggests that this process is not ubiquitous across the inner Solar System. If this phenomenon is,
indeed, unique to the Moon, then some characteristic(s) of lunar thermal evolution or impact
history encourages the formation of mascon-bounding, deep-seated thrust faults as the geometric
consequence of mantle subsidence coupled with the uplift of a crustal collar. This coupling could
be a result of a specific combination of cooling rates, the thermal state of lower lunar lithosphere,
rheological properties of the lunar crust, and the longevity of mantle subsidence coupled with
crustal uplift.

5. Conclusion

Several mascon-bearing lunar basins—Maria Imbrium, Serenitatis, Humorum, Nectaris,
and Moscoviense—host portions of arcuate, elevated topography within their perimeters that
reflect reverse slip along relatively deep-seated (21.8 ± 3.0 km), low-angle (25.0 ± 2.3°) thrust
faults. In most cases, these structures geometrically bound the elevated mantle plug beneath each
basin; this architecture is evident for both near- and far-side basins. The expression of this
geometric arrangement, however, is not uniform for all study basins. Although the processes
responsible for these structures within Serenitatis, Nectaris, and Moscoviense likely share a
genesis with those structures documented for Mare Crisium (Byrne et al., 2015), the growth of
mascon-bounding thrust ring faults has been inhibited, to some degree, for Imbrium and
Humorum. Numerous mascon basins have been identified on Mars and Mercury, but no basins
on either world show as well defined a set of arcuate, elevated topography as those lunar features studied here. Whether the reported structural architecture for basins on the Moon is representative of large mascon-bearing basins on rocky planets in general remains an open question.
REFERENCES


Figure A1. Vertical displacement values (m) from Coulomb model outputs plotted against distance along a cross-sectional profile (km). Each figure inset varies a single input parameter while holding the other parameters constant. Maximum displacement is held constant at 500 m for each model iteration. The relative effect of each parameter, i.e., fault burial depth, fault penetration depth, and fault dip angle, on our model output is shown above. The color of each profile represents the variation in model output as each parameter is increased from a minimum (dark line) to a maximum (light line) value. All model profiles shown above are for homoclinal, i.e., constant dip angle, fault geometries.
Figure A2. Schematic evolution of a representative experimental collapse, summarizing, in four stages, the structural features common to all the performed experiments. From Acocella (2006).
Table A1. Summary table of all modeled fault solutions for each cast-study basin, including those not presented in Figures 10–23.

<table>
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<tr>
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<th>Model ID</th>
<th>Fault Type</th>
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<th>Minimum Dip Angle (degrees)</th>
<th>Penetration Depth (km)</th>
<th>Burial Depth (km)</th>
<th>Maximum Displacement (m)</th>
<th>Analysis Domain (km)</th>
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