

Lunar Multiring Basins and the Cratering Process

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Numerous studies of the lunar gravity field have concluded that the lunar Moho is substantially uplifted beneath the young multiring basins. This uplift is presumably due to the excavation of large quantities of crustal material during the cratering process and subsequent rebound of the impact basin floor. Using a new dual-layered crustal thickness model of the Moon, the excavation cavities of some nearside multiring basins (Grimaldi and larger, and younger than Tranquillitatis) were reconstructed by restoring the uplifted Moho to its preimpact location. The farside South Pole–Aitken (SPA) basin was also considered due to its importance in deciphering lunar evolution. Restoring the Moho to its preimpact position beneath these basins resulted in a roughly parabolic depression from which the depth and diameter of the excavation cavity could be determined. Using these reconstructed excavation cavities, the basin-forming process was investigated. Excavation cavity diameters were generally found to be on the small side of most previous estimates (for Orientale the modeled excavation cavity lies within the Inner Rook Ring). Additionally, with the exception of the three largest basins (Serenitatis, Imbrium, and South Pole–Aitken) the depth/diameter ratios of the excavation cavities were found to be 0.115 ± 0.005 , a value consistent with theoretical and experimental results for impact craters orders of magnitude smaller in size. The three largest basins, however, appear to have significantly shallower depths of excavation compared to this trend. It is possible that this may reflect a different physical process of crater formation (e.g., nonproportional scaling), special impact conditions, or postimpact modification processes. The crustal thickness model also shows that each basin is surrounded by an annulus of thickened crust. We interpret this thickened crust as representing thick basin ejecta deposits, and we show that the radial variation in the thickness of these deposits is consistent with scaling laws obtained from small-scale experimental studies. If multiring basins ever possessed a terraced main crater rim, this terraced zone may be presently unrecognizable at the surface due to the emplacement of ejecta deposits that exceed a few kilometers in thickness exterior to the excavation cavity rim. We also show that the interiors of many basins were superisostatic before mare volcanism commenced. Those basins that were closest to approaching a premare isostatic state lie close to or within an anomalous geochemical province rich in heat-producing elements.

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1. INTRODUCTION

Impact cratering is one of the major geologic processes that operates on planetary bodies early in their evolution. For geologically active planets, such as the Earth and Venus, much (if not all) of this early cratering record has been obliterated by tectonic and erosional processes. The Moon, Mercury, and Mars, in contrast, have ancient surfaces that date back billions of years to this time of early impact bombardment. Even the most casual glance at the Moon will reveal large impact features hundreds to thousands of kilometers in diameter, attesting to the importance of impact cratering as a major geologic process.

Though much can be learned about the cratering process by studying impact craters on Earth, home in many respects is not the ideal place to undertake such a study. Due to the decline in the cratering rate with time, the relatively youthful age of the Earth's surface and high erosion rates, there are comparably few pristine impact craters available for study as opposed to that of our nearest neighbor, the Moon. Though there are some relatively well-preserved simple and complex craters, the Earth presently lacks large impact structures comparable in size to the massive lunar Imbrium and Orientale basins. Impacts of this size also occurred on Earth early in its evolution, and such events would have had drastic environmental effects as is evident by the K-T extinction caused by the "small" Chicxulub impact.

The key to understanding the geology of the Moon is to have an understanding of the processes that form the large multiring basins. These impact events excavate deeply into the lunar crust and redistribute vast amounts of material in the form of ejecta. Many of the samples collected from the Apollo missions have been affected by the largest basins, and after years of analysis, there is still division within the community as to the origin of many of these samples (for example, see Haskin *et al.* 1998). If the original provenance of the returned samples is ever to be determined, it is necessary to have an understanding of how much material was excavated in the multiring basin forming process, what the maximum depth of excavation was, the nature of regional crustal stratification, and how the thickness of ejecta deposits vary as a function of range from the crater's rim. These questions could begin to be addressed if we knew the size

of the excavation cavity for these basins; i.e., that portion of the preimpact crust that is ballistically ejected in the cratering process.

Without large basins on Earth to study directly, the cratering process of the largest lunar basins can only be inferred by other methods. For instance, theoretical scaling laws (e.g., Holsapple 1993), experimental hypervelocity impact experiments (e.g., Stöffler *et al.* 1975, Gault and Wedekind 1978, Schultz and Gault 1990), and computational simulations (e.g., O'Keefe and Ahrens 1993, Pierazzo and Crawford 1998) can all be used to study the details of crater excavation and modification. Scaling laws, however, have only been confirmed empirically over a relatively limited range of impact parameters, and computational models are only as good as the equations of state and built-in assumptions that are employed. The cratering process can also be studied by investigating terrestrial craters such as Meteor Crater, Ries, Manicouagan, and Chicxulub, but the largest of the terrestrial craters (e.g., Sudbury) are highly deformed and eroded.

It is not at all certain, however, whether results obtained from impact experiments, computational simulations, and terrestrial simple and complex craters can be scaled up to basin-sized impact events. Even if these small-scale analogs were valid for the largest basins, one would need to know the diameter of the basin's transient cavity (or equivalently, the diameter of the excavation cavity) in order to obtain quantitative results, such as the volume of impact melt produced in the event. For small complex craters, the transient cavity diameter can be reconstructed by restoring slumped floor material and terraced rim deposits to their original premodification position (Malin and Dzurisin 1978, Settle and Head 1978). Multiring basins, however, do not appear to possess a main terraced rim, and it is not at all clear which basin ring (if any) corresponds to the main crater rim of smaller complex craters (such as Copernicus and Schrödinger). With few exceptions (e.g., Orientale; see Spudis *et al.* 1984) the diameter of the transient cavity for multiring basins is largely unconstrained.

Our limited understanding of large multiring basins has primarily come from investigating these structures on the Moon. The Orientale basin has been most intensely studied due to the fact that it is both the youngest basin as well as the least modified by mare basalt flows. One of the most important results from this campaign has been to constrain the size of this basin's excavation cavity to lie within the outer Rook ring (Spudis *et al.* 1984). This has been accomplished by identifying pre-Orientale landforms that have been partly buried by Orientale ejecta. Early attempts at estimating the volume of material that was excavated during this impact have relied upon an estimate of the diameter of the excavation cavity, in combination with the then current crater and ejecta thickness scaling relationships (Head *et al.* 1975). These techniques, however, produced estimates that varied over an order of magnitude. Alternatively, assuming that small-scale impact results can be scaled up to basin-sized events, Spudis (1993) has used the photogeologically constrained excavation

cavity diameter to estimate the amount of material that was excavated in the Orientale event. Clearly, an alternative approach independent of assumed scaling relations is desirable to address this problem.

The aftermath of the basin-forming process can be independently assessed through an analysis of their associated gravitational and topographic signatures. Using this approach, the subsurface structure of the basin is modeled without invoking scaling laws that may or may not be applicable to the largest craters. For instance, it has been concluded from these studies that the lunar Moho (i.e., the crust-mantle boundary) is substantially uplifted beneath the multirings basins (e.g., Wise and Yates 1970, Bills and Ferrari 1977, Thurber and Solomon 1978, Phillips and Dvorak 1981, Bratt *et al.* 1985). This uplift has commonly been interpreted as resulting from the excavation of large amounts of crustal material and the subsequent rebound of the crust and mantle beneath the basin floor. Using the amount of rebound calculated from these studies, Bratt *et al.* (1985) were able to obtain first-order estimates of the volume of material that was excavated from many nearside basins. These early studies, though, were hampered by the limited coverage of the then current gravity and topography data sets. The recent Clementine mission has resulted in improved estimates of crustal structure (Zuber *et al.* 1994, Neumann *et al.* 1996, Wieczorek and Phillips 1998, Arkani-Hamed 1998) and give us the opportunity to readdress many key questions regarding the basin-forming process.

In this study we have used the dual-layered crustal thickness model of Wieczorek and Phillips (1998) to reconstruct the excavation cavity geometry of some nearside multiring basins (Grimaldi and larger, and younger than Tranquillitatis). The far-side South Pole–Aitken basin was also considered due to its importance in understanding lunar evolution. By restoring the uplifted Moho beneath these basins to its preimpact position, a roughly parabolic depression is formed. We interpret this depression as being a first-order representation of the excavation cavity, from which the depth and diameter of excavation can be determined. Several important results follow from these measurements. Most significantly, with the exception of the three largest basins in our study (Serenitatis, Imbrium, and South Pole–Aitken), the depth/diameter ratio of the excavation cavity was found to be 0.115 ± 0.005 , consistent with proportional scaling laws obtained for craters orders of magnitude smaller in size (Croft 1980). The three largest basins have significantly smaller depth/diameter ratios and may reflect a different physical process of crater formation (e.g., nonproportional scaling), special impact conditions, or postimpact modification processes.

Additionally, assuming that the annulus of thickened crust surrounding these basins represents basin ejecta, we also investigated the thickness of the near-rim ejecta deposits. With the exception of Serenitatis, Imbrium, and South Pole–Aitken, ejecta thicknesses were found to compare favorably with the experimental near-rim scaling results of Housen *et al.* (1983) obtained for craters orders of magnitude smaller in size. Using the above results in combination with the seismically determined

structure of the Chicxulub impact basin (Morgan *et al.* 1997), we also comment on the ring structure of multiring basins. We suggest that the reason a main crater rim with well-developed terraces has not been identified for multiring basins is that this terrace zone has been obstructed from view by ejecta deposits exceeding a few kilometers in thickness. Finally, we show that the interiors of many basins were superisostatic before mare volcanism commenced. Those basins that were closest to approaching a premare isostatic state appear to be located in an anomalous geochemical province rich in heat-producing elements.

2. EXCAVATION CAVITY RECONSTRUCTION

In this study, we have used the recently derived dual-layered crustal thickness model of Wieczorek and Phillips (1998) (recomputed using an improved Lunar Prospector gravity model; see Appendix) to investigate the subsurface structure of the near-side multiring basins. Though gravity modeling is inherently nonunique, we believe this dual-layered crustal model to be a better representation of lunar structure than previously published models that possessed a uniform density crust (see Wieczorek and Phillips 1997, 1998). The dual-layered model is consistent with many observations, including (1) the presence of a seismic discontinuity within the crust beneath the Apollo 12 and 14 landing sites (Toksöz *et al.* 1974), (2) the fact that the composition of basin ejecta becomes more mafic with increasing basin size (Spudis *et al.* 1984, 1996), (3) the common interpretation that mafic impact melts have a lower crustal origin (Ryder and Wood 1977, Reid *et al.* 1977), and (4) the geoid to topography ratios of the highland crust which suggest some form of crustal stratification (Wieczorek and Phillips 1997).

The dual-layered crustal thickness model was constructed assuming that the lunar crust is grossly stratified into an upper anorthositic layer ($\rho_u = 2.8 \text{ g/cm}^3$), and a lower noritic layer ($\rho_l = 3.1 \text{ g/cm}^3$). The gravitational attraction due to the surface topography (Smith *et al.* 1997) was first removed from the observed free-air gravity field. Using the mare thickness model of Solomon and Head (1980) modified by the maximum mare thicknesses of Williams and Zuber (1998), the gravitational attractions of the circular mare ($\rho_m = 3.3 \text{ g/cm}^3$) were also removed from the observed gravity field. The remainder of the gravity field was then assumed to be due to relief along both the intracrustal interface and lunar Moho. Since two interfaces can be modeled in an infinite number of ways to explain a single observable, we first assumed that the remaining gravity field was solely due to relief along the intracrustal interface. Where relief along this single interface could not account for the magnitude of the remaining gravity field (mainly beneath the basins), relief along the lunar Moho was also modeled. Through an iterative process, the crustal model was constrained to match the seismically determined structure beneath the Apollo 12 and 14 sites. The interested reader is referred to Wieczorek and Phillips (1998) for further details. As we discuss later, our conclusions are not particularly sensitive as to whether a single- or

dual-layered crustal thickness model was used in the following analysis.

The most striking (though not unexpected) feature of this model is that the crust is substantially thinned, and the Moho is uplifted tens of kilometers beneath the major basins. For many of the young nearside basins, the entire upper anorthositic crust is absent and the lower noritic crust is thinned as well. This suggests that many of the lunar basins have excavated a significant amount of lower crustal material; material that should be present in the Apollo sample collection. Another feature of this model is that an annulus of thickened crust surrounds each of these basins (see also Neumann *et al.* 1996). Though not a unique interpretation, we use the working hypothesis that this thickened crust represents basin ejecta. Somewhat surprisingly, this dual-layered crustal model also suggests that the enormous South Pole–Aitken basin did not excavate into the lunar mantle. Though this impact apparently excavated the entire upper crust, our model predicts that there is still about 40 km of lower crustal material present beneath this basin's floor.

Our method of reconstructing the excavation cavity of the multiring basins is fairly simple. We assume that the thinned crust and uplifted Moho beneath these features is a direct consequence of (1) the amount of crustal material excavated during the cratering process and (2) the subsequent rebound of the crater floor. We first created azimuthally averaged profiles for the surface topography, mare thickness, intracrustal relief, and Moho relief for each basin (see Fig. 1). We next restored the uplifted Moho and overlying crust to its "preimpact" position. As our first estimate of the preimpact depth of the Moho we used the average depth at two "main rim" radii from the basins center (see Table I). After removing the mare fill, this process resulted in a roughly parabolic surface depression that we interpret as being a first-order representation of the basin's excavation cavity. The initial depth and diameter of the excavation cavities were then determined by fitting a parabola to this surface depression. Using these initial dimensions of the excavation cavity, the above procedure was repeated taking the preimpact depth of the Moho as the average depth at four excavation cavity radii away from the basin center (see Fig. 2).

This approach neglects many processes that may have modified the geometry of the original excavation cavity. The magnitude of these effects is hard to quantify, but it is likely that they are only of second-order importance. For instance, it is well known that postimpact slumping of the crater rim (e.g., Melosh 1989) significantly modifies the transient cavities of smaller complex craters. This process creates terraces within the crater rim; enlarging the crater diameter and reducing the crater's depth. The width of the terraced zone within the crater rim, however, increases only slowly as a function of crater diameter (Melosh 1989, Pike 1976). Additionally, if uplift of the crater floor is rapid following excavation, large-scale slumping along the crater rim may be hindered. These considerations suggest that slumping in multiring basins will be of lesser importance in modifying the initial transient cavity in comparison to smaller complex craters.

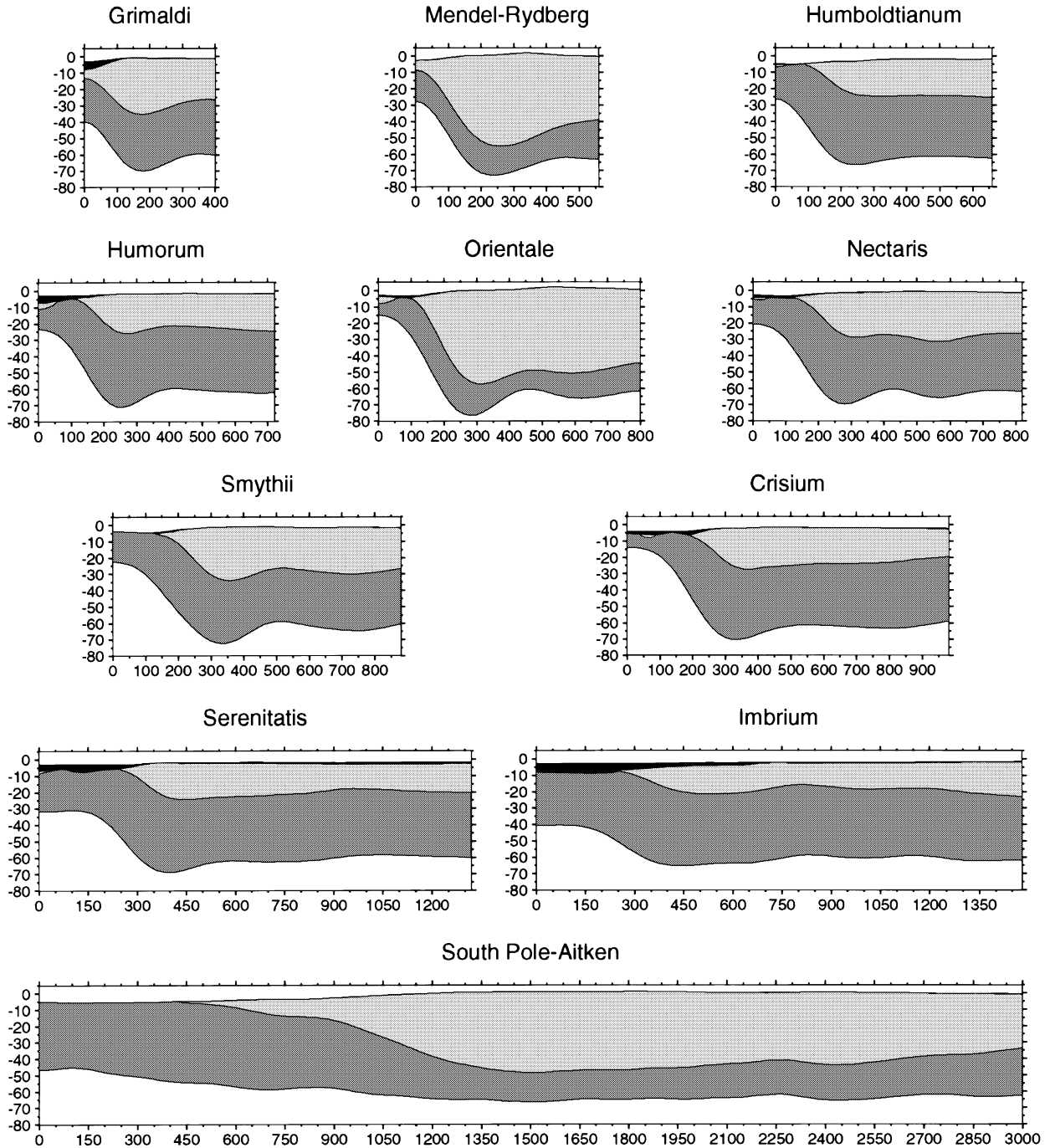


FIG. 1. Azimuthally averaged crustal thickness profiles. Axes are in kilometers with five-times vertical exaggeration, and all plots possess the same scale. With the exception of SPA, all plots are from the basin center out to four excavation cavity radii. Black represents mare fill, light gray is anorthositic upper crust, and dark gray is noritic lower crust.

If slumping was important and we were able to restore these deposits to their original position, our reconstructed excavation cavity diameters would be slightly smaller and the excavation depths larger than those reported here.

There are other modification processes that could affect our reconstructed excavation cavities, but these would probably be

of even lesser importance than rim slumping. For instance, ejecta deposited within the excavation cavity would bias our excavation depths to smaller values. For a low-gravity planet lacking an atmosphere, however, the amount of fallback ejecta is likely to be insignificant (Settle 1980). Additionally, target material is permanently displaced downward and outward by the excavation

TABLE I
Reconstructed Excavation Cavity Measurements

Basin	“Main rim” diameter (km) ^a	D_{ex} (km) ^b	h_{ex} (km) ^b	Volume (10^6 km^3)	Mass (10^9 kg)
South Pole–Aitken	2500	2099 ± 128	17.6 ± 2.8	29.6 ± 8.3	83.0 ± 23.1
Imbrium	1160	744 ± 37	29.6 ± 3.4	6.34 ± 1.36	17.9 ± 3.9
Serenitatis	920	657 ± 28	37.3 ± 3.3	6.21 ± 1.08	17.9 ± 3.2
Crisium	740	487 ± 10	50.9 ± 4.0	4.64 ± 0.56	13.6 ± 1.7
Smythii	740	443 ± 10	40.1 ± 2.5	3.04 ± 0.33	$8.66 \pm .96$
Nectaris	860	414 ± 8	45.0 ± 4.6	2.97 ± 0.41	8.49 ± 1.21
Oriente	930	397 ± 10	51.6 ± 4.2	3.13 ± 0.41	8.77 ± 1.17
Humorum	425	358 ± 6	44.7 ± 3.1	2.20 ± 0.23	$6.32 \pm .67$
Humboldtianum	650	331 ± 21	37.7 ± 6.2	1.59 ± 0.47	4.53 ± 1.36
Mendel–Rydberg	420	281 ± 21	36.4 ± 3.1	1.12 ± 0.26	$3.12 \pm .72$
Grimaldi	440	198 ± 11	25.5 ± 1.8	$0.389 \pm .069$	$1.09 \pm .19$

^a Taken from Spudis (1993).

^b The diameter of the excavation cavity, D_{ex} , is equivalent to the diameter of the transient crater. h_{ex} is the depth of excavation.

flow field (e.g., Melosh 1989). This would cause the initial transient cavity to be slightly larger than the excavation cavity and is responsible for structural uplift of the crater rim. If small-scale experiments (e.g., Stöffler *et al.* 1975) can be scaled up to basin-sized impacts, this effect should only be of minor importance in modifying our reconstructed excavation cavities.

One other topic that should be considered in the following analyses is the actual shape of the excavation cavity. Though the gravity modeling suggests that the excavation cavity is roughly parabolic (see Fig. 2), this shape may be a byproduct of the modeling procedures and low spatial resolution of the lunar gravity field. The results from the gravity modeling should give an accurate representation of the mass deficit associated with the excavation cavity. Additionally, the diameter of the excavation cavity should be reliable since the diameters of multiring basins greatly exceed the spatial resolution of the gravity field. Though the internal structure of the excavation cavity may be smoothed in our modeling, the maximum depth of excavation should nonetheless be good to first order.

Because there are a large number of multiring basins in various states of degradation and with variable degrees of gravity coverage, we have limited our study to a small subset of basins that are likely to be unmodified and representative of initial basin structure. Due to limitations in the knowledge of the lunar gravity field, we have considered only basins that have direct gravity coverage (i.e., the nearside basins; Lemoine *et al.* 1997) and basins that have diameters greater than 365 km (the approximate resolution of the crustal thickness models). Additionally, basins that were as old or older than Tranquillitatis (see Wilhelms 1984) were dismissed from further study due to their highly degraded state. As testimony to their degraded morphology, these basins show little or no uplift along the Moho in our models (see also Bratt *et al.* 1985 for an elaboration of this observation).

These selection criteria leave 10 basins that are likely not to have been significantly modified since their formation (e.g., via

viscous relaxation), and that also have their crustal structure adequately resolved in the adopted gravity model: Imbrium, Serenitatis, Crisium, Smythii, Nectaris, Oriente, Humorum, Humboldtianum, Mendel–Rydberg, and Grimaldi. In addition to these basins, where relevant, we also consider SPA, for even though there is no direct gravity coverage over this basin, the low degree gravity field is fairly well constrained over the backside of the Moon (Lemoine *et al.* 1997). Since SPA is the largest recognizable basin on the Moon (diameter ≈ 2500 km), high-degree gravity data is not crucial in assessing its general crustal structure.

Figure 2 shows plots of our reconstructed excavation cavities for the above basins. Depths (h_{ex}) and diameters (D_{ex}) of the excavation cavity were determined by fitting the profiles to a parabola and are given in Table I. Additionally, the volume of the excavation cavity and the mass of material excavated are also given in this table. Errors for these quantities were estimated using the uncertainty in the gravity field associated with each basin as well as the uncertainty in the depth used for the preimpact position of the Moho for each basin.

3. RESULTS

In this section we discuss the implications that our measured excavation cavity dimensions have for the multiring basin cratering process. First, depth/diameter ratios are compared with those of smaller craters, and the significance that these results hold for proportional and nonproportional scaling laws are discussed. Second, assuming that the annulus of thickened crust surrounding these basins represents ejecta, we compare the near-rim ejecta thicknesses with experimental scaling results. Third, using the structure of the terrestrial Chicxulub basin as an analog, we discuss the significance of our measured excavation cavity diameters in the context of the observed ring structure of lunar basins. We end with a discussion of the isostatic state of these

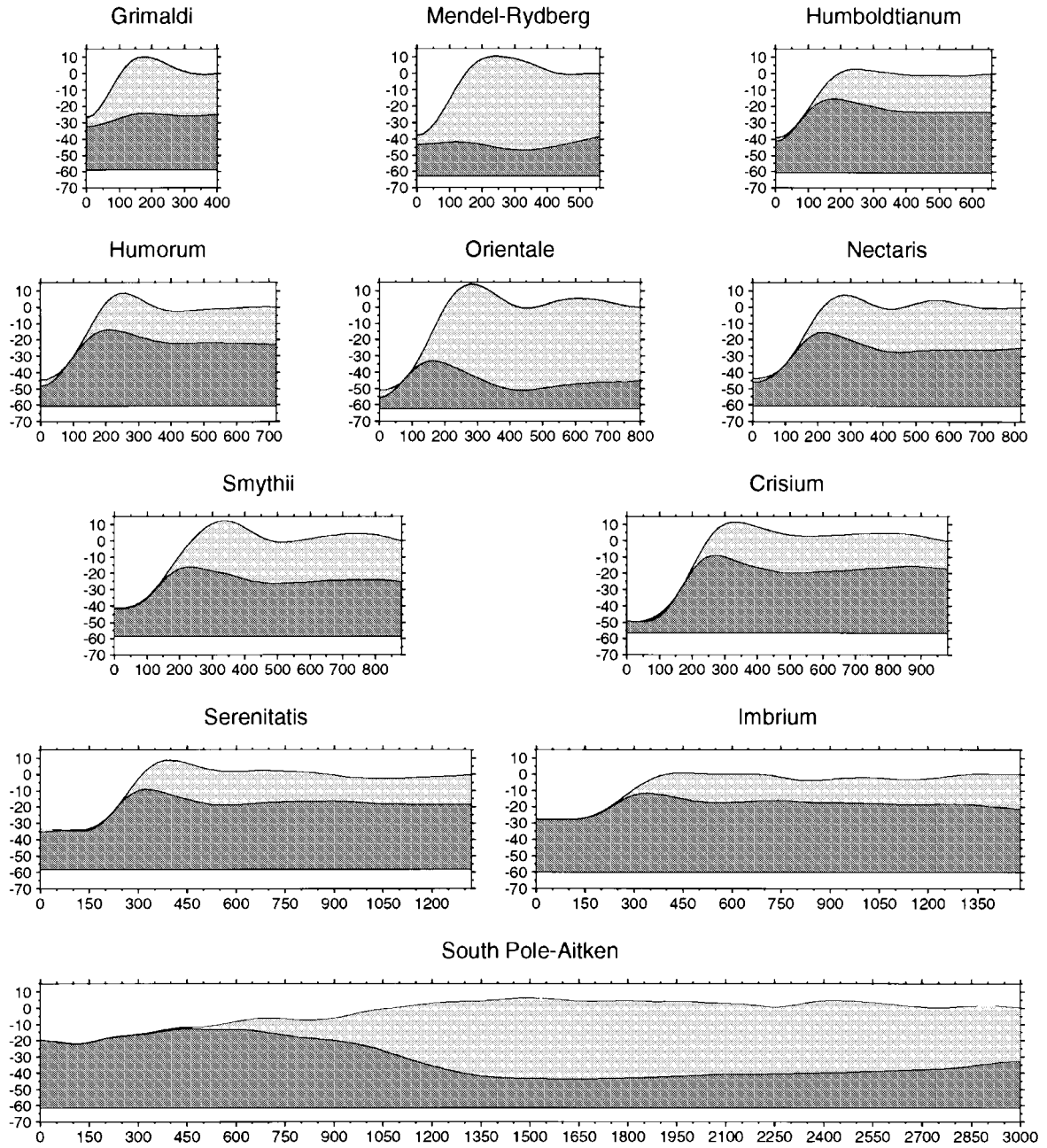


FIG. 2. Azimuthally averaged profiles through the reconstructed excavation cavities. Axes are in kilometers with five-times vertical exaggeration, and all plots possess the same scale. Preimpact Moho depth is taken at four excavation cavity radii. Light gray represents anorthositic upper crust, and dark gray is noritic lower crust.

basins, and what this implies for the time scale of floor uplift and postimpact viscous relaxation.

3.1. Depth/Diameter Ratios

One of the most important quantities in terms of understanding the consequences of large impacts is the depth/diameter ratio of the excavation cavity. Theoretical considerations such as Maxwell's Z-model, hypervelocity and explosion cratering

experiments, computation simulations, and empirical evidence from small terrestrial and lunar craters all suggest that the depth/diameter ratio is approximately 0.1 for craters ranging in size from centimeters up to a few tens of kilometers in diameter (Croft 1980, O'Keefe and Ahrens 1993). This scale-invariance of the excavation cavity over several decades in size is a phenomenon termed proportional scaling. Though there is some theoretical evidence that nonproportional scaling may be of increasing importance for larger craters (see Schultz 1988), most

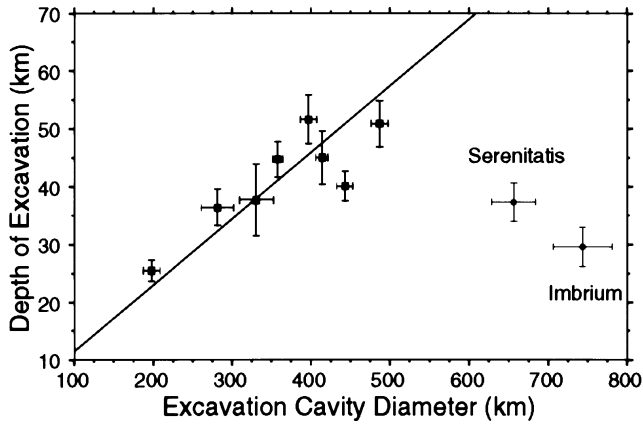


FIG. 3. Depth versus diameter of the reconstructed excavation cavity. Best fit line of the eight smallest basins is $h_{ex} = (0.115 \pm 0.005)D_{ex}$.

recent investigations have assumed that proportional scaling of the excavation cavity is valid for the largest lunar basins (e.g., Spudis 1993).

In Fig. 3 we plot the depth versus the diameter of our reconstructed excavation cavities (excluding SPA). It is seen that with the exception of the two largest basins (Serenitatis and Imbrium), the depth and diameter are linearly related. Furthermore, if these basins are fit to a straight line that includes the origin, the depth/diameter ratio of these basins is found to be 0.115 ± 0.005 . This value is consistent with that of craters orders of magnitude smaller in size, suggesting that proportional scaling is valid for all but possibly the very largest impact structures on the Moon. Given the assumptions that went into the gravity modeling and excavation cavity reconstruction, it is somewhat surprising that there is such little scatter about this relationship for the eight smallest basins in our study.

Figure 4 illustrates the dependence of the depth/diameter ratio as a function of excavation cavity diameter (here plotted in log-log space and including SPA). As was illustrated in Fig. 3,

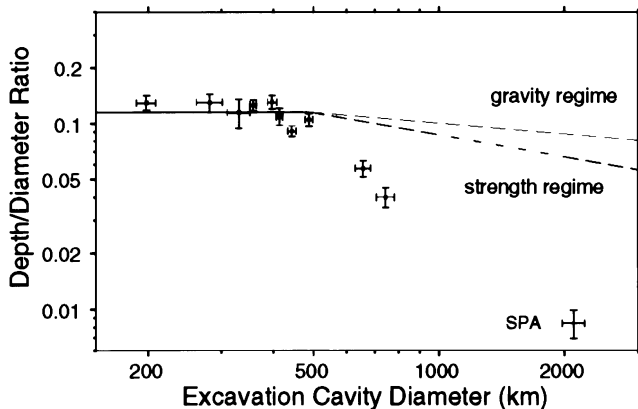


FIG. 4. Depth/diameter ratios of the excavation cavity plotted as a function of diameter of the excavation cavity. Also shown are the predictions of the nonproportional scaling theory of Schultz (1988) in both the strength- and gravity-scaling regimes.

depth/diameter ratios are constant up to a diameter of about 500 km (corresponding to Crisium basin). For craters larger than this (Serenitatis, Imbrium, and SPA), the depth/diameter ratios become progressively smaller. Due to the small sample of large craters, however, it is impossible to judge whether the three largest basins define a real linear trend or not.

Taken at face value, these results imply that the excavation cavity obeys proportional scaling up to a threshold diameter of about 500 km, beyond which the depth/diameter ratios decrease dramatically. Though this may be an accurate representation of the cratering process, it is also possible that this apparent shallowing of the excavation cavity with increasing size is an artifact of assumptions embedded in our crustal thickness model, or the process by which the excavation cavity was reconstructed.

We believe that our crustal thickness model is reliable over the Imbrium and Serenitatis basins, and that their departure from the trend of smaller basins reflects some physical process. As a test of the robustness of our results to our assumed dual-layered crustal structure, we have reconstructed the excavation cavities using the traditional single-layer model as presented in Wieczorek and Phillips (1998). The depth/diameter ratios for the eight smallest basins in this case were found to be 0.100 ± 0.009 ; only slightly smaller than the result obtained from the dual-layered model. The reconstructed excavation cavity for Imbrium and Serenitatis also did not differ significantly from that obtained from the dual-layered model. We additionally tested the robustness of our results for Imbrium and Serenitatis on our assumed mare thickness model. As an extreme scenario, we recomputed the dual-layered crustal thickness maps assuming that there was no mare fill within these two basins. Due to the similarity in density contrast at the Moho and between the mare and upper crust, removing the mare's gravitational contribution over these basins had little effect on the geometry of the reconstructed excavation cavity. Another possibility is that our neglect of a possibly large differentiated melt sheet could have biased our results for the largest basins. Since our results appear to be insensitive to the type of crustal thickness model that is employed, it is probable that differentiation of a melt sheet would not have a significant effect on our reconstructed excavation cavity geometries. The impact melt within the excavation cavity may redistribute itself within the crater, but the volume of excavated material would, nonetheless, remain unchanged.

Our inclusion of SPA in this discussion could also be criticized since there is no direct gravity coverage over this farside basin, and the ancient age of this basin could have led to significant postimpact viscous relaxation. Nonetheless, we believe that our results for SPA are consistent with the remote sensing data for this basin. Although there is some debate among the remote sensing community as to whether the regolith of this basin contains any material excavated from the mantle (Pieters *et al.* 1997, Lucey *et al.* 1998), it is very clear from the Clementine iron concentration maps (Lucey *et al.* 1995) that the highlands surrounding this basin are extremely iron poor. In fact, if the thickened crust north of this basin represents ejecta from a possibly oblique

impact (Zuber *et al.* 1994), the iron concentration of this putative SPA ejecta is among the lowest anywhere on the Moon (≈ 3 FeO wt%). If proportional scaling was valid for this basin, we would have expected the SPA event to have excavated into the lunar mantle. About half of the ejecta would have had an origin in the mantle (≈ 11 – 20 FeO wt%; see Lucey *et al.* 1998), about a quarter from the noritic lower crust (≈ 8 FeO wt%), and an additional quarter from the upper anorthositic crust (≈ 3 FeO wt%). If our results for SPA were in error and proportional scaling was valid for this basin, we would have expected the FeO concentration of the ejecta from this basin to be well over 8 wt% if all the ejected material was homogeneously mixed. Since this prediction is inconsistent with the remote sensing data, we are confident that the excavation cavity of SPA was indeed significantly shallower than proportional-scaling laws would predict.

Assuming that our crustal thickness model is accurate for the basins in this study, there are three classes of explanations that could be used to explain the small depth/diameter ratios for the Serenitatis, Imbrium, and SPA basins: (1) nonproportional scaling is a natural consequence of the cratering process for large basins; (2) the small depth/diameter ratios for these basins represent special impact conditions; (3) the depth/diameter ratios of these basins reflect modification processes that occurred during or after the impact event. Without advocating any specific process, we discuss the implications of each of these suggestions below.

Nonproportional scaling. Perhaps the simplest explanation for the apparent shallowing of the excavation cavity of Serenitatis, Imbrium, and SPA is that this effect is a natural consequence of the cratering process for large basins. There is some theoretical support for this interpretation. For instance, Schultz (1988) presented a theory of nonproportional scaling that was consistent with the available experimental data. He showed that the depth/diameter ratio of impact craters should be constant below a critical excavation cavity diameter, and above this critical value, the depth/diameter ratio should decrease with increasing crater size. This phenomenon was shown to be directly related to the time that it takes the impactor to penetrate and transfer energy to the target. When the time of energy transfer to the target was small, the resulting excavation flow field could be approximated by a point source origin. Under these conditions, the cratering process was self-similar, and proportional scaling was valid. When the time of energy transfer to the target became sufficiently long, however, a point source origin of the excavation flow was no longer a valid assumption.

In Fig. 4, we plot the predictions of Schultz's (1988) nonproportional scaling theory in both the gravity- and strength-scaling regimes. Though he originally suggested that the transition between proportional and nonproportional scaling should occur at a diameter of about 10 km on the Moon, we arbitrarily set the transition to the diameter of Crisium's excavation cavity. As is easily seen, this theory in its present form cannot explain the

magnitude of shallowing that is observed for the Serenitatis, Imbrium, and SPA excavation cavities.

Special impact conditions. Another possible explanation for the small apparent depth/diameter ratios of these basins is that they are due to special impact conditions. For instance, it is well known that the angle of impact, as well as the velocity and density of the impactor, can affect both the shape of the excavation cavity and the volume of material that is excavated (Gault and Wedekind 1978, Schultz and Gault 1990, Schultz and Anderson 1996). This process primarily reflects delayed coupling of the upper portion of the impactor with the target (a process referred to as ricochet). As an example, Schultz (1997) proposed that the apparent shallow excavation of the SPA impact event, as well as the inferred thick downrange ejecta deposits, could be explained by a large (radius ≈ 1000 km), low-velocity (5 km/s), low-density (< 2 gm/cm³), and low-angle ($< 30^\circ$) impact event. In this proposal, a large portion of the original impactor is decoupled (decapitated) from the cratering process, and fails to impact the downrange surface.

Invoking special impact conditions for only the three largest basins, however, reeks of special pleading. If the impact conditions were controlled by a random process, we should have expected there to have been more scatter in the depth/diameter ratios of the smaller basins. This, however, is not the case: the eight smallest basins in our study all lie along a well-defined linear trend, and the three largest basins fall distinctly below this trend. As a possible explanation of this observation, we suggest that the effects of impact angle on crater morphology may become increasingly important as the size of the impactor increases. This could reflect either the effects of planetary curvature on the cratering process or possibly the increased importance of impactor ricochet on the final crater morphology of large basins.

Basin modification. Our last possible explanation for the small depth/diameter ratios of the Serenitatis, Imbrium, and SPA excavation cavities is that these basins formed in accordance with proportional scaling, but post- or concurrent-impact modification effects shallowed the initial excavation cavity. One possibility is that these basins viscously relaxed faster than similarly aged basins. Though larger basins would be expected to relax faster than smaller basins, this size dependence should not have a significant measurable affect on the nearside basins in our study since they are all of the same order of magnitude in size. Additionally, if size were the only factor that controlled the relaxation of basin structure, one would expect a more gradual reduction in the excavation cavity depth with increasing basin size than is observed in Fig. 3. Viscous relaxation of these basins, however, could have been enhanced if the crust beneath these basins was hotter than more typical regions of the Moon.

Another possibility is that extensive volcanism could have filled in the excavation cavity. As was stated in Section 2, though, our models are insensitive to the thickness of *mare* basalt ($\rho_m = 3.3$ g/cm³) within these basins. If the excavation cavity, however,

was filled in by lavas that had a density similar to that of the lower crust, our crustal thickness models would not be able to distinguish between these two compositions; the lavas (as far as gravity was concerned) would “look” like the lower crust. If we were to remove these low-density, postimpact lavas, it would be possible to increase the depth of our reconstructed excavation cavity.

If the apparent shallow excavation cavities of these basins are to be (partially) explained by postimpact lava flooding, this places strict constraints on the composition of this putative lava. The most common extrusive rocks on the Moon, the mare basalts, are relatively iron rich (≈ 20 FeO wt%) and much denser than the lower crust ($\rho_m \approx 3.3\text{--}3.4$, $\rho_l \approx 3.1$ gm/cm³). The only type of lunar basalt that has a density similar to that of the lower crust is KREEP basalt. Since KREEP basalts have been found at the edge of the Imbrium and Serenitatis basins (Apollo 15 and 17, respectively), voluminous KREEP-volcanism occurring in the Serenitatis and Imbrium basins is a distinct possibility.

We speculate that the nearside high-Th geochemical province of Haskin (1998) is directly related to the origin and distribution of KREEP basalts and the anomalous structure of the Imbrium and Serenitatis basins. The confines of this province (as defined by the Lunar Prospector gamma-ray data; Lawrence *et al.* 1998) contain most of Oceanus Procellarum, Imbrium, and Serenitatis. If this geochemical province contained magma chambers having the composition of KREEP basalt, an impact into this region could have tapped this magma, giving rise to voluminous KREEP-volcanism. Additionally, since KREEP basalts are highly enriched in heat-producing elements (they are about 20 times higher than typical feldspathic crust) this province would have been significantly hotter than more typical regions of the Moon. The higher temperatures in this province would have accelerated the viscous relaxation of basins that formed there.

Since the Th concentration of the SPA basin is barely enhanced over that of typical highlands crust, the crust beneath this basin was probably not any hotter than average. Though SPA's basin structure may have been modified by viscous relaxation due to its great size, the composition of the putative ejecta deposits surrounding this basin (see Section 2) seems to argue that SPA did not excavate deeply into the mantle. The premise of proportional scaling is thus likely to be invalid for this basin.

3.2. Near-Rim Ejecta Thicknesses

Surrounding each of the basins in this study is a low-gravity moat in the Bouguer gravity field. When one assumes constant density crustal layers in the gravity modeling, this observation translates directly into an annulus of thickened crust that surrounds each of these basins (see also Neumann *et al.* 1996). Though it is possible that a low-density brecciated ejecta deposit could also account for this gravity signature (Phillips and Dvorak 1981), we use the working hypothesis that the thickened crust in our model is real, and that it reflects near-rim basin ejecta deposits. As we will show, our measurements of near-rim ejecta thicknesses using this hypothesis are consistent with empirical scaling laws.

Though our dual-layered crustal model shows that both the upper and lower crust are thickened outside of the basin (see Fig. 2), due to the nonuniqueness of the gravity modeling we only address the excess thickness of the entire crust in this study. It is possible that a portion of these thickened crustal deposits could be a consequence of the excavation flow field that translates material downward and outward during the excavation stage of the cratering process (a process that results in structural uplift of the crater rim for smaller craters). Experimental hypervelocity impacts, however, suggest that this phenomenon is only important for distances less than ≈ 1.2 transient cavity radii (Stöffler *et al.* 1975). Since the bulk of the thickened crust for lunar basins occurs at distances greater than this, this process can safely be ignored.

In order to determine the ejecta thickness profiles for each basin, we have subtracted an average “preimpact” crustal thickness from the profiles of Fig. 1. For this section, the preimpact crustal thickness was taken as the minimum average crustal thickness between two and four excavation cavity radii. This approach assumes implicitly that crustal thicknesses greater than this “minimum” value represent basin ejecta deposits. Figure 5 shows our averaged results for the eight basins that are consistent with proportional scaling. Following Housen *et al.* (1983), both the ejecta thickness and radial distance have been normalized by the modeled excavation cavity radius of each basin. Also shown are the average ejecta scaling results of Housen *et al.* (1983) derived from explosion and impact centrifuge experiments. As is easily seen, within errors, our empirical results for lunar basins are consistent with the centrifuge scaling results. The ejecta thicknesses of Imbrium and Serenitatis (not shown), however, were found to be significantly thinner than predicted by the above relation; a fact consistent with nonproportional scaling or postimpact modification of these two basins.

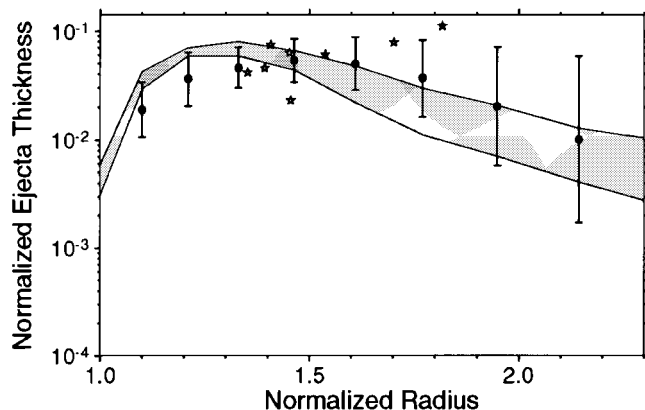


FIG. 5. Ejecta thickness plotted as a function of distance from the basin center. Both quantities are normalized to the modeled excavation cavity radius. Data points with error bars represent the average of the eight smallest basins in our study, stars represent the location of the maximum ejecta thickness for each of these basins, and the shaded region is from the experimentally determined relationships of Housen *et al.* (1983).

This result shows that with the exception of the three largest basins on the Moon, the measured near-rim ejecta thicknesses are consistent with empirical proportional scaling laws. Though we have not tested this hypothesis, this suggests that far-rim ejecta thicknesses can also be described by ejecta scaling laws that invoke proportional scaling (Housen *et al.* 1983). One surprising consequence of this result is that the near-rim ejecta deposits of lunar basins are extremely thick. For instance, the average maximum normalized ejecta thickness is found to be ≈ 0.062 and to occur at a normalized distance of ≈ 1.51 . For Grimaldi and Crisium, this corresponds to a maximum ejecta thickness of approximately 6 and 15 km, respectively.

3.3. The Excavation Cavity, Main Crater Rim, and Basin Rings

There is no ambiguity in identifying a “main crater rim” and assigning a numerical value to its diameter for complex craters. The main rim is clearly marked by a roughly circular escarpment with a zone of interior slump blocks and terraces. Being that the main rim of complex craters results from the collapse and subsequent enlargement of the transient crater, its diameter is not directly applicable for use in scaling relations that are usually dependent upon the diameter of the original transient cavity. The transient cavity diameter of small craters, however, can often be reconstructed by restoring slumped material to its original position (Malin and Dzurisin 1978, Settle and Head 1979). Even if the transient cavity could not be adequately restored, the present main rim diameter would give an upper bound to the transient cavity size.

Multiring basins, however, are unique impact features in that they do not appear to possess a main rim that is morphologically analogous to the rims of smaller complex craters. Specifically, they lack the terrace zone that is so distinctive of complex craters. Despite this fact, it is quite common to find one basin ring identified in the literature as being the “main rim.” The rationale behind this is most overtly stated in Pike and Spudis (1987): “One ring, rather more prominent and/or continuous than the others, is equivalent to the rim crest of nonringed craters ... The topographically ‘strongest’ ring is the ‘main rim’ or ‘topographic rim’ ...” If this assumption was wrong, it is conceivable that estimates of the transient cavity size based upon this premise could be drastically misrepresentative.

Fortunately, most quantitative studies of lunar multiring basins have been concerned with the archetypical Orientale basin, in which the size of the transient cavity *has* been constrained by photogeological studies. Based on the recognition of pre-Orientale impact features found inside of this basin, the transient cavity can be no larger than the Outer Rook ring, and most likely no larger than the Inner Rook ring (see Spudis *et al.* 1984). This photogeological result is consistent with our determination of the transient cavity ($D_{tc} = 397$ km) lying between the Inner Rook ring ($D = 480$ km) and the innermost shelf ring ($D = 320$ km).

In Fig. 6, we plot the diameter of all the recognizable rings for each of the basins in this study (ring diameters taken from Spudis

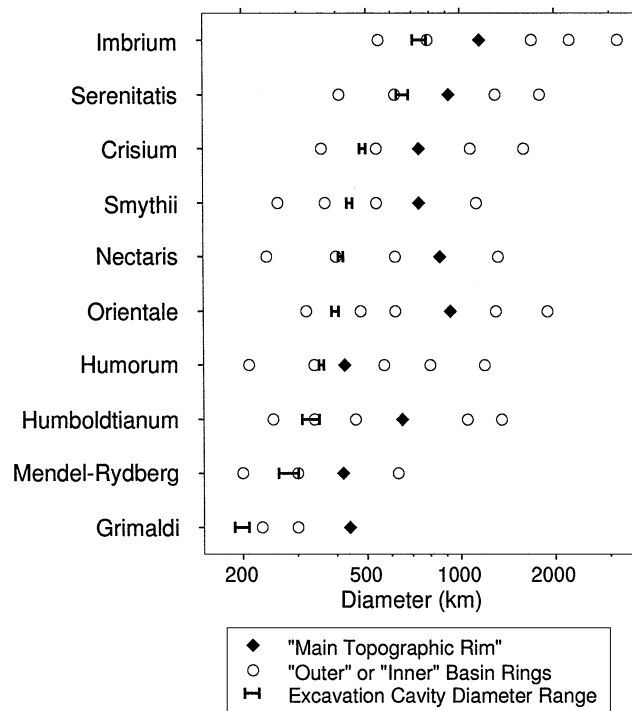


FIG. 6. Plot of recognizable basin rings and modeled excavation cavity diameter for each basin. Diameter of basin rings as given in Spudis (1993).

1993). Also plotted are our estimates for the range in size of the excavation cavity diameter for each basin. As is seen, the excavation cavity always lies within what has typically been called the “main topographic rim.” From these results, however, there is no basis for postulating a simple linear relationship between these two quantities. Additionally, there is no clear association with our estimated excavation cavity size and a specific ring structure. If one had to estimate the size of the excavation cavity on ring diameters alone, however, the second innermost basin ring would best approximate the excavation cavity for the basins in this study.

Recent seismic surveys of the Chicxulub impact structure have shed some light on the structural origin of basin rings and their relationship to the main crater rim of complex craters (Morgan *et al.* 1997). These studies show that the Chicxulub impact basin is a true multiring basin, possessing an interior peak ring (80-km diameter) and at least two additional ring structures exterior to this inner ring (130- and 195-km diameters). Most significantly, the ring structure at 130-km diameter was found to have an associated terrace zone, suggesting that this ring is analogous to the main rim of complex craters. Furthermore, based on the recognition of preimpact stratigraphy in the seismic profiles, the transient cavity diameter was reconstructed and was found to have a value of approximately 100 km, which is intermediate in size between the peak ring and main rim. If the structures found within the Chicxulub impact basin are analogous to the large multiring basins on the Moon, this suggests that the main rim of lunar basins should be the ring structure just larger than the

original transient cavity. As is evident in Fig. 6, the ring structure that is just larger than the transient cavity corresponds to what has been mapped as the main topographic rim for only a few basins. This suggests that what has been called the main topographic rim is not always analogous to the main rim of complex craters.

The seismic evidence from Chicxulub seems to suggest that when multiring basins form, they originally possess a terraced main rim. If this is also the case for larger basins, then why do we not observe these structures on the Moon? Melosh (1982) has suggested that the process of acoustic fluidization may have destroyed these features during collapse of the transient cavity. Though this process may play a significant role for the largest basins, it apparently was not effective at removing the signature of the main rim from the Chicxulub basin. We suggest a simpler explanation that is based upon the ejecta scaling laws presented in the previous section. These scaling laws suggest that ejecta deposits are extremely thick outside of the excavation cavity. For Grimaldi and Crisium, these deposits should reach up to a maximum thickness of 6 and 15 km, respectively. Even at a distance of one excavation cavity radii away from the rim, the ejecta deposits for these craters should be about 1 and 3 km thick, respectively. We propose that the main rims and their associated terrace zones for lunar basins have not been identified because they have been covered and obscured from view by thick ejecta deposits.

3.4. The Isostatic State of Lunar Basins

During the Apollo era it was recognized that the centers of many lunar basins possessed positive free-air gravity anomalies ("mascons"; Muller and Sjogren 1968). The fact that these "mascon" basins also contained thick mare basalt flows implied that the basalt flows contributed significantly to the gravity anomalies. Since a basin in isostatic equilibrium would be expected to exhibit a negative free-air gravity anomaly, it has been widely accepted that the mare flows are superisostatic and that they are supported by the strength of the lunar lithosphere (e.g., Solomon and Head 1980). Though the mascon basins are not presently in a state of isostatic equilibrium, it was common to assume that when the basins formed that they were isostatic (e.g., Thurber and Solomon 1978, Bratt *et al.* 1985). Only when mare volcanism commenced hundreds of millions of years later, was the lithosphere assumed to have the strength to support this superisostatic basalt load.

New gravity data from the Clementine and Lunar Prospector mission cast doubt on the assumption that the lunar basins were in an isostatic state shortly after they formed. Neumann *et al.* (1996, 1998) showed that many of the nearside basins are out of equilibrium, and that some may have been superisostatic before mare flooding occurred. Additionally, improved gravity data from the Lunar Prospector mission (Konopliv *et al.* 1998) has shown that several new "mascon" basins appear to lack evidence for associated mare volcanism (Schiller-Zucchi on the nearside; Hertzprung, Coulomb-Sarton, and Freundlich-Sharonov

on the farside). This suggests that the origin of "mascons" is not necessarily solely related to volcanic infilling as has commonly been assumed.

The simplest explanation for having a positive gravity anomaly in the center of a basin that lacks mare fill is that after the impact occurred, the floor of the basin rebounded above its isostatic position and was subsequently "frozen" in place. We agree with Neumann *et al.* (1996) that this could occur if the crust was acoustically fluidized during the impact event (Melosh 1979, 1982). Due to the Bingham rheology of an acoustically fluidized material, after the seismic stresses in the basin were reduced below a critical value, the material would again behave as a solid. If the lithosphere possessed sufficient strength at this time in lunar history then the superisostatic uplift of the basin floor would be maintained. This model suggests that the basin floor and underlying crust were uplifted to their present positions on the time scale of the basin-forming event. The process of uplifting the lunar Moho beneath the basins is thus not a slow isostatic process controlled by viscous flow, but is rather instantaneous in a geologic context.

We next show that many of the basins in our study, including those with mare fill, support the concept that superisostatic uplift of the basin floor has occurred during the basin forming process. In Fig. 7 we plot the excess vertical load that is being supported beneath the center of each basin as a function of transient cavity diameter. The vertical load is assumed here to be solely due to relief along the surface, the Moho, and the intracrustal interface. The magnitude of this load is indicative of the stresses that exist in the crust and underlying mantle. Since we are concerned with the premare isostatic state of these basins, the excess load in the basin center due to mare basalts were not included. As is easily seen, with the exceptions of Grimaldi and Imbrium, all of the basins are supporting an excess crustal load. This suggests that the basin floor was uplifted beyond its isostatic position and that the stresses due to this load have not yet decayed by viscous

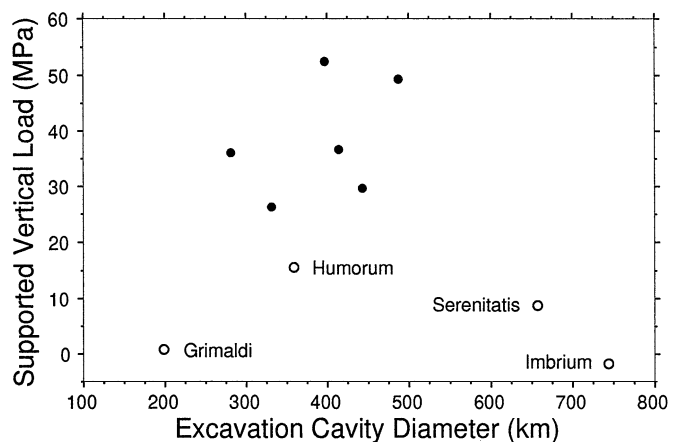


FIG. 7. Plot illustrating the isostatic state of the basins in this study. The vertical axis plots the excess vertical load (excluding mare fill) being supported at the basin's center. Unfilled circles represent basins that are in, or close to, the nearside "High-Th Oval" as revealed by Lunar Prospector.

relaxation. The total vertical load within these basins is not excessive (<53 MPa; <63 MPa if the basalt fill is included) and it is quite plausible that these stresses could have been supported throughout lunar history.

The form of Fig. 7 suggests two possible explanations for the magnitude of the supported load as a function of basin size. First, if Serenitatis and Imbrium are ignored, it could be argued that there is a linear relationship between the supported load beneath the basin and basin size. Such a situation is conceivable. For instance, it is possible that as one goes to larger crater sizes, the importance of acoustic fluidization becomes increasingly important in terms of the amount of uplift that occurs on the Moho. The fact that smaller craters (~ 100 km diameter) are largely uncompensated (Phillips *et al.* 1978) indicates that little floor uplift has occurred for these craters, consistent with this hypothesis.

Alternatively, it is possible that the magnitude of the load that is currently supported beneath these basins is not dependent on the basin's size, but is rather dependent on where the basin formed. If a basin formed in a region of the Moon where the crust was hotter than average, the stresses in this basin would viscously relax faster than basins that formed in a more typical region of the Moon. The Lunar Prospector gamma-ray experiment (Lawrence *et al.* 1998) suggests that such a "hot" province does indeed exist on the nearside of the Moon. This anomalous geochemical province (dubbed the "High-Th Oval" by Haskin 1998) is rich in thorium, potassium, and presumably other incompatible elements. The high concentrations of heat-producing elements in this province would have led to higher temperatures in the crust at the time when lunar basins were forming. Of all the basins in this study, Imbrium and Serenitatis formed within this province, and Grimaldi and Humorum formed on the edge of this province. These four basins are indicated by open circles in Fig. 7, and it is seen that of all the basins, these were the closest to achieving isostasy before they were filled with mare basalts. The near isostatic state of these basins prior to the onset of mare volcanism supports the view that the "High-Th Oval" is indeed rich in incompatible elements, and that the crust in this region was hotter than average. As was suggested earlier, it is possible that a high degree of viscous relaxation in this "hot" province could be the cause of the apparent shallow excavation depths of Imbrium and Serenitatis.

4. SUMMARY AND CONCLUSIONS

Due to tectonic and erosional processes, the Earth currently lacks impact craters the size of the Moon's Orientale and Imbrium basins. Hence, the consequences of basin-sized impacts on the terrestrial planets have generally been extrapolated from small-scale experiments, small terrestrial craters, and computational simulations. Since the Moon's surface dates back billions of years and records much of its early impact bombardment, the Moon is an ideal place to study multiring basins and the cratering process.

Using a new dual-layered crustal thickness model for the Moon, we have modeled the geometry of the excavation cavity for some young multiring basins. With the exception of the three largest basins (Serenitatis, Imbrium, and SPA) we have shown that the basin-forming process obeys proportional scaling. Specifically, the size of the excavation cavity and the thickness of near-rim ejecta are both found to be scale-invariant from the smallest experimental impacts, up to craters hundreds of kilometers in diameter.

The observation that the thickness of near-rim ejecta is consistent with empirical scaling laws suggests a resolution to a long-standing issue in the study of multiring basins. Complex craters on the terrestrial planets all possess terraced crater rims, and recent seismic profiling of the Chicxulub basin suggests that this multiring basin also possesses a main terraced rim. Why is it that lunar multiring basins appear not to possess a terraced rim? We suggest that lunar multiring basins in fact *do* possess terraced rims, but that they have been obscured from view by ejecta deposits that exceed a few kilometers in thickness.

Our analysis also suggests that when basins form, their floors are uplifted above their isostatic position. "Mascons" are thus not solely due to uncompensated mare flows. As was suggested by Neumann *et al.* (1996), this is probably a result of material beneath the basin floor being acoustically fluidized during the impact event and subsequently being frozen into a nonisostatic configuration. This suggests that the time scale for forming this superisostatic crustal uplift is roughly the time scale of the basin forming process itself; i.e., floor uplift is instantaneous in a geologic context. Though these conclusions have been based on geophysical crustal thickness modeling of lunar basins, the Lunar Prospector mission has dramatically confirmed this result by identifying small mascon basins that possess no evidence of mare infilling.

Although most of the basins in this study are consistent with proportional scaling, the three largest basins considered (Serenitatis, Imbrium, and SPA) appear to have excavated shallower than would have been expected from these scaling laws. Due to the fact that the putative ejecta from SPA is extremely anorthositic, we are fairly confident that the apparent shallow depth of excavation of this basin is in fact real. However, the apparent shallow excavation depths of Imbrium and Serenitatis only suggest, but do not require, that proportional scaling is invalid at these large scales.

Though special impact conditions or nonproportional scaling could possibly explain the apparent shallow excavation depths of Imbrium and Serenitatis, the available evidence seems to suggest that these two basins impacted an anomalous region of the lunar crust. Global gamma-ray data from the Lunar Prospector mission show that the Imbrium and Procellarum region of the Moon is highly enriched in heat-producing elements (the high-Th Oval of Haskin 1998). Higher crustal temperatures in this region of the Moon could have affected the structure of basins that formed in, or close to, this province. The fact that the only basins in our study that are close to achieving isostatic equilibrium lie within,

or close to, this province suggests that this interpretation is not without merit.

We speculate that Imbrium and Serenitatis initially formed in accordance with proportional scaling laws but that these basins were subsequently affected by postimpact modification effects. The higher temperatures that were likely present in the Procellarum/Imbrium region of the Moon could have led to significant viscous relaxation of basin structure, or proximity to a KREEP-rich magma chamber could have resulted in KREEP basalt volcanism that filled in the excavation cavities of these basins. Since the Apollo 15 and 17 missions landed on the rims of these two basins, understanding the processes that formed these two basins is fundamental in interpreting the significance of the returned samples from these sites.

APPENDIX

The dual-layered crustal thickness model of Wieczorek and Phillips (1998) was recomputed using an improved gravity model from the Lunar Prospector mission (JGL75D, Konopliv *et al.* 1998). This new gravity model possesses more short-wavelength power than the previous Clementine model of Lemoine *et al.* (1997) and has improved resolution over the poles. In the modeling of Wieczorek and Phillips (1998), a filter was applied to the Bouguer correction in order to compensate for the “over-damped” nature of the Clementine gravity model. In recomputing the crustal thickness model, the magnitude of this filter was substantially reduced to

$$f_m = m/35 \quad \text{for } m > 35$$

$$f_m = 1 \quad \text{otherwise.}$$

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