The long wavelength topography of Beethoven and Tolstoj basins, Mercury

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[1] Topography derived from Mariner 10 stereo images is used to characterize the interior structure of two mercurian basins, Beethoven and Tolstoj. Beethoven and Tolstoj basins are shallow (~2.5 km and ~2 km deep, respectively) and relatively flat-floored. Beethoven basin has an interior topographic rise near the northwest margin. The topography of Beethoven and Tolstoj basins is similar to that of lunar mare-filled basins. Well-developed basin-concentric wrinkle ridges and arcuate graben associated with lunar mascons are absent in both Beethoven and Tolstoj basins. The lack of mascon tectonic features suggests that either 1) the mercurian basins have a relatively thin veneer of fill material, 2) Mercury's elastic lithosphere was too strong for significant lithospheric flexure and subsidence to occur, or 3) the basin fill material has little or no density contrast with the surrounding crust and thus exerts little net load on the mercurian lithosphere. **Citation:** André, S. L., T. R. Watters, and M. S. Robinson (2005), The long wavelength topography of Beethoven and Tolstoj basins, Mercury, *Geophys. Res. Lett.*, *32*, L21202, doi:10.1029/2005GL023627.

1. Introduction

[2] Impact basins represent fundamental structural features of the mercurian crust. *Spudis and Guest* [1988] compiled a comprehensive list of over 20 impact basins within the region imaged by Mariner 10. Until recently, there has been little topographic data available to characterize the structure of impact basins on Mercury. The three Mariner 10 encounters had similar illumination conditions, providing ideal lighting for stereo analysis [*Strom et al.*, 1975a]; however, very little stereo analysis was performed after the mission's completion. New camera positions and orientation data have allowed for an improved control network for Mercury [*Robinson et al.*, 1999].

[3] We examine the long wavelength topography of two impact basins on Mercury, Beethoven and Tolstoj, to investigate their overall structure. Our new topographic measurements represent the best data currently available for investigating basin structure on Mercury. Beethoven and Tolstoj are compared to the well-characterized lunar basins Serenitatis and Orientale. These lunar basins have different amounts of mare basalt fill, have associated mascons [*Neumann et al.*, 1996; *Konopliv et al.*, 1998], and are comparable in size and general morphology with Beethoven and Tolstoj basins.

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2. Methods

[4] New digital elevation models (DEMs) of mercurian topography were generated using automated stereo-matching software, Stereo Matching Tool Kit (SMTK) [*André et al.*, 2004]. After the best possible points from which to start the matching process are automatically determined (using an adaptive least-squares algorithm), all of the corresponding points of the stereo pair are matched using a combination of the adaptive least-squares algorithm and a sheet growth algorithm. A camera intersection model is used to determine the three-dimensional coordinates for all matched points, which are then used to create a DEM. Uncertainties in height are calculated based on the convergence shifts for each matched point.

3. Beethoven Basin

[5] Mariner 10 imaged Beethoven basin (20°S, 124°W, Figure 1) under high sun angles, hindering morphologic interpretations of features within the images [*Strom et al.*, 1975a]. However, previous studies conclude that Beethoven basin has a subdued rim (diameter 625 km) and no other observable rings [*Strom et al.*, 1975a; *Spudis and Prosser*, 1984; *Spudis and Guest*, 1988; *King and Scott*, 1990]. The floor of Beethoven basin was resurfaced with smooth plains material [*Spudis and Prosser*, 1984; *Spudis and Guest*, 1988; *King and Scott*, 1990] that may have buried interior basin rings [*Spudis and Guest*, 1988].

[6] Beethoven is shallow with a subdued rim; its highest point (4 km of relative relief) is at the southern edge and its average depth is ~2.5 km relative to rim height. The topographic profiles through Beethoven basin (Figure 1) indicate an interior trough (1 km deep) inside the northwestern basin rim. Interior to the margin, there is a broad topographic rise that appears in the DEM as an arcuate band across the northern region of the basin. The rise extends inwards for ~120 km, and the elevation again lowers at the center of the basin; the elevation of the rise is ~500 m above the center of the basin. It is difficult to determine if the rise is present throughout the basin interior due to a series of small impact craters (diameters 34 km, 50 km, 55 km, 155 km) that disrupt the southeastern portion of the basin floor and rim. We interpret the arcuate topographic rise to be an interior basin ring.

4. Tolstoj Basin

[7] Tolstoj Basin (16.5°S, 163.6°W) is an ancient and degraded multi-ring basin (Figure 2) partially flooded with

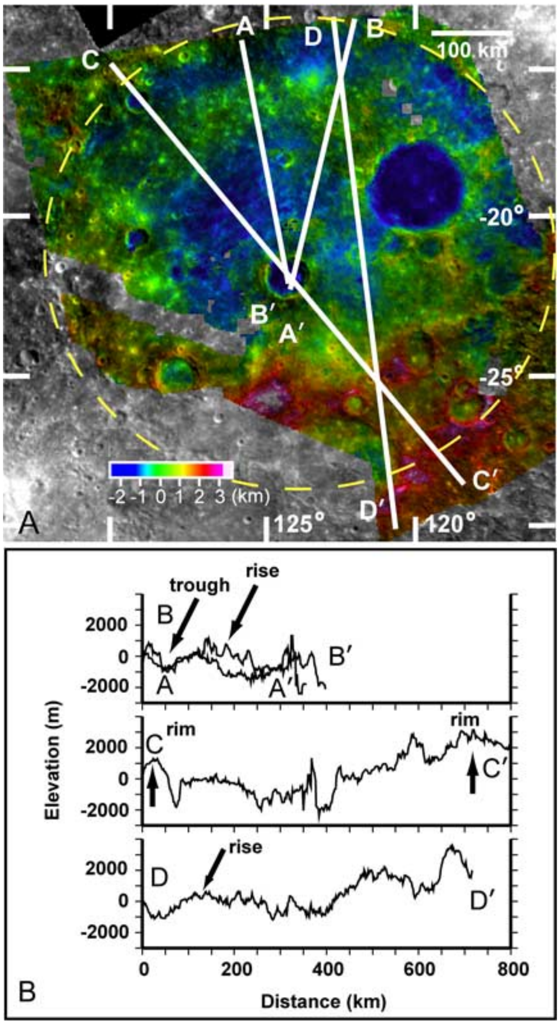

Figure 1. a) Digital elevation model of Beethoven basin overlaid on a Mariner 10 image mosaic. The Beethoven DEM was constructed from 15 stereo pairs, and the estimated relative height accuracy is ±300 m. The dashed circle indicates the subdued rim of the crater. Elevations are in km relative to the 2439 km radius of Mercury. b) Topographic profiles crossing Beethoven basin. The locations of profiles are shown in (a).

smooth plains material interpreted either to have formed as a result of the Caloris impact, or as post-Caloris volcanic flows [*Schaber and McCauley*, 1980]. Topographic profiles indicate that the average depth of Tolstoj is ~2 km from rim crest to basin floor (Figure 2). There is a 170 km diameter flat-floored depression within the center of the basin covered with smooth plains material. The deepest part of the basin is located along the northern margin of this central depression; it is ~400 m lower than the rest of the central depression; however, this topographic low at the northern margin may not be significant given the height accuracy of the regional DEM (~±500 km). The other margins of the central depression of the basin are of the same elevation.

[8] *Spudis and Guest* [1988] identified four rings, located at 260 km, 330 km, 510 km (basin rim), and 720 km, varying in continuity and prominence. In contrast, we identify two prominent rings (440 km and 640 km diameters) and a partial third ring (785 km diameter). Using the new topographic data, we did not detect the innermost ring described by *Spudis and Guest* [1988]. In addition, the long wavelength topography of Tolstoj indicates that most of the smooth plains unit that infills the basin is relatively featureless; there is no evidence of an interior ring as in the case of Beethoven. The location of our rings more closely concur with those of *Schaber and McCauley* [1980] who identified the partial southern margins of the two prominent rings (356 km and 510 km) and the partial southeastern ring (466 km).

5. Comparison With Lunar Basins

[9] Serenitatis basin (~600 km diameter) is shallow (~2 km relief), with a topographic high in the central region of the basin that is higher than the interior margins [i.e., *Watters and Konopliv*, 2001]. Gravity data for Serenitatis basin indicates that it, like the other nearside basins, is a lunar mascon [see *Konopliv et al.*, 1998]. Extensional and compressional tectonic features indicate subsidence of the

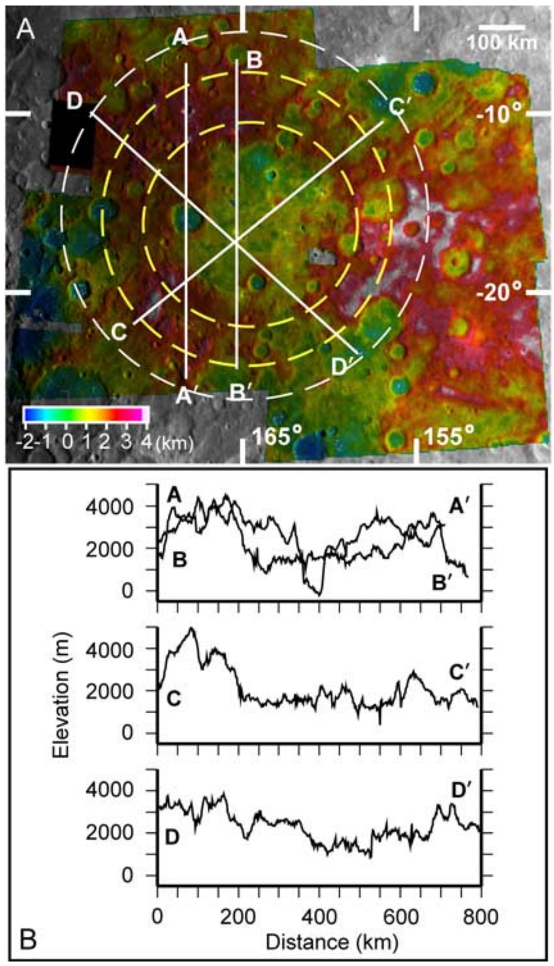

Figure 2. a) Digital elevation model of Tolstoj basin overlaid on a Mariner 10 image mosaic. The Tolstoj DEM was constructed from 13 stereo pairs and the estimated relative height accuracy is ±500 m. Both the Tolstoj and Beethoven DEMs are sampled at 2 km/pixel. The dashed circles indicate the locations of subdued (yellow) or possible (white) crater rings. Elevations are in km relative to the 2439 km radius of Mercury. b) Topographic profiles crossing Tolstoj basin. The locations of profiles are shown in (a).

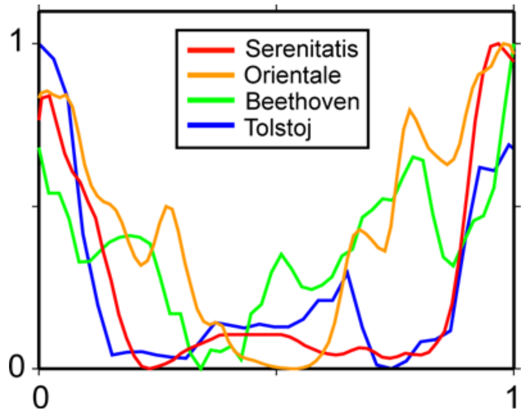

Figure 3. Normalized profiles of the four basins: Orientale (orange), Serenitatis (red), Tolstoj (blue), and Beethoven (green). Topographic profiles of Serenitatis and Orientale basins were obtained from a global lunar DEM generated from data collected from the Clementine laser ranging instrument [*Zuber et al.*, 1994; *Smith et al.*, 1997]. Profiles are normalized to the main diameter and maximum depth. The shape of Serenitatis and Tolstoj are very similar, while Beethoven has some similarities to Orientale.

mare basalts and flexure of the lunar lithosphere [cf. *Solomon and Head*, 1980] in response to a non-Gaussian-shaped, superisostatic load from the mare basalts [cf. *Watters and Konopliv*, 2001].

[10] Orientale is a well-preserved multi-ring lunar basin, ~900 km in diameter. The basin displays a nested structure with the lowest elevation within the central depression of the basin; the overall relief of Orientale is ~7 km [*Smith et al.*, 1997]. Inflections in the topographic profiles indicate the locations of rings [i.e., *Head*, 1974]. The interior of Orientale contains areas of mare fill [i.e., *Head*, 1974; *Greeley*, 1976], and the basin also has an associated mascon.

[11] Beethoven and Tolstoj have about the same amount of relief (~2 km) as Serenitatis (~2 km), but much less relief than Orientale (~7 km). The topographic profiles show that Beethoven and Tolstoj have flat floors. However, normalized profiles (Figure 3) suggest that the shape of Beethoven has some similarities to Orientale. This may indicate that the pre-fill basin shape of Beethoven was more similar to that of Orientale. The long wavelength topography of Tolstoj more closely resembles that of Serenitatis. Tolstoj and Serenitatis are both flat-floored basins; however, the center of the smooth plains surface of Tolstoj is not higher than its margins.

6. Discussion

[12] Currently, there is no gravity data for mercurian basins and thus it is not possible to determine if Beethoven and Tolstoj have associated mascons. However, Mare Serenitatis and other lunar mascon basins have characteristic tectonic features such as interior basin-concentric wrinkle ridge systems and extensional troughs or grabens near their margins [i.e., *Strom*, 1972; *Bryan*, 1973; *Wilhelms*, 1987]. The tectonic suite of wrinkle ridges and graben is thought to result from subsidence caused by lithospheric flexure in response to the superisostatic load induced by the mare basalts [cf. *Watters and Konopliv*, 2001].

[13] Few tectonic features have been identified within Beethoven and Tolstoj basins. Although the floor of Beethoven basin appears devoid of wrinkle ridges, it is possible that wrinkle ridges may not be visible in the Mariner 10 data due to the incidence angle (22°–39°) of the images. However, some tectonic features can be observed. A low-relief scarp extends ~320 km along the western margin of the basin and a narrow, irregular trough ~1–3 km wide and ~100 km long is present within the basin floor [see *Spudis and Prosser*, 1984]. In Tolstoj, where the incidence angle (59°–89°) is more favorable, a few small (each less than 50 km in length) ridges are visible near the margins of the basin fill [see *Schaber and McCauley*, 1980].

[14] We discuss three hypotheses to explain why the mercurian basins exhibit little evidence of tectonic deformation relative to their lunar counterparts. The lack of apparent subsidence and deformation within the Beethoven and Tolstoj basins may indicate that: (1) the thickness of the interior smooth plains fill is relatively small (and thus provides insufficient load to cause flexure of the elastic lithosphere), or (2) the elastic lithosphere at the time the basins were flooded was too thick for significant subsidence to occur, or (3) the basin-fill material has little or no density contrast with the surrounding crustal material, resulting in no significant load on the lithosphere.

[15] To determine if the interior fill of Beethoven and Tolstoj is a thin veneer of material, we estimate the thickness of the fill. Even though the depth-diameter relationship for simple and complex craters on Mercury has been examined [cf. *Pike*, 1988], the relationship for basin-sized features has yet to be determined. *Williams and Zuber* [1998] used Clementine LIDAR measurements to construct a depth-diameter relationship for lunar basins and calculated the thickness of mare fill by predicting the pre-mare depths of the basins. Because of the greater acceleration due to gravity on Mercury, it is unlikely that the depth-diameter relationship for basins on Mercury and the Moon will be identical. *Pike* [1988] concludes that external influences on basin shape, such as gravity, decline with increasing basin diameter. Based on extrapolation of Pike's relationship [*Pike*, 1988] for large impact craters (>100 km diameter) to Beethoven and Tolstoj basin diameters, the differences in depth-diameter are not expected to be significant. Applying the depth-diameter relation for lunar basins to Beethoven (diameter 650 km) and using average and maximum depths, we estimate the range of fill thickness to be 1.5 km to 3 km. For Tolstoj (diameter 440 km), we estimate the range of fill thickness to be 1.7 to 3.2 km. These estimates suggest that the thickness of the smooth plains volcanics within the basins is not a thin veneer.

[16] Current estimates of Mercury's elastic thickness (T_e) vary from 25 to 30 km based on lobate scarp thrust faults [*Nimmo and Watters*, 2004] to up to 100 km from tidal despinning models [*Melosh*, 1977]. Modeling of extensional troughs in the Caloris basin suggests T_e of about 50 km [*Watters et al.*, 2005] to 75 to 125 km [*Melosh and McKinnon*, 1988]. *Solomon and Head* [1980] concluded that the arcuate graben associated with Mare Serenitatis were consistent with T_e of 40 to 50 km at the time of formation. Given identical elastic thickness and flexural rigidity on Mercury and the Moon, the thickness of mare basalt-like fill needed to induce flexure will be smaller on Mercury than the Moon due to Mercury's greater gravity.

[17] The absence of apparent deformation of the interior fill of Beethoven and Tolstoj is in contrast to the much larger Caloris basin. Wrinkle ridges in the floor material of Caloris indicate that the basin interior has undergone compression, possibly the result of flexure due to loading from the interior fill [*Strom et al.*, 1975b; *Melosh and McKinnon*, 1988], with a component of the compressional stress from global contraction [see *Watters et al.*, 2005]. This suggests that the interior fill in Caloris has a significant density contrast with the surrounding crustal material and thus a positive mass anomaly. A positive mass anomaly associated with Caloris is suggested by its location near Mercury's hot pole [cf. *Melosh and McKinnon*, 1988]. Although the large range of estimated elastic thickness for Mercury (T_e of 25 to 125 km) does not exclude the possibility of lithospheric flexure in response to loading from smooth plains volcanic material in Beethoven and Tolstoj, the absence of tectonic features suggests that the T_e could have been too great for loads from volcanic fill to induce flexure.

[18] Alternatively, if the smooth plains material has little or no density contrast with the surrounding crustal materials, the load on the lithosphere could be relatively small. Mariner 10 color-derived parameter images (used to interpret FeO and maturity) of Tolstoj basin indicate that the smooth plains are compositionally distinct from the surrounding crustal material; however, the smooth plains fill has an FeO abundance comparable to that of the average mercurian crust [*Robinson and Taylor*, 2001]. If the basin fill has no density contrast with the crust, it may explain the absence of mascon tectonic features within Tolstoj and Beethoven basins.

[19] In summary, we conclude that based on a likely depth-diameter relationship for the mercurian basins, Beethoven and Tolstoj have significant interior fill (>2 km). If the mercurian basins have comparable amounts of lunar mare-like fill and elastic thicknesses, some flexural response to the loads should be expected. However, the absence of tectonic features suggests that little subsidence has occurred. The large range in estimates of Mercury's elastic thickness does not exclude the possibility the lithosphere was too thick for loads from mare-like volcanic fill to induce flexure. If the basin fill consists of material with a density comparable to that of the surrounding crust, the load may be insufficient to induce flexure. Data collected by the MESSENGER mission to Mercury [*Solomon et al.*, 2001] will help address these questions by determining the composition of the basin fill and by better constraining the elastic thickness of Mercury's lithosphere.

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