VISCOUS RELAXATION ON MERCURY? P. Surdas Mohit[1] and Catherine L. Johnson[2], [1]Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, La Jolla, CA, 92093 (pmohit@ucsd.edu), [2]Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, Canada.

Introduction: The mechanism responsible for Mercury's high iron fraction remains a mystery, although several have been proposed, including metal-silicate fractionation due to aerodynamic drag in the solar nebula, vaporization of silicates in a hot solar nebula, and removal of the crust and mantle by giant direct impact or hit-and-run collision [1,2]. While the fractionation hypothesis would result in a thick primordial crust, the other two involve removal of this crust, suggesting that only a secondary crust produced by partial melting of the mantle -- both due to the catastrophe and later volcanism -- would remain. As a result, placing constraints on the crustal thickness of Mercury would shed some light on its formation.

Several attempts have been made to constrain the crustal thickness. Anderson *et al* [3] measured the equatorial ellipticity and C_{22}, the corresponding spherical harmonic gravity coefficient. Assuming isostasy, they estimated a depth of compensation of 200 +/- 100 km. However, this calculation tends to overestimate the thickness, producing depths of compensation of ~ 80 km for the Moon and 400 km for Mars, whereas their actual crustal thicknesses are thought to be closer to 35-45 and ~ 50 km, respectively. The discrepancies likely stem from uncompensated tidal deformation on the Moon and the flexurally supported Tharsis volcanic complex on Mars. As Mercury appears to occupy a Cassini state [4], it should also possess a forced equatorial ellipticity.

Other authors have placed an upper bound on the crustal thickness using faulting [5] and viscous relaxation models [6,7]. Together these studies suggest a maximum crustal thickness of 100-140 km. However, these models assume that mercurian impact basins have not relaxed. As there is evidence of basin relaxation on the Moon and Mars, this assumption is far from robust and is the subject of this study.

Data Analysis: We examine the topography of the Beethoven and Tolstoj impact structures using recent stereo-derived digital elevation models (DEM) [8] with the goal of determining whether their topographic expressions show signs of modification. The morphologies of the basins show that they are very old, with younger smooth plains units covering the floors. Beethoven has a diameter (*D*) of ~ 600 km, and a rim-to-floor depth (*d*) of ~2.5 km (see Fig. 1), while Tolstoj has *D* = 440 km and *d* ~ 2 km [8]; the topographic uncertainty of the DEM's is ~ 0.5 km.

These basins are anomalously shallow, compared to those on the Moon and Mars. Lunar basins in a similar size range show depths of 4.2-6 km [9] (5.2-6 km excluding Humboldtianum, whose depth of excavation was limited by thin crust). The only well-preserved basin on Mars with *D* < 1000 km, Newton (*D* = 305 km), has a depth of ~ 4 km [10,11].

There are three possible explanations for this observation: 1) deposition of the smooth plains material accounts entirely for the shallow nature of the basins [8], in which case the deposits must be > 2 km thick; 2) the basins relaxed by viscous flow in the lower crust; or 3) the crust is very thin, allowing the impacts to excavate it entirely. The first explanation is hard to reconcile with the observation that no wrinkle ridges -- indicative of flexure of the lithosphere under the load -- are found in these basins, while they are common in the lunar mare basins. Since Mercury has more than double the surface gravity of the Moon and almost 50% greater radius (reducing the effect of membrane stress in supporting loads), its lithosphere should experience greater flexure under a given load.

The structure of the Beethoven basin bears a striking similarity to certain relaxed basins on the Moon and Mars. In particular, the altitude of the topographic ring inside the basin is similar to that of the outer rim, mirroring comparable structures in two proposed relaxed basins of similar size: Keeler-Heaviside on the Moon and Huygens on Mars (Figure 2). By contrast, the corresponding feature in the unrelaxed lunar Mendel-Rydberg and Orientale basins is terraced over 1 km below the rim. It is worth noting, however, that relaxed basins on the Moon and Mars show less than the 2-2.5 km of relief observed at Beethoven and Tolstoj.

When a basin excavates the entire crust, the subsequent crater collapse (whether isostasy is reached or not) reduces the depth such that the sum of the depth, amplitude of Moho uplift, and melt sheet thickness is equal to the regional crustal thickness. As a result, there will be a maximum basin depth d_{max} that is proportional to the regional crustal thickness. Beethoven and Tolstoj may be shallow because they excavated the entire crust, in which case d_{max} = 2-2.5 km. Recent stereo DEM's with partial coverage of Rabelais crater (*D* ~ 140 km) and a broad area in the southern hemisphere [12] are also consistent with this scenario.

Knowing d_{max} should allow us to place bounds on the thickness of the crust. For isostatic basins, it should be proportional to the ratio of the crust/mantle density contrast to the crustal density, although it is not clear whether this is true for non-isostatic crustal structure.

On the Moon, d_{max} varies from 4.2 km (Humboldtianum) to ~5.5 km (Orientale) to 8.5 km (South Pole-Aitken) in crust 40, 55, and ~ 80 km thick, respectively [13]. For Moon-like values of crust and mantle density, the crustal thickness would be ~20 km. If the crust is more dense than that of the Moon (as is likely if it is of secondary origin) then this would increase – up to 30-40 km for a density equal to that of lunar mare basalts (~ 3200 kg/m^3).

Modeling: In order to test the relaxation hypothesis, we use a spherical, self-gravitating viscoelastic model [14] to determine conditions that can produce the observed topographic structures of Beethoven and Tolstoj by viscous flow. As the early thermal evolution and crustal thickness of Mercury are poorly constrained, we consider a wide range of models. However, we note that modeling of the formation of the lobate scarps suggests a crustal thickness of < 140 km and effective elastic thickness ~ 25-30 km [5].

Preliminary results show that the observed basin structure is difficult to reproduce for a wet rheology, in part due to the high surface temperature. Relaxation occurs readily for crustal thickness > 50 km, but little topography is retained for realistic values of heat flux.

Discussion: The topographic information extracted from Mariner 10 images suggests that the two major mercurian basins Beethoven and Tolstoj are shallower than would be expected for their size. We propose that the most likely explanations for this observation are 1) viscous relaxation of relief by flow in the lower crust, or 2) complete crustal excavation due to low crustal thickness (~20-40 km). These hypotheses have very different implications for the early history of Mercury. If relaxation occurred, a relatively thick crust and low heat flow is required, favoring the fractionation model for Mercury's formation; complete crustal excavation requires a thin crust, favoring the other two models.

The Mercury Laser Altimeter (MLA) will record a topograhic profile during the January 14 flyby. The maximum range of relief and the depth-to-diameter ratio of any craters along the track, combined with stereo topographic data as it becomes available, should aid in distinguishing between the two hypotheses. If excavation dominates, we would expect to see a *d* vs *D* curve that increases monotonically up to d_{max}; relaxation would produce a more complex signature involving a decrease of *d* with increasing *D* and age.

The topographic and gravity mapping performed by MESSENGER from orbit should allow one of these hypotheses to be unequivocally rejected, as relaxed and unrelaxed basins would be expected to have very different gravity signatures. Relaxed basins tend to show low-amplitude negative gravity anomalies, while an unrelaxed shallow basin would likely be underlain by a substantial Moho uplift.

References. [1] S. C. Solomon, *Earth Planet. Sci. Lett.* 216, 441, 2003. [2] E. Asphaug *et al.*, *Nature* 439, 155, 2006. [3] J. D. Anderson, *et al.*, *Icarus* 29, 690, 1996. [4] J. L. Margot *et al.*, *Science* 316, 710, 2007. [5] F. Nimmo and T. R. Watters, *Geophys. Res. Lett. 31,* L02701, 2004. [6] F. Nimmo, *Geophys. Res. Lett*. 29, 1063, 2002. [7] D. Breuer and M. Grott, Icarus, submitted, 2007. [8] S. L. Andre, T. R. Watters, and M. S. Robinson, *Geophys. Res. Lett.* 32, L21202, 2005. [9] K. K. Williams and M. T. Zuber, Icarus *131*, 107, 1998. [10] J. B. Howenstine and W. S. Kiefer, *Lunar Planet. Sci.* 36, 1742, 2005. [11] P. S. Mohit and R. J. Phillips, *Geophys. Res. Lett.* 34, L21204 (2007). [12] S. L. Andre and T. R. Watters, *Lunar Planet. Sci*. 38, 2155, 2007. [13] H. Hikida and M. A.Wieczorek, *Icarus* 192, 150, 2007. [14] P. S. Mohit and R. J. Phillips, *J. Geophys. Res.* 111, E12001, 2006.

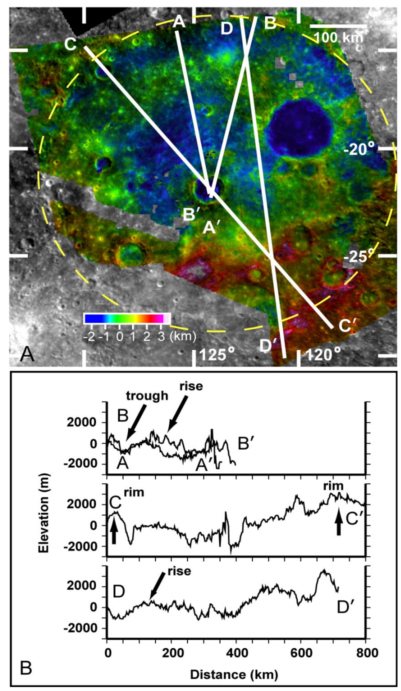

Figure 1. A) Stereo topography map of Beethoven basin. B) Topographic profiles along traverses indicated in A. Reproduced from [8].

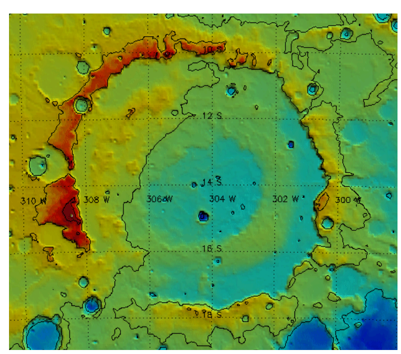

Figure 2. Topographic map of Huygens basin on Mars. Contours are drawn at 1 km intervals.