A TEST FOR DEVELOPING LONG-WAVELENGTH LITHOSPHERIC FOLDING ON MERCURY. J. P. Kay[1] and A. J. Dombard[1], Dept. of Earth and Environmental Sciences, University of Illinois at Chicago, 845 W. Taylor St. (MC-186), Chicago, IL, 60607 (jkay5@uic.edu, adombard@uic.edu).

Introduction: Models of the surface strain history of Mercury must be compatible with its thermal evolution [1-4], which suggested pervasive and ongoing planetary contraction. There is ample evidence that Mercury has contracted since the Late Heavy Bombardment (LHB), which includes lobate scarps, wrinkle ridges, and high-relief ridges [3, 5-9]. The lobate scarps are believed to be asymmetric hanging wall anticlines atop a thrust fault [5, 8] and are larger than wrinkle ridges. Wrinkle ridges are a low relief feature that is an anticlinal fold that also sits above a blind thrust fault [11]. These two features have preserved the contraction that Mercury has undergone since the LHB and have been used to estimate a decrease in planetary radius of 1-7 km [5, 8-10].

Another subtler consequence of global contraction may have been the formation of long-wavelength, low-amplitude topography. This type of topography has been predicted to exist on Mercury, which is believed to have formed as a result of folding of the lithosphere [2-3]; however, it was not until the MESSENGER spacecraft began acquiring data of Mercury that the existence of long-wavelength topography was identified [11, 12]. For example, altimetry and gravity data acquired in the Caloris impact basin (~60°N/115°E) showed that the smooth plains interior to the Caloris impact basin display long-wavelength variations in topography [11, 13]. Portions of the northern floor of the basin lie higher in elevation than the basin rim, with variations in topography that can reach as high as 3 km [11-13]. The northern portion of the Caloris floor has been observed to be part of a quasi-linear rise that trends west-southwest–east-northeast and extends over half of the circumference of Mercury, and only occurs at mid-latitudes [12]. The wavelength of the observed features has been estimated to be nearly 1000 km with an amplitude of ~3 km [14, 15]. Balcerski et al. (2012) also observed that the tilts of superimposed, volcanically flooded impact craters were consistent with the modification of Mercury's long-wavelength topography that postdates both the volcanic plains emplacement and the pre-LHB formation of the Caloris basin [14, 16].

Is this long-wavelength topography evidence of the predicted folding of the lithosphere? Here, we test this idea using a finite element approach than employs a more realistic elastic-viscous-plastic rheological model than the semi-analytic viscous-plastic model that was used in the previous assessment [2].

Methodology: For this work, we use the commercially available MSC.Marc finite-element package, which has been well vetted in the study of lithospheres of icy satellites and rocky bodies [e.g., 17-19]. This code employs a rheological model more consistent with the observed deformation of geologic materials, where the response of the material is elastic on short time scales, viscous on long time scales, and with plastic failure for stresses higher than the depth-dependent cohesion of the material.

For each simulation, we begin with the construction of a finite element mesh, which contains between 5000 and 15000 elements. Our initial meshes are a two-layer axisymmetric mesh of Mercury, approximating an unwrapped version of one-hemisphere of Mercury (this approximation would not include membrane lithospheric resistance). We set the size of the mesh to be 3,835 km (¼ the circumference of Mercury) wide and 500 km deep (the depth of the mantle). The upper 100 km is composed of crustal material, while the remaining 400 km is mantle material. Mesh resolution in the crust is 25 km horizontal and 10 km vertical. The mantle has a similar resolution, but a small vertical bias is applied to decrease resolution in the deep mesh away from the primary deformation. The crustal density is 2900 kg m^{-3}, and the mantle density was 3200 kg m^{-3}. We apply the rheologies of dried Columbia diabase for the crustal material [23] and dried olivine for the mantle materials [24].

Planetary contraction is simulated by a forced lateral displacement of the outer vertical boundary. We assume that the shortening that is associated with planetary contraction is equivalent to a change in planetary radius of 1 km (surface strain of 0.026 %) every 100 Myr, with a total run time of 300 Myr. This contraction results in the formation of a lithosphere whose thickness is largely governed by the thermal state. We test three different thermal models: a constant surface temperature of 440 K and surface heat flows of 6, 25, and 40 mW m^{-2}, which bound the range of expected values for Mercury [25-26].

Unstable deformation (e.g., folding) amplifies existing perturbations. Thus in order to break the lateral homogeneity of the mesh, a small (10 m amplitude) harmonic perturbation in surface topography is applied, coupled with several scenarios for the crust-mantle boundary: fully compensated (Airy), flat, and uniform crustal thickness. We test a range of wavelengths in order to identify the fastest-growing, dominant wavelength. In our axisymmetric system that approximates an unwrapped half of Mercury, our applied perturbations are equivalent to the even number zonal spherical harmonics at degrees 6-24. For reference, the observed long-wavelength topography on Mercury is equivalent to roughly degree 14.

Results: For each of our 90 simulations (permutations of heat flow [3 cases], wavelength [10 cases], and scenario for the crust-mantle boundary [3 cases]), we calculate the amplification factor as a ratio of the final to initial surface topographic amplitudes. In the majority of our simulations (82/90), no positive amplification was observed (amplification < 1). In eight of our simulations, the amplification was only marginally greater than one (1.01-1.07). These simulations are for the spherical harmonic degrees 10-24 in fully compensated initial topography with a heat flow of 6 mW m^{-2}, with peak amplification occurring at the degree-12 harmonic. Extrapolating these results to several billions of years of horizontal shortening yields less than a doubling of the initial topographic amplitude.

Discussion: Our results demonstrate that an origin for the long wavelength topography on Mercury via lithospheric folding is unlikely, in contrast to the predictions from semi-analytic models using a more simplistic rheology [2]. Amplifications using this more realistic rheology are significantly lower, consistent with recent work exploring periodic topography in the outer solar system [27]. Indeed, our low amplification factors imply a kilometer scale perturbation to yield the observed 3 km of topographic amplitude, which is of course unlikely. The resolution to this paradox in the outer solar system is to necessitate larger amounts of horizontal shortening (levels > 10%) in order to amplify a reasonable perturbation into observable topography [27]. We test some of our simulations with significantly higher degrees of shortening (10 %) at much higher strain rates (though we find little sensitivity to strain rate). We find much greater amplification (~10 times), but there is no physical evidence or theoretical reason for Mercury to have shrunk by the requisite 244 km needed for this degree of horizontal shortening.

These results imply that there must be an alternative mechanism for the formation of the observed long-wavelength topography within and around Caloris. A corollary is that decreasing amplitudes of all cases except for the lowest heat flow under initial compensation, including the near complete collapse of our constant crustal thickness scenarios, indicate that the lithosphere of Mercury cannot support topography at this horizontal scale without buoyant support. Indeed, the observed gravity anomalies of Mercury are consistent with isostatic support of this topography [28]. Thus, future work should be directed at understanding mechanisms to produce compensated high topography at large horizontal scales. To end on pure speculation, we suggest extensive magmatic thickening of the crust over sheet-like convective upwellings in the mantle.

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