CONSTRAINTS ON THE EVOLUTION OF IAPETUS FROM SIMULATIONS OF ITS RIDGE AND BULGE. A. J. Dombard[1] and A. F. Cheng[2], [1]Dept. of Earth and Environmental Sciences, Univ. of Illinois at Chicago, 845 W. Taylor St. (MC-186), Chicago, IL 60607 (adombard@uic.edu), [2]Johns Hopkins Univ. Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD 20723.

Introduction: The equatorial ridge and bulge on Iapetus challenge our understanding of the evolution of this enigmatic satellite. The shape [1] is well-fit as an oblate spheroid, suggesting a rotational bulge raised under a regime with a spin period of ~15-16 hr, depending whether the moon is differentiated [1]. Iapetus currently spins once every 79 days, indicating an epoch of tidal despinning, also a challenge given the large distance to the primary [e.g., 2]. In addition, Iapetus has an equatorial ridge spanning at least 75% of the circumference of the satellite (though not continuously) [3]. The ridge is ~100-200 km wide and reaches up to 20 km in elevation [4]. On the leading hemisphere, there appears to be a flanking trough ~100 km wide and a few kilometers deep along sections of the ridge; however, this trough grades into high-standing rim topography from an old, degraded basin. The ridge appears to be quite old [3, 4], and the morphology suggests uplift of pre-existing terrain [4].

Several groups have sought to explain the formation of the bulge, the ridge, or both. Ip [5] proposed that the ridge is accreted material from an ancient ring system around Iapetus. Czechowski and Leliwa-Kopystyński [6] proposed that the ridge is the product of upwelling in a hemispherical pattern of convection within the satellite. Castillo-Rogez et al. [2] suggested that short-lived radionuclides (^{26}Al and ^{60}Fe) created a warm, dissipative interior that permitted an initial phase of tidal despinning from a spin period of ~7 hr to ~15-16 hr. Here, the lithosphere was thin (effective elastic thickness of ~15 km), such that the satellite's shape could adjust to this new spin state. Presumably, the ridge also formed during this epoch as a result of the large shape change of the satellite and collapse of initial porosity. About 0.5-1 Gyr after the formation of Iapetus, the interior was still sufficiently warm and dissipative for a second epoch of despinning from ~15-16 hr to the current 79 days. Here, the lithosphere was thick (230 km or greater), freezing in the bulge.

In general, these models can be tested by consideration of how the ridge and the bulge are supported. Isostatic support will be minor because of the small rock mass fraction (the mean density is only 1083 kg m^{-3}) [4], so these features must be supported by the strength of the lithosphere. To date, only simple elastic-lithosphere models have been employed [2, 4]. In this abstract, we describe our finite-element simulations of the response of Iapetus to both ridge and bulge loads, using a more realistic viscoelastic rheology, and discuss the implications for satellite's evolution.

Methods and Results: We use finite-element methods described previously [e.g., 7-9]. Because the material is viscoelastic, a lithosphere naturally develops in response to the stress and thermal state of the system, as opposed to being set a priori as in elastic-lithosphere models. Because the composition of Iapetus is uncertain, we assume the mechanical and thermal properties of water ice [see references in 7 and 8], following Castillo-Rogez et al. [2]. To prevent self-compaction under application of a gravity load, we set the elastic properties to be nearly incompressible and adjust the elastic Young's modulus to maintain flexural rigidity [8]. The results from a steady-state thermal simulation are imported into a separate mechanical simulation employing full large-strain formulism.

The Ridge. Castillo-Rogez et al. [2] advocated that when the ridge likely formed, the elastic lithosphere was ~15-20 km thick (defined as the depth to the 170-K isotherm). To test whether the lithosphere can support the ridge, we apply a heat flow of 18 mW m^{-2}, which, assuming an equatorial surface temperature of 90 K, results in an isotherm depth of ~20 km. The finite-element mesh is constructed assuming plane-strain conditions and taking advantage of symmetry across the ridge, with the far-side and bottom boundaries placed sufficiently distant to affect negligibly the solution. The ridge-load is directly simulated as a set of elements with a triangular shape, extending 100 km from the ridge axis and initially 18 km tall.

We show the resultant topographic profiles in Fig. 1, which indicates that the lithosphere cannot support the ridge under these conditions. The ridge rapidly sinks, shedding almost half its initial height, while a flexural trough develops that is ~5 km deep. It is conceivable that pre-existing compressive stresses could change the strength of the lithosphere, so we have also simulated a case with an applied planar stress of 10 MPa. The results are negligibly different.

The Bulge. To simulate the evolution of the bulge, we take advantage of axisymmetry and symmetry across the equator to construct a finite-element mesh of the entire satellite, with a difference of 35 km between the polar and equatorial radii. We assume full differentiation (a distinct possibility [2]) and that this core is immobile and spherical, with a radius of 300 km. The mesh is divided into radial columns of ele-

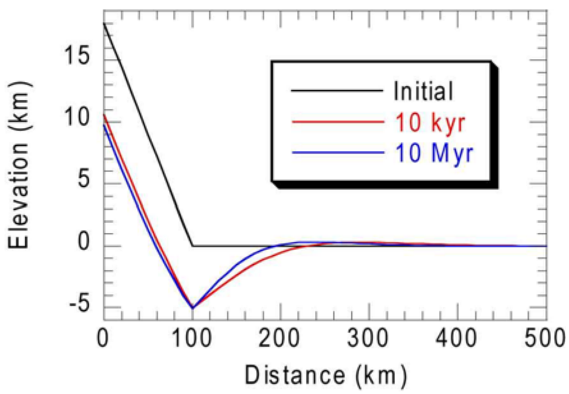

Figure 1. Elevation profiles from simulation of ridge flexure on Iapetus, showing initial shape and profiles after 10 kyr and 10 Myr.

ments, with an applied constant gravitational acceleration equal to the average surface value (0.222 m s^{-2}). (Strictly speaking, the magnitude of gravity will increase by ~25% down to the base of our mesh; however, the load that drives the response is determined by the density contrast at the surface, justifying this simplification.) Here, Castillo-Rogez et al. [2] advocated an elastic lithospheric thickness of 230 km, which can be achieved by applying a heat flow at the core-ice boundary of 6 mW m^{-2} (geometric spreading results in a surface heat flow of ~1 mW m^{-2}). We consider 2 cases, one with a constant surface temperature of 90 K, and one where the temperature drops as the cosine of latitude down to an assumed polar value of 70 K.

The results indicate a reduction of 2-3 km in the size of the bulge as support for the bulge transitions from centrifugal force to the lithosphere. Subsequent to this initial evolution, there is progressive creep at the base of the lithosphere, which thins it and allows relaxation of the bulge. After 1 Gyr, the bulge has relaxed by an additional 4.5-5 km for the case of constant surface temperature, and 3-3.5 km for the variable surface temperature case. It is doubtful this heat flow could be maintained for 1 Gyr; however, the simulations show an additional 2-3 km of bulge relaxation after 10 Myr.

Discussion: Of the discussed models for the formation of the ridge and bulge, the one of Castillo-Rogez et al. [2] seems the most tenable, but even it has issues that need to be addressed. Although our results are not directly applicable to the exogenic model of Ip [5], Giese et al. [4] has argued that this model is not consistent with the observed morphology of the ridge. Furthermore, the mass of the ridge is of order 10^{18} kg, comparable to the C-ring of Saturn. It is doubtful that Iapetus could be encircled by such a massive ring. Our results for the flexure of the ridge pose a problem for a convective origin. For a convective upwelling to deform an overlying lithosphere on a scale comparable to the width of the ridge (100-200 km) would require a lithosphere substantially thinner than the one we have simulated, which demonstrates deformation on a scale of 500-600 km. It is unlikely that the ridge could then be maintained after loss of the convective support.

In the model of Castillo-Rogez et al. [2], the ridge presumably formed during a despinning epoch when the lithosphere was thin; however, we have demonstrated that such a thin lithosphere flexes considerably under the ridge. A trough ~150 km wide and ~5 km deep forms rapidly. There are observations of a flanking trough along at least one section of the ridge [4], but it is unclear whether this trough is characteristic of the ridge system. Moreover, the observed trough is of a somewhat smaller scale than the simulated flexural trough (~100 km wide and ~2-3 km deep). Thus, it appears that the lithosphere would have been thicker during the formation of the ridge, although this conclusion needs to be tested more thoroughly. Forming the ridge on thicker lithosphere becomes problematic for this model, but it is conceivable that the ridge did not form during this ancient epoch [2].

While the lithosphere can maintain most of the rotational bulge, there is substantial relaxation. A model of an elastic shell 240 km thick flexes ~2 km [2]; however, our simulations employing a more realistic viscoelastic rheology indicates that the bulge can relax by 4 km or more. There are 2 plausible implications. First, the lithosphere could have been thicker (but not so thick as to preclude a dissipative deep interior). Second, the present shape does not record the shape of a satellite rotating once every 15-16 hr, but instead records the shape of a faster spinning satellite with an initially larger and now modestly relaxed bulge.

By simulating the response of the lithosphere to the ridge and bulge, we have gleaned information on the thermal and mechanical conditions present during the history of this satellite. These constraints can be used to refine future models for the evolution of Iapetus.

References: [1] Thomas P.C. et al. (2007) *Icarus, 190*, 573-584. [2] Castillo-Rogez J.C. et al. (2007) *Icarus, 190*, 179-202. [3] Denk T. And Cassini Team (2007) *Eos Trans. AGU, 88* (52), Fall Mtg. Suppl., P22C-01. [4] Giese B. et al. (2008) *Icarus*, in press. [5] Ip W.-H. (2006) *GRL, 33*, L16203. [6] Czechowski L. and Leliwa-Kopystyński J. (2008), *Adv. Space Res.*, in press. [7] Dombard A.J. and McKinnon W.B. (2006) *JGR, 111*, E01001. [8] Dombard A.J. and McKinnon W.B. (2006) *JSG, 28*, 2259-2269. [9] Dombard A.J. et al. (2007) *JGR, 112*, E04006.