UNSTABLE DEFORMATION AND THE FORMATION OF THE EQUATORIAL BULGE OF IAPETUS J. P. Kay and A. J. Dombard, 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: The shape of Iapetus, Saturn's third largest moon, is well fit by an oblate spheroid for which the difference between equatorial radius, a, and polar radius, c, is 35.0 ± 3.7 km [1, 2]. Initially, this flattening was attributed to a rapid rotation rate [1, 2]. The observed figure of Iapetus was believed to have come from an equilibrium spin period of ~16 hours, compared to the current spin period of 79.33 days [2]. The expected bulge based on the current spin rate is ~10 m, substantially less than the observed amount [2]. Thermal modeling of this problem showed that an initially porous satellite would need to take its present shape within ~5 Myr of formation of the solar system based on the available short-lived radioactive isotopes (SLRI) [2, 3]. Such a scenario allows the tidal despinning of the satellite and possesses a lithosphere sufficiently thick to freeze in the bulge after loss of rotational support. In contrast, an initially porous satellite with only long-lived radioactive isotopes (LLRI), while being despun, possesses a lithosphere to thin to support the bulge. These results place severe timing constraints on the formation Iapetus and the stabilization of its surface.

These efforts hinge, however, on the *assumption* (albeit a reasonable one) that the bulge is rotational in nature. Could it have instead a tectonic origin, thereby bypassing these timing constraints? Another proposal suggested that heating by LLRI warmed the interior and led to a loss of porosity [2-3], and in order to account for the loss of volume, the entire ice shell deformed. Sandwell and Schubert [4] applied a buckling model of a uniform elastic shell and found that for shell thicknesses > 120 km, the preferred wavelength of buckling is at degree 2. Axisymmetric degree-2 buckling could explain the currently observed flattening. The problem with the proposed elastic buckling model is that stress required to buckle the lithosphere is far greater than the strength of the lithosphere (280 MPa vs. 12 MPa) [4]. This is a common shortcoming of elastic buckling models [e.g., 5].

A typical resolution to this paradox is to consider unstable deformation (folding in compression and necking in tension) of a lithosphere utilizing a more realistic rheology [6-9]. Here, we explore the possibility that the observed bulge is the product of long-wavelength folding of the lithosphere in an elastic-viscous-plastic Iapetus.

Methods: We use the commercially available MSC.Marc finite element package, which has been well vetted in the study of the thermal and mechanical properties of the lithospheres of icy satellites [e.g., 9, 10]. The code employs a composite rheology that describes the general behavior of geologic materials: elastic on short time scales and viscous on long time scales, with brittle failure (continuum plasticity) for high enough stresses. We use material, thermal, and rheological parameters for water ice that have been measured in the laboratory [see 8-10].

Our simulated domain is one radial slice in an axisymmetric, planar Iapetus. This geometric simplification captures the notion of less surface area at high "latitudes" but does not include membrane effects. This radius of this cylinder is 1115 km (a quarter the circumference of Iapetus). The thickness of the domain is 400 km, the approximate depth of a rocky core in a fully differentiated Iapetus.

Following [4], we consider a thermal model of a porous Iapetus and LLRI [2]. An epoch of porosity loss lasts of order 100 Myr and produces ~10% horizontal shortening of the lithosphere, with a surface heat flux of order 1 mW m^{-2}. We first perform a steady-state thermal simulation to determine the temperature field. We consider 2 cases: a constant surface temperature of 90 K and a latitudinally varying (via a cosine) surface temperature of 90 K at the equator and 70 K at the pole. The results of the thermal simulation are piped into a mechanical simulation. We assume a density of 950 kg m^{-3}, a gravity of 0.22 m s^{-2}, and an ice grain size of 1 mm.

Results: Our initial results demonstrate the development of an equatorial bulge when the surface temperature varies with latitude. Because of a thinner lithosphere at low latitudes, the deformation is concentrated at low latitudes, preferentially lifting the surface relative to high latitudes. The transition in surface uplift is smoothly varying, following the transition in surface temperature (and hence lithospheric thickness); however, the deformation is skewed ~10-20° equatorward away from a cosine shape. The growth in the difference between equatorial and polar radii is shown in Figure 1 for the simulation with the latitudinally varying surface temperature. (We have not shown the uniform surface temperature simulation, because the domain simply gets uniformly thicker.) In the first 100 kyr of our simulation, we see only 20 m of difference between the equatorial and polar radii. After 1 Myr, only a few 100 m of difference has developed. It is not until 10 Myr that we see the currently observed amount of deformation, ~40 km. At this point the yield strength envelope becomes saturated and the only way to accommodate the strain is through continued unstable deformation. At 100 Myr, the difference is ~100 km, far in excess of the observed difference.

Discussion and Conclusions: With our simulations, we can produce ~100 km of radial difference, much greater than the amount current observed. We have not fine turned the parameters to get the exact amount of deformation, merely showing that this mechanism is plausible for producing an oblate spheroid shape. Additionally, it is likely that initial bulge was much larger and has subsequently relaxed over time [3, 10], and therefore any model that explains the bulge must be able to produce a larger bulge than is currently observed.

The horizontal shortening of a laterally homogenous domain results in uniform thickening. In models of unstable deformation, something must break this lateral homogeneity. Typically, models consider the amplification of pre-existing topography of different wavelengths, looking for the faster growing harmonic [6-9]. A standard result of these models is the dominant wavelength scales with the thickness of the lithosphere. Under this thermal scenario, the lithosphere of Iapetus (defined by the brittle-ductile transition) is ~100 km, thereby likely forcing the folding to long-wavelengths. Whether degree 2 is dominant is unclear (we will test these scenarios next); however as argued in [4], a large topographic seed in the form of a small rotational bulge might force the deformation to an oblate spheroidal shape. Here, we break the homogeneity with a variation in lithospheric thickness caused by latitudinally varying surface temperatures. In actuality, the surface temperatures will vary not as a cosine, but be skewed towards higher latitudes because of the 4^{th} order relationship between temperature and absorbed solar flux, conceivably shifting our predicted deformation towards higher latitudes and more closely reproducing a true oblate spheroid (a scenario also to be tested).

Our simulations implicitly assume a differentiated Iapetus; however even if Iapetus is undifferentiated, the bulk density of the satellite is so low that Iapetus would be essentially a dirty ice ball. Experiments have indicated that a low volume fraction of hard particulates in ice only stiffen the ductile creep by a modest degree [11], so we therefore do not expect our conclusions to change much. There are also implications of the chosen geometry. Membrane support in a spherical (not cylindrical) domain will make the lithosphere more resistant to deformation at long wavelengths. However, the deformation that we produce is several times greater than what is observed, and therefore inclusion of membrane support likely will not affect our conclusions.

Thus, our expectation is that as long as there is a pole-to-equator variation in surface temperature, a heat flow was of order 1 mW m^{-2}, and as long as there was a change of volume and surface shortening of the satellite, a tectonic origin for the bulge seems almost inescapable. Perhaps the distinct oblate spheroidal shape of Iapetus is not a frozen rotational bulge.

References: [1] Thomas et al., (2007) Icarus, 190, 573-584. [2] Castillo-Rogez et al., (2007) Icarus, 190, 179-202. [3] Robuchon et al., (2010) Icarus, 207, 959-971. [4] Sandwell D. and Schubert G (2010) Icarus, 210, 817-822. [5] Turcotte and Schubert, Geodynamics,. Wiley, 118-119., 2002 [6] Fletcher R.C. and Hallet B. (1983) J. Geophys. Res., 88(B9), 7457–7466. [7] Zuber et al., (1986) J. Geophys. Res., 91(B5), 4826–4838. [8] Dombard A.J. and McKinnon W.B. (2006a) J. Geophys. Res., 111, E01001. [9] Dombard A.J. and McKinnon W.B. (2006b) J. Struct. Geol., 28, 2259- 2269. [10] Dombard A.J. and Chang A.F. (2008) LPSC XXXVIII, Abstract #2221. [11] Durham W. B. et al. (1997) JGR, 102, 16,293-16,302.

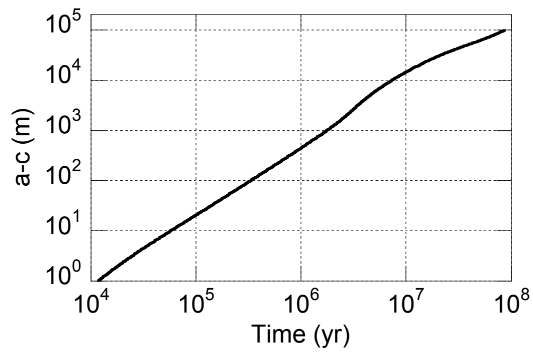

Figure 1. This figure shows the size of the difference of the equatorial and polar radii (*a* – *c*) as a function of time. This log-log plot shows that the bulge grows roughly exponentially with time.