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Formation of the bulge of Iapetus through long-wavelength folding of the lithosphere

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A R T I C L E I N F O

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A B S T R A C T

Previous models that attempted to explain the formation of the pronounced oblate shape of Iapetus suggested that it was a preserved rotational bulge. These models found that heating was provided by short-lived radioactive isotopes that decayed rapidly and allowed the excess flattening of the lithosphere to be locked in by a thickening lithosphere, but placed severe timing constraints on the formation of Iapetus and its bulge. Here, we show that finite element simulations with an elastic-viscous-plastic rheology indicate it is possible to form the bulge through long-wavelength folding of the lithosphere of Iapetus during an epoch of contraction combined with a latitudinal surface temperature gradient. In contrast to models of a frozen rotational bulge, heat generated by long-lived radioactive isotopes warms the interior, which causes porosity loss and forces Iapetus to compact by ~10%. Our simulations are most successful when there is a 30 K temperature difference between the pole and the equator. Tectonic growth of the bulge is not sensitive to the time scale over which the moon contracts, and lithospheric thickness primarily controls whether a fold can form, not fold wavelength. In addition, long term simulations show that when no stress is applied, the mechanical lithosphere is strong enough to support the bulge, with negligible relaxation over billion year time scales.

1. Introduction

The distinctly oblate shape (and peerless equatorial ridge) on Saturn's moon Iapetus is unique in our solar system (Porco et al., 2005; Thomas et al., 2007) (Fig. 1). The shape of Iapetus is best fit by an oblate spheroid where the difference between equatorial radius and polar radius is 35.0 ± 3.7 km (Thomas et al., 2007; Castillo-Rogez et al., 2007), yielding an ~4.5% flattening of the moon. (For comparison, the Earth's flattening is ~0.5%, an order of magnitude less.) This flattening has generally been attributed to a frozen-in shape from an epoch with a more rapid rotation rate (e.g., Thomas et al., 2007; Castillo-Rogez et al., 2007), because the observed figure of Iapetus is consistent with a body in hydrostatic equilibrium with a spin period of ~16 h, different from the current spin period of 79.33 days (Castillo-Rogez et al., 2007).

Researchers have sought to understand how the lithosphere of Iapetus could fossilize and preserve an ancient rotational bulge (Castillo-Rogez et al., 2007; Robuchon et al., 2010). These coupled thermal, orbital, and mechanical models showed that an initially porous satellite would need to have accreted within ~5 Myr of formation of the solar system. This finding is based on the available short-lived radioactive isotopes (SLRI) that are present in compositional models (Castillo-Rogez et al., 2007), and was the only situation revealed by these models in which there was tidal despinning of the satellite but a lithosphere sufficiently thick to freeze in the bulge after loss of rotational support. However, a satellite with the same high initial porosity but with only long-lived radioactive isotopes (LLRI), while still slowing down rotationally, possessed a lithosphere too thin and weak to support the bulge. These results thus suggested that there are severe timing constraints on the formation Iapetus and the stabilization the its surface.

These efforts, however, hinge on the assumption that the bulge is a remnant rotational structure. Could it instead have a tectonic origin, thereby bypassing these severe timing constraints that the SLRI place upon the formation of the bulge? As modeled by Castillo-Rogez et al. (2007) and Robuchon et al. (2010), heating by the LLRIs ^{40}K, ^{232}Th, ^{235}U, and ^{238}U would have warmed the interior of Iapetus and led to the loss of initial porosity, which in turn would have driven the entire icy lithosphere to deform to account for the loss of internal volume. Previous work by Sandwell and Schubert (2010) applied a buckling model of a uniform elastic shell and found that for shell thicknesses larger than 120 km, the preferred wavelength of buckling is at spherical harmonic degree 2, a buckling mode consistent with an oblate spheroid. Thus,

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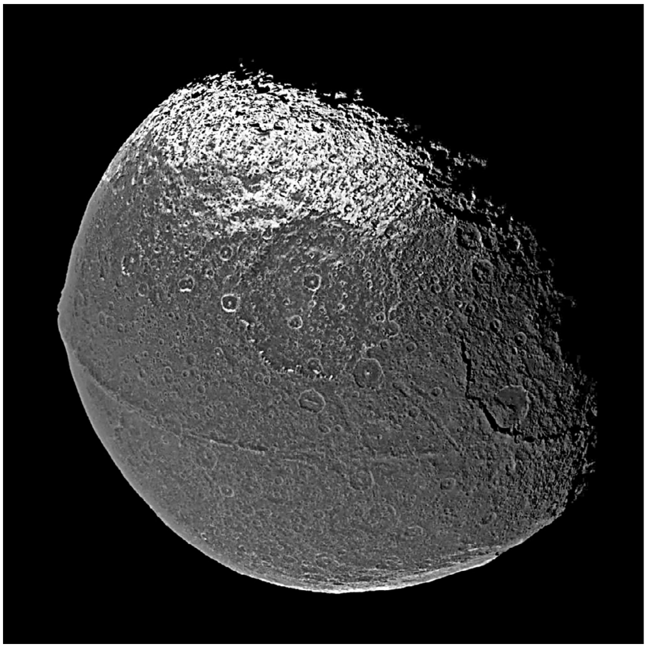

Fig. 1. Saturn's moon Iapetus, with its distinctly oblate spheroidal shape and prominent ridge. (Courtesy NASA/JPL-Caltech PIA06166).

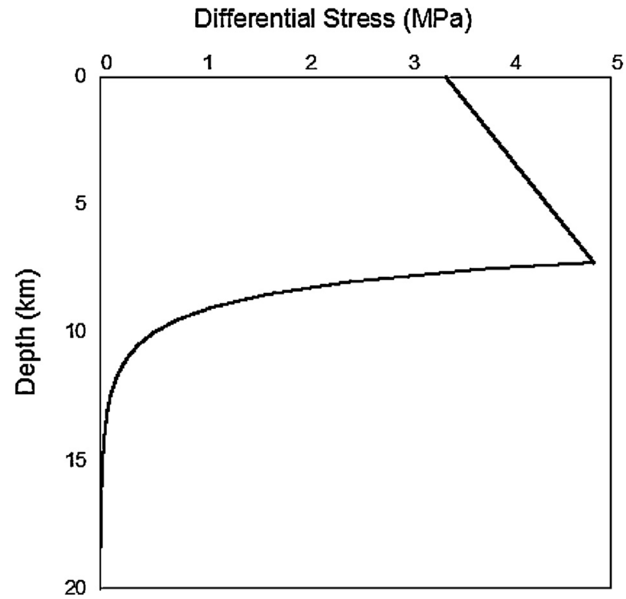

Fig. 2. Example compressional yield envelope for Iapetus' lithosphere. For this model, T_s is 90 K, the strain rate is 10^{-12} s^{-1}, and a conductivity of $651/T$.

axisymmetric degree-2 buckling could explain the currently observed flattening. The problem with the proposed elastic buckling model is that stresses required to buckle the lithosphere are far greater than the strength of the lithosphere – ~280 MPa vs. ~12 MPa (Sandwell and Schubert, 2010). This stress paradox is a common shortcoming of elastic buckling models of lithospheres (e.g., Turcotte and Schubert, 2014).

In this paper, we propose an alternative hypothesis: by simulating a variation in lithospheric thickness due to a pole-to-equator surface temperature during an epoch of planetary contraction while invoking a more realistic rheology (elastic-viscous-plastic vs. elastic), it is possible to reproduce tectonically the observed shape of Iapetus through folding of the lithosphere. Folding is the process by which layer parallel compression of mechanically competent layers can be accommodated, and has been well studied (e.g., Schmalholz and Mancktelow, 2016, and references therein). In general, thinner lithospheres result in shorter folding wavelengths. Folding also requires a perturbation in order the break the lateral homogeneity (otherwise, the layers would just get uniformly thicker). We show here that a large hemispherical perturbation from the surface temperature variation strongly biases the folding wavelength. Thus, this alternative formation mechanism of the bulge might make it possible to remove the severe time constraints that the rotational bulge models require.

2. Methods

We simulate the unstable deformation of a lithosphere, using an approach applicable for both long- and short-wavelength situations (e.g., Kay and Dombard, 2017a,b). For this project, we use the Marc finite element package (http://www.mscsoftware.com), which solves for force or thermal balance using standard numerical techniques. Marc has been well-vetted in the study of the thermal and mechanical properties of the lithospheres of icy satellites and rocky planets (e.g., Dombard and McKinnon, 2000, 2001, 2006a,b; Dombard et al., 2007; Dombard and Cheng, 2008; Damptz and Dombard, 2011; Karimi et al., 2016). 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.

Thus, we use a rheological model more consistent with observed deformational behavior of geologic materials, utilizing constitutive relations for elastic, viscous, and plastic (e.g., Gammon et al., 1983; Beeman et al., 1988; Goldsby and Kohlsedt, 2001) behavior linked in series (i.e., a Maxwell viscoelastic solid extended to include a plastic component):

$$\epsilon_{total} = \epsilon_{elastic} + \epsilon_{viscous} + \epsilon_{plastic} \quad (1)$$

where ε is strain.

For this type of composite rheology, the mechanical behavior can be explored with a Yield Strength Envelope (YSE), which is defined as the strength of the material under planetary conditions (i.e., temperature and pressure increasing with depth) and subjected to uniform, planar, horizontal contraction (or extension) at a constant rate (Fig. 2).

Two primary regimes are seen (e.g., Fig. 2 in Dombard and McKinnon, 2006a,b): 1) a shallow zone where strength is controlled by the brittle, frictional strength of the material (modeled here as continuum plasticity) and 2) a deeper zone in which ductile creep limits the strength, with the Brittle Ductile Transition (BDT) separating the two (e.g., Dombard and McKinnon, 2006a,b, and references therein). Within the envelope, deformation is accommodated elastically. The brittle regime is assumed to have a strength that increases linearly with depth (i.e., pressure), following a "Byerlee's rule" for cold ice (Beeman et al., 1998). This region is defined by a frictional slip criterion with finite cohesion and is largely independent of temperature and strain rate. For low confining stresses, experimental data have shown two relationships, one with finite cohesion and one with zero cohesion:

$$\tau = 0.55\sigma_n + 1.0\text{MPa} \quad (2)$$

$$\tau = 0.69\sigma_n \quad (3)$$

where, τ is the shear stress required for slip and σ_n is the normal stress (Beeman et al., 1998). While these shear failure criteria are both consistent with the experimental data, we use Eq. (2) to preclude strengthless material in our numerical approach. The code employs Drucker–Prager plasticity, which is a simplified version of