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Bounds on compressional features in Enceladus' ice shell from terrestrial ice sheet models

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Abstract

Enceladus' South Polar Terrain (SPT) features the now-famous "tiger stripes", four parallel fractures whose existence has been attributed to active tectonics above an observed hotspot in the subsurface. The fractures themselves are source regions for the observed icy plume emanating from the region, and have previously been modeled as active cryovolcanic sources. It has been suggested that the tiger stripes are analogous to terrestrial mid-ocean ridge spreading centers, as have the double-ridge features on Europa. Unlike our own planet, where extensional tectonic features like mid-ocean ridge spreading, there is no clear surface evidence for subduction on Enceladus. Assuming significant mass is not somehow ejected into space, extension then requires that old "crust" is either shortened by compression at a point away from the spreading centers, as in collisional tectonic zones on Earth or redistributed vertically. In this study, we examine whether a semi-circular ring of mountainous features surrounding the SPT, which has previously been attributed as a convergent feature, can be explained through such a mechanism. Though the aesthetic similarity between the mountains fringing the SPT and terrestrial continental convergence zones is obvious; the physical limitations of such formation have not been addressed. Here we use appropriately modified ice sheet/shelf models to examine upper and lower bounds on the height of topography formation at the SPT, assuming continuous and/or episodic spreading.

1. Introduction

The South Polar terrain (SPT) of Enceladus is the youngest region of the satellite's surface with an age of <10 Myr [3]. The "tiger stripe" fractures at the center of the region, along with their associated active plume venting, have been the subject of past studies. In fact, it appears that many sections of Enceladus may have seen action in the past, showing signs of dormant activity in various "tectonized terrains" [7] around the globe. The tiger stripes are peculiar parallel cracks in the ice shell, about 150 km long and 30 km apart. It has been suggested that they are analogous to terrestrial mid-ocean ridges, (e.g., [8], [1], popular articles); it has also been hypothesized that the SPT region undergoes mobile lid convection [2] which induces horizontal motion of the near-surface ice at the SPT. At the border of the region is a circular cliff system that has been attributed to convergence [10], i.e., that this feature may be an icy variation of a terrestrial fold/thrust [6] or orogenic belt. Whether or not spreading is currently taking place, it is the aim of this study to investigate the plausibilty of, and place bounds on, the hypothsized mountain-building scenario at Enceladus using simple terrestrial models of ice sheet flow and fold-thrust mechanics.

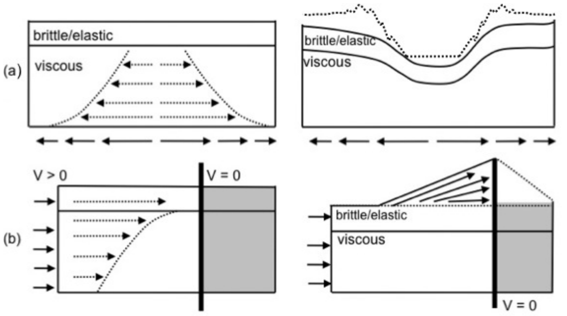

Figure 1: Two models. (a) vertical shear causes topography and uplift at sides; (b) flow into a zero-velocity "wall" causes build-up of material.

2. Building an icy mountain belt

At convergent plate boundaries, which has been suggested as the active mechanism in creating Enceladus' mountainous cliff boundary at the SPT, crustal contraction, or shortening, leads to surface uplift. Orogenic ("oro-" from the Greek for "mountain" and "-

genesis" from "building") belts are zones of thickened crust that form as a result of convergence between lithospheric plates. Using thin viscous sheet theory [9] to model movement of SPT ice as "glorified" terrestrial ice sheet/shelf flow, we assume that this thinned section of crust flows outwards from the tiger stripes (central SPT). This outflow of ice would require a "consumption" point where the mass being produced is subtracted at an equal rate (assuming Enceladus' size remains the same over time), or as in our case, topography must be built upwards instead). This model is analogous to snow piling in front of a snow plow ([4]) and tectonic collisions, such as those that give rise to the Himalayan mountain belt (e.g., [5]).

3. Approach

There are two modes in which we can conceptually approach designing a numerical experimental setup. The basic approach assumes one thin viscous layer representing the ice crust of Enceladus with a thin weak semi-brittle layer. In the first model (Fig. 1a), we assume horizontal flow in a subsurface layer creates a conveyor belt-like velocity at the base of the viscous layer, driving the flow outwards due to convection or other cause. This causes vertical shear within the overlying crustal layer and begins to form a basin at the center point of motion and pile-up of material at the edges. The second model (Fig. 1b) involves the same layer model, but this time we impose a horizontal velocity through the entire crust (simulating some large-scale tectonic compressional force, analogous to, e.g., the opening of the tiger stripes) on one side of the model and impose a zero-velocity "wall" at the other end of the domain, into which the moving icy material flows and builds upwards as a result. In these two models, we determine the resulting topography and subsequently compare it to observations of the SPT in order to determine constraints on various parameters, most importantly surface velocity and topographic height. In a third conceptual model, we focus on the brittle failure of ice instead of the viscous flow and treat the ice as a collection of discrete particles rather than a cohesive sheet and set conditions upon the boundaries of the model. This enables us reenact brittle failure of ice as it is allowed to flow in the scenarios above.

4. Conclusion

The goal of this research is to determine conditions that would allow for the formation of the SPT boundary cliffs in an orogenic fashion using modified terrestrial ice sheet models. With published values for possible surface velocities (e.g., [2], [8]) and nominal values of the strength and rheology of ice deduced from terrestrial ice sheets, we can determine whether or not the height of the mountains fringing the SPT is compatible with an extensional tectonics explanation of the SPT without subduction. Calculations may prove helpful in determining (or corroborating) bounds on other conditions, such as ice thickness, density, and surface age of the region, many of which are currently only loosely constrained at best.

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