THE GROWTH OF OUTER SATELLITES ICY SHELLS: CONVECTION AND CRYSTALLIZATION. A. P. Green[1], L. G. J. Montesi[2], and C. M. Cooper[1], [1]Department of Geology, Washington State University (austin.green@wsu.edu), [2]Department of Geology, University of Maryland, College Park (montesi@umd.edu)

Introduction: Geodynamic modeling has proven a successful approach to constraining the physical properties and internal structures of the icy shells of outer planetary satellites. Notably, thermodynamic modeling has been widely used to generate estimates of the current thickness of the ice shell of Europa (e.g., [1]). Recently the timing of ice shell growth has been modeled by analogy with the Stefan problem [2] which describes a the cooling and solidification of a layer of magma. For icy satellites, the liquid water ocean is analogous to magma and the solid ice shell is analoguous to the solidifies basalt. In the traditional Stefan problem, however, heat is transferred solely by conduction [2,3]. By contrast, the shells of icy satellites such as Europa and Ganymede are highly likely to convect [4]. Here, we modify the Stefan Problem to consider the effect of a convective layer beneath the conductive ice shell. This approach provide insight into how convection can change the crystallization history and rheological structure of an ice shell.

Model Overview: The model considered here is a continuation of previous work described in [6]. For the purposes of this analysis, we assume icy satellite shells convect in the stagnant lid regime (Figure 1). The lid is immobile with heat transfer dominated by conduction. The temperature difference across the lid comprises the greater part of the shell's thermal profile, allowing the ice beneath the lid to be treated as a near-isothermal, and therefore isoviscous, convecting layer. The stagnant lid and convecting ice are regarded as two different layers whose thicknesses are the main variables solved for in this model. Conceptually, we equate the stagnant lid to the "lithosphere" of the shell, providing a first-order estimate of the thickness of this rheological layer in icy satellites. This solution to the Stefan problem utilizes the basic differential equation describing the one-dimensional movement of a crystallization front b: $db/dt = Q_b/\rho L$; [3] where Q_b is the heat flux across the crystallization boundary, ρ is the density of ice, and L is the latent heat of fusion of ice. When applied to a conductive layer, Q_b is simply the thermal gradient at the base of the shell. However, the heat flux at the base of a convective layer is less simple to describe. 3D numerical convection models by [7] found that Q_b can be estimated by considering the heat flux through the upper TBL, Q_t, and the heat generated by both tidal flexure (H) and by the change in internal temperature T_i. When this heat balance is evaluated and substituted for Q_b in the above relation, the relationship describing the movement of the freezing front becomes:

$$\frac{db}{dt} = \frac{Q_t - Hb}{\rho L + \rho C_p \, dT_i/db} \qquad (1)$$

Results:

Reference Model. Figure 2 presents the primary results of a reference model with parameters matching the current consensus state of Europa's ice shell. Figure 2 presents the evolution over time of the thickness and internal structure of the shell, starting from an initial

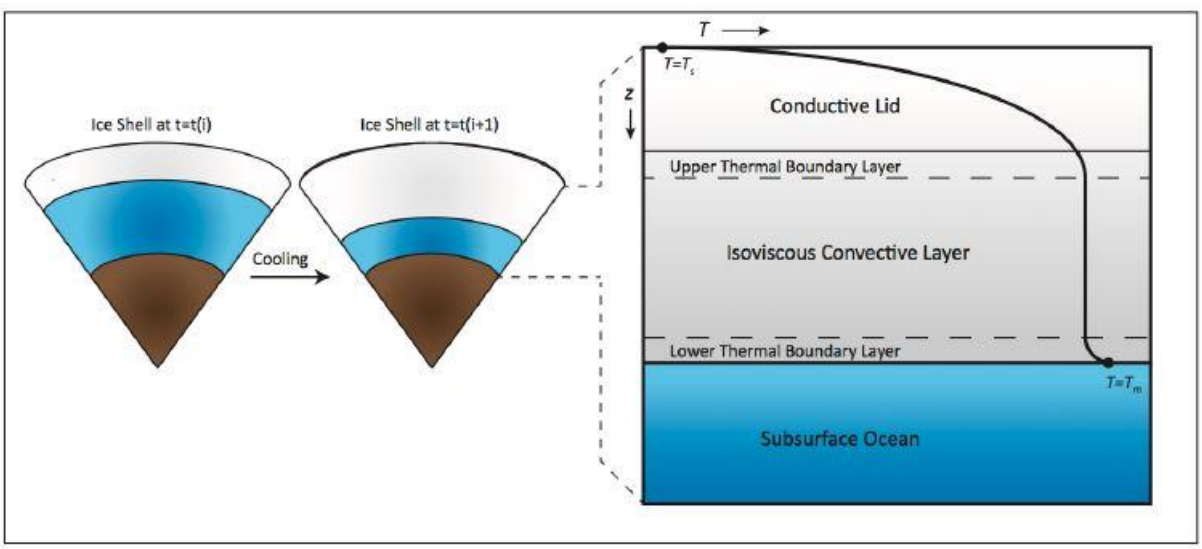

Figure 1: Schematic diagram of the model described here.

thickness of 200 m. After a long time, this model reaches a steady-state thickness with an ice shell ~28 km thick. This result is in agreement with the consensus range of thicknesses derived from thermodynamic modeling [1] as well as more specific agreement with a similar model using a solution to the Stefan Problem by [2] in the absence of a convecting sublayer. However, most of the shell is convecting, with only the top ~3 km of ice forming a stagnant lid (Figure 2). When thermal equilibrium is reached, the Rayleigh Number of the reference model shell is $1.2\text{x}10^6$ in good agreement with [8] and [9]. These results are strongly indicative of the verisimilitude of this new approach to solving the Stefan Problem in the presence of a convecting layer.

In this reference model, the shell reaches a steady state thickness in only about 1 Myr and the conductive layer reaches its final thickness in less than ~0.1 Myr (Figure 2). By comparison, [2]'s entirely conductive approach to shell crystallization modeling found crystallization times on the order of 64 Myr, nearly two orders of magnitude greater than the model considered here. The difference between these models illustrates the increased efficiency of heat transport a convecting sublayer provides.

Variations in Tidal Strain Rate. A suite of models under Europan conditions were run for a range of tidal heat dissipation rate inside the shell (Figure 3). The heat production is controlled primarily by strain rate induced by tidal flexure. The strain rate in the reference model was 10^{-10} s^{-1} but it could reach $3\text{x}10^{-10}$ s^{-1}, according to the flexural strain rates thought to be experienced in the present day by Europa, which depend chiefly on latitude and longitude [9,10].

The thickness of both conductive and convective layers in the model decreases steadily with increasing tidal strain (Figure 3). However, the two layers' relative thicknesses do not stay constant: The overall thickness of the shell is governed by a power-law relationship, where the shell thickness is proportional to $\dot{\varepsilon}^{-1.577}$ whereas the lid thickness decreases linearly with increasing strain rate. This leads to a possible shell thickness variance of ~22 km over the range of tidal strain rates experienced by Europa, but a comparatively smaller variance in the thickness of the conductive lid, thinning by approximately 1 km. This is most likely indicative of the greater efficiency with which the convective sublayer transports heat, which would lead to increased sensitivity to small variations in heat production by tidal flexure when compared to the response of the conductive lid. These results, combined with the rapidity at which the model reaches thermal equilibrium (<1Myr) imply that the Europan shell's thickness may be strongly inhomogeneous, even in the presence of non-synchronous rotation.

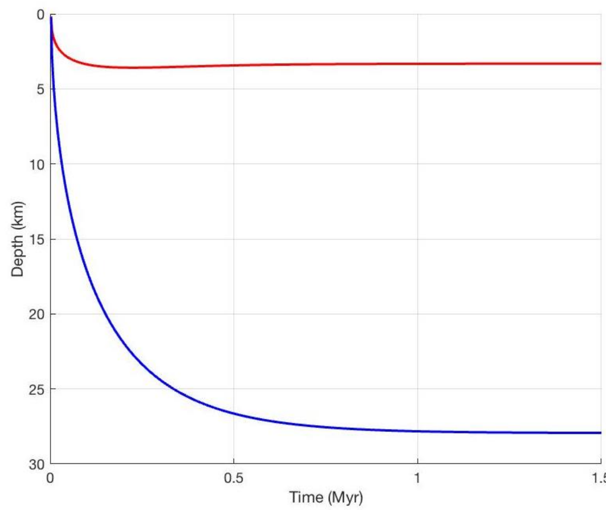

Figure 2: Reference model results. The red series represents the thickness of the conductive lid, and the blue series represents the depth to the base of the shell.

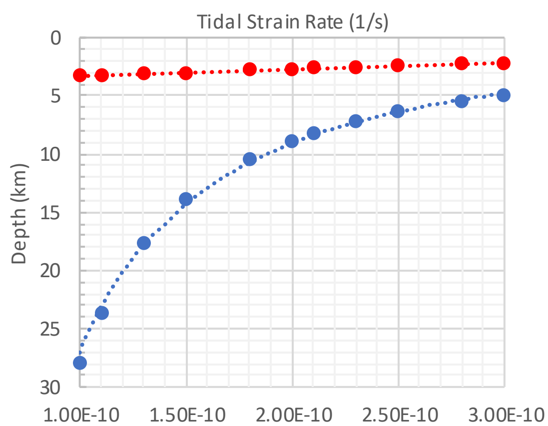

Figure 3: Comparison of shell thickness to tidal strain rate. The red series represents the thickness of the conductive lid, and the blue series represents the depth to the base of the shell.

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