**Thermal Evolution and Overpressurization of Europa’s Subsurface Ocean**

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**Thermal Evolution Model**

**Overview**

Several alternative hypotheses concerning the formation mechanism of ridges at the surface on Europa have been proposed. The best studied mechanism to date involves shear heating on a tidally-loaded crack [1]. However, computational analyses have up to now been limited to the formation of a single ridge. The ice shell, may also form ridges [2, 3]. One issue with this model is that water intrusions are difficult to form due to the higher density of liquid water compared to ice intrusions. In turn, this may not form simply as the result of buoyancy-driven motion and would require the liquid subsurface ocean to be pressurized and for water to force partially into the ice shell.

The possibility of cracking the base of the ice shell is explored using a two-stage thermal/stress model with MARSyas. The thermal evolution model considers an ice shell undergoing conduction cooling and heating by tidal flexure. If heat is lost at the base of the shell, the subsurface ocean crystallizes, thickening the ice layer. Mass transfer of ocean water to the ice shell is used in a stress evolution model to estimate the formation of a ridge and evaluate the amount of vertical water transport in the shell.

**Numerical Implementation**

The heat equation is solved using Matlab’s ODE solver ODE45. The spatial derivatives are computed by finite differences. However, the standard scheme using a time-independent grid or discretizing (T) lead to numerical issues as the position of the freezing front was often between grid points.

To better account for the movement of the freezing front, the grid where the temperature solution is defined is updated at each time step to conform to the change in ice thickness. (Fig. 2). This allows the discrete grid points to be used as a new computational mesh.

The solution to the Stefan problem is well known. It is given by the following equation:

\[
H = \frac{2H_{0z}}{d_{0z}}
\]

where

\[
H_{0z} = \frac{\eta \rho f}{\eta \rho f}
\]

\[
\eta = \frac{3}{2} \frac{c_p}{c_p} \frac{\kappa}{\kappa}
\]

\[
T = \frac{T_{m} + \frac{z}{\lambda}}{z}
\]

where \(\eta\), \(c_p\), \(\kappa\) are determined by the physical properties of the material, and \(T\) is the temperature.

**Development of Overpressurization**

The increase in excess pressure \(P_{ex}\) on the ocean related to increasing soil thickness is determined by [5]:

\[
\frac{dP_{ex}}{dz} = \frac{\rho w \rho i - \rho w \rho i}{H_{0z}}
\]

However, the lower portion of this soil will deform viscously, causing an upward radial displacement \(u_r\) and reducing the overall excess pressure. The radius \(r\) at which the transition between elastic and viscous deformation occurs in the ice shell is taken as the depth where the temperature in the ice shell reaches 100 K.

**Works Cited**


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**Stress Evolution Model**

**Results**

These results indicate that the maximum excess pressure experienced by the ocean under the conditions of this model is approximately 30 MPa. Manga and Wong (2007) found that water was not able to erupt onto the surface of Europa by pressure alone, but the possibility may still exist that partial intrusion into the ice shell occurs. A comparison of the results of this model with a calculation of the excess pressure necessary for extrusive crystallization, over time also shows that extrusion is impossible by overpressure alone. Water will still rise some distance through the ice shell, however, there is not enough pressure to extrude water on the surface. Over time, the depth to which water will rise increases from 10 to 20 km of the initial 10 km to 25 to 30 km of the ice shell’s total thickness over a 100 years. As the initial value of overpressure is treated as a zero, it could be that extrusion is possible because of the relative rise through the ice shell, with the relative densities of water and ice accounting for the majority of pressures.

**Conclusions**

Overpressurization of ice shell has led to an impact on Europa’s crystallization as was once thought. Other mechanisms of transporting water up the shell should be considered for. Although water does rise through a significant portion of the ice shell according to this model, that rise is chiefly accounted for by the relative rise of water and ice. There are several parameters considered in this model that are still uncertain on Europa, and these may require an overpressure and water intrusion, but it seems that the effect would be either negligible or negligible due to the thickness of the ice shell. These results ultimately indicate that crystallization sill is still a possibility that merits further investigation.

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**Thermal Evolution Model**

**Results**

When applied to Europa, the thermal evolution model that the ice shell would reach a steady-state thickness of approximately 20 m in approximately 13 million years. If the installation of crystallization is taken at the time of Europa’s formation, 4.5 Ga, this result makes an overpressure an unlikely cause of recently formed surface features on Europa, as viscous flow at the base of the ice shell would probably have dissipated the pressure generated early on in the satellite’s history. However, Europa almost certainly has undergone orogenic evolution throughout its history. As shown in Fig. 7, changes in total strain rate have a large effect on ice thickness and crystallization speed. A doubling in total strain, due for example to increased eccentricity, would lead to a five-fold increase in crystallization and pressurization process would restart when Europa adopted its current orbital parameters.

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