TIME EVOLUTION OF ICE-SHELL THICKNESS: EFFECT OF EPISODIC VARIATIONS IN TIDAL HEATING.
D. Allupeddinti[1] and A. R. Rhoden[1], [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287.

Introduction: Europa exhibits a variety of surface features with aligned chemistry that seem to indicate recent geological activity [1], [2]. Both the thickness of the ice-shell and the tidal heating are critical in understanding the formation of these different morphological features and the potential communication across the ice-ocean system. The feedback between shell thickness and the tidal heating within Europa could produce changes in ice-shell thickness consistent with the origin of different surface features as the ice-ocean system evolved over geological time.

Tidal heating within Europa's ice-shell is generated due to its interaction with Jupiter's gravity field as a result of its eccentric orbit around the gas giant [3]. The magnitude of tidal heating within Europa is amplified due to its 4:2:1 resonance with Ganymede and Io [3]. However, as Europa's orbit around Jupiter evolves over time, it is suggested that the resulting oscillations in its orbital eccentricity cause variations in tidal heating within the moon over geological time [4]. These variations in the tidal heating rate are expected to affect the ice-shell thickness.

We perform numerical experiments on self-consistently forming ice-ocean systems to study the magnitude and period of episodic changes in tidal heating rate within the ice that can produce variation in the shell thickness with possible implications for surface feature formation.

Methods: The Citcom 2D code for thermochemical convection [5], [6] is used to model the two-phase ice-ocean system. It solves the equations for conservation of mass, momentum and energy under the Boussinesq approximation.

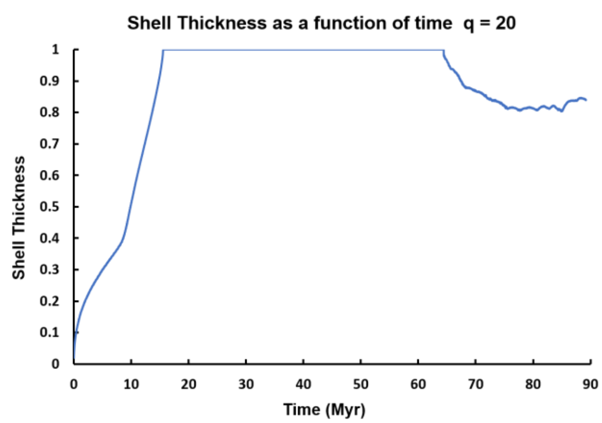
A temperature dependent viscosity formulation [7] is employed for pure water ice with a melting viscosity of 10^{16} Pa-s. A low viscosity proxy fluid that sufficiently decouples the convection in the ice and ocean layers is used instead of liquid water [6]. The proxy fluid is ~ 100x less viscous than the lowest viscosity ice.

Numerical Model. The numerical experiments begin from an initially warm ocean that is 100 km thick which is allowed to cool from the top. The velocity boundary conditions of the domain are free-slip. The temperature at the top boundary is isothermal (set to zero) while the bottom temperature boundary is insulating (no heat flow).

Tidal Heating. Pure water-ice on Europa behaves as a viscoelastic solid according to the Maxwell model [7], which is used to determine the tidal heating generated within the ice as a function of viscosity. For numerical experiments with uniform tidal heating, a heating rate $q = q_0$ is applied throughout the ice-shell.

Discussion: In order to study the effect of episodic tidal heating on ice-shell thickness, we first perform numerical experiments where uniform tidal heating within ice is turned on and off at regular time intervals. The ice-shell thickness is examined as the system cools over time.

Figure 1 below shows the ice-shell thickness as a function of time for a case where a uniform tidal heating rate (non-dimensional value of 20) and a case with a slightly higher heating rate (q = 30) is applied to the ice-shell every 10 million years. In both cases, the ice-shell forms from a cooling ocean and grows in thickness until it eventually freezes over. At a later time in the calculation, the ice-shell begins to melt and decreases in thickness. Compared to cases where uniform tidal heating rate is applied continuously, the cases in this study show significant changes in ice-shell thickness including remelting of a completely frozen shell.



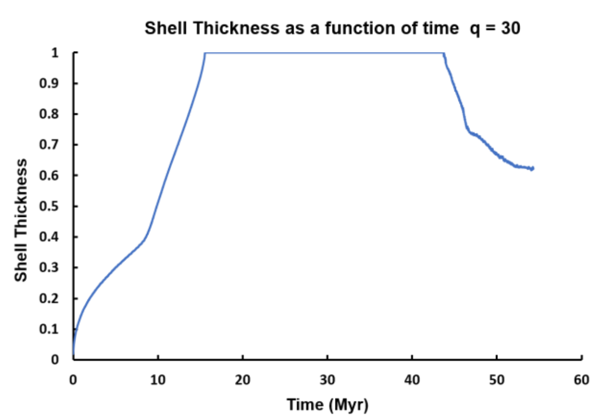


Figure 1. *Plots of the non-dimensional ice-shell thickness on the y-axis as a function of time in Myr on the x-axis for cases with uniform heating rate q =20 (top) and q = 30 (bottom). The ice-shell is growing with time until it freezes completely around ~ 16 Myr. However at a later time, the ice-shell begins to melt and further change in shell thickness occurs as the tidal heating within the ice is switched on and off every ten million years.*

Analysis of cases with different oscillating periods of tidal heating in the ice-shell and their effect on the magnitude of shell thickness variations can be used to estimate the surface stresses and potentially determine the formation mechanisms of the observed surface features on Europa.

References: [1] Kattenhorn S. A. and Hurford T. (2009) *Europa, Univ. Ariz. Press,* 199-236. [2] Zolotov M. Y. and Kargel J. S. (2009) *Europa, Univ. Ariz. Press,* 431–451. [3] Greenberg R. and Geissler P. (2002) *Meteoritics & Planet. Sci., 37,* 1685-1710. [4] Hussmann, H. and Spohn, T. (2004) *Icarus, 171,* 391-410. [5] McNamara A. K. et al. (2010) *Earth Planet. Sci. Lett., 299,* 1-9. [6] Allu Peddinti D. and McNamara A. K. (2015) *GRL, 42,* 4288-4293. [7] Showman A. P. and Han L. (2004) *JGR, 109,* E01010.