TIDAL DISSIPATION IN EUROPA'S ICE SHELL WITH A HETEROGENEOUS TEMPERATURE DISTRIBUTION.

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Introduction: Heterogeneous tidal dissipation in Europa's ice shell has been suggested as a mechanism to generate tectonic features on the surface [1-3]. Several authors have proposed that Europa's pits, uplifts, and chaos terrains resulted from surface deformation by convection within the ice shell [1,4-5]. If tidal heating were temperature dependent, as predicted for a homogeneous material with Maxwell viscoelastic rheology [6], then warm, ascending convective plumes might experience greater tidal heating than the cooler background ice, promoting a thermal runaway that induces localized heating, partial melting, and surface disruption [2-3]. Mitri & Showman [7] showed with simple analytical models that, even when a warm convective plume is surrounded on all sides by colder, stiffer ice, the tidal heating in the warm plume is strongly temperature dependent if the material obeys Maxwell rheology. To date, however, convection models that investigate temperature-dependent tidal heating all adopt a heating dependence on the local temperature corresponding the predictions of the *homogeneous* Maxwell model rather than self-consistently calculating the heating for the *heterogeneous* shell under consideration [2,8-10].

Here, we present numerical simulations of the tidal oscillation process to study the temperature and spatial dependence of tidal dissipation in a heterogeneous ice shell. These preliminary simulations provide guidance on the relationship between tidal dissipation and temperature for a range of creep mechanisms. An advantage to this numerical approach over the analytic models of Mitri & Showman [7] is that both non-Newtonian and Newtonian rheologies can be explored. Our eventual goal is to perform such simulations for more complex 2D and 3D temperature distributions and finally to self-consistently couple such tidal-heating calculations to fully nonlinear models of the thermal convection.

Model and Methods: We use the two-dimensional finite-element code Tekton [11] to solve the tidal oscillation process in Europa's ice shell. Following Mitri & Showman [7], we adopt a 2D model with a circular region of temperature T_{plume} surrounded by background ice of a different temperature T_{back}, representing a horizontal cross section through an isolated, vertically oriented convective plume. We adopt viscoelastic rheology, which is important because the tidal period is close to the Maxwell time. The Young's modulus is 10^{10} Pa and Poisson ratio is 0.25.

The rheology of ice can be described using the power-law relationship[12-13]

$$\dot{\epsilon} = A \frac{\sigma^n}{d^p} \exp\left(-\frac{Q}{RT}\right) \tag{1}$$

where $\dot{\epsilon}$ is strain rate, A is material parameter constant, σ is stress, n is stress exponent, d is grain size, p is grain-size exponent, Q is activation energy, R is gas constant, and T is temperature. We explore three different creep flow mechanisms: diffusion, grain boundary sliding (GBS), and dislocation creep. See Table 1 for the rheological parameters. While the grain sizes are unknown, estimates have suggested 0.1–1 mm [15-16]. To bracket this range, we will explore values spanning 0.1–1 mm.

Table 1: **Rheological Parameters (See [14]**

Creep Mechanism	log(A)	n	p	Q(kJ/mol)
Diffusion	-3.46	1	2	60
GBS	-2.4	1.8	1.4	49
Dislocation	5.1	4.0	0	61

In the numerical models, the calculation domain is a square with dimensions 20 km × 20 km and a resolution of 100×100 finite elements (200 m grid spacing). We use free-slip boundary conditions on the top and bottom of the domain, and periodic (sinusoidal) tension and compression on the sides to simulate the tidal oscillation process in Europa's ice shell. Consistent with estimates of Europa's global tidal flexing amplitude [6], the magnitude of strain in our models is 1.25×10^{-5}, with an oscillation period equal to Europa's orbital period of 3.5 Earth days.

We run the simulation for 5-10 tidal cycles until the initial transients die out and a periodic solution is achieved. Each tidal cycle is resolved with 85 timesteps. We then calculate the tidal dissipation rate at each cell of the 2D domain by integrating stress times strain rate over a tidal cycle, yielding a heating rate per volume:

$$q(x,y) = \frac{1}{\Delta\tau} \oint \sigma_{ij}(x,y,t)\dot{\epsilon}_{ij}(x,y,t)\, dt \tag{2}$$

where q is tidal heating rate, σ_{ij} is stress tensor, $\dot{\epsilon}_{ij}$ is the strain-rate tensor, t is time, and $\Delta\tau$ is the tidal cycle period. Subscripts correspond to the x and y coordinate axes; repeated indices imply summation.

Results. Figure 1 displays the tidal dissipation rate from models with a homogeneous (spatially independent) temperature distribution. Each point corresponds to a distinct simulation; the curves connect families of simulations with the same rheology but different temperatures. Under diffusion-creep rheology with an ice grain size of 0.5 mm (corresponding to melting-temperature viscosity at 10^{14} Pa sec), the tidal dissipation rate peaks at a temperature ~ 270 K. If the ice grain size decreases to 0.15 mm (corresponding to melting-temperature viscosity of 10^{13} Pa sec), the tidal dissipation rate peaks at temperature of ~ 250 K. This is consistent with previous estimates of tidal dissipation of uniform temperature structure with diffusion-creep rheology [7]. Under Grain Boundary Sliding (GBS) with an ice-grain size of 0.1 mm, our results show that

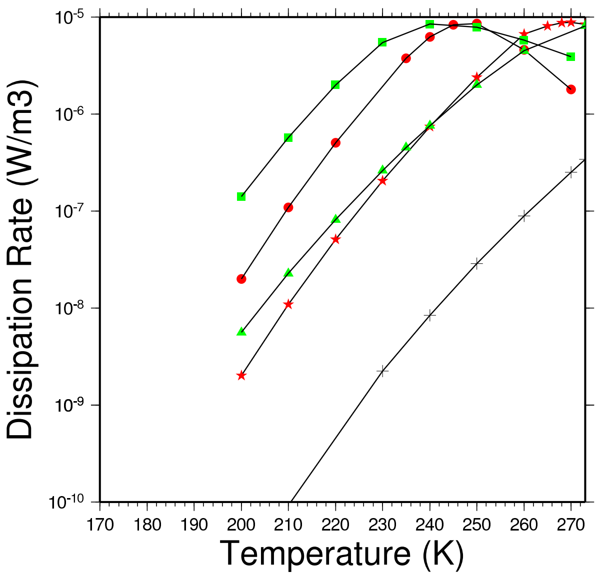

Figure 1: *Volumetric tidal dissipation rate as a function of temperature in a homogeneous material. Different symbols represent results from models with different rheological parameters. Star - Diffusion creep rheology with ice grain size of 0.5 mm; Circle - Diffusion creep rheology with grain size of 0.15 mm; Square - GBS creep rheology with grain size of 0.1 mm; Triangle - GBS creep rheology with grain size of 1 mm; Cross - Dislocation creep rheology.*

the tidal-dissipation rate is comparable to that obtained from models using diffusion rheology with a melting-temperature viscosity of 10^{13} Pa sec. When the ice grain size increases to 1 mm, GBS models show that tidal dissipation is very close to diffusion models with a grain size of 0.5 mm. Tidal dissipation rate is about two orders of magnitude smaller if dislocation creep is implemented. However, the tidal stress is small in Europa's ice shell, which means that diffusion or GBS rheology are most relevant for Europa.

Figure 2 considers a heterogenous ice shell containing a plume embedded in an environment of different temperature. The figure shows that the tidal dissipation rate in a convective plume depends strongly on the plume temperature even when the background ice temperature remains fixed. Each point corresponds to a simulation with a convective plume at one temperature and background ice at a different temperature, and the curves connect simulations that hold the background temperature constant (at 200 250, or 260 K) yet consider different plume temperatures. The strong dependence of dissipation rate on plume temperature is qualitatively consistent with Mitri & Showman's [7] results and support the idea that runaway heating can potentially occur in convective plumes for appropriate parameters, as originally suggested by [2]. Nevertheless, our results exhibit some quantitative differences with Mitri & Showman that we are currently investigating. It is worth noting that the behavior to the right of the peak would cause a *negative* rather than positive feedback, and may inhibit runaway partial melting in plumes depending on parameter values [7].

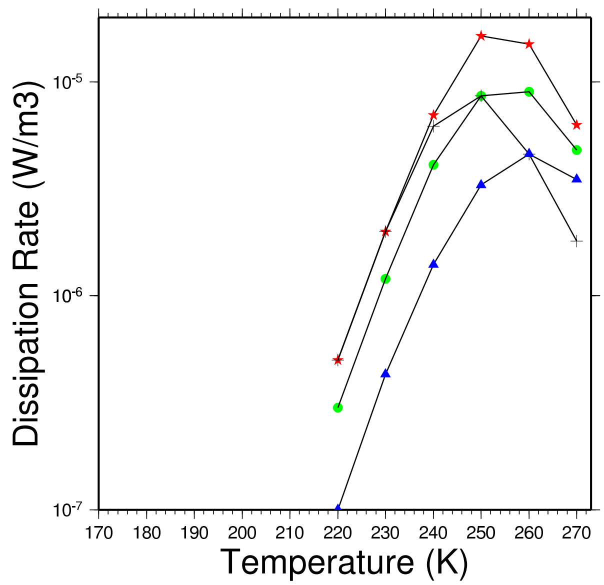

Figure 2: *Volumetric tidal dissipation rate in a plume versus the plume temperature. Diffusion creep rheology (with a grain size of 0.15 mm) is used in the models. Different symbols represent the results from different background temperatures. Stars – Background temperature is 200 K; Circles – Background temperature is 250 K; Triangles – Background temperature is 260 K. Crosses – Homogeneous temperature for comparison.*

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