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Shallow subsurface lakes on Europa? Probably not . . .

Kateřina Sládková (1), Klára Kalousová (1), and Ondřej Souček (2)
(1) Department of Geophysics, Charles University, Czech Republic (kackasladkova@gmail.com),
(2) Mathematical Institute, Charles University, Czech Republic

Abstract

In this paper, we study the heat production and thermal evolution in the vicinity of Europa's strike-slip faults. Following up on the work by [4] and [3], we introduce a model that couples tidally induced deformation of Maxwell body on short timescale with a long-term evolution of a mixture of ice and water described by two-phase formalism. The model includes frictional contact at the fault plane and consistently determines the fault propagation depth and slip velocities. This allows for more realistic estimates of frictional heating at the fault and shear heating in its vicinity. Our results indicate that melting point can be reached locally at the fault at shallow depths ($\sim$ 1.5 km) for certain range of model parameters, however, producing larger partially molten regions or even water pockets in the surroundings of Europa's faults by the considered mechanism is unlikely.

1. Introduction

Europa's strikingly young surface together with the observations of water plumes indicates an ongoing activity in the ice shell. Apart from the global subsurface ocean, water may also be present at shallower depths, as hinted at by the morphology of Europa's surface [2], [5]. Therefore, a mechanism for water production has been sought, and two possible scenarios have been suggested: meltwater produced on the top of the hot plumes by enhanced tidal dissipation [6] or by frictional and shear heating in the vicinity of strike-slip faults [4]. We revisit our previous study on generation and transport of water below the strike-slip faults on Europa [3], where a constant heating amplitude was prescribed, and we improve the model of heat generation.

2. Model

In this study, we couple two models on two different timescales. First, following up on [4], we compute a response of a Maxwellian body subjected to shear motions mimicking the tidal forcing on Europa's day timescale, see Fig. 1. Second, as in [3], the thermal evolution of a mixture of ice and water is described by a two-phase formalism on a viscous timescale (thousands of years). Here, we concentrate on the first part, i.e. the short-term (tidal) viscoelastic deformation in the vicinity of Europa's strike-slip faults. Assuming the faults to be linear and long and postulating negligible variations in the fault direction (along the "y" axis in Fig. 1), the problem reduces to two dimensions. Assuming moreover perfect antisymmetry with respect to z-axis in the x-z plane the computational domain corresponds to the hatched square in Fig. 1.

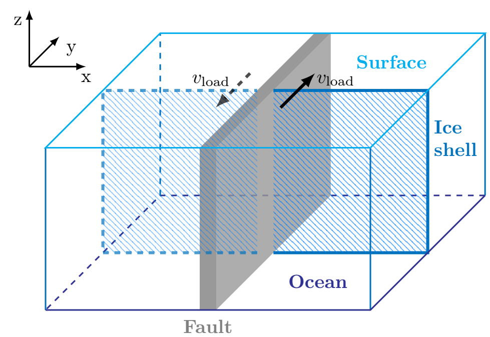

Figure 1: A sketch of a part of Europa's ice shell. The computational domain corresponds to the hatched square with solid borders.

On the top boundary, we mimic the tidal forcing kinematically by imposing velocity in the y direction (periodic in time with the tidal period). The right and the bottom sides are taken as free-slip boundaries. The left boundary representing the fault is approximated through a Navier-slip boundary condition with an effective friction coefficient approximating the activated stick-slip frictional contact with given yield stress. In terms of the traction in the y-direction at the fault, i.e. $\mathbb{T}_{xy}$ component of the Cauchy stress tensor $\mathbb{T}$, we consider the following two regimes:

1. Traction below yield limit, no sliding:
   $|\mathbb{T}_{xy}| < \sigma_Y \Leftrightarrow v_{slip} = 0$,

2. Traction at the yield limit, sliding occurs:
   $|\mathbb{T}_{xy}| = \sigma_Y \Leftrightarrow v_{slip} \neq 0$.

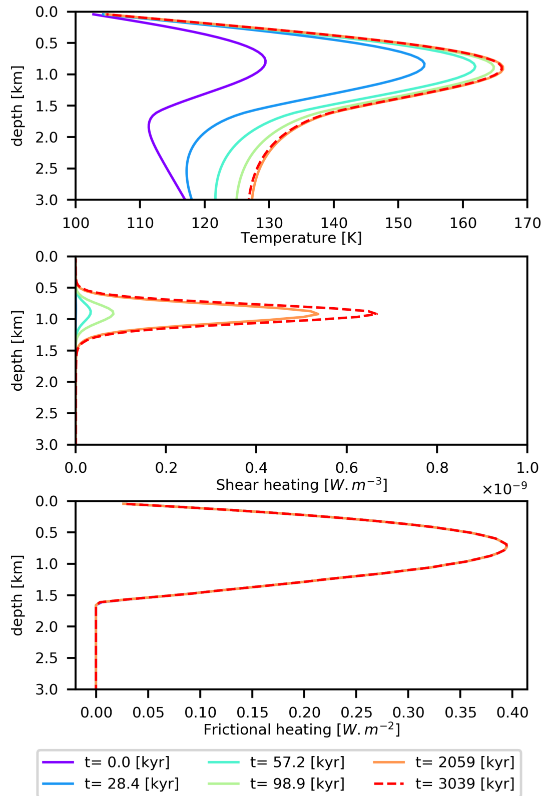

Figure 2: Time evolution of the reference run: temperature, shear and frictional heating are plotted along the fault for different times - denoted by color. Dashed line represents the steady state.

The considered yield stress σ_Y is of a Coulomb type with a constant coefficient of friction μ_f and the normal stress being approximated by overburden pressure, i.e. we assume $\sigma_Y = \mu_f \rho g h$, where h denotes the depth, ρ is the ice density and g is the magnitude of gravity acceleration. The above described model is approximated by a (continuous) Navier-slip boundary condition with an effective friction coefficient β_{eff}:

$$\mathbb{T}_{xy} = \beta_{\text{eff}}\, v_{slip}\,, \quad \beta_{\text{eff}} = \frac{\beta^*}{\left[1 + \left(\frac{\beta^* |v_{slip}|}{\sigma_Y}\right)^{\alpha}\right]^{1/\alpha}},$$

where β^* is an auxiliary friction coefficient parameter, effective in low slip velocity limit and α is an (integer) parameter. The numerical solution is carried out using the open source finite element software package FEniCS [1].

3. Results

Our simulations indicate that the loading velocity determines whether or not meltwater is generated. As a reference value, we choose 1×10^{-5}m.s^{-1}, roughly corresponding to the surface displacement of one meter per orbit. For this value, no meltwater appears, see Fig. 2. With the loading velocity increased by fifty per cent, we obtain three per cent of porosity localised at the fault. On the other hand, varying the friction coefficient modulates the depth of the fault and slip velocity, but it does not significantly affect the water production.

The negligible amount of produced meltwater and absence of any partially molten bulk regions can be explained by the fact that the frictional heating dominates over the shear heating in our simulations (Fig. 2, bottom). Frictional heating is localized at the fault, and once melting is initiated there, further heating of the fault's vicinity is prevented by latent heat consumption. We consider exponential weakening of the frictional contact with the amount of meltwater, which provides strong negative feedback, thus limiting the maximum amount of meltwater that can be produced by this mechanism. In [4] the shear heating in a viscous vicinity of the fault tip was substantial due to the presence of shear singularity. However, for deformation on the tidal time scale, the use of visco-elastic rheology is more appropriate, and our simulations demonstrate that most of the tidal deformation in the fault's vicinity is in the elastic regime, not contributing to dissipative heating.

To conclude, we have developed a numerical model that couples the tidally induced viscoelastic deformation with the frictional contact at the fault and the two-phase convection. Our results show that producing meltwater by shear and frictional heating in the vicinity of strike-slip faults on Europa is possible, but the meltwater is localized at the fault plane, and its amount does not exceed few per cent. Generation of larger shallow subsurface water reservoirs by this mechanism appears very unlikely.

Acknowledgements

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