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Water accumulation below Europa's strike-slip faults

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Abstract

The onset of melting below Europa's recently active strike-slip faults and the gravitational/thermal stability of partially molten ice are investigated by solving the equations for a two-phase compressible mixture of water ice and liquid water in 2D geometry. As a first step, the relative motion between ice and water is neglected, i.e. the meltwater is transported by the flowing ice. Our preliminary results suggest that for sufficiently large shear heating rate of $\sim 2\times 10^{-4}$ W m^{-3} melting can occur at depths as shallow as $\sim$3 km below Europa's surface. Moreover, the reservoirs of partially molten ice with $\sim$5–10% of liquid water can remain within the cold lid for a few hundreds of kiloyears if the underlying ice is sufficiently cold (viscous) and free of fractures.

1. Introduction

Tidal forces due to its eccentric orbit around Jupiter play a significant role in the thermal-orbital evolution of Europa. The associated deflection results in strong heating due to viscous friction which is mostly located in the warm convective part of the ice shell [1] and also along tidally-activated strike-slip faults in the upper part of the ice shell [2]. This heating might locally be strong enough to produce liquid water. The presence of large water lenses at shallow depths may possibly explain the formation of chaos terrains [3], observed in different locations on Europa's surface, as well as the ubiquitous double ridges [4].

The localization of water production and the efficiency of its extraction depend strongly on the thermal structure of the ice shell. In our previous study, we have examined ice melting and subsequent meltwater transport by two-phase flow in a simplified 1D geometry [5]. We found that partially molten reservoirs are not stable at the top of hot plumes. On the other hand, our 1D results suggested that liquid water might accumulate in cold conductive regions subjected to strong shear heating. Here, we concentrate on the latter case (melting at strike-slip faults) and investigate the stability of partially-molten regions in 2D Cartesian geometry.

2. Numerical model

The equations for two-phase flow of a compressible mixture of water ice and liquid water [6] are employed. These allow us to consistently address melting of ice and the subsequent meltwater transport by a combination of porous flow of water through the partially-molten ice matrix and convective Rayleigh-Taylor instabilities. In this work, as a first step, we neglect the relative motion between the ice matrix and the meltwater and consider the impermeable limit of the governing equations (by setting ice permeability equal to zero), thus concentrating on the transport of meltwater that is locked within the ice matrix - for this reason (i.e. assuming no porous flow), the residence times for liquid water should be considered as upper limits. A similar model has already been used in [1], but our approach allows the ice matrix to compact viscously when melting starts.

While water density and viscosity are kept constant and ice density is assumed to depend on temperature only (Boussinesq approximation), the ice viscosity is prescribed as a function of temperature, stress, (constant) grain size, and fraction of water [1,7]. Heating at the strike-slip fault is prescribed as a smooth function of coordinates with a maximum of 2×10^{-4} W m^{-3} [2] located in the middle of a domain 3 km below the surface, and is decreased with increasing amount of water. In some simulations, viscosity-dependent volumetric tidal heating [1] is considered.

3. Results and summary

In our reference simulation with grain size d=0.7 mm and considering only shear heating on the fault (i.e. assuming no volumetric tidal heating), melting starts at a depth of about 3 km below Europa's surface. The porosity (water volume fraction in the ice-water mixture) at the end of the simulation ($\sim$1900 kyr after the onset of melting) is depicted in the top panel of Figure 1. Even though the partially molten reservoir of few ($<$10) percents slowly propagates downwards due to the negative buoyancy of liquid water, the majority of produced meltwater is located in the top 10 km.

For a very small grain size, d=0.1 mm, which can be considered as a lower limit for Europa [8], melting starts at about the same place as in the reference case, however, due to small viscosity below the fault (of the order of 10^{13} Pa s), the partially molten region is not gravitationally stable and collapses downwards after less than 500 kyr from the onset of melting (middle panel of Fig. 1).

Finally, the viscosity-dependent tidal heating with the maximum amplitude of 5×10^{-6} W m^{-3}, which is the mean value for Europa [1], is introduced into the simulation with grain size d=0.7 mm. Melting starts again a few kilometers below the surface and, only a few tens of kiloyears later, the melt appears also at the bottom boundary (and accumulates there since water can only be advected by ice and the bottom boundary is prescribed to be impermeable for ice flow). Due to the faster temperature increase and the associated viscosity decrease below the fault, the partially molten material is less stable than in the simulation without volumetric heating and starts to collapse downwards - approximately 1700 kyr after the onset of melting, the majority of meltwater generated at the fault has already collapsed and is located at depths larger than 10 km (bottom panel of Fig. 1).

Overall, our results suggest that liquid water may be produced only a few kilometers below Europa's surface due to viscous friction at active strike-slip faults. The partially molten reservoirs with ∼5–10% of liquid water might remain within shallow depths for several hundreds of kiloyears, provided that the underlying ice is sufficiently viscous (with grain sizes of at least ∼0.7 mm) and cold (with small, i.e. $<5\times10^{-6}$ W m^{-3}, tidal heating amplitudes). The presence of melting-temperature lowering salts [9], especially in the cold upper part of the ice shell, might lead to earlier onset of melting and longer term stability of these reservoirs. The inclusion of plasticity and a more realistic parametrization of shear heating at the fault may also influence the lifetimes of water lenses. Progress in modeling these different effects and the consequences for melt stability will be presented at the meeting.

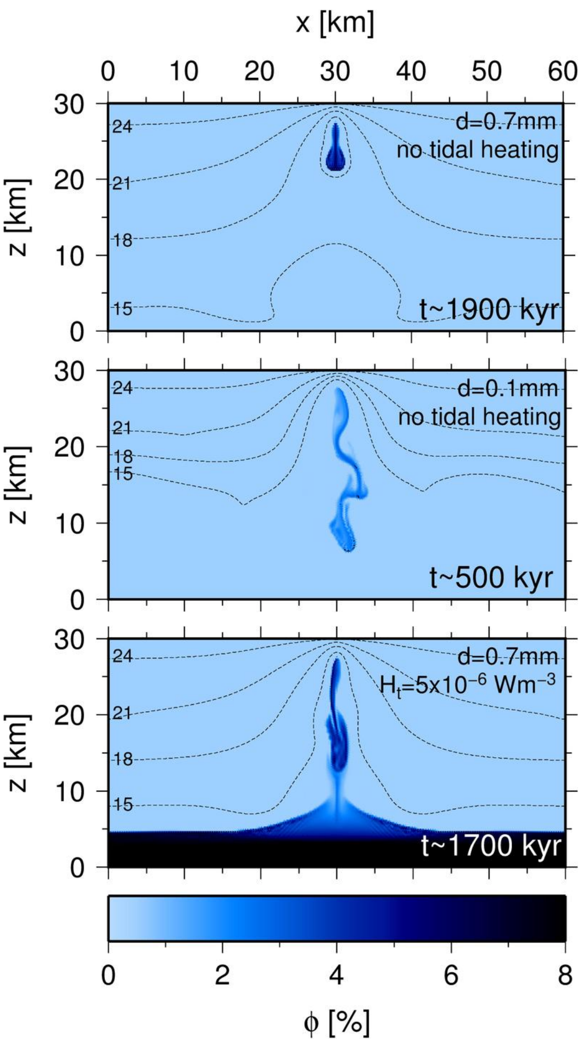

Figure 1: *Top*: Porosity at the end of the simulation with d=0.7 mm and no tidal heating. Time is counted from the onset of melting. Contours depict the logarithm of ice viscosity in Pa s. *Middle*: The same as above but for d=0.1 mm. *Bottom*: The same as above but for d=0.7 mm and $H_{\mathrm{t}}=5\times10^{-6}$ W m^{-3}.

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