EPSC Abstracts
Vol. 11, EPSC2017-466, 2017
European Planetary Science Congress 2017

Water generation and transport through the high-pressure ice layers of Titan and Ganymede

K. Kalousová (1), C. Sotin (2), Gaël Choblet (3), Gabriel Tobie (3), and Olivier Grasset (3)
(1) Charles University, Department of Geophysics, Prague, Czech Republic (kalous@karel.troja.mff.cuni.cz),
(2) Jet Propulsion Laboratory-California Institute of Technology, Pasadena, USA,
(3) Laboratoire de Planétologie et Géodynamique, Université de Nantes, CNRS, France.

Abstract

We investigate the generation and transport of water through the high-pressure (HP) ice layers of Ganymede and Titan using a numerical model of two-phase convection in 2D geometry. Our results suggest that water can be generated at the silicate/HP ice interface for small to intermediate values of Rayleigh number (Ra$\sim10^8$–10^{10}) while no melt is generated for the higher values (Ra$\gtrsim10^{11}$). If generated, water is transported through the layer by the upwelling plumes and, depending on the vigor of convection, it stays liquid (smaller Ra) or it may freeze (intermediate Ra) before melting again as the plume reaches the temperate layer at the interface with the ocean. The thickness of this layer as well as the amount of melt that is extracted from it is controlled by the HP ice permeability. This process may enable the transfer of volatiles and salts that might have been leached from silicates by the meltwater. Since the HP ice layer is much thinner on Titan than on Ganymede [1], it is probably more permeable for volatiles and salts leached from the silicate core.

1. Introduction

The exploration of ocean worlds is prompted by the question of the emergence of life in places where liquid water has been present. A lot of attention is currently given to Europa and Enceladus where the subsurface ocean is expected to be in a direct contact with the silicate mantle [2,3]. Ganymede and Titan, the largest icy moons in the solar system, are believed to possess larger amounts of H_2O so that a layer of HP ice is predicted in their interior that seems to prevent this direct contact [4]. These two moons are very similar in mass and radius but their radial mass distribution is quite different. Ganymede is likely the more differentiated body with a five layer structure (ice I crust, ocean, HP ice layer, silicate mantle, liquid iron rich core [5]) while Titan is probably less differentiated with a rocky core made of hydrated silicates [6].

While the bulk of the deep HP ice layer prevents a direct contact between the ocean and the silicates, the heat and material exchange between these two layers might still be possible. Recent 3D numerical simulations of thermal convection in the HP ice mantles of large moons [7] indicate the occurence of melting for a broad range of model parameters. However, melt transport is not included in these models and instantaneous melt extraction is hypothesized. Here, we study the dynamics of the HP ice layers of Ganymede and Titan using 2D numerical simulations of two-phase convection that allow us to address the meltwater generation and its transport neglected in the previous study.

2. Numerical model

We treat the layer material as a mixture of two components - solid ice matrix and liquid water which allows us to consistently address melting of ice and the subsequent meltwater transport. Dynamics of such a mixture is described by the equations derived in [8]. Depending on the connectivity of the interstitial water veins system, meltwater can either percolate through the convecting matrix (if the pores are connected) or be locked within the deforming ice and advected by it. The governing equations combine the compressible Stokes system with the advection of temperature and transport of water content by convection and porous percolation. The numerical code is implemented in the open source FEM software FEniCS [9].

3. Results and summary

We computed the reference solution with the layer thickness H=200 km, reference viscosity $\mu_0=10^{15}$ Pa s, bottom heat flux q_s=20 mW m^{-2}, and percolation threshold ϕ_c=1% - our results are depicted in the middle row of Figure 1. The left panel shows the temperature profiles (red - maximum, black - horizontal average) while the right panel shows porosity (volume fraction of water in the mixture). The layer can be divided into three regions: (i) interface with silicates ($T_\mathrm{av}=T_\mathrm{m}$, thin layer with $\phi_\mathrm{av}\lesssim1\%$ present);

(ii) convective interior ($T_{\mathrm{av}} < T_{\mathrm{m}}$, a small amount of melt present in the upwelling plumes); and (iii) top temperate layer and interface with ocean ($T_{\mathrm{av}} = T_{\mathrm{m}}$, $\phi_{\mathrm{av}} \sim 1\%$). Let us note that even though melt is present at the bottom boundary and that water is extracted to the ocean, there is no direct fluid path through the whole layer.

Changing the HP ice layer thickness H changes the convection pattern. While for H=100 km (Figure 1, top), we observe a two-cell convection with two upwellings stable in time that transport water through the layer, for H=300 km (Figure 1, bottom), no water is present at the bottom boundary or within the upwellings. This effect of the layer thickness H is similar to that of the reference viscosity μ_0 in a sense that it significantly changes the Rayleigh number. On the other hand, the heat flux from silicates has a second order effect. The thickness of the top temperate layer as well as amount of extracted melt is controlled by the HP ice permeability.

We can distinguish 3 melt patterns: (i) **Direct connection** between the silicates and the ocean, characteristic for a small value of Rayleigh number (small layer thickness, large reference viscosity) - in this case, the melt produced in the contact with silicates is advected through the convecting layer by the upwelling plumes that are stable in time and space and more melt might be produced before its majority is extracted into the ocean; (ii) **Indirect connection** between the silicates and the ocean (reference case) - melt generated at the bottom boundary freezes and melts again during its ascent before being extracted into the ocean; (iii) **No melt** is produced at the silicate/HP ice interface for large values of Rayleigh number (large layer thickness, small reference viscosity) - the heat transfer by solid state thermal convection is so efficient that the temperature at the interface with silicates is below the melting point.

Overall, we show that water can be generated at the silicate/HP ice interface for small to intermediate values of Rayleigh number. Once generated, the water is transported through the layer by the upwelling plumes. Depending on the vigor of convection, it stays liquid or it may freeze before melting again as the plume reaches the temperate layer at the boundary with the ocean. The thickness of this layer as well as the amount of melt that is extracted from it is controlled by the HP ice permeability. This process constitutes a means of transporting non-ice material that might have dissolved into the melt present at the silicate/HP ice interface. As the moons cool down, their HP ice layers become less permeable because they thicken. Also, since a thinner HP ice layer is expected on Titan than on Ganymede, our results indicate that the transport of volatiles from the silicate interior to the deep liquid water ocean may have played a more important role in the evolution of Titan.

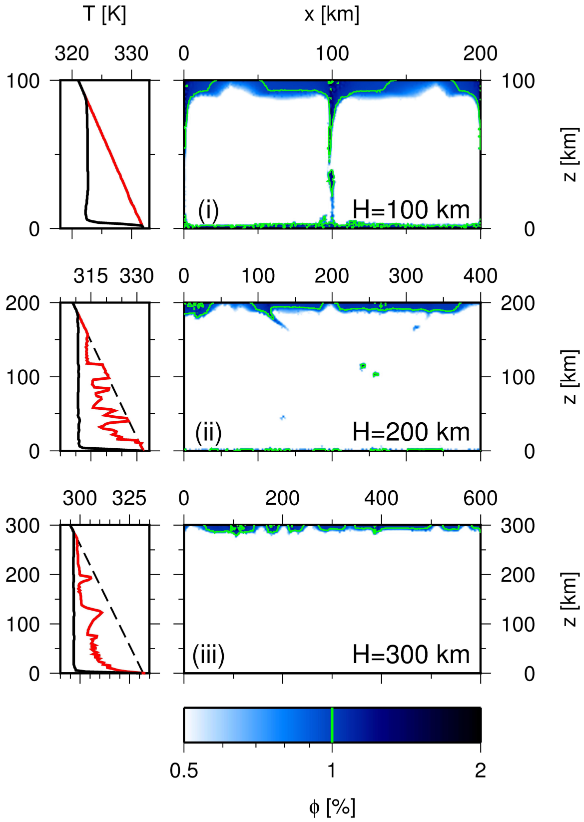

Figure 1: Results for different HP ice layer thicknesses H: 100, 200, and 300 km (top to bottom). *Left*: Temperature profiles - maximum (red) and horizontal average (black). The dashed lines mark pressure-dependent melting temperature (T_{m}). *Right*: Porosity. Numbers in the bottom left corners indicate the melting pattern (cf. text).

Acknowledgements

KK received funding from the Czech Science Foundation through project 15-14263Y. CS is supported by NAI Icy Worlds. This work was also supported by the IT4Innovations Centre of Excellence project (CZ.1.05/1.1.00/02.0070).

References

[1] Sotin & Kalousová (2016), AGU, abstract #P33F-02. [2] Schubert et al. (2009), *Europa*, pp. 353–367. [3] Thomas et al. (2016), *Icarus*, **264**, 37–47. [4] Hussmann et al. (2015), *Treatise on Geophysics*, **10**, 605–635. [5] Schubert et al. (1996), *Nature*, **384**, 544–545. [6] Castillo-Rogez & Lunine (2010), *GRL*, **37**. [7] Choblet et al. (2017), *Icarus*, **285**, 252–62. [8] Souček et al. (2014), *GAFD*, **108**, 639–666. [9] Logg et al. (2012), The FEniCS Book.