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Review of the PhD thesis
Tidally-induced deformation of icy Moons
by Kateřina Pleiner Sládková

The thesis submitted by Kateřina Pleiner Sládková presents a large body of modelling work dedicated to describe various surface features of Europa and Enceladus. Using sophisticated models of viscoelastic deformation, possibly coupled with viscous flow, Kateřina investigated the feedbacks between tidal loading and dissipation leading to melting of Europa's ice shell. Additionally, she delved into the mechanics governing the deformation in the south polar region of Enceladus.

I really enjoyed reading this thesis, which is very well written and largely understandable also for non-experts. The motivation and context of the study are always clearly introduced. The numerical experiments are carefully designed, described, and analysed. The results, whether positive or negative, offer important insights for future research.

The first chapter of the thesis introduces the main surface features of Europa and Enceladus, briefly touching upon the tide-related physical mechanisms underlying various observations. This chapter is quite compact, but also informative and complete. It offers a quick and clear view of the open issues in understanding the geology of these two bodies, effectively highlighting uncertainties and knowledge gaps. It is clear that Kateřina assimilated a large body of geological literature and was able to summarise it effectively and precisely.

The second chapter is dedicated to the numerical modelling of ice deformation on Europa. The work is motivated by two overarching questions, namely how to generate sub-surface meltwater that may be required to explain the formation of double ridges and chaotic terrains, and how to explain lateral offsets of certain structures that may be associated with strike-slip deformation of surface units.

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With respect to the problem of meltwater generation, Kateřina chose an approach that builds upon the work of Nimmo and Gaidos (2002) to setup a strike-slip fault, and Kalousova et al. (2016) to treat the viscous deformation and melting of the ductile part of the ice domain. She extended both above works in several important ways, including the use of a Maxwell rheology to treat the deformation at tidal frequencies, the self-consistent modelling of fault activation, and the thermal coupling with a 2-phase flow code to simulate melting and viscous flow in response to shear heating.

The continuum mechanics and fluid dynamics theory of the problem as well as the approach to solve it numerically are laid out with clarity. Despite the quite significant complexity of the model, all the details that would be necessary to reproduce the numerical experiments are well described. The modelling setup along with all approximations and simplifications are clearly presented and easy to follow. I really appreciated that, where necessary, Kateřina didn't refrain from spelling out the weaknesses of the numerical model, discussing possible ways to overcome them in future works.

After various benchmark comparisons, Kateřina presents the results of a parameter study aimed at assessing the formation of meltwater in dependence of the loading velocity and friction coefficient. The main conclusion is that the magnitude of heating and meltwater produced by this mechanism is typically never large, if not negligible. Perhaps, introducing a quantitative threshold (for example in terms of porosity or melt production rate) that the models should have exceeded to be considered "successful" might have been a useful addition. Overall, the results were considered negative, which is the reason why they were not published. Nevertheless, they contain significant insights that in my opinion would have warranted their publication. In particular, they show the importance of scrutinising apparently successful but rather simplistic models, revealing their limitations when extended to incorporate all relevant physics, which I believe is something worth sharing within the geophysics community

With respect to the problem of surface offset generation, Kateřina simulated numerically the concept of "tidal walking" introduced by Hoppa et al. (1999). The work presented in the thesis forms a publication that appeared in JGR Planets. Kateřina used a modified version of the above numerical model in which the viscoelastic part was extended to account for time-varying normal and tangential stresses, and the viscous part was simplified for numerical reasons to a single-phase flow model. Such a setup was the first attempt at simulating tidal walking in the frame of a coupled thermo-mechanical, and not purely mechanical, model. Kateřina conducted a comprehensive study, where she assessed the influence of ice shell thickness, forcing amplitude, stress phase shift, and friction coefficient on the accumulation of lateral displacement along the fault. By analysing first, a purely mechanical model, and then the full thermo-mechanical model, she concluded that large displacements compatible with observations can only be achieved upon imposing stress amplitudes about an order of magnitude larger than present-day diurnal stresses, which would also lead to sizable heat flux anomalies associated with ice melting. The chapter is concluded by an extensive and informative discussion and by quantitative tests of a number of additional factors and model modifications that can enhance the efficiency of tidal walking as a source for meltwater generation. An important conclusion is that measuring high heat flux anomalies could be an indicator of active strike-slip faulting. In this particular context, it may have been beneficial to include explicit mentions of the Europa Clipper mission, along with a discussion of which measurements would be pertinent for refining the models presented here.

Chapter 3 contains a detailed 3D modelling study of the mechanics of Enceladus' "tiger stripes". Kateřina modelled the dynamics of faults subject to periodic tidal stresses, including, for the first time, the influence of finite friction. The work, which was published in Geophysical Research Letter, extends a series of previous modelling efforts where faults were considered but, different from the present work, the effects of friction were neglected. The theoretical treatment is very rigorous and clearly presented. Kateřina employed a compressible viscoelastic model and introduced a plastic viscosity formulation based on a stress limiter to simulate a spring-slider system that can effectively mimic the mechanical behaviour of a fault with friction. The inclusion of faults amplifies the deformation field in their proximity, suggesting that gravity and altimetry measurements could serve as indicators for inferring the friction coefficient because of the strong impact of this parameter on the model outcomes. This finding is particularly intriguing and might have warranted some further discussion, delving into its implications for existing and future measurements. An additional important finding is that the viscoelastic system coupled with faults and under periodic loading inherently generates a static background stress field overlaid with a time-dependent stress component arising from the intricate geometry and interactions among the faults. While extremely interesting from a theoretical standpoint, it remains to be determined to what extent this behaviour could be verified through some specific observations.

Chapter 4 begins with a thorough review of a number of seminal papers on the interpretation of laboratory experiments on sheared rocks and ice, aimed at characterising the contact region of faults. The chapter continues with a very interesting linear stability analysis of the so-called "rate and state" model of ice-ice friction introduced by Lishman et al. (2011), where the friction coefficient depends on the slip velocity and a memory effect of the contact region is accounted for through an evolving state variable. This model is applied to the spring-slider system, which is shown to exhibit divergent or convergent behaviour depending on the choice of the spring stiffness parameter. Finally, similar to Chapter 3, a series of numerical benchmark tests of the spring-slider model formulated through a Maxwell rheology with stress limiting, plastic viscosity is presented. Although this model wasn't applied to the simulation of Enceladus tiger stripes, it provides a very solid base upon which future work can be built. The thesis is then concluded by a short section, where the key findings are summarised.

Overall, the thesis and the publications that resulted from it are an important contribution to the literature on icy moons modelling. They contain a number of original and useful ideas that can be applied not only to Europa and Enceladus, but to icy bodies in general. The quality of the work and of the presentation are very high throughout the thesis, with the novel material that is introduced in a logical way after carefully reviewing the existing literature and building upon it. This work clearly demonstrates that Kateřina developed all the necessary skills to conduct original research of the highest quality in planetary physics. Therefore, I fully recommend the thesis to be accepted as a PhD work.

A series of specific comments and questions is listed below:

1. The viscous rheology used in the model of Chapter 2 accounts for several deformation mechanisms, including non-linear ones, that depend on a number of parameters that have been kept constant. How well are all these parameters known (from experiments and/or geophysical inference)? Is there one specific mechanism that dominates at certain conditions? And, in general, to what extent is it necessary to employ such a complex composite rheology to obtain an accurate representation of shear heating?

2. In Chapter 2, a viscoelastic model was adopted to treat the short-term deformation at tidal periods, while a purely viscous model was applied to treat the flow at longer timescales. However, even at these timescales, elasticity might have an influence on the deformation, possibly affecting the stress field in the coldest part of the ice shell. Could viscoelastic convection affect the production of meltwater and in turn have an influence on the deformation at tidal periods?

3. In the 2-phase flow approach used in the first part of Chapter 2, the “impermeable limit” is used, according to which the solid and liquid phase are transported with the same velocity. Yet, water and ice don’t have the same density and I would expect water percolation to play at least some role. What can be the consequences of this approximation? And, more in general, since the 2-phase flow approach was dropped in the second part of the study on Europa, how critical is it to account for it in this type of modelling?

4. With Europa Clipper scheduled for launch in October 2024 and an Enceladus “orbilander” recommended as a future flagship mission in the last Planetary Science Decadal Survey, there’s a variety of new observations that will be made at Europa and possibly at Enceladus too. What kind of measurements would be most beneficial to better constrain and improve these models?