EPSC Abstracts
Vol. 12, EPSC2018-622, 2018
European Planetary Science Congress 2018

Enceladus' interior, tectonics, and evolution from tidal analysis

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Abstract

Enceladus is a puzzling world. It has an extreme dichotomy in tectonic activity, with the south pole currently and spectacularly active and the north pole heavily cratered with relatively little tectonism. While tidal stresses have been proposed as a mechanism for controlling plume eruptions, few studies have assessed the role of tidal stress in the formation of the south polar fractures. With regard to Enceladus' interior structure, neither tidal heating models nor analyses of the timing of plume eruptions have matched the current estimates of a very thin shell at the south pole of 12 km or less. Here, we determine the thickness and rheology of Enceladus' ice shell that can best explain the north-south tectonic dichotomy and the orientations of the Tiger Stripe Fractures (TSFs). We compute and evaluate tidal stresses for a suite of interior structure models, and conduct a statistical analysis of each model's ability to reproduce the orientations of the TSFs. We find that the TSFs are strongly correlated with the tidal stresses, implying that tides played a key role in their formation. We further find that, at the time the TSFs formed, Enceladus most likely had a globally thick, convecting ice shell that was at least ~10 km thick at the south pole and ~20 km or thicker at the north pole. As the south polar terrain (SPT) is quite young, and the TSFs are among the youngest features in the region, we expect these conditions are indicative of the present day. We discuss additional constrains and implications, particularly on the failure process and the long-term changes in Enceladus' ice shell.

1. Introduction

Enceladus has an eccentric orbit that can drive daily-varying tidal stress, a global liquid water ocean, and a young, pervasively-fractured region at its south pole [1]. The south polar terrain (SPT) is made up of a background of densely-packed fractures, overlain by a more organized set of fractures [2]. The most prominent of these fractures are called the Tiger Stripe Fractures (TSFs), which are roughly parallel but also have segments that deviate from the orientations of the main set [1]. Plumes emanate from both the main branches and some of these other segments [3][4][5]. The eruptive output of the plumes varies with Enceladus' tidal cycle [6], implying that tides control the eruptions [7][8]. The formation of the Tiger Stripe fractures (TSFs) has also been attributed to tidal stresses [e.g 7], although a non-tidal origin has also been suggested [9]. Curiously, Enceladus' north pole is heavily cratered and displays limited tectonic activity. As tides are a symmetric process, explaining the dichotomy in activity is a challenge.

The magnitude of tidal stress depends on the structure and responsiveness of Enceladus' interior. However, there is no consensus on the interior structure. Model fits to Enceladus' observed librations support a variable shell thickness that is ~12 km at the south pole and thicker at the north pole by ~10 km. Fits to the gravity data provide a range of values depending on the model assumptions, from roughly 10 km or thicker at the south pole [10][11] to a few km or less [12], with the north pole always being thicker than the south. To obtain constraints on Enceladus' interior structure, and better understand what governs tectonic activity on Enceladus, we conduct two related investigations: 1) we identify differences in interior structure that would promote tidally-driven fracturing near the south pole while inhibiting fracturing near the north pole, and 2) identify interior structures, and corresponding tidal stresses, that best match the observed orientations of fractures in the south polar terrain (SPT).

2. Approach

To compute tidal stresses in our layered models, we used the methods of [13], which we have previously applied to Charon [14] and Mimas [15]. We developed interior structure models with ice shell thicknesses of 500 m to 22 km, which spans the range of values inferred for the north and south poles from Enceladus' libration, shape, and gravity [10-13]. We also varied the viscosity of the lower, ductile part of the ice shell and the fraction of the shell that behaves brittlely. Our past work has shown that these parameters have the largest impact on the resulting tidal stresses.

We used the magnitudes of tidal stresses produced with each model to determine the conditions by which tidal fractures would likely form in the south but not in the north, using Europa as a comparison point. We then computed the orientations at which tensile cracks would form, in response to tidal stress, at thousands of individual locations along the TSFs. We applied statistical tools to assess how well the model predictions fit the observed orientations and identified the model that produces the best overall fit.

3. Results

After testing 27 different interior structure models, we find that most models produce stresses comparable to, or greatly exceeding, the magnitude of tidal stress on Europa, which is globally fractured by tidal stress [e.g. 16]. Hence, it is more challenging to explain the limited fracturing at the north pole than the extensive fracturing at the south pole. We find that the north-south tectonic dichotomy can be explained in two ways: 1) a >10 km thick, convecting ice shell at the north pole and a ~5 km thick (or thinner), conducting shell at the south pole or 2) a globally thick, convecting ice shell that is at least 10 km thick in the south and at least 20 km in the north. In either case, to inhibit extensive fracturing in the north, we find that the viscosity of the convecting portion of the ice shell must be somewhat higher in the north (10^{14} Pa*s or higher) than in the south.

When we compare the tidal stress orientations with the orientations of the TSFs, we find that models with a thick shell at the south pole, between 10 and 20 km, provide far superior fits to any of the thin shell models. We also find that, across all models, the TSF orientations are highly correlated with the tidal stress orientations, implying that tidal stresses did play a key role in their formation.

4. Discussion and Conclusions

Our analysis supports a tidal origin for the Tiger Stripe Fractures and an ice shell that is at least 10-20 km thick at the south pole. These results are consistent with interpretations of Enceladus' observed librations and gravity data [10][11], although some more recent studies suggest a much thinner shell at the south pole [12]. Our results are also compatible with the hypothesis that Enceladus' ice shell was thinner in the past, particularly at the south pole, and that it has thickened with time. We find that changes in ice shell thickness can lead to changes in the expected orientations of tidally-driven fractures. Hence, detailed analysis of older fracture sets in the SPT may provide more evidence of its evolution.

If the ice shell at the south pole is found to be less than a few km thick, it would suggest the TSFs were formed by a combination of stresses from tides and an additional, non-uniform source [e.g. 17], and that the exclusion of that stress in our models has led to a preference for a thick shell. We also note that our failure model is rather simplistic, and higher fidelity modeling may improve our understanding of the formation of fractures in the SPT.

Acknowledgements

We wish to thank Michael Bland for helpful discussions about convection in ice shells and the Ocean Worlds Cooperative for their feedback and support.

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