THE RELATIONSHIP BETWEEN ENCELADUS’S DIURNAL CRUSTAL DEFORMATION AND MEAN ICE SHELL THICKNESS

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Introduction: Mean Ice Shell Thickness (MIST) places first-order constraints on several geodynamical quantities at ocean worlds such as heat budget, core size, and potential for habitability [1–3]. Topographic feature analysis, libration measurements, and/or joint gravity-topography analyses allow MIST estimates accurate to within ~25% at Europa and Enceladus. However, each of these methods rely on fortuitous dynamical and structural conditions at investigated bodies and restrictive assumptions regarding interior structure [9–11]. A non-degenerate, universally applicable, and precise way of constraining MIST from measurements is therefore desirable for future investigations at these and other ocean worlds.

Short-period shell deformation analysis (SPDA) is a novel and potentially powerful method for constraining MIST. Shell response to diurnal eccentricity tidal forcing is highly sensitive to its effective bending stiffness (hence, MIST). Measurements of short-period radial surface displacement or deformation-induced time-variable gravity can therefore be used to invert for MIST. SPDA has several advantages over other methods. For example, estimates of MIST are relatively insensitive to assumptions about the deeper interior. In addition, gravity and displacement data allow for independent SPDA analyses which substantially reduces propagated uncertainty compared to methods which consider both measurements jointly. Finally, the amplitude of diurnal radial surface displacements fall within a measurable range (0.1–10 m) for most ocean worlds so that missions do not rely on fortuitous conditions for acquiring useful data for MIST inversions.

Because of its reliance on mapping elastic deformation to MIST, SPDA requires accounting for large-scale non-spherically symmetric structures (‘lateral heterogeneities’) such as variations in ice shell thickness and the presence of major fault structures. To date, few studies specifically perform an SPDA which accounts for these features. Early studies of SPDA developed analytic expressions for calculating diurnal (eccentricity-tidal) love numbers $k_2$ and $h_2$ (i.e., parameterizations of shell shape and gravitational response, respectively) [4] but exclude lateral heterogeneities from their analysis. Following on this work, [5] developed analytic expressions of diurnal $k_2$ and $h_2$ from structural parameters accounting for thickness variations but invoke thin-shelled approximations and exclude the impact of faults. The most sophisticated models to date [6–8] simulate deformation using finite-element shell models with both thickness variations and faults, but do not specifically investigate the relationship between deformation and MIST. Here, we explicitly explore the coupled effects of thickness variations, faults, and MIST on shell response. Such an analysis is crucial for reliably constraining MIST from geodetic measurements of shell deformation in the future.

In this work, we simulate deformation on tidally-loaded quasi-spherical shells using a model which incorporates the effect of lateral heterogeneities. To run simulations, we use the finite-element code Pylith [13], a widely-benchmarked software which incorporates the effects of faulting on deformation. We compare results from four sets of models that vary in the complexity of the shell structure: (1) shells which are radially symmetric (‘Base’), (2) shells with thickness variations (‘LTV’), (3) shells with faults (‘Faults’), and (4) shells with both thickness variations and faults (‘Faults + LTVs’). For each of these families of models, we extract shell structural parameters, fault locations, and thickness variation information from geologic and

![Figure 1: $h_2$ and $k_2$ vs. Mean Shell Thickness (MIST) for Base models, LTV models, Faults models, and Faults + LTV models. We generate curves by simulating deformation on finite element models with no faults or lateral thickness variations (Base), Faults (‘Faults’), Lateral Thickness variations (LTV), and both Faults + LTV for a range of MIST values.](https://example.com figure1.png)
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[1] Roberts and Nimmo (2008), Icarus,
hounkova, and Cadek (2016), Icarus, 328 [7] Be-
hounkova, Soucek, Hron, and Cadek (2017), Astrobiol-
ogy, 17(9) [8] and Soucek et al. (2019), Icarus, 328 [9]
Thomas et al. (2016), Icarus, 264 [10] Hemingway and
344 [12] Segall, P. (2010), Earthquake and volcano de-

Figure 2: Top Row: Difference in the second deviatoric
strain invariant between Base and Faults+LTV
models across a range of MIST values. Blue regions cor-
respond with areas of en-
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Faults + LTV. Bottom Row:
Fault slip corresponding to
deformation patterns. Blue
indicates regions of left-lateral fault slip.