

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

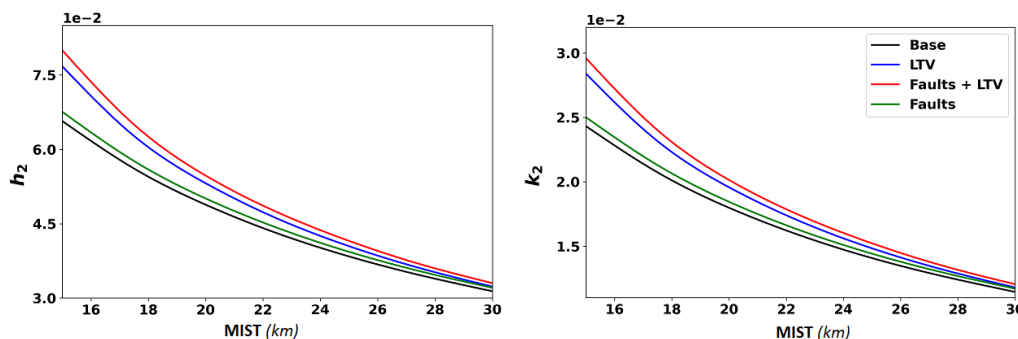


Figure 1: h_2 and k_2 vs. Mean Shell Thickness (MIST) for Base models, LTV models, Faults models, and Faults + LTV models. We generate curves by simulating deformation on finite element models with no faults or lateral thickness variations (Base), Faults ('Faults'), Lateral Thickness variations (LTV), and both Faults + LTV for a range of MIST values.

topographic data at Enceladus. We parameterize shell response by calculating model-derived values of Love numbers k_2 and h_2 . We specifically investigate the relationship between MIST and shell response across a range of MISTs and identify trade-offs between heterogeneity-induced deformation and the influence of MIST. In addition, we identify the characteristic deformation patterns associated with local thickness variations and faults and discuss implications for enhanced deformation along these structures.

Results: The relationship between MIST and response is fairly robust; Figure 1 shows that lateral heterogeneities contribute a maximum variability in prediction in mapping a given value of k_2 and h_2 to a given value of MIST of about 16% in the most extreme case (i.e., MIST= 15 km, Faults+LTV model). The range of possible MIST values for a given measurement of k_2 or h_2 falls off rapidly to less than 7% for MIST values above 20 km (real values of MIST at Enceladus are currently expected to lie between 21–26 km (Thomas et al. 2016). This prediction uncertainty for MIST inversion compares favorably with the uncertainty bounds produced from analysis of shell libration (25% of MIST value) [9] or admittance (25–100% of MIST value) [10–11].

Model results demonstrate that heterogeneities produce different modes of deformation. Thickness variations appear to most substantially influence long-wavelength response. According to Figure 1, LTVs for shell models with MIST values below 20 km incur changes to k_2 and h_2 of up to 15% of these parameters' value. Moreover, LTVs broadly result in local enhancements in deformation in thinned regions and vice versa in thicker regions (Figure 2). Faults contribute to long-wavelength deformation to a lesser degree than do thickness variations. The maximum contribution of

fault structures to k_2 and h_2 values is about 3% of their total value (Figure 1). This slight enhancement follows from Figure 2 which shows that fault-induced deformation creates a strong double-couple displacement pattern producing maximal radial displacement at the fault tips (Figure 2, top) consistent with slip on these structures (Figure 2, bottom) [12]. This slip-induced pattern produces substantial deformation at scales comparable to the size of the fault structures but diminishing displacement at longer wavelengths. Moreover, the complexity of fault structures (i.e., fault-friction, subsurface structural circuitry) will likely lessen true maximal displacement values such that the 3% estimate of changes to k_2 and h_2 represents an upper bound on the influence of these features.

Though we investigate the relationship between k_2 and h_2 and MIST at Enceladus in this work, the applicability of our analysis is not restricted to this body. As such, through this work, we demonstrate that SPDA provides improved bounds on determined values of MIST and could serve as a useful tool for geodetic investigations at other ocean worlds.

References: [1] Roberts and Nimmo (2008), *Icarus*, 194(2), 675–689 [2] Mitri and Showman (2005), *Icarus*, 177(2), 447–460 [3] Hemingway and Mittal (2019), *Icarus*, 332 [4] Wahr *et al.*, (2006), *Icarus*, 200(1) [5] Beuthe (2018), *Icarus*, 302 [6] Soucek, Hron, Behounekova, and Cadek (2016), *Icarus*, 328 [7] Behounekova, Soucek, Hron, and Cadek (2017), *Astrobiology*, 17(9) [8] and Soucek *et al.* (2019), *Icarus*, 328 [9] Thomas *et al.* (2016), *Icarus*, 264 [10] Hemingway and Mittal (2019), *Icarus*, 332 [11] Iess *et al.* 2014, *Science*, 344 [12] Segall, P. (2010), *Earthquake and volcano deformation* [13] Aagaard, *et al.*, (2007). *Eos*, 88(52)

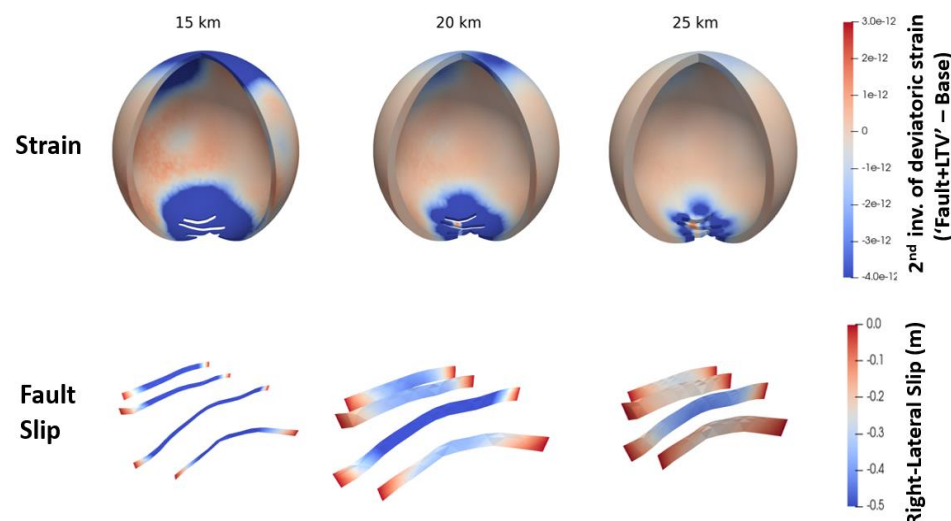


Figure 2: Top Row: Difference in the second deviatoric strain invariant between Base and Faults+LTV models across a range of MIST values. Blue regions correspond with areas of enhanced deformation in Faults + LTV. Bottom Row: Fault slip corresponding to deformation patterns. Blue indicates regions of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