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Folding, faulting, and subduction on Europa & Enceladus

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Abstract

The surface of Europa is dominated by features apparently formed by extension of its icy crust. This extensional deformation must be balanced by crustal shortening elsewhere; however, the mechanism by which shortening is accommodated is unclear. In contrast, the highly modified surface of Enceladus includes both extensional and contractional features (e.g., ridges, fold-thrust belts). Here we describe the results of a numerical investigation of crustal shortening on icy ocean worlds that identifies the conditions that control deformation style, helps explains why Enceladus and Europa appear so different despite both having heavily modified surfaces, and constrains the mechanism(s) by which subduction can (or cannot) occur on Europa.

1. Introduction

The surface of Europa is permiated with extensional bands that disrupt the background ridged plains and account for roughly 5% of the surface material [1]. The prevailing hypothesis for their formation requires complete separation of the crust and emplacement of new icy material: a mechanism that inherently implies large extensional strain [2]. Unlike Ganymede, Europa has not undergone significant global expansion, so the extensional strain must be balanced by crustal shortening elsewhere. Despite this, few obvious shortening features have been identified, leading to numerous hypotheses for “cryptic contraction”, in which shortening is essentially hidden [e.g., 3, 4, 5]. These mechanisms generally have no direct analog on terrestrial planets where shortening results in folding, faulting, and – at the largest scales – subduction. This observation is surprising because extensional features on icy worlds (normal faulting, rifting) generally do have direct terrestrial analogs. Furthermore, shortening features are widely observed on Saturn’s moon Enceladus. There, both isolated ridges [6], and circum-polar fold-thrust belts [e.g., 7] are likely to have accommodated much of the observed extensional strain. These observations clearly indicate that folding and thrust faulting can occur in ice shells.

Here we describe a numerical investigation designed to elucidate the conditions that control the style of deformation on ice-covered ocean worlds. We use the finite element model Tekton (v2.3) [8] to simulate the shortening of an ice lithosphere under a range of temperatures, heat fluxes, gravity, and rheological assumptions relevant to the icy moons of Jupiter and Saturn. In the process, we provide new insight into Europa’s evolution and new constraints on how (and whether) subduction can occur.

2. Numerical results

We find that the thermal conditions of the ice shell (effective surface temperature, heat flux, conductivity) play a critical role in determining the style of tectonic deformation (Figure 1). When the lithosphere is cold and thick (Figure 1A) brittle deformation dominates and shortening results in thrust faulting. In contrast, when the lithosphere is warmer (Figure 1B) shortening is accommodated by folding. These folds are consistent with those simulated by [9]. For intermediate thermal conditions (not shown) a combination of faulting and low-amplitude, very long-wavelength folding occurs (fold wavelength is a function of lithospheric thickness [9]).

We find that these results have little or no dependence on gravity (at least for the low gravity typical of icy worlds). They therefore provide a framework for understanding the differences between Europa and Enceladus. Enceladus’ colder surface temperature relative to Europa favors faulting as the mechanism for accommodating shortening, resulting in thrust-formed ridges [6] and fold-thrust belts [7]. Europa’s warmer temperatures favors folding or a combination of folding and more-subtle faulting. As discussed in [5] and [9], the long-wavelength and low-amplitude of these folds may make them difficult to observe in current datasets.

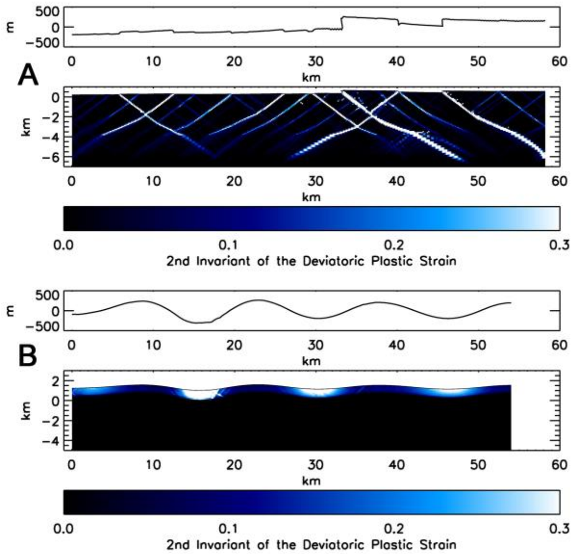

Figure 1: Surface deformation (top box) and cross-section through the crust (black box) for two simulations after 10% crustal shortening under different heat fluxes (*F*) and surface temperatures (T_s). White/blue zones show where brittle deformation is concentration – often linear fault zones. **A.** Cold conditions, T_s=70 K, *F*=50 mWm^{-2}, **B.** Warm conditions, T_s=120 K, *F*=100 mWm^{-2}.

During our investigation we also identified cases of possible incipient subduction [see 10]. These simulations result in a single dominant thrust fault and sufficient bending for the fault hanging wall to begin overriding the footwall (Figure 2). However, the conditions required for this to occur are extreme: cold surface temperatures (70 K), high heat fluxes (≥200 mWm^{-2}), and ice that rapidly looses cohesion as brittle failure occurs. If subduction occurs through such a mechanism, it must be localized and rare – occurring only during excursions of Europa's eccentricity that enable strong tidal heating (see also [11]). Alternative mechanisms for initiating subduction on Europa [e.g., 12] must therefore be considered.

3. Summary and Conclusions

The style of tectonics prevalent on a given icy satellites is a strong function of its surface temperature and heat flux (or conductivity). The occurrence of thrust faulting on Enceladus and its absence on Europa is a direct consequence of this behavior, which ultimately results from the strongly temperature dependent rheology of ice. Our work suggests that much of Europa's "missing" crustal shortening is likely taken up by long wavelength folds (consistent with [5] and [9]) with limited faulting. In rare cases subduction [10] might also occur, although the mechanism by which subduction initiates requires further investigation [e.g., 11].

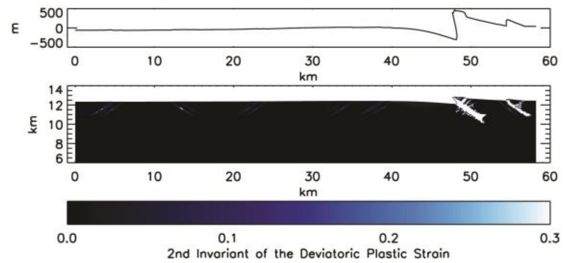

Figure 2: Surface deformation (top) and cross-section through the crust (bottom) for a simulation that may show incipient subduction. T_s=70 K, *F*=300 mWm^{-2}.

Acknowledgements

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