LIKELY LITTLE TO NO GEOLOGICAL ACTIVITY ON THE EUROPAN SEAFLOOR. Paul K. Byrne[1], Henry G. Dawson[1], Christian Klimczak[2], Paul V. Regensburger[3], Steven D. Vance[4], Mohit Melwani Daswani[4], Douglas J. Hemingway[5], Bradford J. Foley[6], Catherine M. Elder[4], Austin P. Green[4], and Christopher R. German[7], [1]Washington University in St. Louis, St. Louis, MO 63130 (paul.byrne@wustl.edu), [2]University of Georgia, Athens, GA 30602, [3]University of Oregon, Eugene, OR 97403, [4]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, [5]University of Texas Institute for Geophysics, Austin, TX, 78758, [6]Pennsylvania State University, University Park, PA 16802, [7]Woods Hole Oceanographic Institution, Woods Hole, MA 02543.

Introduction: Europa is strongly suspected to have a subsurface ocean [1], and is a body of major astrobiological interest [2]. Water–rock interactions at the moon's seafloor have been hypothesized to support a habitable, chemoautotrophic environment there [3–5]. On Earth, such environments are enabled by continuous fracturing that exposes fresh rock to seawater [6,7], allowing for the production of redox couples and the release of dissolved metals into the water column, but the tectonic state of Europa's seafloor is unknown.

Here, we combine rock mechanics techniques with remotely sensed geophysical data for Europa to first derive lithospheric strength profiles and then determine the differential stresses necessary to drive faulting at the moon's seafloor. We further calculate the brittle lithospheric thickness of Europa's rocky interior, and assess whether convection of the silicate mantle could overcome the strength of that lithosphere.

Fault Strength: With a recent interior structure model for Europa [8], we calculate how overburden pressure, P, changes as a function of depth with $\delta P/\delta r = -\rho_r g$, where r is body radius, ρ_r is local material density, and g is acceleration due to gravity. Gravitational acceleration at a given depth is given by $\delta g/\delta r = 4\pi G\rho_r - 2(g/r)$, where G is the gravitational constant) [9].

Our approach assumes that the upper, brittle portion of Europa's silicate interior features pre-existing fractures that, if subjected to stress, will slip. The stresses required to drive movement on those fractures can be determined in terms of their principal stress components, i.e., σ_1 or σ_3, such that $\sigma_1/\sigma_3 = (S_V - P_p)/(S_h - P\text{p}) = (\{\mu^2 + 1\}^{0.5} + \mu)^2$ and $\sigma_1/\sigma_3 = (S_H - P_p)/(S_V - P_p) = (\{\mu^2 + 1\}^{0.5} + \mu)^2$ are the strengths of normal and thrust faults, respectively. S_V is the vertical stress, S_H and S_h are the maximum and minimum horizontal stresses, P_p is the pore fluid pressure, and μ is the coefficient of friction [10].

Rather than calculating a specific porosity–depth profile, we regard pore fluid pressure at a given depth to correspond to the effective stress σ^* at that depth, i.e., $\sigma^* = \sigma_1 - P$, where the overlying material is water and ice (treated as having the same density for this purpose). As a result, our model intrinsically assumes that pore space remains throughout the brittle rock volume and that these pores are hydraulically connected to the seafloor. We report fault strength values at a depth of 1 km below the seafloor since, at the seafloor, the effective stress by definition will be zero.

Finally, we consider values of μ for both unaltered (e.g., peridotite) and altered (e.g., serpentinite) rock, which respectively serve as end members for scenarios under which the seafloor rock is mechanically strong and where, having been mineralogically hydrated by interaction either with seawater or during an earlier phase of heating of the entire interior [cf. 11], it is mechanically weak and more likely to undergo faulting.

The differential normal and thrust fault strengths at a depth of 1 km below the seafloor for the "strong" seafloor scenario are 2.4 MPa and 7.6 MPa, respectively. The corresponding values for the "weak" scenario are 1.8 MPa and 3.2 MPa, respectively. (**Figure 1**).

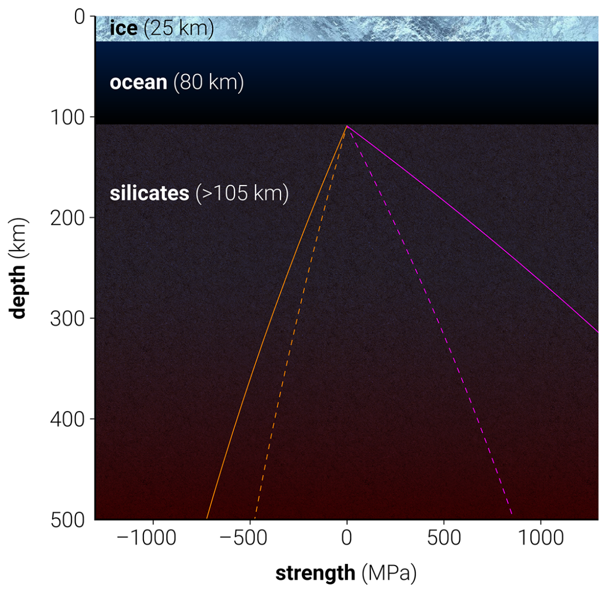


Figure 1. Differential strength profiles for normal (orange) and thrust (pink) thrust faults, for "strong" (solid) and "weak" (dashed) scenarios. Model layer thicknesses are also shown.

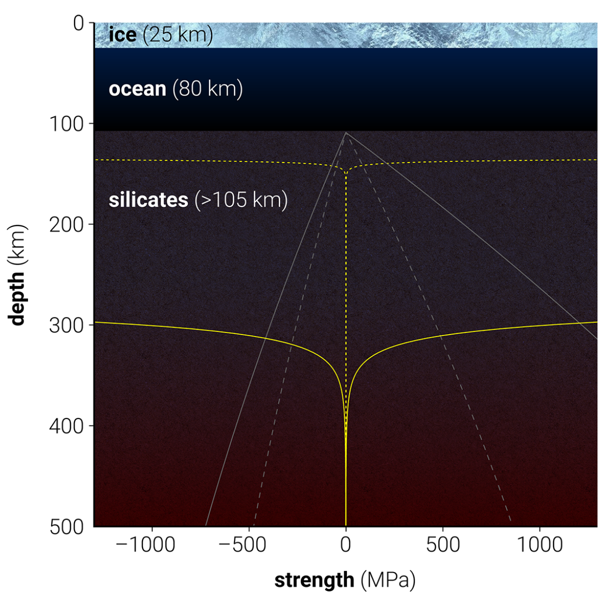
There are several mechanisms that could plausibly act on pre-existing fractures in the seafloor, such as stresses raised by the diurnal tide. However, the maximum tidal stress experienced by the Europan seafloor is 53 kPa [12], only about 3% that needed to drive slip along a favorably oriented normal fault under the "weak" scenario. Although repeated cyclic loading can weaken rock, the fatigue strength is less than 25% that of the normal fault strength [13], i.e., ≥450 kPa—

almost a factor of ten greater than the diurnal tidal stress. Global contraction from secular interior cooling is another means by which the surface of a silicate body can be fractured (by thrusting) [14], but the Europan interior would need to contract by more than 1 km before thrust faults could even start to develop [12]. By this measure, no mechanism obviously capable of driving faulting can match the 1 km-depth strength of Europa's seafloor.

Brittle–Plastic Transition Depth: With increasing depth, brittle failure gives way to plastic deformation. To establish the depth of the transition zone between fracturing and crystal plasticity within Europa's silicate interior, we calculate ductile strength by $\dot{\varepsilon} = C\sigma^n \exp^{-E/RT}$, where $\dot{\varepsilon}$ is strain rate, C is a constant, σ is deviatoric stress, n is the stress exponent, E is activation energy, R is the universal gas constant, and T is temperature [15].

We use values for C, n, and E appropriate to both "strong" and "weak" end-member scenarios (dry and wet olivine, respectively [16]). Similarly, our choices for temperature gradient and strain rate—a modest 3.3 K/km gradient [17] and strain rate of 10^{-16} s^{-1} for the strong scenario, and an Earth-like 20 K/km and a lower strain rate of 10^{-18} s^{-1} for the weak case—are designed to bracket the likely actual but unknown values.

The intersections of brittle and ductile strength profiles give the depths of the brittle–plastic transition (BPT) and, functionally, the thickness of the elastic lithosphere. For the strong case, the BPT is at a depth of 180 km; for the weak case, the BPT is at 30 km (**Figure 2**). The corresponding lithospheric thickness values for the lunar highlands are 13–72 km [18] and as much as 70 km for the Martian uplands in the Amazonian [19]. In other words, the silicate interior of Europa could be considered a smaller version of Earth's Moon.



Mantle Convective Stresses: Stresses from mantle convection can drive deformation at the surface. With scaling laws for mantle motion [20], we compare convective tractions to the peak lithospheric strength values we earlier calculated (**Figure 2**). Convective stresses are dependent on mantle viscosity, but even over three orders of magnitude (10^{18}–10^{20} Pa s, after [17]) those stresses never exceed ~1 MPa—substantially less than even the lowest peak lithospheric strength of ~40 MPa (for normal faults under the "weak" scenario).

Implications for Europan Habitability: Other processes that might expose fresh rock to the Europan ocean include volume increase during serpentinization [21] and thermal expansion anisotropy [22], which we have yet to consider. But neither diurnal tides, cycling loading, nor global contraction seem obviously capable of driving slip along pre-existing fractures, at least in the present epoch, likely limiting any geological activity at the seafloor and the replenishment of redox reactants into the ocean. Together with indications that silicate volcanism is improbable at Europa [23], specific circumstances involving seawater flow through seafloor rocks may be required for sustained habitable conditions at the moon's seafloor [24].

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Figure 2. Ductile strength profiles (yellow) for "strong" (solid) and "weak" (dotted) scenarios. The intercepts of these lines with the fault strength profiles (in grey, with solid and dashed lines corresponding to the strong and weak cases, respectively) give the brittle–plastic transition depths.