DETERMINATION OF ICE CRUST THICKNESS FROM FLANKING CRACKS ALONG RIDGES ON EUROPA. S. E. Billings and S. A. Kattenhorn, Department of Geological Sciences, University of Idaho, Moscow ID 83844-3022. (sandib@uidaho.edu)

Introduction: The response of a planetary lithosphere to an applied load, such as a mountain or range of mountains, is regularly modeled as a plate deflecting under a mathematically defined load. The deflection caused by the load depends on the strength of the plate, which is defined by elastic parameters of the lithospheric material and by its thickness [1, 2].

A "forebulge", where the crust warps upward at the surface, is characteristic of the deflection profile. The forebulge location has been used to characterize the deflection profile and to calculate crustal thickness at the time of load emplacement for locations on Earth [3–5], Mars [6, 7], the Moon [6], and Europa [8, 9]. However, the exact location of a forebulge crest can be difficult to identify in planetary surface images.

Stresses caused by the downward deflection of the lithosphere can produce more readily identifiable extensional features such as cracks and graben between the forebulge and the load. The locations of maximum stresses can be correlated with the location of extensional features [10]. This correlation allows lithospheric elastic thickness at the time of load emplacement to be calculated.

On Europa, the exact thickness of the ice crust is a contentious issue. Various methods have been employed to determine thickness, with results ranging from 0.2–30 km [11].

Lithospheric Flexure Due to Line Loading: Some of the many ridges of Europa are expected to load the ice crust enough to cause deflection [8, 12, 13]. Prior to the *Galileo* mission, Pappalardo and Coon [12] used a line load model developed by Turcotte and Schubert [2] to hypothesize that cracks might be seen flanking ridges caused by the load of the ridges, and that the flanking cracks would be located ~15 to 35 km from the ridge if the lithospheric thickness is ~2 to 6 km. More recent studies used the same method to determine the elastic thickness of Europa's ice crust at two locations in Conamara Chaos: (1) 100 m to 500 m at a mound load [9]; and (2) 123 m to 353 m at a ridge load ("Ridge R") [8]. In both cases, these estimates of ice crust thickness were determined using the distance from the load to the forebulge, which is difficult to locate precisely in Europa images.

Deflection and Stress Due to Line Loading: For a line load on a broken plate (such as is produced by a ridge), the deflection profile is $w=w_0e^{-x/\alpha}\cos(x/\alpha)$ [2], where w_0 is the maximum deflection at the load, x is the distance from the ridge, and the flexural parameter $\alpha=[Eh^3/(3\rho g(1-\nu^2)]^{1/4}$. The flexural parameter comprises Young's modulus E, the thickness of the plate h, density of the plate ρ, the gravitational acceleration on the satellite g, and Poisson's ratio ν. Maximizing the deflection equation gives the distance to the forebulge as $x_b=3\pi\alpha/4$.

The stress profile is obtained from the deflection using the relationships: (1) strain $\varepsilon=-y(d^2x/dy^2)$, where y is the horizontal distance from the center of the plate (downward is positive); and (2) stress $\sigma=\varepsilon\ E/(1-\nu)$. The stress profile can then be maximized to find the distance from the load to the maximum tensile stress. For a broken lithosphere, this maximum tensile stress occurs at the surface at $x_\sigma=\pi\alpha/4$. Tensile features are most likely to form at x_σ and can be used to determine the plate thickness h by rearranging the above equations to obtain $h=(3(4x_\sigma/\pi)^4\rho g(1-\nu^2)/E)^{1/3}$.

Stress and Flexure on Europa: Deflection due to line loading and the induced stress at the surface are shown for three hypothetical crustal thicknesses in Figure 1. In these calculations, appropriate values have been used for Europa: E is 6x10^9 Pa, ν is 0.3; g is 1.35 m/s and ρ is 1186 kg/m^3 [9].

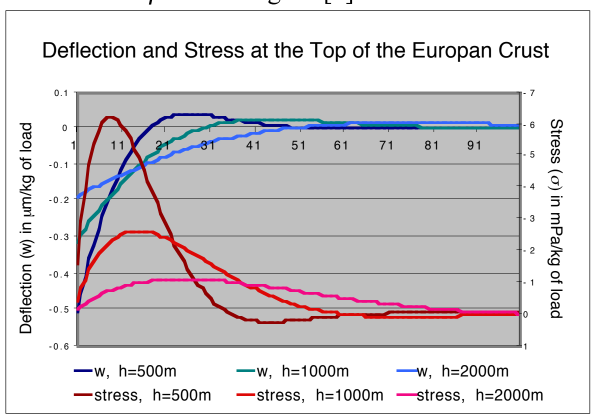

Figure 1. Deflection (w) and stress (σ) normalized to the load in Europa's ice crust due to a line load for ice thickness h = 0.5, 1, and 2 km.

The stress profiles in Figure 1 (reddish colors) show that maximum tensile stress occurs closer to the load than does the forebulge (deflection profiles in blue). These regions of maximum stress are most likely to fail in tension, resulting in cracks. Regions of surface compression beyond the forebulge could manifest in folding or strike slip motion along preexisting cracks. Additionally, since the stresses at the bottom of the plate are of the same magnitude but of opposite sign, tensile stresses would occur at the bottom of the plate at this location. However, these tensile stresses would probably be too small to overcome lithostatic stresses and cause fracturing from below unless liquid water is present below the ice crust with pressures approaching lithostatic.

Lithospheric Thickness Calculations: Androgeos Linea in the Bright Plains region (Figure 2), with clearly defined flanking cracks, has been identified as an example of a line load causing lithospheric flexure [8, 13, 14]. In this analysis, the distances from the center of the ridge to the flanking cracks were measured in five locations and used to calculate crustal elastic thickness at the time of crack formation. Using the potential ranges of *E* for the Europan ice crust of 6×10^7 Pa to 6×10^9 Pa [9], calculated ice thickness ranges from 468 m to 2530 m.

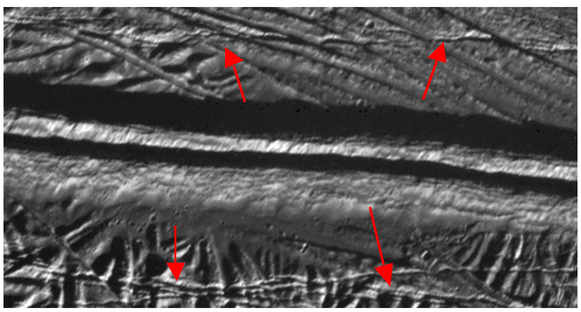

Figure 2. Androgeos Linea, a prominent ridge with flanking cracks (indicated by red arrows). From NASA's Planetary Photojournal, catalog #PIA00589.

Tufts [8] identified two additional ridges with flanking cracks, which he called Ridge R and Ridge C2r. Ridge R is located at 8.4N, 271W and was imaged during the E6 orbit of the *Galileo* spacecraft. Using the forebulge distance, x_b, Tufts determined the crustal elastic thickness at Ridge R to be in the range 123 m to 353 m. We have used the more precisely measurable distance to the flanking cracks, x_σ, at three locations along the ridge, and a broader range of crustal elastic moduli, as described above, to calculate the ice crust thickness to fall in the range 191 m to 1119 m.

Ridge C2r, at 4.7N, 325.7W, was imaged during *Galileo* orbit E4. While Tufts noted the flanking cracks, no calculations of ice crust thickness were presented. By using the flanking cracks as markers for the x_σ distance at four locations, we calculated an elastic thickness range of 421 m to 2633 m.

Results Summary. A summary of the results from calculations at the three locations studied is given in the following Table:

Location	x_σ ave (m)	*h* max (m)	*h* min (m)
Androgeos Lin., 14.7N, 273.4W	2926	2530	468
Ridge R, 8.4N, 271W	1134	1119	191
Ridge C2r, 4.7N, 325.7W	2687	2633	421

Discussion: A broken lithosphere was selected for these calculations based on the ridge formation model of Greenberg et al. [13]. If the ridges are formed by other processes and still create a load on the lithosphere, a continuous plate, which can support more than twice the load of a broken plate, may provide a better model. In such a scenario, ice crust thicknesses are smaller, ranging from ~200 m to 1 km (Androgeos and Ridge C2r) and from ~85 m to 400 m (Ridge R). If the ridges are formed by other processes such as diapiric uplift [15, 16], then the loading on the plate would be imposed from below and flexure would follow a different pattern.

The thickness of the ice crust as calculated here represents the thickness at the time of ridge formation and relates only to the thickness of the elastic portion of the crust. It does not address the thickness of a ductile layer below the crust, if one exists.

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