MODELING SURFACE STRESSES ON EUROPA.

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Introduction: Modeling of the surface stresses on Europa has been performed to date, considering tidal, nonsynchronous, and polar wander sources of stress [3-6]. The results of such models can be used to match lineament orientation with the candidate stress patterns. Moreover, stratigraphic analysis can be used in combination with stress modeling to infer the evolution of Europa's surface back through time [9,12]. We are creating a surface stress model for Europa (in MATLAB) that will facilitate comparison of principal stresses to lineament orientation, and which will be available in the public domain.

Modeling Surface Stresses: Nonsynchronous rotation and diurnal stresses contribute to a stress pattern that affects the surface of Europa, each on a very different time scale. Over the 85-hour orbital period, the diurnal stress pattern acts on the surface, with a maximum magnitude of ~40 kPa [21]. The nonsynchronous stress pattern sweeps over the surface due to the faster rotation of the icy shell as compared to the tidally locked interior of the moon, and occurs with a period of >10,000 years [21]. Polar wander (reorientation of the icy shell with respect to the axis of rotation) may contribute to the surface stress pattern on Europa [4]. When added, the resulting stress pattern can be used to predict the orientations of lineaments, as well as the regions within which faulting should occur [e.g. 3].

Mechanisms and timescales for reorientation of the icy shell of Europa have been considered using various geophysical models [16-21]. One approach toward understanding the surface stresses on Europa is to determine the stress difference induced by a change in flattening [e.g. 4]. We employ a different method, based on calculating the surface stresses from the Love numbers.

Stressing the surface of a planetary body can be modeled by calculating the vector components of displacement **s** at the surface, which are functions of the potential V:

$$V = A(r/a)^2\Sigma_{m=0}^{1}Y_2^m(\cos\theta)\exp(i\omega t).$$

A is a constant, θ is colatitude, ω is the angular rate of rotation of the icy shell, and t is time.

We calculate the degree 2 Love numbers h_2, k_2, and l_2 for various thicknesses of the icy shell. The Love numbers are used to obtain the deformation at the surface. Displacement vector components are calculated from the Love numbers:

$$s_r(a) = (h_2/g)V\div_{r=a},$$
$$s_\theta(a) = (l_2/g)\partial_\theta V\div_{r=a},$$
$$s_\varphi(a) = (l_2/g)(\sin\theta)^{-1}\partial_\varphi V\div_{r=a}.$$

Radial dependence of the potential V is evaluated at the radius of Europa, a; g is the gravitational acceleration at the surface of Europa.

The vector **s** is used to determine the strain tensor ε, the components of which are multiplied by the shear modulus μ of the surface material in order to produce the components of the stress tensor τ:

$$\tau = \begin{bmatrix}\tau_{\theta\theta} & \tau_{\theta\varphi}\\ \tau_{\varphi\theta} & \tau_{\varphi\varphi}\end{bmatrix}.$$

τ is subsequently diagonalized in order to obtain the eigenvectors and eigenvalues of the tensor, which are the directions and magnitudes of the principal surface stresses.

Boundary conditions require the radial components of the stress tensor are zero at the surface. For the diurnal case, $A = [(GMa^2)/R^3]e$. Stresses due to diurnal tides are approximately 45 kPa, as calculated from $\tau \sim [\mu l/(ag)][(GMa^2)/R^3]e$, which is in agreement with [21]. Here G is the gravitational constant, M is the mass of Jupiter, a is the radius of Europa, R is the semi-major axis of Europa's orbit, r is the distance from the center of Europa, and e is the eccentricity of the orbit.

Geological Context: The hypothesis of conjugate shear failure in Europa's "Equatorial Compression Zones" (ECZs) [13,14], where both principal surface stresses are compressional, necessitates a new approach to predicting lineament orientation based on modeling of the surface stresses of Europa. Lineaments can no longer be predicted to only form perpendicular to the direction of greatest tension, but in the ECZs must be understood to form in conjugate pairs, each ~30° (for frictionally controlled ice) from the direction of greatest compression [1,2]. Consequently a revisiting of stress model predictions is vital to considering the hypothesis of conjugate shear failure.

Creation of a surface stress model that is widely accessible is motivated by recent evidence in support of the hypothesis of conjugate shear failure in the

ECZs, and its implications for the satellite's geological history. At the leading point of Europa, two statistically significant directions of lineament orientation are observed (Figure 1), as would be expected by conjugate shear formation. No evidence is found to support formation of lineaments in this region due to either nonsynchronous rotation of the icy shell through an Equatorial Tensile Zone (ETZ) or due to diurnal stresses. Both ETZ and diurnal stresses in this region would produce east-west structures, which are particularly lacking in the study area. Similar results are found in the satellite's trailing hemisphere [14].

These results not only support the hypothesis of conjugate shear failure, but also provide an upper limit on the number of degrees on nonsynchronous rotation of ~90°. This supports some previous estimates of shell rotation [3,4,7,8]. Other analyses have predicted greater amounts of rotation [9-12], but these analyses have neglected the important fact that tensile failure is not possible within Europa's ECZs [13,14]. The difference of principal stress magnitudes in the ECZs is large enough to induce failure, as predicted by a Mohr diagram. Although shear failure is expected to produce faults with opposite stripe-slip sense, diurnal stresses are ultimately expected to govern the fault offsets [15].

Model Applications

Although we apply the model for calculating surface stresses to the Jovian satellite Europa, with intent to compare faulting predictions with observed lineament orientations, this general stress model will work for any reorientation of the surface of any satellite, and for instance could be applied to Ganymede and Io as well.

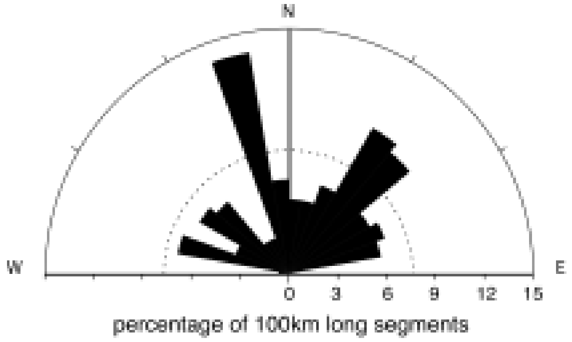

Figure 1. The average orientation of each of the 52 mapped lineaments is depicted, as represented by 174 segments of 100km length. The dashed half-circle represents √N, the number below which orientations are not statistically significant. Note the distinct lack of E-W orientations, as well as the statistical significance of only two directions (N40E and N15W), suggestive of formation in an ECZ [13].

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