CONSTRAINTS ON THE OPENING RATE OF BANDS ON EUROPA. M. M. Stempel, A. C. Barr, R. T. Pappalardo. Laboratory for Atmospheric and Space Physics (LASP), University of Colorado at Boulder, Campus Box 392, Boulder CO, 80309-0392 (stempel@colorado.edu).

Introduction: The opening rates of two bands on Europa, inferred to be sites of spreading of the icy lithosphere, are constrained based on a mid-ocean-ridge analog model. Estimates of brittle-ductile transition depth combined with a conductive cooling model limit active band lifetimes to 0.24 - 35 Myr and strain rates of $8.1 \times 10^{-13} - 8.2 \times 10^{-15}$ s^{-1}. These values suggest tensile strengths for ice on Europa of 0.46 – 2.3 MPa, consistent with nonsynchronous rotation as the dominant driving mechanism for band opening.

Background. Europa exhibits varied surface morphology, including long linear features of a variety of types and a range of widths [1, 2]. The most narrow (~500 m) linear features are troughs. Double ridges are ridge pairs ~2-5 km wide with an axial trough. The widest linear features are bands up to 25 km across, some of which are inferred to be sites of separation and spreading of the icy lithosphere [3, 4, 5]. It is inferred that troughs develop to form ridges, which in turn can develop into bands [6].

Bands themselves are not all alike: some appear to be a complex interweaving of double ridges, some are relatively smooth, and some express both characteristics [7]. *Prockter et al.* [8] examined several Europan bands and ascertained a continuum of morphologies, interpreted to perhaps represent varying rates of spreading. Fast spreading rates may create smooth bands, whereas slower spreading rates might produce features analogous to that of mid-ocean-ridge (MOR) spreading on Earth, where extensional stresses produce block faults, in turn straddling a neovolcanic zone adjacent to the central trough.

Two bands are explored in this study, Yelland and Ino Lineae, are both located at approximately -16 latitude and 196 longitude, where Yelland crosscuts Ino. Both display a prominent axial trough straddled by a hummocky zone, in turn flanked by subparallel ridges and troughs with clearly defined boundaries against the surrounding terrain. These morphologies may be indicative of "slow-spreading" bands [8], where extension and faulting occur slowly enough for the icy lithosphere to cool and fault as opening proceeds, in contrast to smooth "fast-spreading" bands which may open too rapidly for lithospheric cooling to support internal band deformation.

Given the width of the hummocky zone and the width of fault blocks within a band, a simple lithospheric cooling model can be used to constrain the band opening rate. From the inferred spreading rate and width of a band, its active lifetime can be estimated and driving mechanisms inferred.

The Model: MOR spreading on Earth can be modeled as instantaneous cooling of the oceanic lithosphere in a semi-infinite half-space, with the surface held at a constant temperature [12]. This model is useful as an analog to band spreading on Europa, where analogous tectonic features are observed [8].

In the MOR cooling model, isotherms, including that describing the brittle-ductile transition (BDT) temperature, fall off like the square root of distance from the spreading center. The cooling model is coupled to a description of the BDT isotherm, and self-consistent values for the BDT temperature and the spreading rate of the bands are constrained. Measured parameters are average observed fault block width x_b, the width w from the central trough to the edge of the band, and the width from the central trough to the edge of the hummocky zone x_L. The distance x_L is measured from the axial trough to the first high albedo lineation. Block width x_b is the average distance between lineations. Estimates of fault block width-to-depth ratios provide a range of possible depths of faulting y_l, assumed to equal the local BDT depth.

Although the MOR model defines the depth at the spreading center as zero, in reality a thin shell of brittle material would exist in the vicinity. Solving the heat equation for both conduction and advection, and assuming the system is in steady state, the minimum depth of this thin shell is on order 10 m, which is much less than the relevant dimentions of Yelland Linea: x_L = 700 m, x_b = 350 m, w = 3600 m. Measured dimentions of Ino Lineae are of similar orders of magnitude: x_L = 860 m, x_b = 530 m, w = 7800 m. Thus, our MOR model provides a sufficient first-order representation of the shape and depth of the BDT isotherm.

For a cooling oceanic lithosphere in an infinite half space, the relationship between depth y_l, horizontal distance x_L from a spreading center, and half spreading rate u can be expressed as

$$u = [\ x_L\,(2\ \mathrm{erfinv}\,(\,(T_{BDT} - T_s)\,/\,(T_w - T_s)\,)\ /\,y_L)^2\ ] \quad (1)$$

[12] where erfinv is the inverse error function, T_{BDT} is the temperature at the BDT, T_s is the surface temperature (which we take as 110 K for Europa), T_w is the temperature of the ductile ice (260 K), and is thermal

diffusivity (1×10^{-6} m^2 s^{-1} for ice). The half spreading rate is used to obtain the strain rate $\dot{\ } = u/x_L$.

A "Byerlee's law" for ice [13] describes the strength of the brittle lithosphere as $= {}_1 - {}_3$, where ${}_1$ is greatest compressional stress (lithostatic in the extensional case: ${}_1 = gy_L$), ${}_3$ is least compressive stress (here horizontal: ${}_3 = {}_1 / \{ 2 \ [({}^2 + 1)^{1/2} + \ ] + 1 \}$), is the coefficient of internal friction (0.69 [13]), is density of ice (920 kg m^{-3}), and g is gravitational acceleration for Europa (1.3 m s^{-2}). To describe the strength of the lower ductile lithosphere, we adopt the flow law for ice creep in the grain boundary sliding regime [14]:

$$= ((\dot{\ } \ d^p) / A)^{1/n} \exp (Q / (n R T_{BDT})) \quad (2)$$

where d is grain size (assumed to be 1 mm), p, A, and n are experimentally determined constants (1.4, 3.9 x 10^{-3} [need to include the bizarre-looking units of A], and 1.8 respectively), Q is the activation energy for creep (49 kJ mol^{-1}), and R is the gas constant. The BDT occurs at a depth where the brittle and ductile failure strengths are equal:

$$T_{BDT} = Q \{ n R \ln [({}_1 - {}_3) (({}_{dot} d^p) / A)^{1/n}] \}^{-1}. \quad (3)$$

For each band, we solve iteratively for T_{BDT} and u, for a variety of fault block width-to-depth ratios. We choose 1/10 as a reasonable lower limit, and 1/2 as an upper limit based correspondence to the upper limit for reasonable T_{BDT} of 190 K [15].

Results: Estimates of BDT depth combined with a conductive cooling model limit active band lifetimes to 0.24 - 35 Myr and strain rates of 8.1 x 10^{-13} – 8.2 x 10^{-15} s^{-1} (see figure). These ranges correspond to half-spreading rates between 22 and 0.22 mm yr^{-1}.

The above values also suggest tensile strengths for ice on Europa of 0.46 – 2.3 MPa (= ($g \ y_L$) / 3). These stress levels are consistent with nonsynchronous rotation as the dominant driving mechanism for band opening [2].

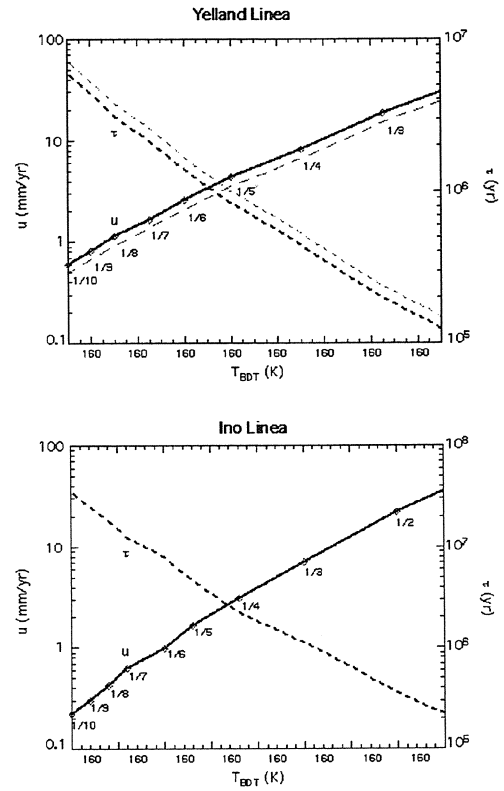

Figure 1: Half spreading rate u and active lifetime are plotted versus T_{BDT} for Yelland and Ino Lineae. The relationship changes with the width-to-depth ratio of fault blocks, as labeled along the curves. The lighter dashed lines in the plot for Yelland Linea are the model results when using x_L = 580 m [as per 8].

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