WHAT IS (AND ISN'T) WRONG WITH BOTH THE TENSION AND SHEAR FAILURE MODELS FOR THE FORMATION OF LINEAE ON EUROPA. S. A. Kattenhorn, Department of Geological Sciences, University of Idaho, PO Box 443022, Moscow, ID 83844-3022; simkat@uidaho.edu.

Introduction: An unresolved problem in the interpretation of lineae on Europa is whether they formed as tension- or shear-fractures. Voyager image analyses led to hypotheses that Europan lineaments are tension cracks induced by tidal deformation of the ice crust [1]. This interpretation continued with Galileo image analyses, with lineae being classified as crust-penetrating tension cracks [2]. Tension fracturing has also been an implicit assumption of nonsynchronous rotation (NSR) studies [e.g. 1-4]. However, recent hypotheses invoke shear failure to explain lineae development [5-6]. If a shear failure mechanism is correct, it will be necessary to re-evaluate any models for the evolution of Europa's crust that are based on tensile failure models, such as NSR estimates. For this reason, it is imperative that the mechanism by which fractures are initiated on Europa be unambiguously unraveled. A logical starting point is an evaluation of the pros and cons of each failure model, highlighting the lines of evidence that are needed to fully justify either model.

Types of Lineae: Numerous classification schemes have been developed to describe the range of lineae morphologies observed on Europa's surface [2-4, 7]. It is generally accepted that there is an evolutionary sequence of lineae development from fractures/isolated troughs, to proto-ridges/raised-flank troughs, to double ridges, and finally complex ridges.

Strike-Slip Faults. Many lineae on Europa show lateral offsets of relatively older structures. These strike-slip faults vary considerably in both morphology and size. Many resemble double ridges [6, 8] having small offsets (~100s of m); others are hundreds of km long and occur as several km-wide, internally deformed, dilational bands with offsets of up to 10s of km [9-10]. These features attest to the fact that shear failure is a major deformation mechanism on Europa.

Formation Mechanisms: A number of mechanisms have been proposed to explain the origin of lineae [11]. The two most prominent models are the tension and the shear failure models; however, neither model is undeniably more acceptable than the other.

Tension Models. Tension fracturing is assumed to be the result of stretching of the ice crust in response to the combined effects of diurnal tides and NSR (Fig. 1). Tensile stresses of <1 MPa are predicted to occur [2]. Orientations of fractures are dictated by principal tidal stress orientations. For such a model, there is only one preferred orientation of fractures forming at any one point in time.

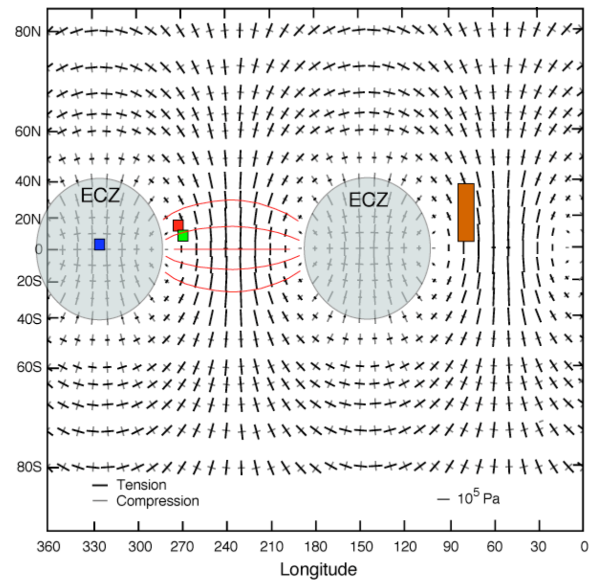

Figure 1. Principal tidal stresses at 1/8 orbit after apojove with 1° of NSR [2]. Gray areas are equatorial compressive zones. Red lines show expected locations and orientation ranges of tension fractures. Mapped regions: orange: [3], red: [4], blue and green: [6].

Shear Models. Shear failure is hypothesized to occur in equatorial compressive zones (ECZs), where tidal stresses are predicted to be compressive (Fig. 1). Frictional heating during shearing causes melting and possibly extrusion that gradually builds up ridges [5]. The Coulomb criterion for shear failure allows for a conjugate set of shear fractures. In the shear failure model, there are thus two potential orientations of fractures forming at any one point in time.

In Support of Tensile Failure Models: Other than in ECZs, tensile tidal stresses are common. Brittle materials are characteristically weaker in tension than in compression and ice on Europa is hypothesized to have a low tensile strength (<1 MPa) [2]. Orientations of major lineae agree remarkably well with orientations of tidal stresses (adjusting for NSR reorientation of the ice shell). Fracture mapping in both the leading and trailing hemispheres has shown a consistent rotation of fracture orientations through time [3-4], and no ambiguous cross-cutting relationships, agreeing with NSR model predictions for tensile fracturing.

Problems with Tensile Failure Models: There are also many aspects of lineae that are not supported by tensile failure models. The most obvious problem arises with lineae having orientations that could only have occurred in the ECZs. In several mapped regions affected by ECZs (Fig. 1), lineae should have orientations within ~30° of E-W. However, such orientations are rare (Fig. 2), except for smooth bands, which are typically ~E-W oriented, extensional features [3-4]. Also unclear is how surface fractures evolve into ridges. Models for ridge development that invoke tapping into an underlying ocean have been criticized because they implicitly require a thin ice shell, which is inconsistent with mounting evidence for convection-driven diapirism in the crust, implying an ice thickness of at least 15km [12].

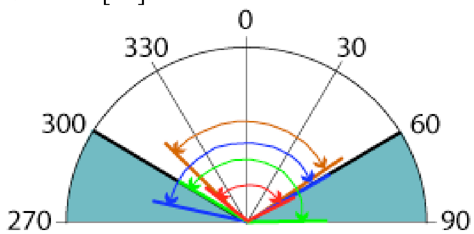

Figure 2. Expected range of orientations of tension cracks (light blue shaded areas) in the regions of the boxes in Fig. 1. Colored arrows show actual ranges of lineae in these regions (color scheme as in Fig. 1).

In Support of Shear Failure Models: The obvious appeal of shear failure models is that they can account for lineae development in the absence of tensile stresses in the crust. Furthermore, lineae orientations (Fig. 2) seem to agree with predicted conjugate set orientations in the ECZs (NW-SE and NE-SW) rather than those predicted by tension models [6]. Shear activity is supported by the existence of major strike-slip faults. If slip events are rapid, frictional heating along the fault walls provide a source for ridge-building material without the need to tap into an underlying ocean.

Problems with Shear Failure Models: At present, there is no convincing geological evidence that conjugate sets of similar-aged lineae exist in near-equatorial regions. This may be a reflection of a lack of explicit identification of such features rather than a lack of the features themselves. In a conjugate set, neither fault is more or less likely to form than the other; therefore, conjugate sets should show ambiguous cross-cutting relationships. Evidence of this has not been documented. Furthermore, inconsistent shear sense along features with identical orientations [6] is inconsistent with Coulomb failure predictions. The typical lack of offsets along most double ridges is also difficult to reconcile with lineae evolving as shear fractures. Finally, lineae at latitudes >±40°, where tensile stresses occur, are not morphologically different from ECZ lineae, raising the possibility that they have identical formation mechanisms (whether in tension or shear).

Discussion: Detailed mapping from Galileo images must continue across all latitudes and longitudes to clarify fracture sequences, cross-cutting relationships, the mechanics of fracture propagation, and contrary fracture behaviors in different locations. For example, [6] suggest that there is no clear sequence of rotating fracture orientations through time in the E4 and E6 regions, but rather superposed conjugate sets. In contrast, I have found no ambiguous cross-cutting relationships or evidence of conjugate fracture sets in the Bright Plains (BP) region, very near the E6 region of [6]. The BP shows a clear time progression of resolved shear sense on fractures in different orientations, in response to the rotating NSR stress field. The angles between BP double ridges with stratigraphically similar ages are not constant, ranging from 19-86°. The angle, □, between conjugate faults is purely a function of the coefficient of sliding friction of Europan ice, □, such that □ = $\tan^{-1}$ (1/□). For a reasonable range of □ [13], □ should be restricted to 60-90°, suggesting that BP double ridges are not conjugate sets (but not disproving that they may be shear fractures). Fracture orientations in the BP (red in Fig. 2) do not fall within a stress field that permits tension fracturing, which may either imply shear fracturing, or may entail the existence of a stress component (such as fluid pressure) that superimposes tidal stresses. Finally, assuming that all fractures in the BP are tension fractures, the amount of NSR is estimated to be as much as 900° [4]. But if BP double ridges are conjugate shear fractures, NSR estimates must be reduced by at least 180°. This discrepancy clearly indicates that our inferences about the rotational history of Europa are inherently flawed by our lack of certainty about the origin of lineae.

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