TIDAL STRESS ON EUROPA: NON-SYNCHRONOUS ROTATION AND DIURNAL VARIATIONS.
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The linear ridge structures on Europa, including many that are global in scale, probably correspond to crustal cracks whose orientations and geometry reflect global stress patterns. Major sources of global stress include tidal deformation due to (a) "diurnal" changes as Europa moves in its eccentric orbit around Jupiter [1] and (b) possible non-synchronous rotation slowly reorienting Europa relative to the direction of Jupiter [2,3].

Geissler [4,5,6] has shown that the major linear structures within a few hundred km of the intersection of the Cadmus and Minos Linea have a systematic variation of orientation with their age, such that more recent lineaments are rotated clockwise relative to older ones. Qualitatively, that trend supports the prediction of possible non-synchronous rotation [2] according to the following argument: Because the non-synchronous component of the rotation rate is very slow (<2°/100yr [3]) stress cannot build elastically for more than ~1° of rotation. The stress field in a thin ice shell for rotational displacement was computed by [7]. A recomputation by us, based on the theory of [8] and [9], confirms that result and allows us to plot, for the first time, amplitude and direction of the principle stresses as shown in Fig. 1 (for the case of 1° of rotational displacement). For all the cases shown here we assume a shear modulus of 3.57x10^9 Pa and a Poisson ratio of 0.33 [10]. As non-synchronous rotation proceeds, geographical regions move from west to east across this stress field. According to Fig. 1, the Cadmus/Minos intersection region has moved through a 90° wide region of tension, to which ice is most vulnerable for cracking, and the direction of the stress field has rotated clockwise during that transit. Thus the discovery of such systematic rotation of crack formation in the geologic record [4,5,6] has been taken as strong indication of non-synchronous rotation.

Our quantitative mapping of the stress field shows that this scenario fits the evolution for the trend for the older lineaments (up to the formation of Minos Linea), where cracks are orthogonal to the tensile stress at the time of their formation. The orientation of the oldest lineaments in the region is consistent with the stress field at a location backwards in rotation by ~40°. However, this scenario fails to explain the orientation of the most recent cracks (and even Cadmus Linea), whose orientation would not be produced until Europa continued to rotate at least 10° further ahead from its current position.

This problem can be ameliorated by including the stress due to the diurnal tidal component. For example, Fig. 2 shows the diurnal stress pattern at Europa's apocenter, where the amplitude of the tidal bulge is at a minimum, creating an isotropic zone of compression around the sub- and anti-Jupiter points, and a band of tension 90° away from those points. The sum of the non-synchronous and diurnal stresses approaches maximum tensile stress (the condition under which ice fails most readily) in the Cadmus/Minos region about 1/8 of an orbit after apocenter. The combined field of the diurnal tide at that orbital phase plus the non-synchronous tidal stress is shown in Fig. 3. This field has stress magnitude great enough to allow tensile cracking (the maximum stress of 1.5x10^5 Pa is comparable to the strength of 3x10^5 Pa for sea ice, and may be above the effective strength of a large imperfect crust) with the

Figure 1: Tidal stress pattern due to 1° of non-synchronous rotation.

Figure 2: Tidal stress pattern at apocenter due to orbital eccentricity ("diurnal" variation)
stress direction consistent with the above scenario for sequential formation of lineaments in the Cadmus/Minos region. The stress patterns also fit other major crack geometries, and also can be used to explain ongoing activation of specific lineaments [11].

In this model, non-synchronous rotation gradually builds up stress, which is superimposed on the periodically changing diurnal stress. Eventually, one day, shortly after apocenter, the stress reaches a magnitude that produces a crack and relieves the stress. Then non-synchronous stress begins to rebuild, eventually leading again to a crack one day, but only after the region under consideration has rotated to a position where the stress orientation is further clockwise.

The success of this model at fitting large scale lineaments in various regions provides evidence for the presence of a liquid-water layer, as well as for non-synchronous rotation. If the mantle were solid or viscous, instead of liquid water, the diurnal tidal amplitude would be much smaller than the 50m tidal height used in our calculations, while the non-synchronous component could still have the full km-scale amplitude. In that case, the combination of tidal stress components (shown in Fig. 3) required to fit the large-scale crack patterns would not be attained. The water mantle is required in order to have a significant amplitude to the diurnal component; non-synchronous rotation alone cannot explain the evolution in the Cadmus/Minos region.