A SEA ICE ANALOG FOR THE SURFACE OF EUROPA;

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The surface of Europa is crossed by bands and ridges of a variety of specific morphologies [1,2,3]. Reconstruction of gray and wedge-shaped bands indicates that they formed through opening and separation of lithospheric blocks atop a liquid or ductile substratum [4,5], perhaps broadly analogous to processes that operate in terrestrial sea ice [4,5,6]. Furthermore, theoretical models of thermal balance suggest that a liquid water ocean may underlie the icy surface of Europa [7,8]. We have begun investigation of whether the landforms of Europa can be explained through analogy to terrestrial sea ice processes. We propose a sequence in which cyclical tensional and compressional stresses (predicted from nonsynchronous rotation [9,10]) open and close lithospheric scale ice plates to produce dark bands, triple bands, and ridges.

Europa's landforms. Europa's lineaments can be simply classified as dark bands, triple bands, and ridges [6]. Topography is well recognized only along the satellite's terminator; features are apparent only as albedo markings under higher sun. Europa's dark bands are up to 30 km wide, with patterns that are regional or global in organization [2,3,6]. Their relatively low albedo is probably due to endogenic contaminants and perhaps a relatively large ice grain size [2,4,5,11] and may indicate youth and lack of a surface frost coating [5]. Ridges seen along the terminator form the most prominent topography on Europa [1,6,12], with widths of ~5 to 10 km, heights of up to a few hundred meters, and lengths that can reach hundreds of kilometers. Ridges in Europa's equatorial region are generally linear in overall plan. Those seen at high southern latitudes show a repeating cycloidal pattern, and are not accounted for in our modeling. A triple band is a dark band which shows a bright stripe along its center [2]; the axial feature might be a ridge like those recognized along the terminator [6].

Sea ice processes. Mechanical processes can produce cracks, leads, and pressure ridges in a terrestrial sea ice cover due to relative motions of the ice. Vertical cracks of long horizontal dimension are common in sea ice, most easily formed through tensile failure induced by bending. Crack formation allows an initially continuous piece of sea ice to separate due to geophysical stresses. If a crack opens to significant width, the resulting open water area is referred to as a lead. A lead is immediately covered with a skin of ice that thickens with time. When leads close, the thin and weak lead ice is broken into rubble and pushed into a pile called a pressure ridge [13]. Pressure ridges are composed of blocks of dimensions similar to the thickness of the lead ice that is incorporated into the ridge.

Sea ice analog for Europa. In drawing an analogy to terrestrial sea ice processes, we assume that Europa's brittle lithosphere lies above an inviscid layer such as liquid water. The thickness of Europa's brittle lithosphere has been estimated as ~2 to 6 km [14], and we equate this to the thickness of the floating ice plate. We suggest that Europa's principal landform types can be explained through a 4-phase sequence analogous to processes that shape terrestrial sea ice:

1. Opening along cracks: Wedge-shaped and gray bands apparently have opened along preexisting fractures [2,4,5], suggesting that on Europa as in sea ice, cracking precedes opening. Cracks that penetrate Europa's lithosphere can result from non-synchronous rotation [10] or perhaps other tensile stress, creating lines of weakness along which the lithospheric plates can separate in response to subsequent stress. Water replaces displaced lithosphere in the region of opening and rapidly freezes over to form "lead ice." This relatively thin ice would cool downward, thickening with time. Opening is likely progressive, so the lead ice will be thinnest along its axis of opening, likely along the center of the band. This process could create dark bands, including wedges and gray bands, with contaminants and large ice grains promoting their dark appearance.

2. Closing begins: The relatively thin ice of dark bands will be fractured by a variety of processes known to cause cracking of terrestrial lead ice: cooling will produce thermal contraction cracks which may be concentrated along the lead's central axis; buoyant ice freezing onto the lead ice base will cause upward arching and fracture; and a bending moment induced by the misaligned axes of the compressional stresses that act on the thick lithospheric plate and the thinner lead ice will induce flexure and fracture of the lead ice. As closing of the lithospheric plates ensues, the fractured lead ice rubble will raft, piling up to build a pressure ridge. If such a ridge forms along central axis of the band, where the ice is expected to be thinnest and most fractured, the resulting morphology may resemble a triple band (which we term a Type I triple band).

3. Closing continues: As the lithospheric blocks close, rubble is compressed, squeezed out, and piled onto the block edges to form a broad pressure ridge. Such a ridge could grow to a limiting height, above which the load P it imposes will fracture the lithospheric plate in bending, allowing the broken block to adjust isostatically. If a lithosphere of thickness H, Young's modulus E, and tensile strength T floats on an inviscid substratum of density ρ_w and is loaded by a triangular ridge segment of length L, height h, density ρ_i, and porosity 30%, the load imposed on the lithosphere is: $P = 0.35(Lh\rho_i g)$ and the lithosphere cracks when $h^2 = [(0.076TH^2)/(\rho_i g)]\cdot[(\rho_w g)/(Eh^3)]^{0.25}$. For a ~2-6 km lithosphere, ridges on Europa could obtain heights of ~200-400 m before lithosphere failure occurs, consistent with ridge heights estimated from Voyager images. Ridge-parallel cracks should be produced at a distance from the ridge where bending is at a maximum: $x = \pi/2\lambda = (\pi/2)\cdot[(Eh^3)/(3\rho_w g)]^{0.25}$, predicting that Galileo should observe cracks ~15-35 km from Europa's largest ridges.

4. Downwarping: If additional ice were added to a ridge pile following lithospheric failure, ridges would load down the lithosphere isostatically, thus prohibiting the ridges from growing taller relative to a base level. If the lithosphere is very thin, flooding would be promoted alongside the ridge. Flooding would occur when the

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amount of downwarping due to the ridge load exceeds the depth to the waterline. The base of a rectangular ridge of height η and porosity 30% will float at a height d above the waterline: $d = H(1-\rho_i/\rho_w) - 0.7\eta(\rho_i/\rho_w)$. A 200 m ridge will induce flooding at its base if the lithosphere is very thin, $H \leq 2$ km. Some triple bands on Europa (here termed Type II triple bands) may be central ridges that have induced flooding by darker material to either side, indicating formation in a region of thin lithosphere. The Type I and Type II models for triple band formation are both consistent with the cross-cutting relationships of triple bands as determined from Voyager images [4]. Galileo images will permit these formation models to be tested and distinguished.

Implications. Because Europa's ridges are at most few hundred meters high, a pressure ridge analog implies that the thickness of the lead ice from which they are built is of lesser dimension, $\lesssim$100 m. Ridge volume considerations place a similar constraint on lead thickness, if ridges are built from the accumulated rubble of leads ~20 km wide. This maximum thickness limits the lead ice age to a few hundred years or less [15] before a compressional phase begins. In turn, this constrains the period of nonsynchronous rotation to $\lesssim$1000 yr, grossly consistent with the uncertain time scale for the nonsynchronous rotation of a Europan shell [8,9].

Europa's lineaments may have formed as a consequence of the relative motions of lithospheric scale ice plates, by means analogous to the processes which shape terrestrial sea ice. Gray and wedge shaped bands and other dark lineaments may be analogous to leads resulting from plate separation. Ridges with overall linear planform might be analogous to pressure ridges. Triple bands may represent a central pressure ridge running along the central axis of a dark band, or a large ridge that has induced downwarping and flooding of adjacent lithosphere. Galileo imaging will provide tests of this sea ice analog model.

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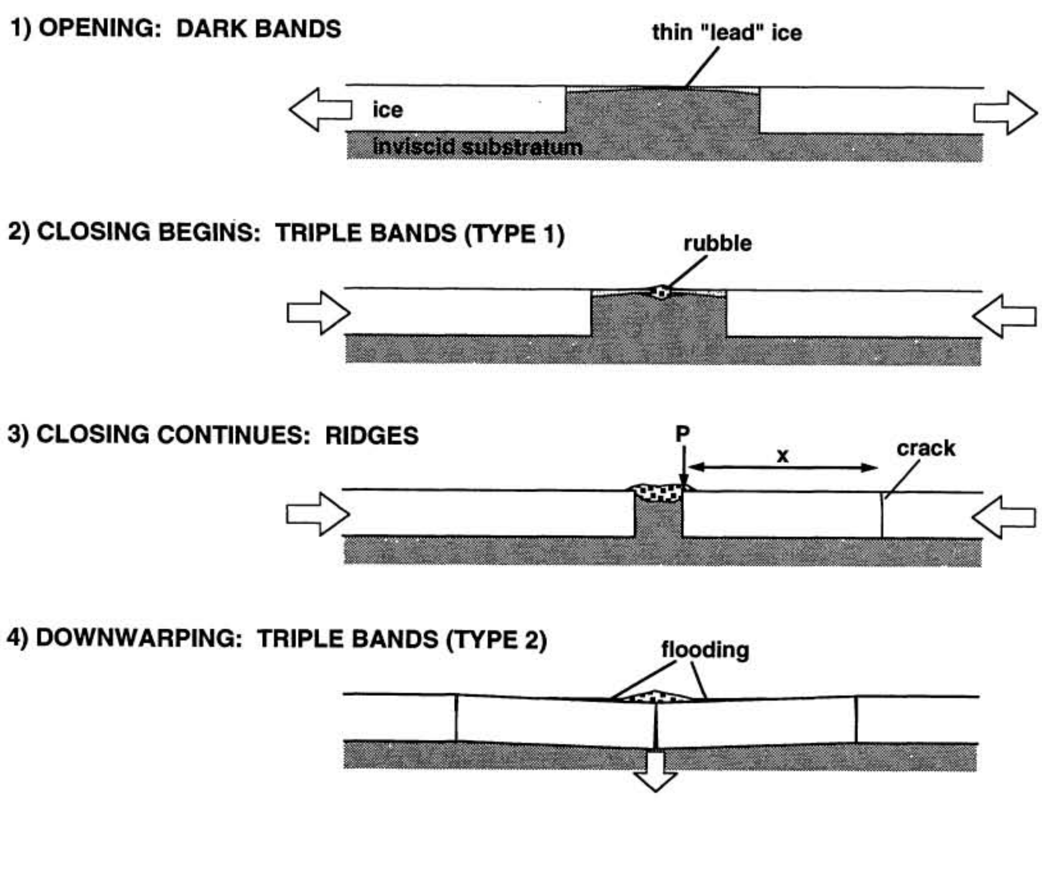

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