BANDS ON JUPITER'S MOON EUROPA: GEOMETRIES, MORPHOLOGIES, CLASSIFICATION, AND FORMATION MECHANISMS

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1. Overview

The surface of Jupiter's moon Europa is disrupted by multiple types of geologic features. Bands form prominent extensional, tabular features with contrasting albedo and/or surface texture to the surrounding terrain [1-4]. They represent sites of new crustal creation through plate-like opening or spreading. The surface of Europa is geologically young (perhaps no more than ~90 my)[5], indicating that some combination of processes must rapidly resurface this icy moon. Bands may be a major contributor to this process. Nonetheless, how and why bands form remains an open question. We have developed a new classification system for bands focused on geometry in relation to the breadth of morphologies observed and infer a range of potential top-driven formation mechanisms. Bands may change morphology across the width or along the length of the band. Geometric elements include band shapes, association with other structures, opening vectors, and the ratio of dilation to band length. By matching piercing points of older features along the margins of the bands and accounting for internal morphology changes, we reconstruct the dilation phases from initial opening of a pre-existing fracture to the current state of maximum dilation (up to ~30-40 km). We identify patterns where the morphology of a band changes from smooth to lineated in response to the opening vector becoming highly oblique, resulting in primarily lateral motions. This obliquity could have implications for the rate or mechanism by which material is transported to the surface. Understanding the driving mechanisms behind band formation will shed insight into how the surface of Europa was formed and possibly is still being resurfaced. If bands are a conduit through which material is transported to the surface from deeper and warmer portions of the ice shell, they may provide key sites for the search for life on Europa and priority targeting by future missions to this icy moon, such as NASA's Europa Clipper mission.

2. Methods

This study utilizes the USGS Europa global mosaic and Galileo spacecraft images to map and characterize bands from nine regions: Argadnel Regio, Yelland Linea, Argiope Linea, Castalia Macula, Echion Linea, Sarpedon Linea, Libya Linea, Astypalaea Linea, and Falga Regio. Spatial and geometric analysis utilized Galileo SSI and Voyager 2 images input into an ArcGIS 10.6 environment and stitched together as a global mosaic with 3 projections to the Europa_2000 reference system (north pole, south pole, and Mercator). Images range in resolution from 28 to 250 m/pixel. Details of broad scale features were mapped within the constraints of image resolutions and our ability to reconstruct or interpret features. Lower resolution images (500 m/pixel) were used to describe broad scale feature characteristics including albedo changes or regional geometry changes. Higher resolution images (~20-60 m/pixel) were used to describe detailed feature characteristics including polyphase band openings, internal morphologies, and variations in morphologies within the same band. Band opening vectors are measured using piercing points (matching features on opposite sides of a band), opening distance was measured parallel to the opening vectors, and band width was measured perpendicular to the band.

3. Geometric Band Classification

Bands can be classified geometrically based on distinct band shapes and associations with pre-existing weaknesses such as strike-slip faults, cycloids, ridges, or older bands. Although the majority of bands display distinct dilational evidence (i.e., piercing point indicators along opposing band margins) and can thus be simply reconstructed, band-like features may also form through convergence or non-dilational extensional deformation, and lack piercing point indicators.

Inherited, Arcuate: Arcuate bands are curvilinear dilational bands with curved or cuspate structures that form chains of arcuate segments linked at sharp cusps. Dilation may be orthogonal to the boundary, but is typically oblique given the changing orientation of the boundary relative to the opening direction. (Fig. 1).

Inherited, Non-Arcuate: Non-Arcuate bands do not adhere strictly to any specific geometry, but rather are dilation of a ridge or crack.

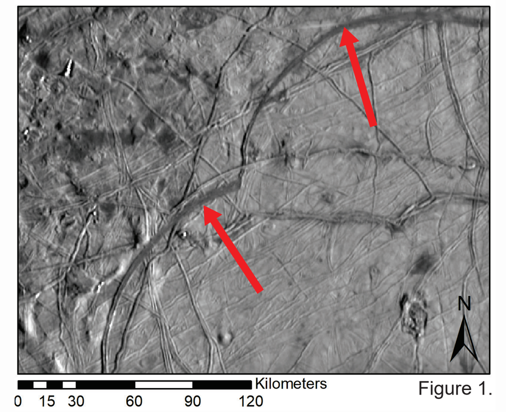

Figure 1.

Rhomboidal: Rhomboidal bands are always located between overlapping segments of laterally offset or en echelon strike-slip or transform faults. Bounding ridges typically define the long axis edges of rhomboidal bands , which also comprise the fault segments along which initial strike-slip motion occurred (Fig. 2. along the strike-slip fault Astypalaea Linea in the south polar region).

Inherited, Transform: Although associated with strike-slip faults, these do not originate between strike-slip segments, but rather it dilates the strike-slip fault itself (Fig. 3. blue arrow).

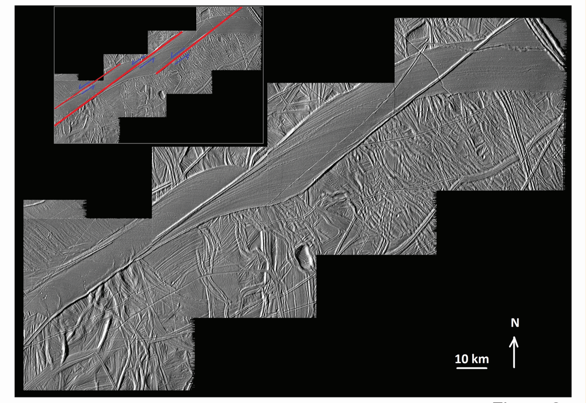
Figure 2.

Wedge-shaped: Bands with a wedge-shaped geometry can be identified based on their differential opening widths along the length of the band. The wide end emanates from the tip of a linear discontinuity along which strike-slip motion is predominant. As such, these bands resemble tailcracks along terrestrial strike-slip faults [11]. Opening widths decrease somewhat linearly towards the distal tip of the band. (Fig. 3. located in Argadnel Regio)

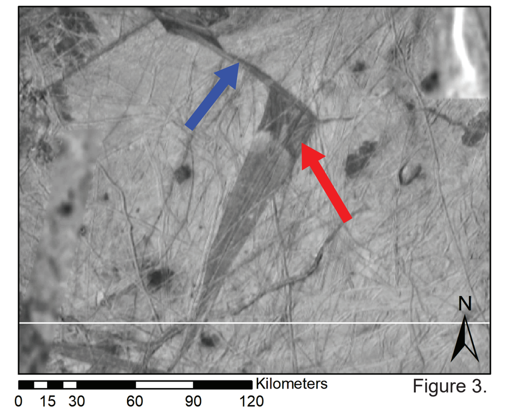

Figure 3.

Braided: Braided bands are geometrically complex, with evidence of multiple distinct phases of band formation and with younger band boundaries crosscutting older band boundaries, resulting in an interweaving or braided pattern. Opposing margins of these bands cannot be matched or reconstructed (i.e., no identifiable piercing points). These bands may represent sites of local convergence or surface area removal (Fig. 4. located in Argadnel Regio directly south of Phaedra Linea)

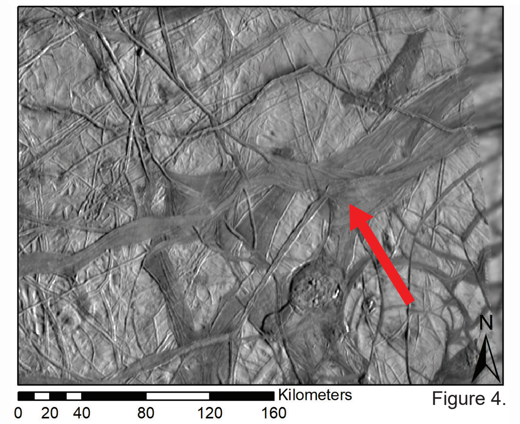

Figure 4.

Convergence Band: Convergence bands are identified by a distinct mismatch of terrain beyond their irregular non-symmetrical margins. Features truncated against convergence bands do not have matching piercing points and often the terrains on opposite sides of the band differ greatly. This band type is not included in the focus of this study. (Fig. 5. located in northern Falga Regio)

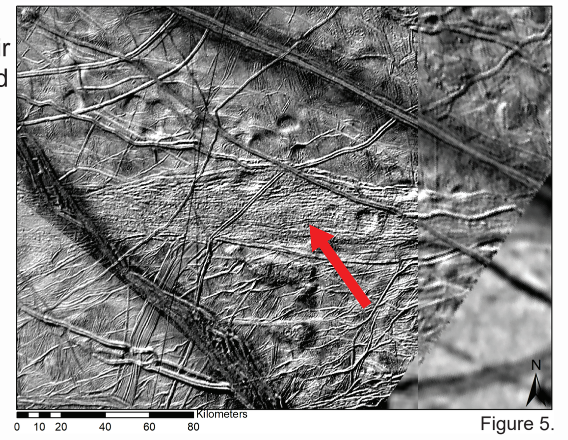

Figure 5.

4. Reconstruction of Bands

To fully understand the process of band formation it is necessary to reconstruct the band one phase of opening at a time. Phases of opening (i.e. dilation, lateral motion, etc.) can by identified in the following ways: piercing points and cross-cutting relationships. Piercing points are pre-existing features to either side of the band in contact prior to opening of the band. Cross-cutting relationships are used to identify the order in which each opening phase occurred. By combining piercing points and cross-cutting relationships, we can reconstruct some bands in reverse sequence to see the relative motions accross the bands to produce what we observe today.

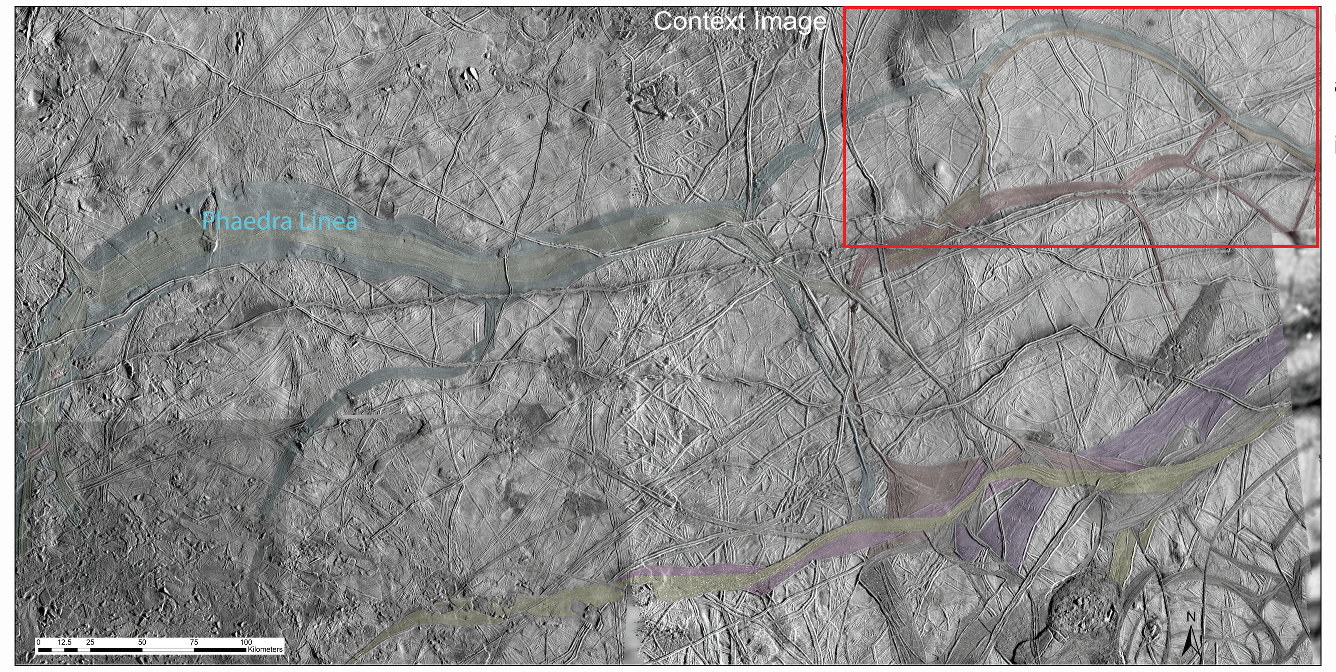

Figure 6. Arcuate bands near Castalia Macula, including Phaedra Linea. Different colors within bands indicate distinct opening phases. Image is a mosaic of high-resolution images from the Galileo SSI instrument from NASA/JPL. The red box in the north eastern section is reconstructed incrementally in figure 6a, 6b, 6c, and 6d.

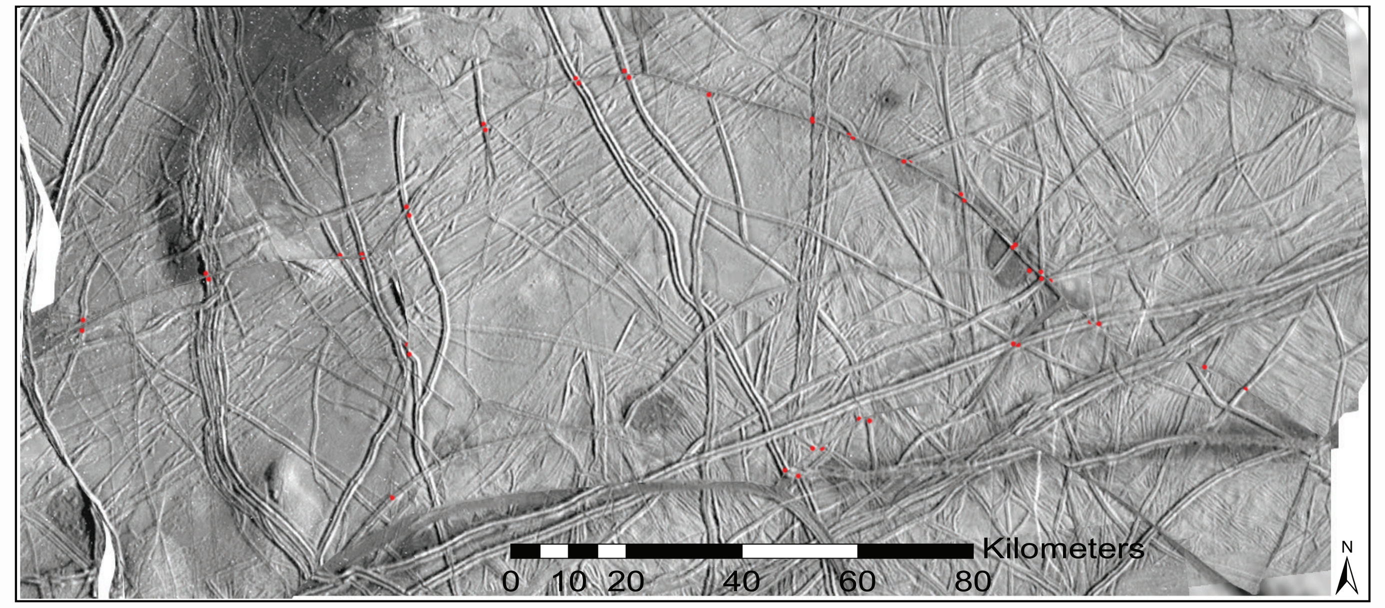

Figure 6a. Reconstructed image of the eastern section of Phaedra Linea near Castalia Macula. Image shows what the region would have looked like before band formation. Red dots indicate piercing points that have been matched together to reconstruct the band. Initial conditions are double ridges with arcuate shapes that resemble smaller versions of cycloids, and narrow arcuate bands in the southern section.

Dilation Phase 1

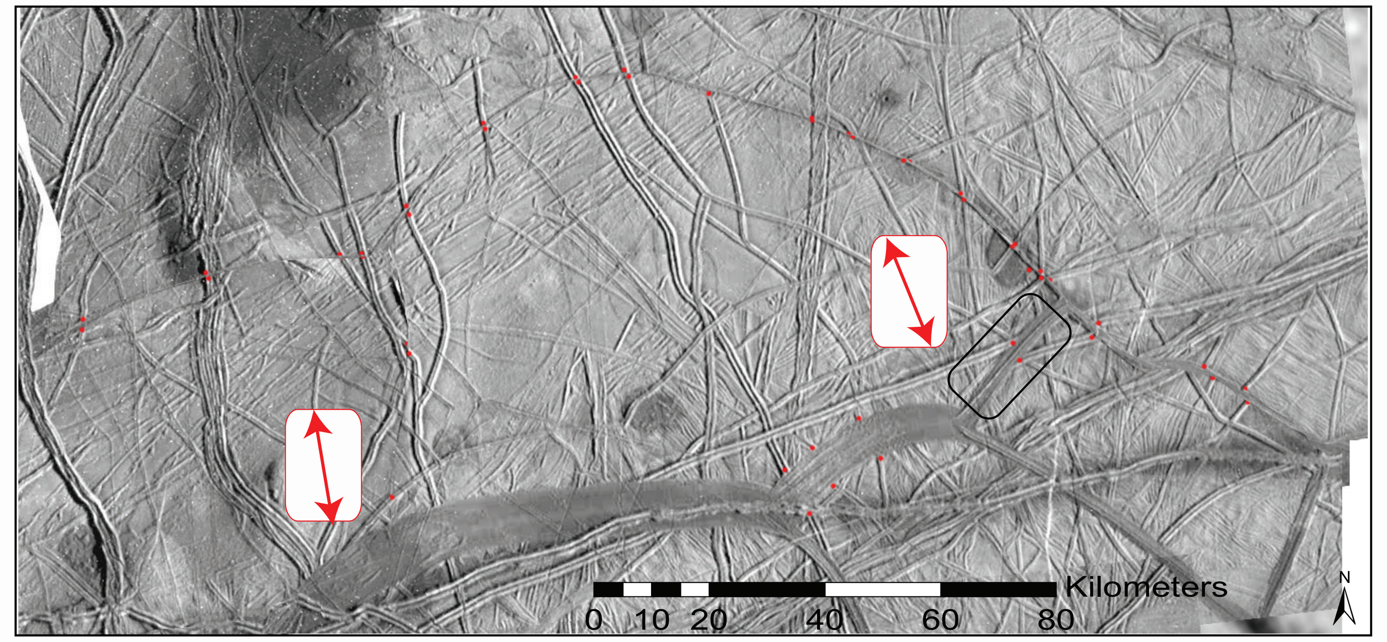

Figure 6b. During the initial phase of opening, the southern band utilizes a smaller pre-existing band as a weakness to dilate. Opening vectors in the western section trend strongly south, south-east while in the east trend more east, south-east, indicating a slight rotation during dilation. The boxed area has a pervasively lineated morphology due to a dominant lateral motion component.

Dilation Phase 2

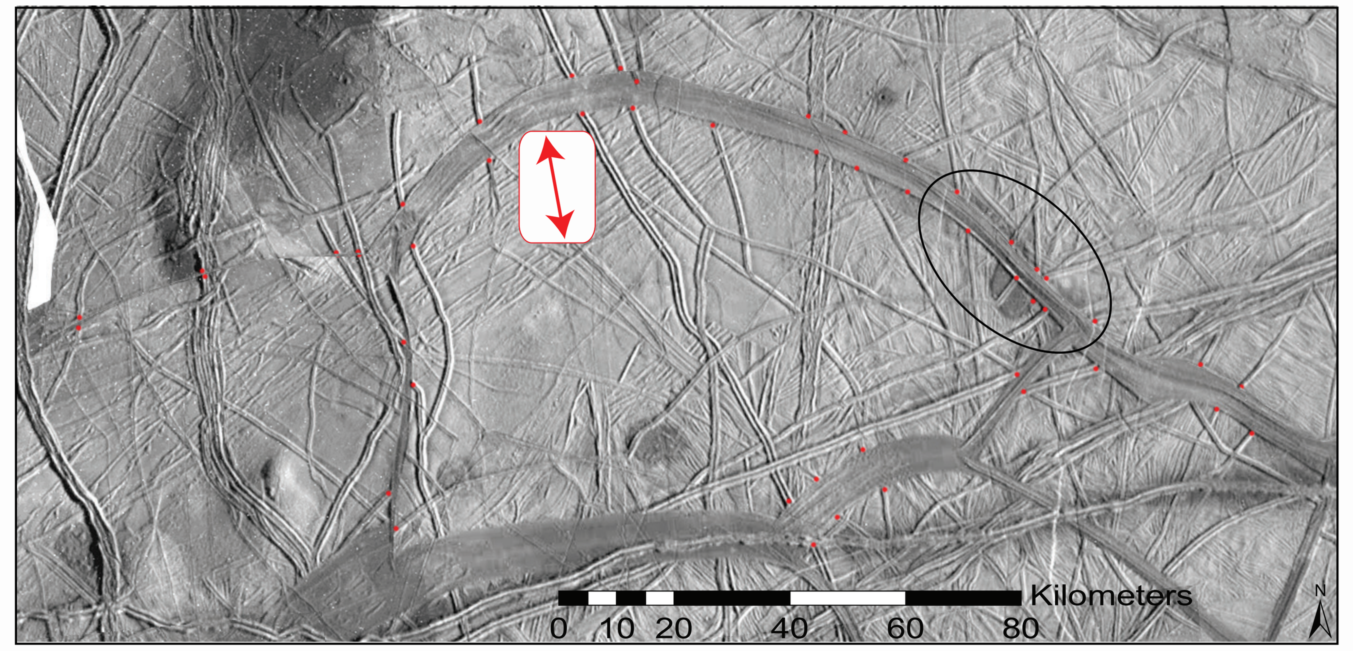

Figure 6c. Dilation on northern band and continued dilation on western section of southern band.Opening vectors across the length of the band are uniform, indicating there is little to no rotation. Circled area is being dilated more obliquely than most of the band and displays the lineated morphology related to lateral motion (see section 5).

Dilation Phase 3

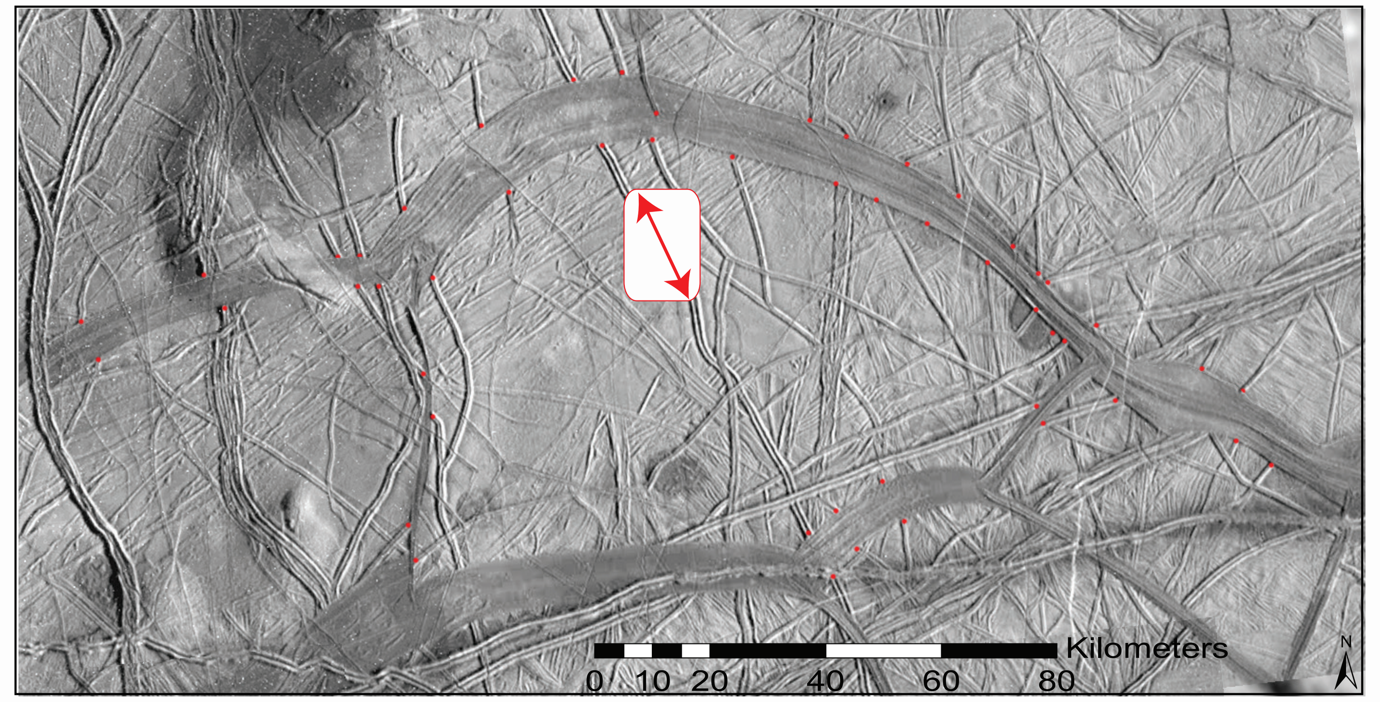

Figure 6d: Current network of arcuate and rhomboidal bands forming a set of discrete microplates in the region of Castalia Macula. At least three phases of motion with differing vectors are revealed by reconstructing the eastern section of Phaedra Linea. The final stage of opening reactivated using the weakness of the older band/ cycloid but extended further to the west facilitated the initial phase of opening for the largest section of Phaedra Linea (see context image).

5. Morphology of Bands

Band morphology may be impacted by multiple factors including obliquity, number of opening phases, band geometry, and rate of spreading. Three primary morphologies are identified; smooth, lineated, and ridged. In the observed bands, smooth morphologies (Fig. 7,9) occur most often where there is low obliquity between the opening vector and the band margin. As obliquity increases beyond ~45° lineations are often present in the same band. A lineated morphology most often occurs where obliquity is high and lineations trend parallel to the band margins, or in rhomboidal bands where opening is parallel to adjacent strike-slip segments. A change in morphology within the same band most often occurs in arcuate geometries where the obliquity of the opening vector progressively increases (Fig. 8). A morphology change also occurs where multiple phases of opening exist in one band, indicating potentially varying spreading rates, or motion vectors during each phase.

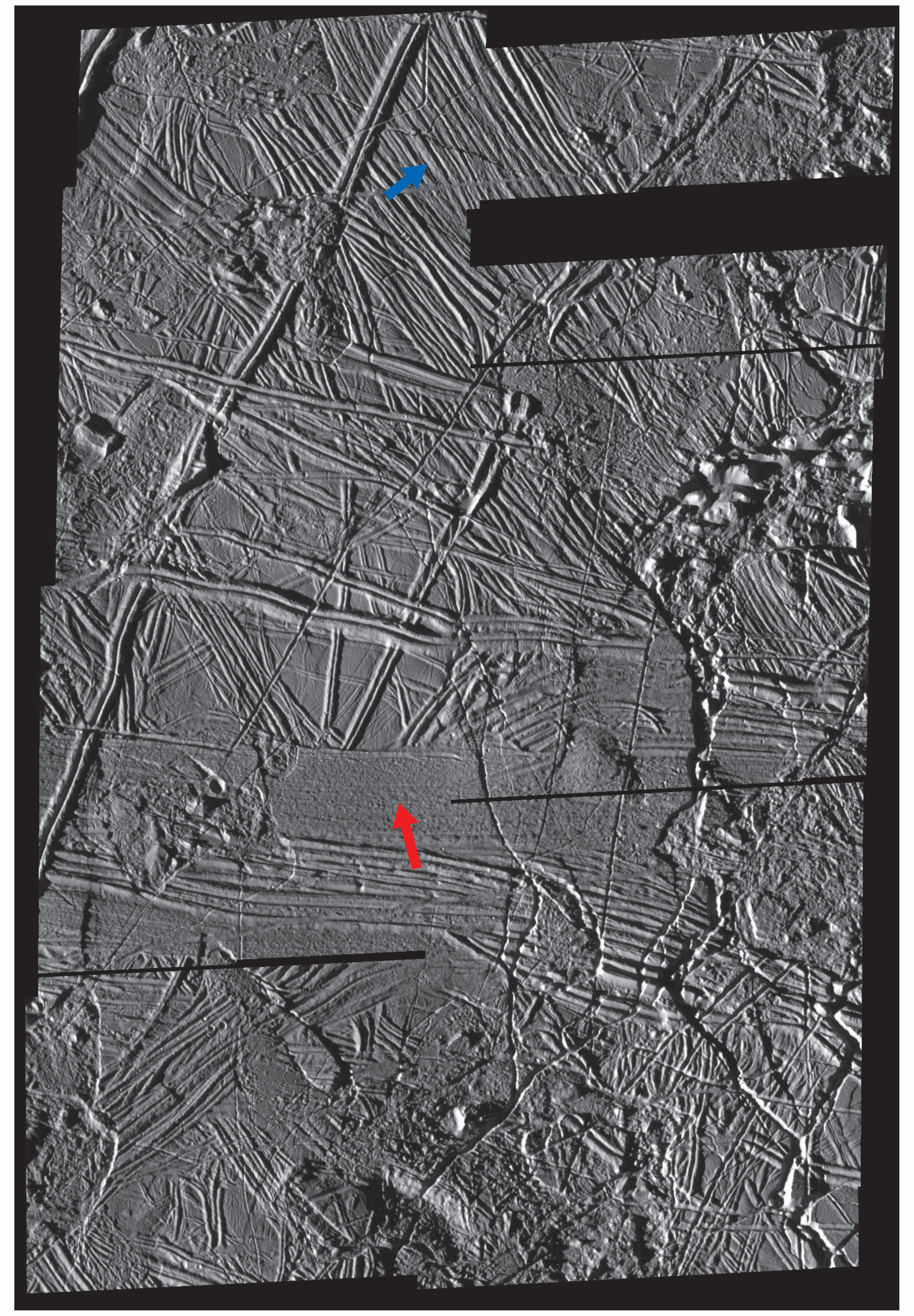

Figure 7. Non-spacially rectified image taken during E11 orbit, showing a heavily disrupted region that contains varied band morphologies including smooth band morphology (red arrow) and ridged band morphology (blue arrow).

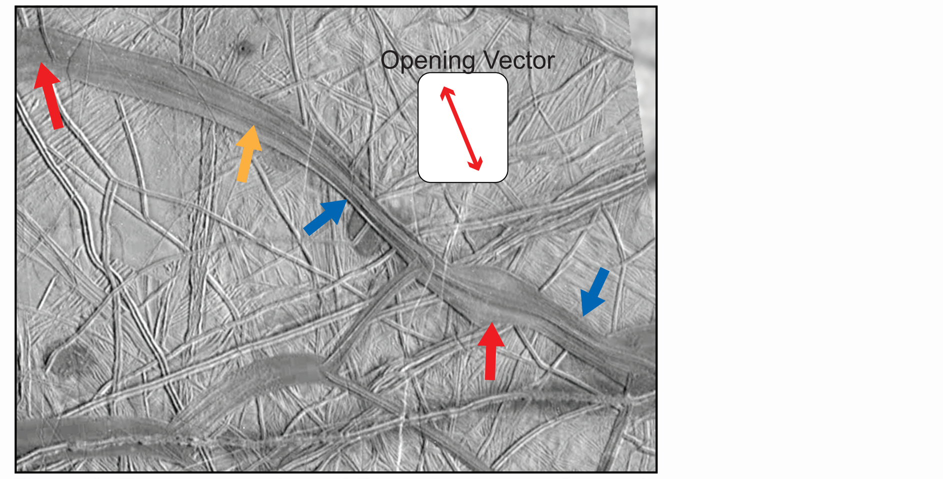

Figure 8. Eastern section of Phaedra Linea. Smooth morphology occurs where opening vectors are ~45°-90° to the band margins (Red arrows). As obliquity reaches 45° (yellow arrow) lineations appear. At high obliquity (blue arrows) lineated morphology is dominant.

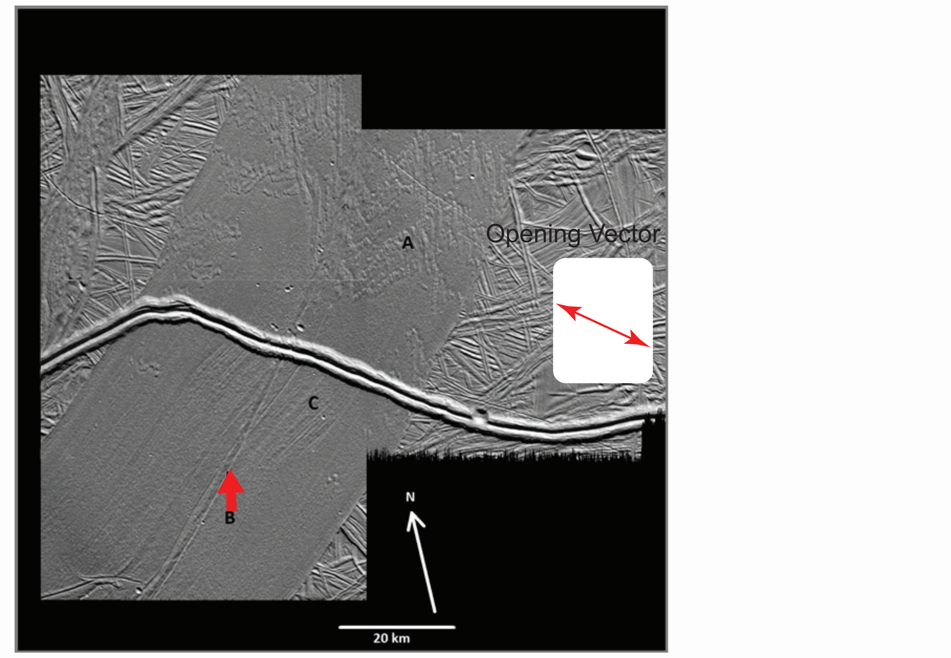

Figure 9. A portion of Thynia Linea where the opening vector is orthagonal shows typical smooth band morphology with a central trough (B). Fine striae run parallel to the bands margins (C) and small whale-backed hummocks (A) become more abundant in the northern section of the band. Image stitched together using images 17E0071, 17E0072, 17E0073, and 17E0074.

6. Conclusions

We find that band geometry is directly related to the underlying controls on band formation.

- Tailcracks between en echelon segments of a strike-slip fault open because of ongoing strike-slip motions, generally producing rhomboidal band geometries. Isolated tailcracks form wedge-shaped bands.
- Bands almost always utilize preexisting features to accommodate opening, often resulting in later phases of bands opening inside existing bands, identifiable through a change in morphology related to some unknown change in emplacement mechanism (e.g., spreading rate, ice chemistry, regional stress state, etc.).
- The internal morphology of a band during a single phase of opening can alternate between lineated and smooth, with more lineations appearing as the obliquity of the opening vector increases.

We thus infer that **band dilation and infill from below is a passive response to a localized surface-driven process** (e.g., plate motions; strike-slip activity), rather than being driven by local thermodynamic instabilities in the underlying warmer ice, which may rather be a consequence of the dilation.

- Formation of bands in the region resembles desaggregation through microplate motions.
- Microplate motion is consistent with a unidirectional driving mechanism.
- Bands that form in close enough proximity to one another to mechanically interact can create linked networks of bands that define boundaries around isolated sections of the icy crust, forming small mobile units or microplates. Where this occurs, triple-junction band geometries may develop.
- Both the morphology and geometry of bands seem to be inherently linked to the formation mechanism and opening kinematics. Existing band classifications primarily focus on internal morphology [2, 10], the differences in which remain loosely explained.

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