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Failure modes of the lineaments on Jupiter's moon, Europa: Implications for the evolution of its icy crust

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Abstract

Lineaments referred to as ridges, troughs, bands, and faults on the icy surface of Jupiter's moon, Europa, have long been interpreted as extensional structures due to brittle fracturing of ice and intrusion of mobile materials from the interior of the satellite. Based on detailed mapping and possibly analogous structures present on Earth, we propose that the kinematics and failure mechanisms of these structures are variable and more complex than previously thought. A dense network of structures of multiple generations, forming the background on the surface of the planet, is here interpreted as localized zones of volumetric strain, likely compaction and/or dilation bands. The next class of linear failure structures is shear bands with significant offset of pre-existing markers. A few additional phases of less pervasive but more prominent volumetric deformation bands overprint the shear zones and background network. The mode of younger features can be characterized as sharp, dilational, brittle fracturing and subsequent shearing, thereby producing comminution and fragmentation in various sizes, leading to a series of younger faults with detectable lateral, as well as vertical, offset. This rich variability in the nature of the distribution, localization, kinematics, and formation mechanisms, if true, suggests that the conditions prevailing within the crust of Europa must have changed dramatically over time. The implication of this conclusion is that structures interpreted to be compaction/dilation bands and shear bands on Europa are composed of deformed materials similar to the surrounding ice, whereas only the younger faults, developed by brittle fracturing and fragmentation, may be conduits for mobile substrate to reach the surface and thus offer the highest potential for recovering evidence for life in the satellite.

Keywords: Europa satellite; Europa lineaments; Planetary faults; Failure modes; Bands; Ridges

1. Introduction

The Galileo spacecraft was launched in 1989 and reached Jupiter in 1995 and provided images of the surface of Jupiter's icy moon, Europa, displaying astonishing arrays of lineaments (see http://galileo.jpl.nasa.gov). These images, with resolutions of up to 2 km/pixel for the Voyager and up to 6 m/pixel for the Galileo, have helped to form a consensus that the lineaments were originally brittle, dilational fractures in ice (Buratti and Golombek, 1988; Collins et al., 1998; Fagents et al., 1999; Greenberg et al., 1998; Head et al., 1998; Hoppa et al., 2000; Pappalardo and Sullivan, 1996; Pappalardo et al., 1999; Schulson, 2002; Sullivan et al., 1998; Turtle et al., 1998), which were subsequently intruded by material from a mobile substrate (Carr et al., 1998; Collins et al., 1998; Pappalardo et al., 1999; Prockter et al., 2002). Fig. 1 presents a collage of the extant models for the Europan lineaments, based primarily on opening-mode fractures and their subsequent filling (Fig. 1A–D) in various structural settings. One model assumes shear heating which is only applicable to large dynamic faults, if any. These notions, along with geophysical data inverted for subsurface physical properties, offer a structural connection between a subsurface environment potentially hospitable to life and the possible recovery of evidence for this extraterrestrial life from the surface of the satellite by a future lander (Chyba and Phillips, 2001; Greeley and Johnson, 2004).

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This study presents mapping of selected areas on Europa and a new framework for the nature of the lineaments thereon. The bases of the new interpretation are potentially analogous failure modes and the kinematics, geometry, and texture of corresponding structural products in Earth materials. Because inversion of images of the Europan lineaments for their physical, architectural, and hydraulic characteristics is inherently nonunique, additional information derived from analogous Earth structures may be helpful in remote studies of planetary objects. Although a long list of potentially analogous Earth structures and their tectonic environments was offered by previous workers (Pappalardo et al., 1995; Figueredo and Greeley, 2004), the present study is an attempt to focus on the failure modes of, and the physical processes responsible for, the linear structures on the surface of Europa providing new insights for the mechanical nature of the deformation in the icy crust of the satellite.

2. Structural data

2.1. The lineaments in the Bright Plains region

Solid State Image mosaics of the Bright Plains region in the trailing hemisphere of Europa (Fig. 2, inset) have been used by several investigators (Carr et al., 1998; Fagents et al., 2000; Greenberg et al., 1998; Head et al., 1999; Kattenhorn, 2002; Spaun et al., 2003) for structural mapping and analyses due partly to the exceptional quality of the images and diversity of their structural features. The region is crossed by three major lineaments (Fig. 2): Asterius Linea and Agave Linea, intersecting at about 14°N, 273°W, and Androgeos Linea, located north of the intersection of the first two and somewhat less prominent than the others. The area in the upper right corner of the mosaic (Fig. 2) contains most of the common linear structures seen on Europa as well as other icy satellites. We have mapped this area in detail (Fig. 3), in order to establish the sequence of formation of the lineaments and their geometric, textural and kinematical characteristics. The color code in the legend for Fig. 3 represents the structural and geological elements, while the order of the numbers reflects their temporal occurrences (relative ages) based upon the cross-cutting relationships between intersecting classes of structures (Groups).

Group 1 (green code in Fig. 3) includes the oldest structures (#1 in Fig. 3), which are parallel multiple ridges and troughs or grooves. These ridges and troughs, with characteristic bright and dark striped patterns, respectively, occur in zones up to 20 km wide, as bracketed by dashed thin green lines in the map. Networks of multiple ridges and troughs in various orientations criss-cross each other and form an interwoven web of background structures, usually referred to as plains (Carr et al., 1998; Kattenhorn, 2002) in a tectonomorphic sense. However, within this group, relatively younger ridges and troughs with wide spacing and fewer structural elements (#2 in Fig. 3) also occur. Three of these lie in orientation approximately N–S in the lower west quadrant of the image and are highlighted by thick green lines in order to distinguish between the wide zones made up of multiple ridges and relatively simpler ridges in isolation. Generally, it is difficult to detect lateral or vertical offset across older broad zones as opposed to relatively younger, isolated lineaments due to the fragmented and interspersed nature of the plains and the lack of clear and regular boundaries of the early broad zones.

The next group of structures, Group 2 (red code or #3 and 4 in Fig. 3), is an easterly trending, curvilinear set of lineaments, each defined by single, double, or multiple stripes. When both dark and bright stripes occur along a simple double band, the location of the bright stripe varies; an effect that is apparently due to variation in topography and the direction of illumination. These structures extend several tens of kilometers in length and have a regular spacing of about 10 km. They show clear evidence of displacement discontinuity in both apparent right- and left-lateral sense on the order of several kilometers, based on the displaced pieces of older lineaments in the background as reference markers (Fig. 4A). The magnitude and sense of lateral offset are unambiguous for thinner, isolated, and younger lineaments (#4 in Figs. 3 and 4A). Given this relative confidence in detecting offset markers, the variation in the sense and magnitude of lateral shearing across the

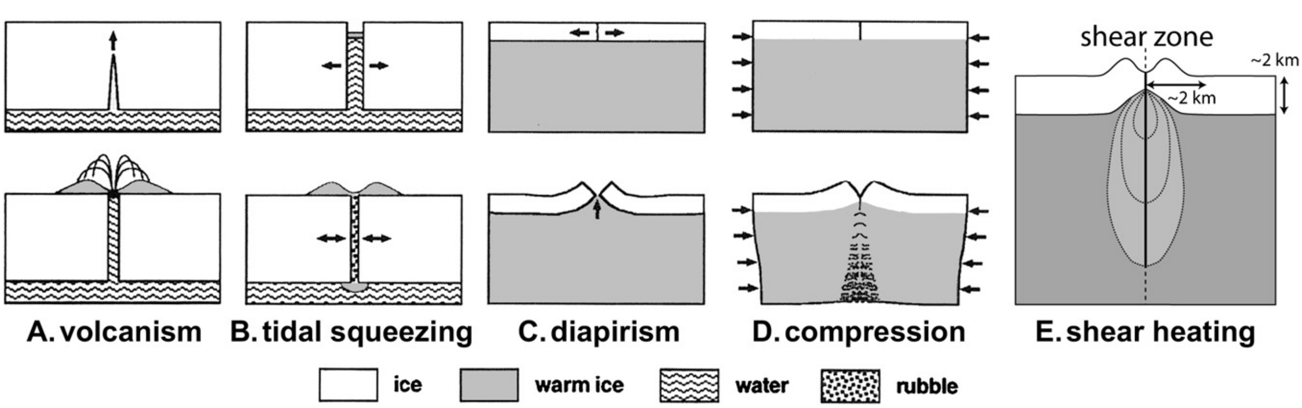

Fig. 1. The current models for the formation of the lineaments on Europa. All (A–D) but one (E) assume or imply the presence of an initial crack-like dilational fracture near or on the surface of the satellite, which was later intruded by a mobile substrate by a variety of possible mechanisms. (A–D). From Pappalardo et al. (1999). (E) Depicts increasing temperature due to shear heating associated with dynamic faulting and possible surface expression of the ensuing deformation (simplified from Nimmo and Gaido, 2002).

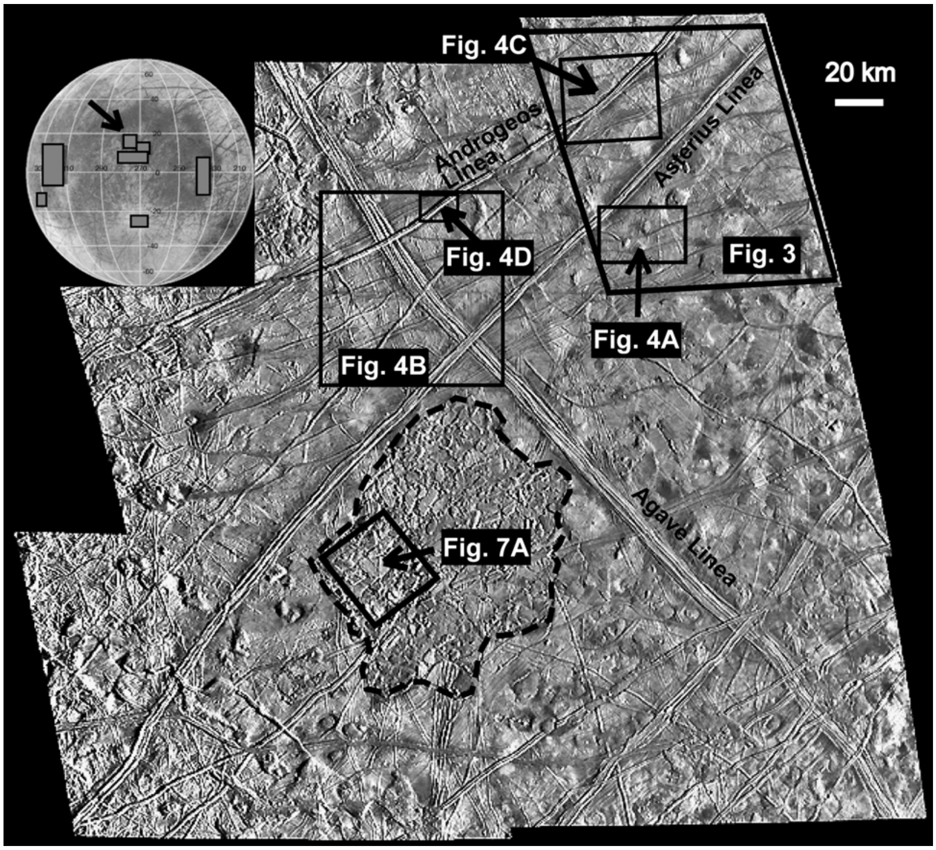

Fig. 2. Image of the Conamara Chaos region showing the locations of the detailed figures with the three major lineaments, Asterius Linea, Agave Linea, and Androgeos Linea, as reference markers. Inset (upper left) shows the northern trailing hemisphere with arrow pointing the location. Locations of Figs. 4A–D and 7A are also marked.

elements in Group 2, along a given structure, as well as from one structure to another, is remarkable (see, for example, the offset markers enlarged in Fig. 4A). It appears that the fault traces are curvilinear and the angular difference between the segment orientations may account for the observed variability. For example, the eastern parts of the lineaments trend about N 70°E, whereas the western parts trend about E–W. However, this alone cannot explain the significant variation in the magnitude and sense of shear. A more plausible mechanism for the observed variation is the possible presence of a fault-normal component of the displacement discontinuity. Thus, not only the local orientation of the lineaments (red in Fig. 4A) but also the relative orientation of the displaced markers (green in Fig. 4A) may have played a role in the variation of the apparent offsets. Based on this alternative, it is likely that the fault-normal strain is contractional for at least one clear case (see the wedge-shaped geometry of the displaced markers in the lower part of Fig. 4A). For this case, the amount of estimated fault-normal contraction may be twice as large as the apparent largest strike-slip component across the fault traces.

Several members of Group 2, defined by dashed, reddish-brown lines on the map (#3 in Fig. 3), appear to have more complex interior architectures. Detailed examination of these wider zones reveals that they are made up of more than one pair of sub-parallel dark and bright stripes with partially overprinting patterns. The kinematical properties of these zones are less certain. It is difficult to match older markers on either side of these zones with certainty. In a few cases, a relatively intact zone of older background structure (bracketed by dashed green lines in central part of Fig. 3) was sheared by these lineaments for greater than 10 km.

Group 3 structures (blue color code and #5 in Fig. 3) are the least conspicuous of all lineaments. They appear as fuzzy, bright, curvilinear discontinuities and are precursors for regions of disturbance and uplift. The best examples of these are located in the central part of Fig. 3.

Group 4 structures (mustard color code or #6 in Fig. 3) are composed of four NNW-trending lineaments with a central dark stripe, shouldered by two bright stripes, one on each side in perfect symmetry. These structures have a rugged appearance and are more crooked with respect to the other lineaments described so far. The westernmost two lineaments lie close to each other and they inosculate (converge and diverge) locally.

Group 5 (light yellow color code or #7 in Fig. 3) includes the two most prominent lineaments, Androgeos in the north and Asterius at the center of the study area (Fig. 3). These two lineaments have a northeasterly trend and cut across a northwesterly trending lineament, Agave Linea, (Figs. 2 and 4B) without any shear offset detectable as marked in

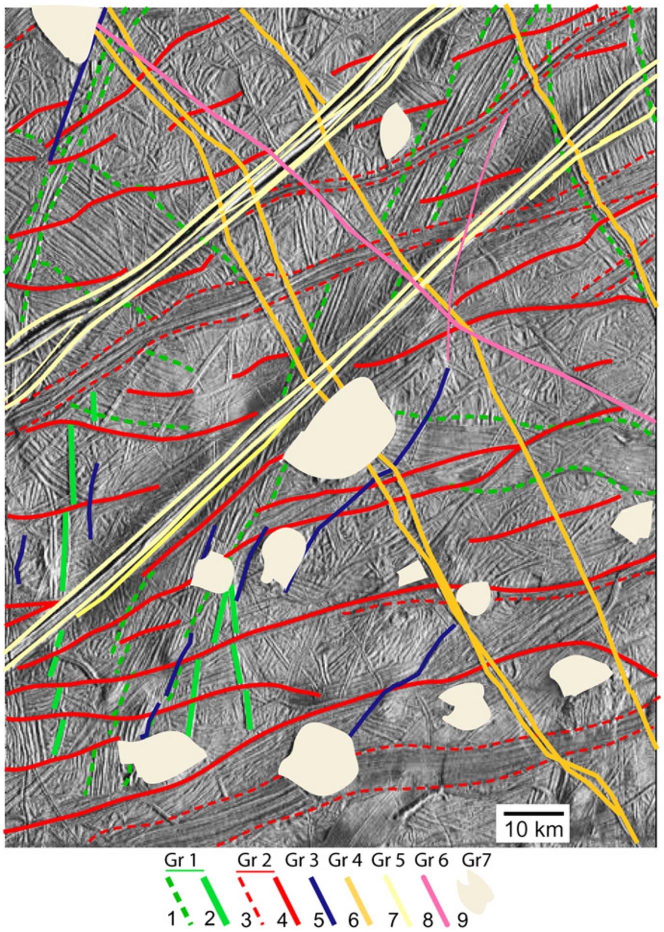

Fig. 3. Structural map showing lineaments and intersection relationships in the Bright Plains area (see Fig. 2 for location). Color codes and numbers mark different structures and their relative ages. Green for Group 1 (#1 and 2 on the image) highlights volumetric bands. Red for Group 2 (#3 and 4) marks shear bands. Blue for Group 3 (#5) and mustard for Group 4 (#6) are fractures. Yellow for Group 5 (#7) represents overlapping volumetric deformation bands. Pink for Group 6 (#8) marks the youngest fractures. Cream-colored patches (#9) mark Group 7, the freckles or lenticulae.

Fig. 4B. Considering that consistent displacement discontinuity of a left-lateral sense across Agave Linea (arrows in Fig. 4B) is quite clear in the image (also see Kattenhorn, 2004 for additional evidence for shearing across this structure), the lack of evidence for shearing across the Androgeos Linea and Asterius Linea is highly conspicuous.

All three lineaments extend for hundreds of kilometers beyond the study area. Upon closer inspection, it is possible to recognize different elements within each of these lineaments; each element having a central dark stripe, sandwiched by two wide and bright stripes. The forked and lenticular geometry of Androgeos Linea and its intersection with the two westernmost structures in Group 4 (#6 in Fig. 3) reveal that this structure is composed of at least two overlapping elements, each with a symmetrical striped pattern (Fig. 4C). The southeastern element (labeled "1" in Fig. 4C) is older because it is being cut by the two westernmost members of Group 4 (labeled "2"). The northeastern one (labeled "3") is younger, given that it cuts across the aforementioned structures in Group 4 (labeled "2"). Hence, it appears that Androgeos Linea had a two-stage development: The first stage, which is represented by the southern strand, occurred prior to the formation of the Group 4 structures. The second stage is represented by the reactivation of the deformation in the form of the northern strand following the Group 4 phase. Finally, the entire Androgeos Linea structure was cut across by a simple lineament (color-coded pink or #8 in Fig. 3, and labeled "4" in Fig. 4C.

Fig. 4D shows a higher resolution (20 m/pixel) image of Androgeos Linea in an area southwest of the detailed map location (see Fig. 2), where the northern strand of the lineament diverges from the compound structures in the northeast. This structure, where isolated, is expressed as a dark central stripe sandwiched by two bright stripes (Fagents et al., 2000; Kattenhorn, 2002) corresponding to low and high topography, respectively. The structure is about 1.8 km wide and was referred to as a ridge or double-ridge structure. Considering that the illumination is from the southeast, the darker shadow on the northwest side is due to the high topography of the ridge, estimated to be on the order of 200 m (Head et al., 1999).

The architecture of the Asterius Linea is similar to that of the Androgeos Linea, in that it is composed of multiple elements with overprinting geometries (Fig. 3). Here, the strands are closer to each other and the southeastern strands overprint the northwestern strands. The fundamental aspect of the pattern, however, is the same: overprinting, symmetrical, sub-parallel striped patterns, each made up of a dark center and two bright shoulders probably reflecting the morphology of the structure(s) and its response to oblique sun angle.

Group 6 is represented by two structures (pink color code or #8 in Fig. 3) each with a sharp, dark, central stripe with somewhat irregular bright, thin shoulders similar to those in Group 4. As noted earlier, one of these structure cuts across all others described earlier (Figs. 3 and 4C) and is, therefore, the youngest lineament in the study area.

Group 7 includes many domes or pits with roughly rounded, rectangular or elliptical geometries (white infill or #9 in Fig. 3), representing highly disrupted and fragmented spots on the satellite. Each of these structures is also called freckles, lenticulae, or microchaos (see Figueredo et al., 2002). The formation of these structures was not emphasized in this paper due to our focus on the prominent lineaments.

Fig. 5 shows a map of an area, centered approximately at 20°N and 225°W, slightly north and east of the area shown in Fig. 3. This image is often used to illustrate the geometry and distribution of the freckles, or lenticulae, at the center of the frame. However, it also displays all the structural elements that were identified in Fig. 3: the background structures in the form of single, double, and multiple ridges and bands without noticeable shear offset, and excellent examples of faults with apparent strike-slip (Hoppa et al., 1999a). Here, our purpose is to show the internal architecture of the two large faults that transect the image from lower left to upper right for a distance greater than 150 km. The northern fault is made up of five major strands arranged in echelon geometry similar to many terrestrial strike-slip faults. The three strands in the

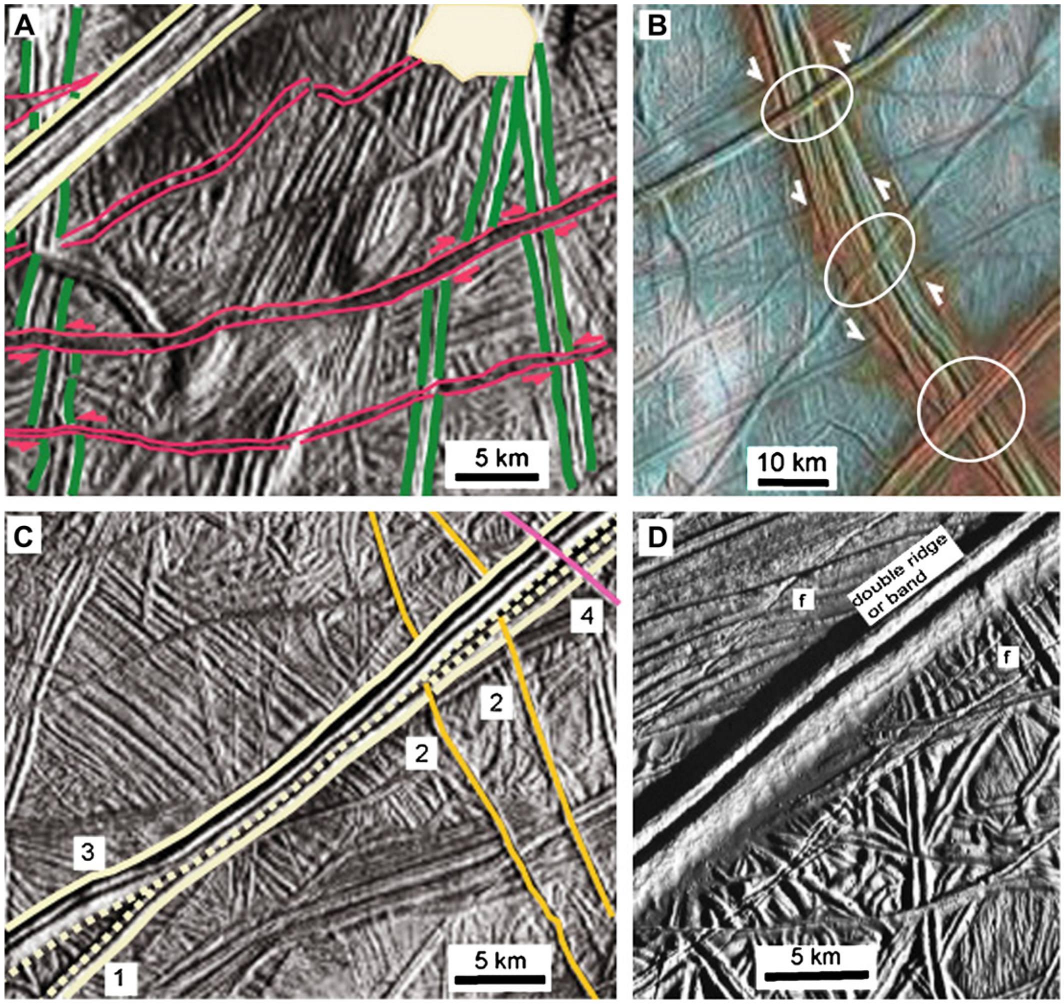

Fig. 4. (A) Details of displacement discontinuities and their variation across the lineaments in Group 2. (B) Intersecting relationships of several lineaments showing apparent left-lateral slip for Agave Linea (arrows) but lack of slip across the two strands of Androgeos Linea (top two circular marks) and Asterius Linea (bottom circular mark). (C) Details of overprinting and diverging strands of Androgeos Linea. Numbers indicate the order of formation. The inner boundaries of the overlapping bands are dashed. (D) Details of the northern strand of Androgeos Linea. "f" marks opening-mode fractures. See Fig. 2 for locations.

northeastern part of the northern fault step to the left, which indicates extensional stepovers (or releasing bends) for left-lateral strike-slip faults. Notice that there are multiple bands within these dilational bends between the northeast-trending straight strands. Furthermore, these strands have splays veering away to the WNW or ESE from the major fault zone (Fig. 5), which also have a banded appearance. These splays should have been subjected to increasing compression perpendicular to their traces, according to the apparent slip sense.

The southern fault has the largest slip (>6 km) and is made up of three major strands with NE trends and two strands with WNW trends (Fig. 5). According to the slip sense, the shorter strands in WNW orientation should have been subjected to increasing compression perpendicular to their traces. These structures also comprise multiple bands with overprinting patterns. In essence, the information revealed by the two fault zones indicates that the features found in various locations and orientations, inferred to have been subjected to contraction, dilation, or shear along the fault zones, have bands with more-or-less the same image characteristics.

These characteristics are similar to those described from other major strike-slip faults of Europa. The best known example in this category is the Astypalaea Linea with 42–56 km right-lateral slip (Fig. 6A and B) (Hoppa et al, 2000; Tufts et al., 1999; Kattenhorn, 2004). Along this fault zone major pull-apart structures have been identified, based on the sense of slip. The ridges and grooves within these apparent pull-apart structures were interpreted to be brittle fractures filled by material from mobile ice or water from the interior of the planet. This issue will be revisited in the discussion section but it suffices to state that there is little difference between the images of those structural elements described earlier and those within the Astypalaea Linea.

2.2. Fracture networks and fragmentation zones in the Conamara Chaos region

We use an image from the western parts of the Conamara Chaos, or the rafted terrains, a disturbed rectangular region south of the intersection of Asterius Linea and Agave Linea

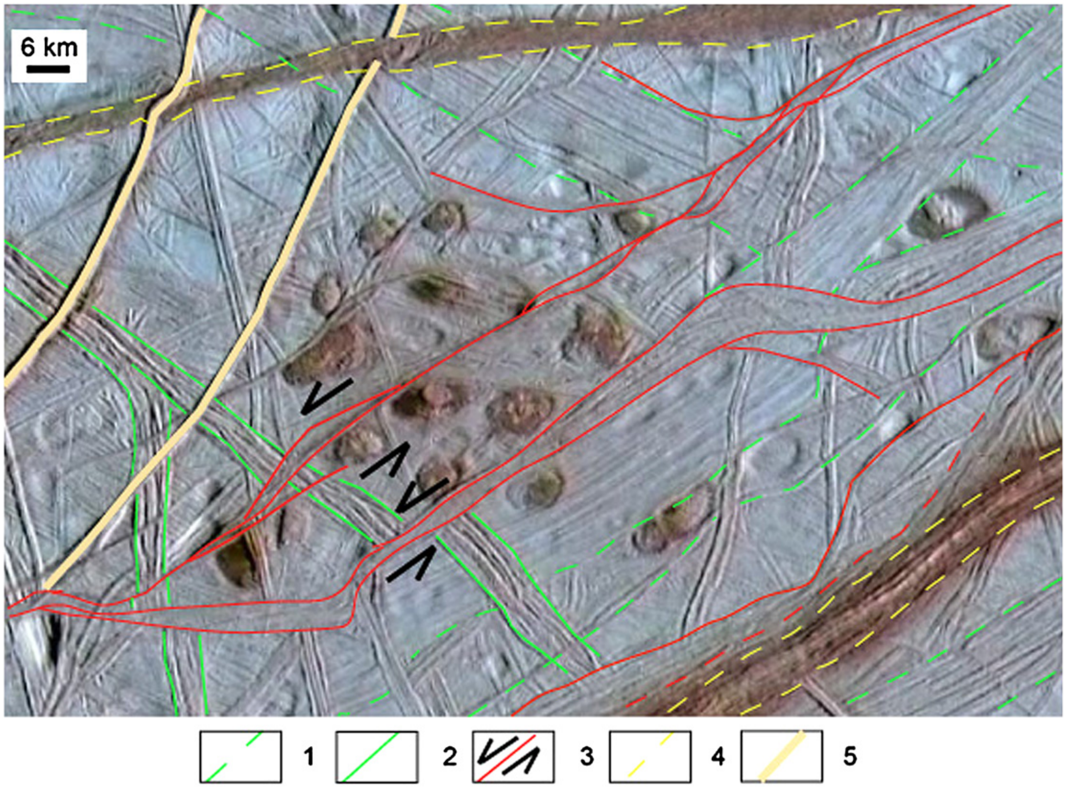

Fig. 5. A system of bands with up to 6 km apparent left-lateral slip. The bands are commonly segmented or bent, resulting in sections inferred to be dilated or contracted. Splays (trending NNW–SSE) associated with segment ends are inferred to be subjected to increasing compression based on the relative sense of lateral motion. The image is centered at about 225°W and 20°N in the trailing northern hemisphere.

(Fig. 2), to introduce another type of structure with offset but in clear contrast to those lineaments with offset shown in Figs. 3–6. The image in Fig. 7A shows a number of polygonal blocks of ice with older surface structures similar to those in the background area in Figs. 3–5. The polygonal blocks are bounded by lineaments, some with clear lateral and vertical offset, and some others with gaps between the blocks (Carr et al., 1998; Spaun et al., 1998) indicating dilation normal to their boundaries. There are also two lineaments, the youngest, with no lateral offset cutting across the image in a NW–SE orientation, which are similar in appearance, temporal evolution, and kinematics (e.g. lack of shear displacement discontinuity) to the structural elements in Groups 4 and 6.

We mapped an area (Fig. 7B), centered approximately at 36°N and 86°W, in order to understand the nature of the original structures leading to the fragmentation and faulting of the icy crust in, for example, the Conamara Chaos region. Fig. 7B shows colored lines tracing either continuous, dark stripes or boundaries of ice blocks of various sizes. Many of the lineaments on the surface of these blocks are sharp and thin, overprint the single and multiple bands in the background, and show no evidence of lateral or vertical slip. However, the boundaries of many blocks (thick solid lines in Fig. 7B) are commonly associated with fragmentation, tilting and significant translation. Note that within the mapped area, there are also several apparently cryoclastic deposits (e.g. Fagents et al., 2000). These are characterized by smooth surfaces and several of them are marked in the figure (semitransparent light patches) for completeness but this subject is out of the scope of the present paper.

3. Hypotheses

3.1. Volumetric deformation bands and shear bands

The lack of any lateral offset across the lineaments in groups 1, 4, 5, and 6 in Fig. 3, and in the background in Figs. 4, 5, and 7, indicates that the displacement discontinuity characterizing the kinematics of these lineaments is predominantly perpendicular to their traces. That is, the boundaries defining each structure moved primarily either away from each other or towards each other. We here propose a new hypothesis for the nature of these lineaments, which honors the aforementioned kinematical boundary conditions but differs from the extant models in terms of the failure mode and compositional make-up of the lineament: these lineaments are most likely to be localized zones of volumetric strain known in geomechanics as compaction and dilation bands (Fig. 8A), depending on whether the deformation involves volume decrease or increase, respectively (Aydin et al., 2006). Note that in this context, the term "band" denotes a localized zone of deformation as opposed to the common descriptive use of the word in the literature on the Europan lineaments (including the most recent ones such as Greenberg, 2004; Kattenhorn, 2004),

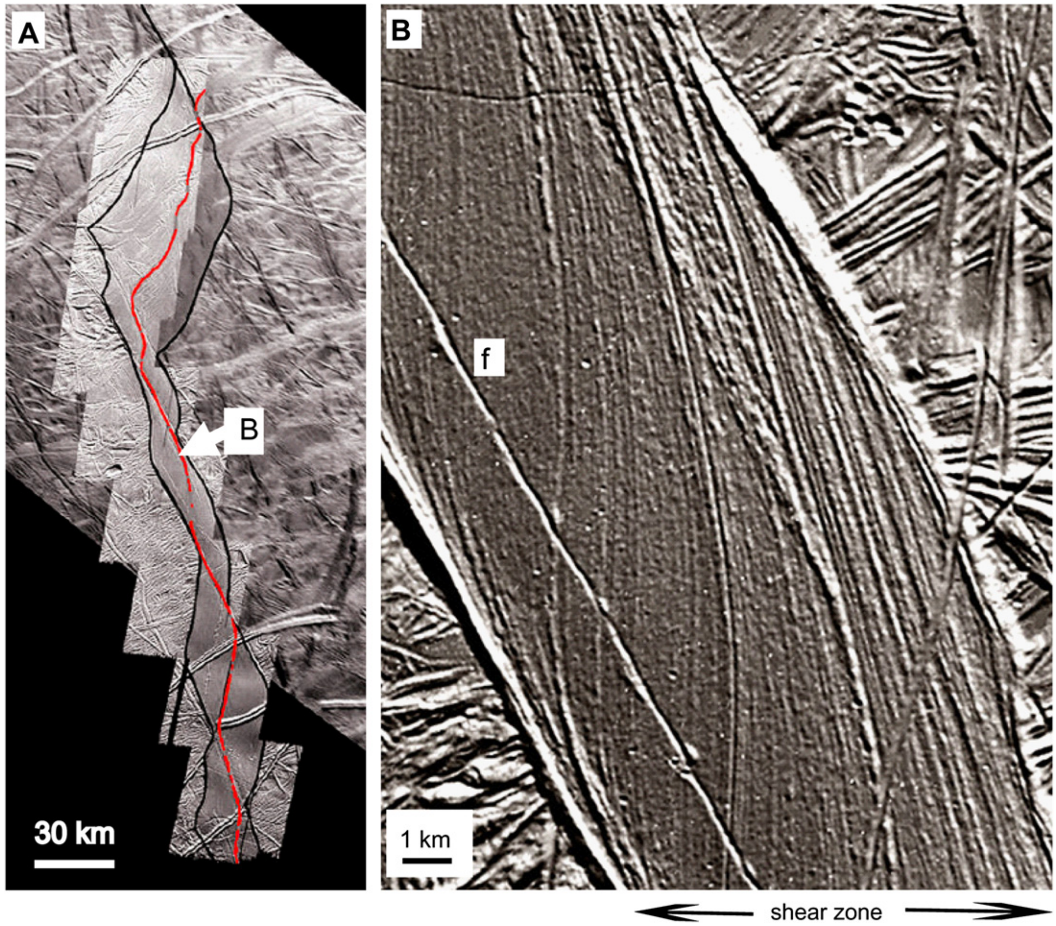

Fig. 6. (A) Astypalaea Linea is a large strike-slip fault with about 42–56 km of right-lateral slip as mapped and interpreted by earlier workers (Hoppa et al., 2000; Tufts et al., 1999). The detailed image in (B) shows a series of ridges and grooves interpreted by earlier workers to be filled dilational fractures. The sub-parallel ridges and grooves are here interpreted to be localized volumetric deformation bands. However, there are a few dilational fractures with possible later shearing within the image. One of these is marked by "f" in the photo.

irrespective of the formation mechanism and the actual geometry of the referred structure underneath the image.

The lineaments with clear offset are faults. In addition, some of these faults also have internal architecture in the form of tabular bands (Group 2 in Fig. 3, and those in Figs. 5 and 6). Therefore, we affirm our earlier assessment (Aydin, 2003) that these structures are shear bands (Fig. 8B). Although only the kinematics of these structures (the sense and magnitude of apparent shear displacement discontinuity) is observable, it is likely that volumetric deformation also takes place within the deformed zones as inferred from a few examples (e.g. Fig. 4A). If a volumetric component of deformation, in addition to the shear component exists, then the structure should be referred to as a compactive or dilatant shear band (Aydin et al., 2006), whichever is appropriate. In the case of the faults in Group 2, the fault-normal component of strain is contractional (Fig. 4A), and therefore, the structures may be referred to as compactive shear bands. Some bands in "splay" or "tail" orientation, with respect to the major segments of the shear band faults (Fig. 5), are reminiscent of similar associations documented in Earth materials and are likely to be compaction or dilation bands representing the end products.

3.2. Mode-I fractures and their shearing, leading to fragmentation and large faulting

The lineaments in Groups 4 and 6 in Fig. 3, and those in Fig. 7B without fragmentation, appear to be true brittle fractures of mode-I type (Fig. 8C), each characterized by two walls and the associated aperture. Generally, these lineaments lack the well-defined, wide, bright shoulders, characteristic of the bands. However, in most cases, these images appear to have discontinuous, faint, thin, bright shoulders indicating that most of them are still open and/or the shoulders are uplifted. Since this type of structure has been described in sufficient detail in the literature by earlier workers (see, for example, Hoppa et al., 1999b; Schulson, 2002; Kattenhorn, 2004), we will focus on faults formed by shearing of these initial mode-I fractures.

The system of faults shown in Fig. 7 is a dominant feature of the Conamara Chaos region, south of the intersection of Asterius Linea and Agave Linea (Fig. 2). We propose that the mechanism of failure that resulted in the formation of this type of fault is through mode-I (opening-mode) failure and sliding across the initial mode-I fractures (Fig. 8D). The

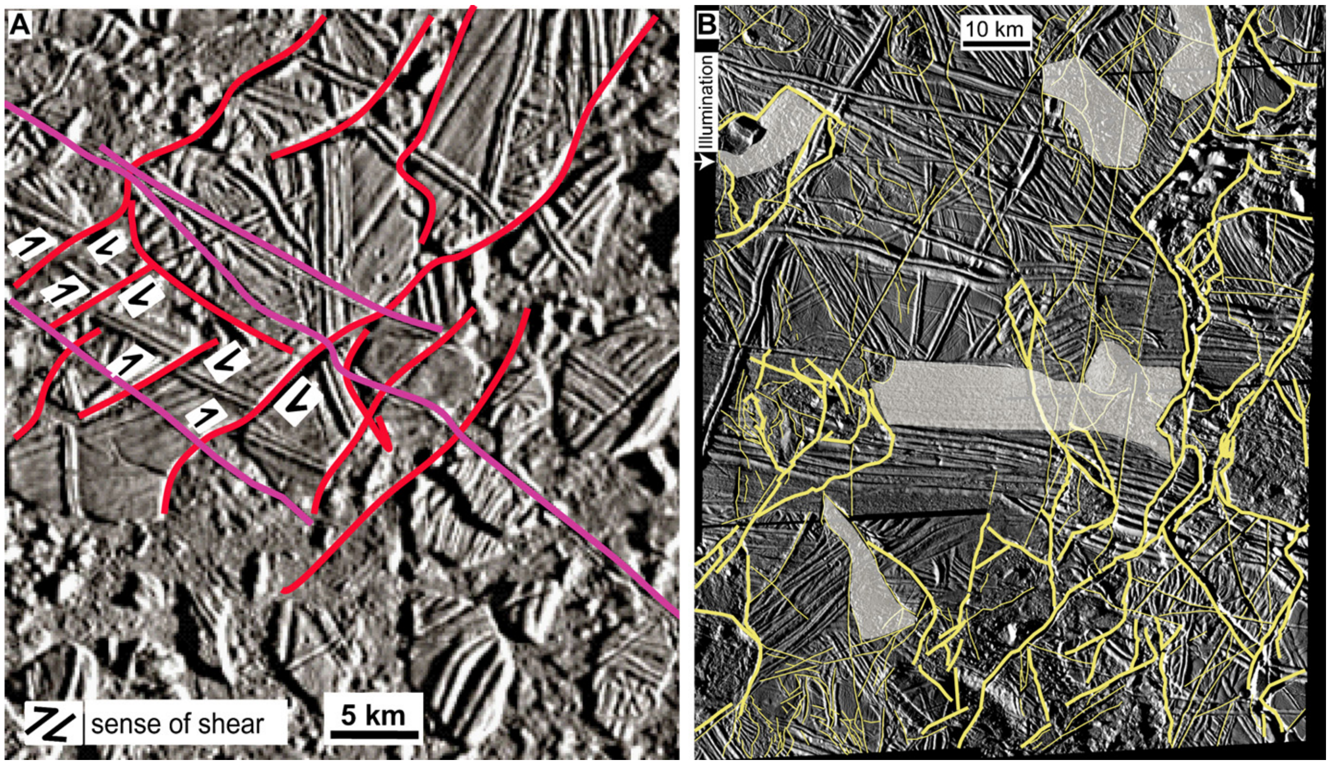

Fig. 7. (A) Map showing western part of the Conamara Chaos region (see Fig. 2 for location). Various sizes of polygonal blocks defined by boundary structures with lateral and vertical offset as well as gaps. (B) Image centered about 36°N and 86°W shows network of fractures (thin lines), some with fragmentation and offset (thick lines). Shearing of opening-mode fractures and the associated splay (tail) fracturing were interpreted to be the mechanisms for brittle faulting and fragmentation of ice. Somewhat irregular and curved geometry of the major faults with fragmentation zones are due to the splay fractures. Note that there exist several what appear to be cryoclastic deposits (light patches) with smooth surfaces.

observation that both lineaments, with or without detectable offset, and fragmentation zones with offset, occur sub-parallel to one another as part of the same network and within the same location justifies this interpretation (Fig. 7A and B).

In summary, the fundamental failure mode of the deformation is opening-mode failure and the subsequent shearing of the opening-mode fractures. Thus, the mechanism of faulting is elastic or ‘‘brittle’’, and is in contrast to the mechanism of localization of strain into shear and volumetric deformation bands, which is ‘‘ductile’’ or elastic/plastic.

3.3. Analogous structures on Earth

Volumetric and shear deformation bands are known to form in a variety of engineering and geologic materials. In this section, we provide a few examples and compare their geometric and physiographic characteristics with those seen on the surface of Europa.

Figs. 9 and 10 show examples of volumetric deformation bands (compaction bands) and shear bands in the Mesozoic sandstones of the western United States. Fig. 9A displays a set of compaction bands in the Aztec sandstone in the Valley of Fire, Nevada. Here the element on the right is rather simple. In fact, at first it appears to be a single compaction band with a raised rib-like morphology. However, the image has a central darker through between two wide, high shoulders, a geometry reminiscence of the volumetric bands, for example those in Fig. 4B and C, on the images from Europa. The element on the left-hand side of the photograph appears to be multiple bands reminiscent of the architectures of the Asterius Linea, Androgeos Linea, and Agave Linea. Individual bands are parallel or sub-parallel to each other. Fig. 9B shows bands adjacent and sub-parallel in the central area, but diverging into two distinctive strands at the edges, reminiscent of the splitting of the two strands of Androgeos Linea. Note that the diverging pattern of bands, here interpreted to be volumetric deformation bands, is strikingly common along the background structures in the Bright Plains and elsewhere on the satellite.

Fig. 10A displays a network of shear bands with increasing complications. The top two members of the set in diagonal orientation are single bands, the middle diagonal strand is made up of double bands, and the bottom diagonal element is a zone composed of three or more bands. The double bands trending from top to bottom are the youngest and show relative offset with the left side down. Fig. 10B shows a zone of shear bands with a raised relief offsetting an older single band. The zone has distinct overlapping bundles or sub zones made up of individual bands or strands.

The form, sequential development, and patterns of these structures formed by strain localization in sandstone on the surface of the planet Earth and the lineaments on the icy surface of Jupiter's moon, Europa, are strikingly similar. It is

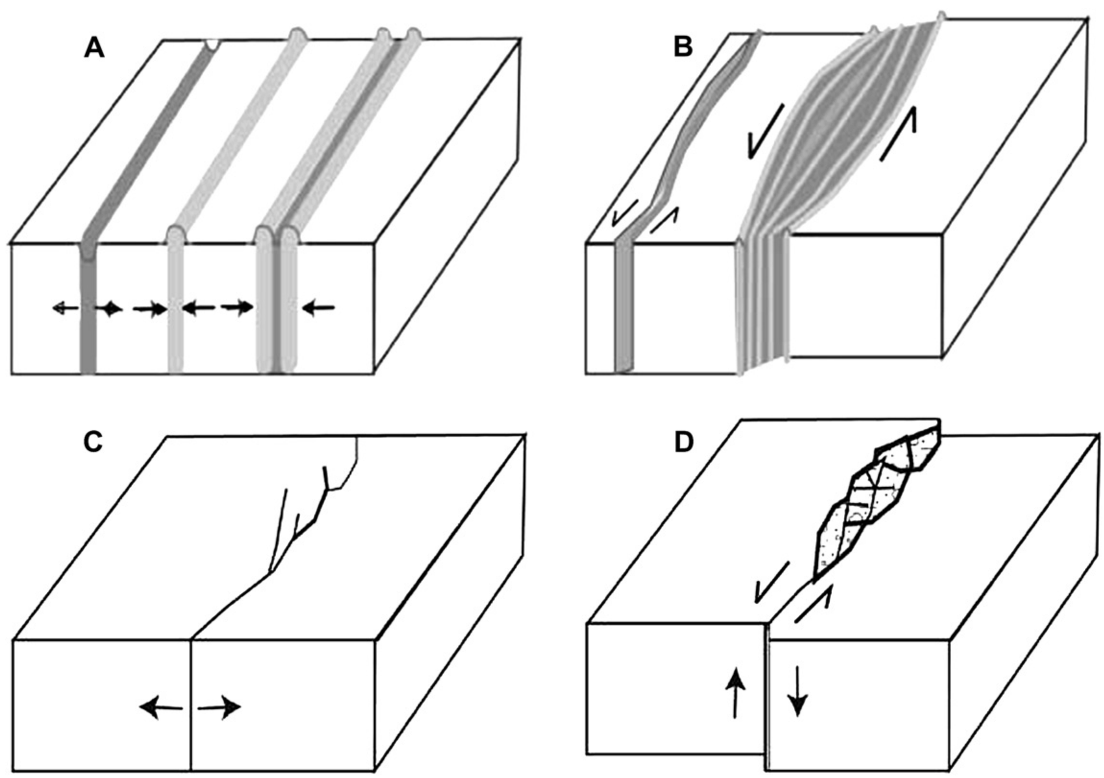

Fig. 8. Conceptual models of failure modes for the lineaments on the surface of Europa: (A) volumetric deformation bands, (B) shear bands, (C) opening-mode fractures, and (D) shearing of opening-mode fractures leading to brittle faulting with fragmentation.

reasonable to suggest that these similarities may stem from similar mechanical processes responsible for the corresponding structures in both environments.

4. Discussion

Most of the extant models assume that the boundaries defining ridges and bands in ice moved away from each other and are analogous to those of idealized mode-I fractures. More important, they assume that the initial opening was later filled by material from a ductile or viscous substrate. We propose an alternative hypothesis that satisfies the same kinematical boundary conditions but differing significantly from the extant models in the mode of failure and the characteristics of the material within the deformed zone with respect to the adjacent undeformed ice. A majority of the ridges and bands in the study area are equally likely to be zones of localized strain, based on the similarity between the geometry, kinematics, and architecture of the Europan lineaments and those of localized bands in Earth materials. We have distinguished between shear and volumetric deformation bands. However, whether the bands inferred to be volumetric deformation bands and not associated with shear structures are contractional or dilational is not clear at this point. The potential for the occurrence of the whole spectrum of localization between isochoric shear and volumetric deformation with either dilation or compaction modes poses serious challenges for interpretation of the images of the lineaments on Europa and other icy satellites. First of all, it is difficult to identify the volumetric component of deformation across the lineaments if the magnitude of volume change is small. Second, it is likely that if there is a slight, discernable, apparent shear component across a lineament, it is immediately classified as a fault. Finally, the possibility of occurrence of failure structures with various modes precludes using a single kinematical representation of all the lineaments on Europa

Previous workers identified dilational (Pappalardo and Sullivan, 1996; Carr et al., 1998; Hoppa et al., 1998; Tufts et al., 2000; Prockter et al., 2000, 2002; Kattenhorn, 2004) and contractional (Patterson and Pappalardo, 2002; Sarid et al., 2002; Greenberg, 2004) volumetric strain. Some of these appear to be predominantly dilational in origin and others are primarily volumetric components of strike-slip faulting. It is difficult to interpret some of the earlier models without the fundamental failure structures being identified.

Michalski and Greeley (2002) reported that echelon ridge and trough structures with similar appearance and orientation inferred to be subjected to compression at some locations and extension in some other locations. We have presented data on areas and orientations inferred to be either contractional or dilational bands with similar characteristics along shear zones. Some of these characteristics can also be recognized within a series of pull-apart structures along the Astypalaea Linea. The ridges and grooves along this shear zone have previously been interpreted to be brittle fractures (Tufts et al., 1999; Hoppa et al., 2000) filled by ice formed from the mobile substrate from the interior of the planet. However, contrary to this

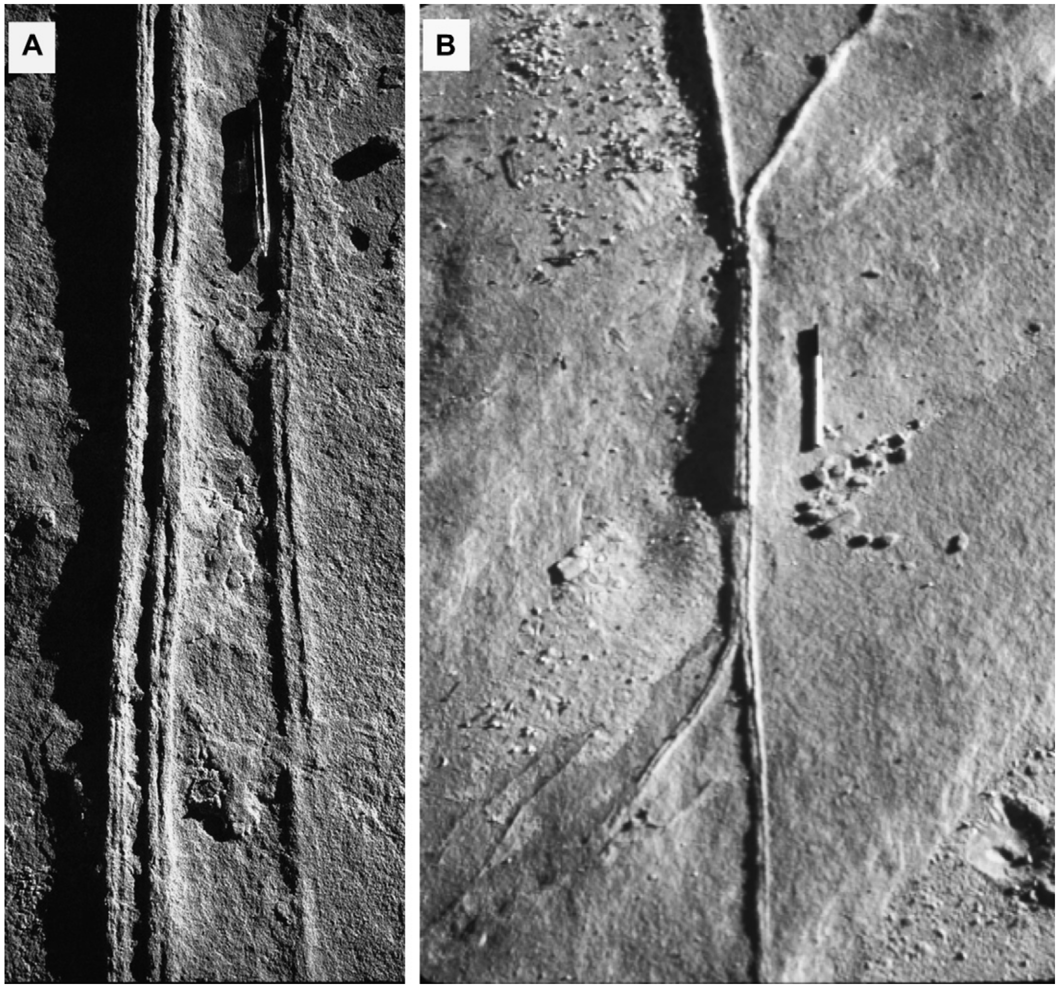

Fig. 9. Examples from volumetric deformation bands of compaction type formed in sandstone, Valley of Fire State Park, southeastern Nevada. (A) Double bands on the right side and multiple bands on the left side. Sun light from the right-hand side (pen for scale). (B) Converging and diverging compaction bands, a common pattern in deformed Earth materials.

widespread notion, the ridges are not symmetric about an axis of presumed intrusion, analogous to mid-ocean ridges, and their appearance is in clear contrast to the actual fractures identified on the same image (marked by "f" in Fig. 6B). It is possible that these structures are volumetric bands of either contraction or dilation or compactive and dilatant shear bands, depending on the specific orientation and the local stress state therein. This conclusion is consistent with the essence of that reached by Mickalski and Greeley (2002) on certain band structures along the strike-slip faults on Europa, indicating either compression or dilation.

Based on these results as well as those in this study, it is likely that lineaments with dilation and contraction both are present on Europa. This conclusion is significant in order to avoid unreasonable expansion or contraction of the crust of the satellite if all the bands, ridges, grooves, fractures and faults were only either contractional or dilational. In any case, the distribution of volumetric strain within the satellite remains to be determined.

There are various mechanisms for strain localization in geologic and engineering materials. Strain localization as a bifurcation instability from a homogeneous strain field is one potential mechanism (Rudnicki and Rice, 1975; Issen and Rudnicki, 2000; Borja and Aydin, 2004; Aydin et al., 2006). This mechanism is based on a yield surface that allows pure dilational and compressional plasticity and thus predicts both compaction and dilation bands as well as shear bands with compaction and dilation components. In respect to applicability of this mechanism to Europa, the role of material porosity should be discussed. Currently, all reported examples of compaction and dilation bands in the Earth's upper crust are known to occur in high porosity materials (see Aydin et al., 2006 for a summary). This evidence suggests that perhaps volumetric deformation bands, especially compaction bands, occur only in high porosity materials; after all, compaction bands imply considerable volume decrease. Certainly, a similar prerequisite can also be made for compactive shear bands. The possible range of physical properties of Europa's icy surface is estimated to be from "extremely compacted" to "fluffy" (Buratti, 1995). Ground-based photoelectric measurements combined with Voyager images suggest that Europa's surface is characterized by a persistent roughness down to centimeter

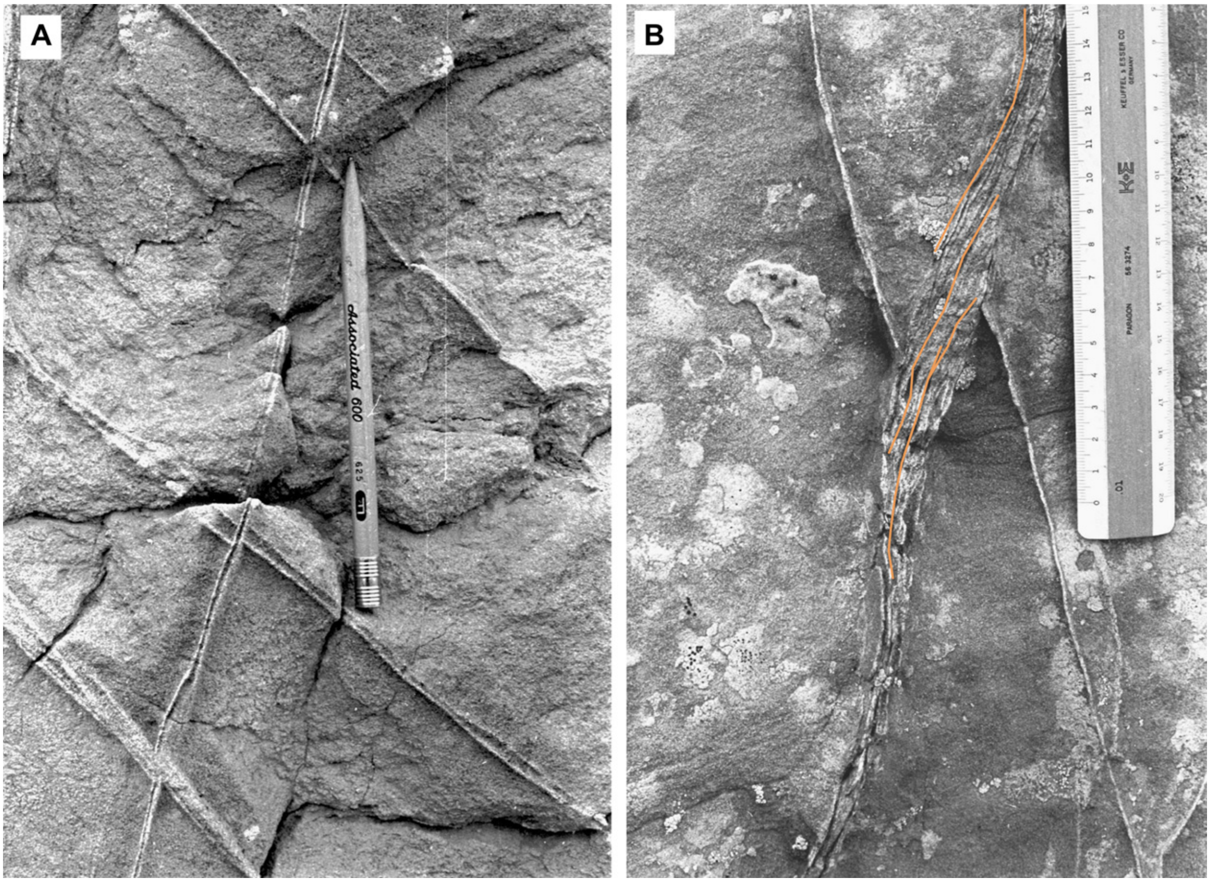

Fig. 10. (A) Network of shear bands in sandstone from the San Rafael Desert, southeastern Utah. The double band parallel to the longer dimension of the picture offsets the inclined system which includes, from top to the bottom, a single, double, and multiple bands. (B) A zone of shear bands comprised of several bundles of bands that offset an older single band.

scale and a high porosity on the order of 96% (Domingue et al., 1991). It was suggested that the porosity value for the interior of the crust could be larger than 33% (Lee et al., 2005). Nimmo et al. (2003b) inferred porosity variation across the deformed ice in the range of 2–20%. It is, thus, possible that the icy surface of the satellite may have enough porosity to have behaved in a compactive manner for at least some period of time during the satellite's crustal evolution.

Phase transformation is an alternative mechanism that may produce large volume change leading to band formation without the pore collapse required in the previous mechanism. In fact, Bennett et al. (1997) have produced what appear to be compaction bands in ice in the laboratory. These are bands in the form of rhombohedral ice-II transformed from hexagonal ice-I. There is a significant volume decrease (~20%) associated with such a transformation; however, it requires pressures in access of 100 MPa (Bridgman, 1912; Bennett et al., 1997). Schuh and Dunand (2002) have already suggested that a mechanism based on transformation strain may be responsible for the structures on the surface of Europa.

Adiabatic shear bands (Bai and Dodd, 1992), which usually occur in metals, alloys, and glass powder under dynamic loading conditions, present an alternative mechanism for shear band formation. In fact, adiabatic shear bands produced in metal alloys in the laboratory are quite similar to the images of shear zones on Europa (see, for example, Leech, 1985; Carsley et al., 1988).

Finally, Nimmo and Gaidos (2002) proposed a mechanism for fault-related structures based on shear heating. These last two mechanisms are only relevant to considerable shearing under earthquake rupture-like dynamic conditions such as large strike-slip faults, not to the faults developed from dilatant fractures and other lineaments with volumetric deformation only.

Clearly, the differences in scale between the structures on the icy satellite and in the Earth materials presented in this paper must be addressed. First, the dimensions of the icy crust of Europa, about 25 km in thickness (Nimmo et al., 2003a) and practically infinite in lateral extent, are several orders of magnitude larger than those of a terrestrial sandstone unit of a few hundred meters in thickness and limited lateral extent. This contrast may be significant because there is evidence that material thickness (Pekarskaya et al., 2001), sample size (Jia et al., 2000), hardness (Leech, 1985), and grain or crystal size (Muhlhaus and Vardoulakis, 1987; Zhu et al., 1997) may influence the width of bands. We note that the issues related to the scale dependence of dimensions of localized deformation bands are not well understood.

The critical implication of this hypothesis is that many of these lineaments are composed of more or less autochthonous materials deformed in situ, as opposed to being composed of intrusive or extrusive materials transported from somewhere else. The proposed structures are generally poor conductors for fluids, whereas the earlier models indicate that the structures were once very effective conductors. Thus, it follows that only certain discontinuities in the icy crust of the satellite may have provided pathways for the interior fluids to reach the surface. These are the brittle mode-I fractures with a certain mechanical aperture and faults formed by shearing of the brittle fractures, thereby creating pull-apart openings and fragmentation.

We documented two distinct modes of discontinuities. The first is in the form of localized, either volumetric or shear, bands (e.g. Aydin et al., 2006) and the second kind is of sharp, brittle, mode-I fractures (e.g. Pollard and Aydin, 1988). Fault zones developed by this mechanism are characterized by widespread fragmentation and brecciation. This is a well-known phenomenon in faulted rocks (e.g. Martel et al., 1988; Myers and Aydin, 2004). However, Schulson (2004) has recently described similar fault zones with significant fragments in arctic ice. This confirms that it is the brittle behavior of the materials, irrespective of their specific composition, which controls the failure modes and the internal architecture of their products.

In the Earth's surface, the respective products of the ductile and brittle deformation processes often occur sequentially in the same region, with the brittle structures generally overprinting the ductile bands, as illustrated in Fig. 11 (Davatzes and Aydin, 2004). It is interesting to note that the sequence of the two kinds of failure modes on the surface of Europa is the same as it is on Earth.

There is a rich spatial and temporal variability in the localization, formation mechanisms, and kinematics of the Europan lineaments, suggesting that the conditions prevailing within the crust of Europa must have changed dramatically over time and from one place to another. First, the background structures on the satellite's surface, which are interpreted to be volumetric deformation bands, have several generations of overprinted and interwoven broad zones (Group 1). Then,

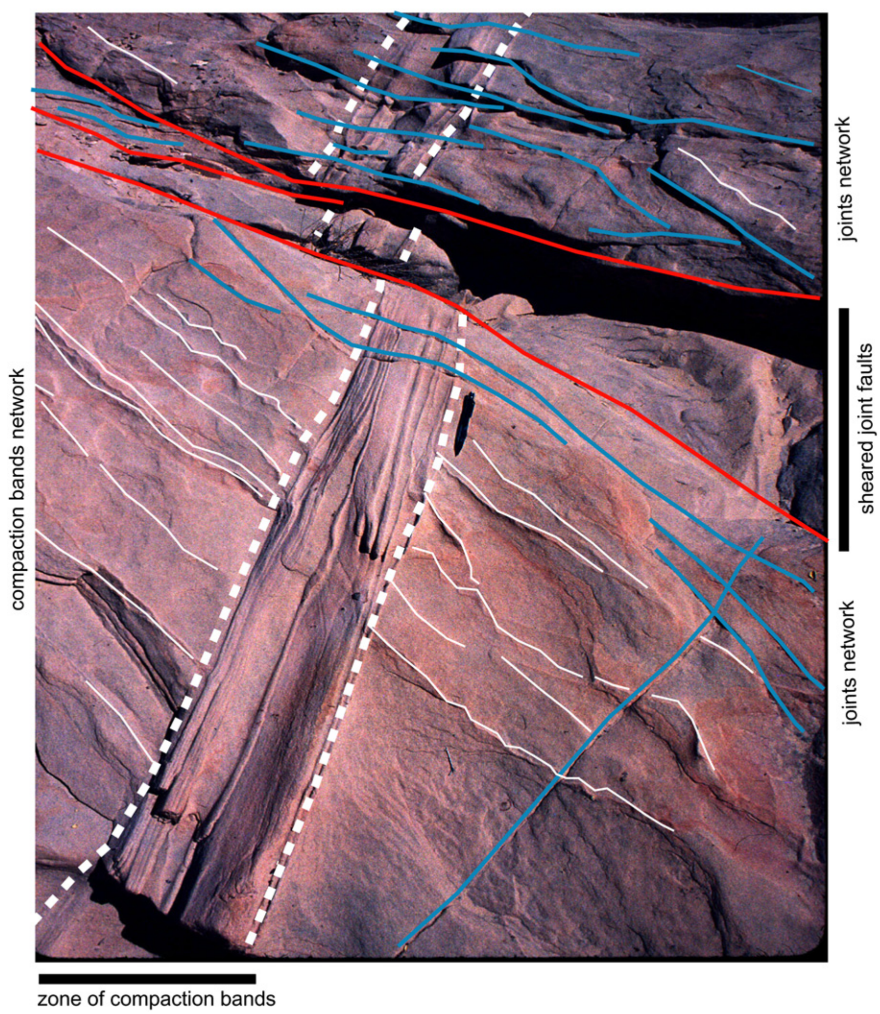

Fig. 11. A zone of compaction bands (delineated by dashed lines) transected by opening-mode fractures (blue lines) and offset by left-lateral faults (red lines) formed through shearing of the opening-mode fractures. The compaction bands (white lines) represent a failure mode involving localization of ductile strain into narrow bands, whereas the sharp opening-mode fractures and their shearing represent brittle failure mode.

a distinct shearing deformation episode (Group 2) occurred, producing faults with shear band architecture with considerable regularity in spacing and orientation. These stages were followed by at least three distinct episodes of what appear to be opening-mode fracturing (Groups 3, 4, 6) with only intermittent reoccurrence of deformation band mode (Group 5). It is proposed that these opening-mode fractures, when sheared, lead to faulting recognized in the Conamara Chaos and similar regions on the satellite.

The observed changes in the density and distribution pattern from the background structures to younger forms of more widely spaced, simpler bands and to isolated chaos patches concur with that proposed by Figueredo and Greeley (2004). They suggested that these trends are associated with the thermal evolution of the satellite, or cyclic or irregular tectonic and cryovolcanic activity. Based on the identified failure modes described earlier in this paper, it is possible to be more specific about the characteristic behavior of the Europan ice: elastic–plastic (ductile) in early stages and elastic (brittle) in the younger stage. While ductile or brittle rheology of crystalline and granular ice is possible, the specific conditions leading to these contrasting behaviors on Europan ice are not certain due to the large number of potential parameters involved. Loading and strain rate, as well as temperature, appear to be important in the rheological behavior of ice. For example, ductile deformation of ice above $-20\,^{\circ}\mathrm{C}$ is predominant in laboratory tests at strain rates $<10^{-7}\ \mathrm{s}^{-1}$, whereas ice deforms by brittle fracturing for strain rates $>10^{-6}\ \mathrm{s}^{-1}$ (Petrenko and Whitworth, 1999).

Recently, Schulson (2004) interpreted ductile and brittle modes of failure in terms of rate dependent stress build-up and relaxation. The author, based on his experimental study of ice and other in situ measurements, concluded that the brittle fracturing of arctic sea ice leading to sliding lineaments (in his terminology) or faults may occur under uniaxial compressive stresses within a range from $\sim$10 kPa to 300 kPa. These numbers, according to Schulson, are ‘‘rough estimates’’. In any case, they provide a likely scenario for the stresses that may have operated during the brittle phase of deformation on Europa. On the other hand, the ductile phase probably requires three-dimensional stresses based on the theoretical models for strain localization in the form of shear, compaction, and dilation bands (Issen and Rudnicki, 2000; Borja and Aydin, 2004). The potential magnitudes of the stress components are difficult to estimate without specifying the constitutive behavior of ice and further modeling.

The proposed structural models raise serious questions about the results of stress modeling in which the ridges, troughs, and bands were assumed to have formed originally in the principal planes subjected to the greatest tension or least compression (Geissler et al., 1998, 1999; Greenberg et al., 1998; Kattenhorn, 2002). The possibility of the occurrence of compaction bands in icy planets makes it difficult to use the lineaments on the planetary surfaces for stress models based solely on the assumption of opening-mode fractures for their origins. Thus, testing of certain deformation scenarios for driving stresses on Europa that is based on the opening-mode origin for the lineaments on the surface of the satellite appears to be a highly risky endeavor.

5. Conclusions

Various forms and types of failure modes are proposed for the lineaments on the surface of Europa. These can be summarized as follows:

- Some ridges and bands are interpreted to be zones of localized volumetric deformation.
- Other ridges and bands with detectable shear displacement discontinuity are interpreted to be zones of shear bands. In one case, a significant amount of fault-normal contraction is evident.
- Some sharper linear and curvilinear features are interpreted as mode-I fractures. Networks of these brittle fractures are generally younger than the volumetric and shear bands.
- The brittle mode-I fractures and their subsequent shearing are known to result in another mode of faulting involving comminution of material within the faults. It is proposed that this mechanism is responsible for the faults in the chaos regions.
- Thus, two distinct modes of faulting are proposed: the first kind is in the form of localized shear, either via simple mechanical bifurcation or transformation or via super plasticity, and the other is shearing of previously formed brittle mode-I fractures.
- The sequence of the prevailing failure modes on the surface of Europa and in Earth materials is generally consistent. The earlier structures are dominantly strain localizations in the form of bands and the later structures are opening-mode fractures and their shearing.

These conclusions have important implications for Europa and perhaps for other icy satellites of the solar system. A few of these are noted below.

- The most ubiquitous structures on Europa, ridges, and bands are volumetric deformation bands with a good possibility of being of both compactional and dilational type. If so, the potential for the presence of compaction bands is in clear contrast to the kinematics of all the previous conceptual models for the ridges and bands on Europa and elsewhere. This may also cast doubt on most of the inferred stress orientations on Europa and on the tests for a specific driving mechanism for these structures based on the opening-mode origin of the lineaments.
- The failure modes proposed here potentially have both negative and positive volumetric strain components and, therefore, the perceived dilemma of the overwhelming imbalance between the dilational strain and its missing contractional counterparts in the crust of the planet may not be real.
- It is quite likely that most of the linear structures, interpreted to be localized bands of deformation, may have

never been pathways to the potential subsurface ocean and, therefore, may not contain evidence for living beings. The most likely candidate for such a conduit is the type of faults formed by shearing of brittle opening-mode fractures such as those in the chaos areas.

- The transition from the mode of localized deformation to that of sharp brittle discontinuities marks a major change in the environmental conditions prevailing in the icy crust of Europa. The cause of this important change would be an excellent subject for future investigations.

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References

Aydin, A., 2003. Analysis of faults on the icy surface of Jupiter's moon Europa based on failure modes. American Geophysical Union. EOS Transactions 84 (46). Fall Meet. Suppl., Abstract, F954.

Aydin, A., Borja, R., Eichhubl, P., 2006. Geological and Mathematical framework for failure modes in granular rock. Journal of Structural Geology 28, 83–98, doi:10.1016/j.jsg.2005.07.008.

Bai, Y., Dodd, B., 1992. Adiabatic Shear Localization: Occurrence, Theories, and Applications. Pergamon Press, Oxford.

Borja, R.I., Aydin, A., 2004. Computational modeling of deformation bands in granular media, I: geological and mathematical framework. Journal of Computational Mechanics and Engineering 193, 2667–2698.

Bennett, K., Wenk, H., Durham, W., Stern, L., Kirby, S., 1997. Preferred crystallographic orientation in the ice I–II transformation and the flow of ice II. Philosophical Magazine A—Physics of Condensed Matter Structure Defects and Mechanical Properties 76, 413–435.

Bridgman, P.W., 1912. Water, in the liquid and five solid forms, under pressure. Proceedings of the American Academy of Arts and Sciences 47, 441–558.

Buratti, B.J., 1995. Photometry and surface structure of the icy Galilean satellites. Journal of Geophysical Research 100, 19061–19066.

Buratti, B., Golombek, M., 1988. Geologic implications of spectrophotometric measurements of Europa. Icarus 75, 437–449.

Carr, M., Belton, M., Chapman, C., Davies, A., Geissler, P., Greenberg, R., McEwen, A., Tufts, B., Greeley, R., Sullivan, R., Head, J., Pappalardo, R., Klaasen, K., Johnson, T., Kaufman, J., Senske, D., Moore, J., Neukum, G., Schubert, G., Burns, J., Thomas, P., Veverka, J., 1998. Evidence for a subsurface ocean on Europa. Nature 391, 363–365.

Carsley, J.E., Fisher, A., Milligan, W.W., Aifantis, E.C., 1988. Mechanical behavior of a bulk nanostructured iron alloy. Metallurgical and Materials Transactions A 29A, 2261–2271.

Chyba, C., Phillips, C., 2001. Possible ecosystems and the search for life on Europa. Proceedings of the National Academy of Sciences of the United States of America 98, 801–804.

Collins, G., Head, J., Pappalardo, R., 1998. Formation of Ganymede grooved terrain by sequential extensional episodes: implications of Galileo observations for regional stratigraphy. Icarus 135, 345–359.

Davatzes, N.C., Aydin, A., 2004. Overprinting faulting mechanisms in high porosity sandstones of SE Utah. Journal of Structural Geology 25, 1795–1813.

Domingue, D.L., Hapke, B.W., Lockwood, G.W., Thompson, D.T., 1991. Europa's phase curve: implications for surface structure. Icarus 90, 30–42.

Fagents, S., Greeley, R., Sullivan, R., Pappalardo, R., Prockter, L., The Galileo SSI Team, 2000. Cryomagmatic mechanisms for the formation of Rhadamanthys linea, triple band margins, and other low-albedo features on Europa. Icarus 144, 54–88.

Fagents, S.A., Greeley, R., Sullivan, R.J., Pappalardo, R.T., Prockter, L.M., The Galileo SSI Team, 1999. A cryomagmatic origin for low albedo features on Europa. Lunar and Planetary Science Conference, Houston.

Figueredo, P.H., Chuang, F.C., Rathbun, J., Kirk, R.L., Greeley, R., 2002. Geology and Origin of Europa's "Mitten" feature (Murias Chaos). Journal of Geophysical Research 107 (E5), doi:10.1029/2001JE00191.

Figueredo, P.H., Greeley, R., 2004. Resurfacing history of Europa from pole-to-pole geologic mapping. Icarus 167, 287–312.

Geissler, P., Greenberg, R., Hoppa, G., Helfenstein, P., McEwen, A., Pappalardo, R., Tufts, R., OckertBell, M., Sullivan, R., Greeley, R., Belton, M., Denk, T., Clark, B., Burns, J., Veverka, J., 1998. Evidence for non-synchronous rotation of Europa. Nature 391, 368–370.

Geissler, P., Greenberg, R., Hoppa, G.V., Tufts, B.R., Milazzo, M., the Galileo SSI Team, 1999. Rotation of lineaments in Europa's Southern Hemisphere. Lunar and Planetary Science Conference, Houston.

Greeley, R., Johnson, T., 2004. The Jupiter Icy Moons Orbiter project: the scientific rationale. EOS, Transactions, American Geophysical Union 85, 337, 343.

Greenberg, R., 2004. The evil twin of Agenor: tectonic convergence on Europa. Icarus 167, 313–319.

Greenberg, R., Geissler, P., Hoppa, G., Tufts, B., Durda, D., Pappalardo, R., Head, J., Greeley, R., Sullivan, R., Carr, M.H., 1998. Tectonic processes on Europa: tidal stresses, mechanical response, and visible features. Icarus 135, 64–78.

Head III, J.W., Pappalardo, R.T., Greeley, R., Sullivan, R., the Galileo Imaging Team, 1998. Origin of ridges and bands on Europa; morphologic characteristics and evidence for linear diapirism from Galileo data. Lunar and Planetary Science Conference, Houston.

Head III, J.W., Pappalardo, R.T., Sullivan, R., 1999. Europa: morphological characteristics of ridges and triple bands from Galileo data (E4 and E6) and assessment of a linear diapirism model. Journal of Geophysical Research, E, Planets 104, 24223–24236.

Hoppa, G., Greenberg, R., Tufts, B., Geissler, P., Phillips, C., Milazzo, M., 2000. Distribution of strike-slip faults on Europa. Journal of Geophysical Research Planets 105, 22617–22627.

Hoppa, G., Tufts, B.R., Greenberg, R., Geissler, P., 1999a. Strike-slip faults on Europa: global shear patterns driven by tidal stress. Icarus 141, 287–298.

Hoppa, G., Tufts, B.R., Greenberg, R., Geissler, P., 1999b. Formation of cycloidal features on Europa. Science 285, 1899–1902.

Issen, K., Rudnicki, J., 2000. Conditions for compaction bands in porous rock. Journal of Geophysical Research, B, Solid Earth and Planets 105 (21), 21529–21536.

Jia, D., Ramesh, K., Ma, E., 2000. Failure mode and dynamic behavior of nanophase iron under compression. Scripta Materialia 42, 73–78.

Kattenhorn, S., 2002. Nonsynchronous rotation evidence and fracture history in the Bright Plains region, Europa. Icarus 157, 490–506.

Kattenhorn, S., 2004. Strike-slip fault evolution on Europa: evidence from tailcrack geometries. Icarus 1172, 582–602.

Lee, S., Pappalardo, R.T., Macris, N.C., 2005. Mechanics of tidally driven fractures in Europa's ice shell. Icarus 177, 367–379.

Leech, P.W., 1985. Observation of adiabatic shear band formation in 7039 Aluminum alloy. Metallurgical Transactions A 16A, 1900–1903.

Martel, S.J., Pollard, D.D., Segall, P., 1988. Development of simple fault zones in granitic rock, Mount Abbot quadrangle, Sierra Nevada, California. Geological Society of America Bulletin 100, 1451–1465.

Michalski, J.R., Greeley, R., 2002. En echelon ridge and trough structures on Europa. Geophysical Research letters 29 (10), doi:10.1029/2002GL01956.

Muhlhaus, H., Vardoulakis, I., 1987. The thickness of shear bands in antigranulocytes-materials. Geotechniques 37, 271–283.

Myers, R., Aydin, A., 2004. The evolution of faults formed by shearing across joint zones in sandstone. Journal of Structural Geology 26, 947–966.

Nimmo, F., Gaidos, E., 2002. Strike-slip motion and double ridge formation on Europa. Journal of Geophysical Research 107 (E4), 5021, doi:10.1029/2000JE001476.

Nimmo, F., Giese, B., Pappalardo, R., 2003a. Estimates of Europa's ice shell thickness from elastically-supported topography. Geophysical Research Letters 30, 1233.

Nimmo, F., Pappalardo, R.T., Giese, B., 2003b. On the origin of band topography, Europa. Icarus 166, 21–32.

Pappalardo, R., Sullivan, R., 1996. Evidence for separation across a gray band on Europa. Icarus 123, 557–567.

Pappalardo, R.T., Belton, M.J.S., Breneman, H.H., Carr, M.H., Chapman, C.R., Collins, G.C., Denk, T., Fagents, S.A., Geissler, P.E., Giese, B., Greeley, R., Greenberg, R., Head III, J.W., Helfenstein, P., Hoppa, G., Kadel, S.D., Klaasen, K.P., Klemaszewski, J.E., Magee, K., McEwen, A.S., Moore, J.M., Moore, W.B., Neukum, G., Phillips, C.B., Prockter, L.M., Schubert, G., Senske, D.A., Sullivan, R.J., Tufts, B.R., Turtle, E.P., Wagner, R., Williams, K.K., 1999. Does Europa have a subsurface ocean?: evaluation of the geological evidence. Journal of Geophysical Research, E, Planets 104, 24015–24055.

Pappalardo, R.T., Greeley, R., Moore, J.M., Schenk, P.M., Nash, D.B., 1995. A review of the origins of subparallel ridges and troughs; generalized morphological predictions from terrestrial models. Journal of Geophysical Research, E, Planets 100, 18985–19007.

Patterson, G.W., Pappalardo, R.T., 2002. Compression across ridges on Europa. Lunar and Planetary Science Conference, XXXIII. Abstract #1681, Lunar and Planetary Institute, Houston (CD-ROM).

Pekarskaya, E., Kim, C., Johnson, W., 2001. In situ transmission electron microscopy studies of shear bands in bulk metallic glass based composite. Journal of Materials Research 16, 2513–2518.

Petrenko, V.F., Whitworth, R.K., 1999. Physics of Ice. Oxford University Press.

Pollard, D.D., Aydin, A., 1988. Progress in understanding jointing over the past one hundred years. Geological Society of America Bulletin 100, 1181–1204.

Prockter, L., Head, J., Pappalardo, R., Sullivan, R., Clifton, A., Giese, B., Wagner, R., Neukum, G., 2002. Morphology of Europan bands at high resolution: a mid-ocean ridge-type rift mechanism. Journal of Geophysical Research—Planets 107, 5028.

Prockter, L.M., Pappalardo, R.T., Head III, J.W., 2000. Strike-slip duplexing on Jupiter's icy moon Europa. Journal of Geophysical Research 105, 9483–9488.

Rudnicki, J.W., Rice, J.R., 1975. Conditions for the localization of deformation in pressure-sensitive dilatant materials. Journal of the Mechanics and Physics of Solids 23, 371–394.

Sarid, A.R., Greenberg, R., Hoppa, G.V., Hurford, T.A., Tufts, B.R., Geissler, P., 2002. Polar wander and surface convergence of Europa's ice shell: evidence from a survey of strike-slip displacement. Icarus 158, 24–41.

Schuh, C., Dunand, D., 2002. Transformation superplasticity of water ice and ice containing SiO2 particulates—art. no. 5101. Journal of Geophysical Research—Planets 107, 5101.

Schulson, E., 2004. Compressive shear faults within arctic ice: fracture on scales large and small. Journal of Geophysical Research 109, C07016, doi:10.1029/2003JC002108.

Schulson, E., 2002. On the origin of a wedge crack within the icy crust of Europa. Journal of Geophysical Research—Planets 107, 5107.

Spaun, N.A., Head, J.W., Collins, G.C., Prockter, L.M., Pappalardo, R.T., 1998. Conamara Chaos region, Europa: reconstruction of mobile polygonal ice blocks. Geophysical Research Letters 25, 4277–4280.

Spaun, N.A., Pappalardo, R.T., Head, J.W., 2003. Evidence for shear failure in forming near-equatorial lineae on Europa. Journal of Geophysical Research—Planets 108 (E6), 5060, doi:10.1029/2001JE001499.

Sullivan, R., Greeley, R., Homan, K., Klemaszewski, J., Belton, M., Carr, M., Chapman, C., Tufts, R., Head, J., Pappalardo, R., Moore, J., Thomas, P., the Galileo Imaging Team, 1998. Episodic plate separation and fracture infill on the surface of Europa. Nature 391, 371–373.

Tufts, B.R., Greenberg, R., Geissler, P., Hoppa, G., 1999. Astypalaea Linea: a large-scale strike-slip fault on Europa. Icarus 141, 53–64.

Tufts, B.R., Greenberg, R., Hoppa, G., Geissler, P., 2000. Lithospheric dilation on Europa. Icarus 146, 75–97.

Turtle, E.P., Melosh, H.J., Phillips, C.B., 1998. Europan ridges: tectonic response to dike intrusion. EOS Transactions, American Geophysical Union 79, S203.

Zhu, X., Carsley, J., Milligan, W., Aifantis, E., 1997. On the failure of pressure-sensitive plastic materials part I. Models of yield & shear band behavior. Scripta Materialia 36, 721–726.