Europa: Morphological characteristics of ridges and triple bands from Galileo data (E4 and E6) and assessment of a linear diapirism model

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Abstract. Galileo solid-state imaging (SSI) images of Europa provide high-resolution data on the morphological characteristics of ridges and permit the development of nomenclatural schemes for their description and classification. Key observations are that ridges (1) are remarkably consistent in their along-strike linearity, width, and height, (2) form long linear features in which preexisting structures can sometimes be traced up the outer slopes of the ridges and in other cases appear to be buried, (3) contain narrow apical zones of small-scale, ridge-parallel faulting, (4) are sometimes flanked by narrow troughs and ridge-parallel fractures, and (5) often display associated color variations. On the basis of the characteristics and associated features of ridges, we find that a process in which initial fracturing (most plausibly related to tidal deformation) of a brittle layer overlying a buoyant ductile substrate leading to linear diapirc upwelling provides a consistent explanation for the observed features. In this process the upwelling linear diapir causes flexure (bending and faulting) of the region marginal to the fracture, the deformation and uplift of adjacent plains material and its preexisting structures to form the apical part of the ridge, the exposure of the inner walls of the crack, and the mass wasting of the inner and outer walls of the ridge to modify, but often not completely destroy, the preexisting structure of the adjacent plains. Specifically, this mechanism can account for many characteristics of the ridges, including their linearity, their consistent and regular morphology over their great lateral extent, their positive topography, the presence of preexisting structure on the outer ridges (caused by upwelling of background ridged plains), the formation of marginal troughs (as diapirc rim synclines), the detailed nature of their outer and inner slopes (caused largely by faulting and mass wasting processes), and their sequential formation with multiple orientations (related to tidal deformation processes). Linear diapirism also provides a possible explanation for color and albedo characteristics, related to thermal effects of the upwelling warm ice (e.g., inducing volatile migration and grain-size variations). As the vast majority of deformation is vertical in this scenario, this mechanism minimizes the necessity for complementary compressional deformation required by some other models.

1. Introduction

Voyager images of Europa revealed the presence of a variety of surface features. These included (1) lineae [Davies, 1982], structural features in plains extending hundreds to even thousands of kilometers and most commonly interpreted to be of tectonic origin, and (2) pits, mounds, domes [Malin and Pieri, 1986], and molten terrain characterized by an abundance of pits [Lucchitta et al., 1981; Lucchitta and Soderblom, 1982] thought to be of endogenic origin. Among the lineae are (1) dark bands, defined as linear albedo features which often transform into ridges near the terminator, and (2) triple bands, described as 10-20 km wide low albedo linear features with a central high-albedo stripe.

Galileo SSI high resolution observations of Europa [Belton et al., 1996; Sullivan et al., 1997, 1999; Head et al., 1997a, b, 1998a-c; Pappalardo et al., 1998a-d, 1999; Greenberg et al., 1998a, b, 1999; Geissler et al., 1998a-c; Greeley et al., 1997, 1998a, b] documented the nature of these two major types of features superposed on the very lightly cratered, tectonically deformed, background plains. These investigations have shown that pits, spots, and domes (lenticulae, informally referred to as PSDs) have a variety of detailed morphologies; Pappalardo et al. [1998a], Head et al. [1997a, b, 1998a, manuscript in preparation, 1999], and Spaun et al. [1999] have proposed that they represent a continuum of features related to the rise of diapirs from depth and the upwelling and disruption of a brittle surface layer [see also Rathbun et al., 1998]. The Galileo SSI data further show that many lineae are topographic ridges with a wide range of morphologies and complex intersecting relationships, including triple bands (low-albedo bands usually about 10-20 km wide with medial higher-albedo stripes) (Figure 1). Theories of origin for ridges and triple bands have included magmatic intrusion, extrusive volcanism, explosive...
volcanism, sea-ice analogs (including fracturing, separation, freezing, and deformation), tectonic processes, and combinations of these [e.g., Finnerty et al., 1981; Golombek and Bruckenthal, 1983; Crawford and Stevenson, 1988; Pappalardo and Coon, 1996; Sullivan et al., 1997, 1998a, b, 1999; Greenberg et al., 1998a, 1999; Kaula et al., 1998, Turile et al., 1998; Geissler et al., 1998a-c] (see reviews by Greeley et al. [1998b] and Pappalardo et al. [1999]). In addition, ridge formation on icy Uranian satellites has been attributed to solid-state ice extrusion or very high viscosity ice volcanism [e.g., Junkowski and Squire, 1988; Schenk, 1991].

High-resolution Galileo imaging of portions of Europa’s surface (Figure 1) reveals that its late-stage geology is often dominated by circular to elliptical pits, domes, and dark spots about 7-15 km across and spaced from 5 to 20 km apart. A sequence of increasing surface disruption appears to be represented by these features (Figure 2). Domes provide evidence for upwarping and deformation of the preexisting surface, pits commonly show chaotic texture suggestive of collapse, and spots are suggestive of localized extrusion and/or thermal alteration of the surface. The morphology and structure of these features, their areal density, and the interpreted associated vertical motion, localized heat, and magmatism suggest that they are the manifestation of relatively warm subsurface ice diapirs [Head et al., 1998a c, manuscript in preparation, 1999; Pappalardo et al., 1998a, c]. A possible mechanism for their formation is solid-state convection of Europa’s icy shell, which is predicted theoretically if the ice is sufficiently thick and underlain by a warm layer, such as liquid water [Pappalardo et al., 1998a, 1999]. Estimates for likely effective ice viscosity suggest that solid-state convection would initiate in a Europian ice shell of about 10 km thickness [Pappalardo et al., 1998a, 1999]. This scale is similar to the observed spacing of pits, domes, and spots, consistent with a thermal convection origin for these surface features (J. W. Head et al., manuscript in preparation, 1999).
In this paper we first examine and document the nature of bands in several areas of Europa, including where PSDs are common (Figure 1), and then discuss the range of features observed and a candidate evolutionary sequence. Finally, we address the questions: Could ridges and triple bands have originated through the same type of diapirc process that has been proposed to form the leucite? How would the process of linear diapirism work and are the characteristics of ridges and triple bands consistent with this hypothesis?

2. Nature and Morphology of Ridges and Triple Bands

Galileo SSI data have revealed or clarified the following general characteristics of ridges and triple bands [Belton et al., 1996; Sullivan et al., 1997 1998a, b, 1999; Head et al., 1997b, 1998a, b; Pappalardo et al., 1998b, c; Greenberg et al., 1998a, 1999; Geissler et al., 1998a; Helfenstein et al., 1998; Greeley et al., 1998b]. Prominent local relief (up to about 200 m) characterizes many ridges and triple bands. In some cases, triple bands are observed in which the low-albedo flanks break up into symmetric or asymmetric discontinuous patches (e.g., Rhadamanthys Linea), sometimes appearing similar to pits, spots, and domes. The SSI color data show that the low-albedo component of spots, ridges, and triple bands contains the highest percentage of nonice materials on Europa [Helfenstein et al., 1998; Clark et al., 1998]. Crosscutting relationships show that the low-albedo component brightens with time [Geissler et al., 1998a, c]. A range of relationships is observed between ridges and triple bands (e.g., triple bands merging into bright and dark bands), and high-resolution data have shown that the medial ridge consists of a series of complex parallel ridges often with a prominent medial trough.

We now examine the detailed nature of ridges at very high resolution (20-30 m/pixel) in the E4 and E6 coverage (Figure 1) and compare these characteristics to ridges seen in lower-resolution SSI data elsewhere to assess whether these areas are representative.

2.1. Ridges

Ridges, their associated morphological features, and their surroundings can be subdivided into several components (Figure 3) whose characteristics are important for constraining models for their formation and evolution. The ridges themselves are linear features up to about 200 m high which consist of paired ridges, each with an outer and inner slope (Figures 1b,
forming the apical region. In this area, shadows cast by the ridges (Figure 3b) illustrate that the widest paired ridges are also topographically most prominent and that stratigraphically older ridges tend to be smaller and less prominent. Ridges in plan view can be extremely straight (Figure 1), curved to arcuate (Figure 3b, left and second from left), and somewhat sinuous (Figure 3b, right), and they can be cut by subsequent fractures and ridges (Figure 3b, left and middle), sometimes involving shear (Figure 3b, right and second from right). Some ridges are characterized by a third inner ridge, whose crest is commonly at a lower elevation and may have a medial fracture or trough. Ridges and triple bands commonly crosscut and are superposed on background ridged plains that contain a tremendous diversity of interlaced and interwoven ridges exhibiting a wide range of azimuthal orientations (Figure 3b) [e.g., Head et al., 1998b; Spence et al., 1998a, b].

2.2. Marginal Troughs and Associated Deposits

Ridges and triple bands in this area are sometimes flanked by marginal troughs, which are shallow low-lying linear depressions developed along the margins of the ridges at the base of their outer slopes (Figure 3b, left and middle; 3c). These features often extend beyond the base of the outer ridge slope out to about one half of the ridge width (Figure 3c, right). Although they appear of relatively consistent width at lower resolution (Figure 1), higher-resolution data show that they are of irregular width and depth (compare Figure 3c, left and right) and are commonly correlated with the prominence of the ridges in the background topography which they crosscut (Figure 3a; also, compare top and bottom parts of Figure 3c, left). Photoclinometric data suggest that ridges are up to about 200 m in height and that the depressions are typically a few tens of meters in depth relative to the surrounding plains [Sullivan et al., 1997, 1998a, b; Greenberg et al., 1998a; R. Kirk, personal communication, 1998]. If the heights of ridges in Figure 3 are a maximum of 200 m, then maximum average slopes of the outer flanks of the ridge would be about 12° [e.g., Kadel et al., 1998].

Marginal troughs have a wide variety of surface textures. In some places they simply reflect a depression in the linear background plains (Figure 3c, left). In other cases these linearized structures are apparently darkened and sometimes appear to be mantled with dark material, subduing their morphology (Figure 3d, middle). In still other cases the trough is occupied by dark plains that appear to embay and cover preexisting background ridged plains (Figure 3c, right). Smooth plains and related deposits seen marginal to the outer ridges display both embayment and mantling relationships to surrounding ridges of the background ridged plains and in many cases appear superposed on them, suggesting that they are relatively younger. Although data to determine detailed true albedo and color relationships are not available in most of the cases studied, similar relationships seen elsewhere in SSI color data show that these types of dark areas correspond to a low-albedo component of ridges and triple bands and contain a high percentage of nonice materials [e.g., Helfenstein et al., 1998; Clark et al., 1998; Geissler et al., 1998a, c].

2.3. Margin-Parallel Fractures and ‘Washboard’ Texture

Marginal troughs also exhibit associated structural features apparently not related to the background ridged plains. One such feature observed in the E4 data, here called the “washboard” texture, is characterized by a set of narrow parallel ridges and troughs oriented parallel to the ridge, each ridge of the washboard typically a few tens of meters across. The washboard texture is superposed on background ridged plains (Figure 3d), is relatively evenly distributed, and extends out about a ridge width from the base of the ridge. This texture occurs only on some ridges.

Margin-parallel fractures (Figure 3e) are characterized by narrow troughs (presumably fractures) several tens of meters wide that are superposed on the background ridged plains and are the stratigraphically youngest feature of these plains. The fractures and troughs run parallel to subparallel, and occasionally tangentially, to the ridges. They crosscut each other, and some of the tangential fractures extend across the marginal trough to the base of the ridge. Fractures often occur as groups of 2-4 and are located on the outer margin of the marginal trough at or within a few hundred meters of the area where the
terrain becomes regionally flat. A few of the fractures and troughs show en echelon patterns and some show variations in width, suggesting a pinch-and-swell structure. Close examination reveals that the pinch-and-swell structures are the surface trace of fractures in rough topography and are not likely to represent volcanic vents. There is some evidence (primarily, shading variations and photoclinometry) that suggests that the region of development of margin-parallel fractures may be a local high. In some cases, only the washboard texture is developed adjacent to a ridge, in other cases, only the margin-parallel fractures are developed, and, in a few cases, both are developed.

2.4. Relationship of Background Structure to Ridges

The upper apical parts of the inner and outer slopes of the ridges usually do not display the prominent distinctive linear texture of the background ridged plains and instead have a variety of textures (see next section) that are oriented more parallel to the ridge (outer slope) or are more consistently normal to it (inner slope) (see summary of observations in Figure 3a). Examination of the texture of the outer slope walls in numerous places, however, reveals evidence of degraded extensions of background ridged plains structural trends up onto the outer slope walls (Figures 4a and 4b). For example, several prominent ridges of the background plains extend underneath the dark plains and mantling material up to above the base of the outer slope of the outer ridge (Figure 4b), and, in a few cases, the most prominent ridges extend up to the top of the outer ridge scarp (Figure 4a). Shadow measurements, photoclinometry, and topographic relationships show that these ridges have been elevated above the surrounding plains and that the ridge extensions are topographically higher than they are in the surrounding plains, suggesting that they have been uplifted, relative to the surrounding plains. However, the majority of the ridges and troughs of the background plains do not extend further than the middle of the outer slopes of the ridges, and few
(usually the most prominent) extend to the top. Many of the less prominent background ridges appear to extend underneath the ridge and be covered by material derived from higher on the ridge slope. We now turn to a detailed examination and characterization of these parts of the ridges in order to provide further data to test theories of ridge origin.

3. Detailed Morphology of Ridge Inner and Outer Slopes

Detailed examination of high-resolution images of the outer and inner slopes of ridges and adjacent marginal troughs shows a wide range of morphologic features (Figure 5).

3.1. Inner Ridge Slopes

Inner slopes of ridges are characterized by linear alternating ridges and grooves (or troughs) that are parallel to each other and are normal to the strike of the ridge (Figure 5b, area 1). Bright areas tend to be ridges, and the intervening lows and troughs appear dark. In many cases the dark areas become wider toward the bottom of the inner slopes and have the distinctive somewhat triangular shape of talus fans, although their bases are not visible, being obscured by the shadow of the crest of the opposite ridge (Figures 5a and 5b, area 2). These grooves appear to be “talus chutes” by which material is moving off of ridges and downslope, accumulating in talus fans.

If the ridges and fractures in the adjacent background terrain extended to depth as discontinuities, perhaps these inner slope ridges and grooves might represent the traces and cross-sectional exposure of these fractures and faults. Although some of the more prominent ridges and grooves on the inner ridge slope occur along the strike of prominent ridges in the adjacent background plains (Figure 5b, area 2 and lower part of area 1), there is such a wide range of sizes and orientations of exterior ridges and grooves that we were unsuccessful in confidently matching patterns from the background plains that should have intersected the inner walls. Correlations are made more difficult by the presence of the ridge shadow separating the plains ridges and the inner wall structure. We conclude on the basis of the relatively constant size of the grooves and ridges on the inner walls, and the lack of firm correlation with exterior ridges of a variety of sizes, that the inner wall grooves and troughs originate predominantly from erosion and downslope movement.

Also observed on the inner slopes are dark stripes that are oriented parallel to the ridge crest and extend for a few hundred meters up to 1-3 km along the inner wall (Figure 5b, area 3). These have irregular upper and lower boundaries, appear dark and smooth-textured in relationship to the surrounding, orthogonally oriented ridges and grooves, and appear to be located on breaks in slope, or terraces, on the inner slopes. Ridges and grooves appear to terminate as they intersect these dark areas, and some of the dark chutes appear to be shedding material into the area of the dark bands (Figure 5b, area 2). These features are morphologically similar to terraces on the interior walls of impact craters, and we interpret them to be regions of slumping and faulting along the inner walls of ridges. The dark material is interpreted to be due to downslope movement of material which is then trapped along the break in slope at the terrace to form the dark band. At moderate resolution the crests of the ridges appear extremely sharp and linear. At higher resolution the ridge is flatter and rougher and sometimes has linear fault-like scarps associated with it (Figure 5b).

On the basis of these observations we conclude that slumping and local faulting parallel to the ridge, followed by mass wasting, are important processes in the formation of the inner wall.
3.2. Outer Ridge Slopes

The outer ridge, between the ridge crest at the top and the base of the slope in the marginal trough, can be subdivided into four units (Figure 5a), the upper three of which are commonly observed almost everywhere along the ridge. The uppermost unit is the rough-textured upper slope (Figure 5c, area 1), which makes up commonly one half, but up to two thirds, of the outer wall width. The defining character is the rough texture, composed of topographic elements in the 50-150 m range. These elements may consist of rectangular blocks oriented randomly, or aligned into somewhat linear ridges that are commonly parallel to subparallel to the ridge, or into ridges and grooves oriented normal to the ridge and similar to the features on the inner walls. In a given area the brightness of this unit is variable but lower than that of the inner wall. Hummocks and high topography are brightest, and intervening lows and smooth areas are darkest.

The next outer wall unit is composed of low-albedo terraces flanked downslope by higher-albedo scarps (Figure 5c, area 2). Although the terraces are similar in general appearance to those on the inner walls, they appear rougher in nature. The high-albedo scarps appear to be areas that are locally steeper, and their brightness may be due to exposure of fresh material on steeper slopes. This unit is discontinuous along the strike of the ridge, and when it occurs, it may form up to 20-30% of the width of the ridge. The third unit is the lower slope unit of intermediate albedo (Figure 5c, area 3). This unit is distinguished by its uniform smooth texture and its uniform intermediate to low albedo. It makes up 10-20% of the width of the outer slope. It is intimately related to the high-albedo scarps in that it occurs just downslope of these. It shows embayment relations with ridges and troughs in the background ridged plains in the adjacent marginal trough (Figure 5c, area 4).

The nature and close association of the terraces, high albedo scarps, and these deposits leads us to interpret them as slump terraces and faults, with material shed off the steeper slopes, exposing fresher (brighter) icy material, and accumulating in the adjacent lows as talus, forming the intermediate brightness lower slope material. This latter material is thick enough that it embays and covers ridges and troughs of the background ridged plains, so it must have local thicknesses of several tens of meters. The often linitated morphology of the upper ridge unit, and the parallelism of these linear ridges to the strike of the larger ridge itself, leads us to suspect that they may be faults related to the deformation of the inner, near-crestal parts of the ridge.

A fourth unit, a hummocky low-albedo deposit, is sometimes observed along the outer ridge at the base of the slope (Figure 5c, area 4). This unit is locally very hummocky (several tens of meters) and appears to represent a break in slope between the intermediate-albedo, talus-like material upslope and the smoother plains downslope. We interpret this unit to be local accumulations of larger slump and talus blocks at the base of the slope. This interpretation is supported by the presence of three large isolated hummocks several tens of meters in diameter that occur nearby in the smooth low-albedo plains (Figure 5c, area 5). We interpret these features to be individual talus blocks, similar to those that form the surface of the hummocky low-albedo deposit.

Relatively smooth plains characterized by relatively low brightness are observed in the marginal troughs in several forms. Commonly, they occur as local deposits in low-lying areas between ridges, and they appear to be related to shedding of material off the adjacent local highs (Figure 5c, east of area 1 and 3). In other cases, material from the intermediate-brightness slope deposits grades laterally downslope into lower-
brightness smooth deposits that occur between and among ridges and troughs of the background plains (Figure 5c, east of area 2). In still other cases some material with low brightness appears to be a mantle on ridges of background ridged plains (Figure 5c south of area 4). Finally, there are local deposits of smooth material embaying and burying ridges and troughs of the surrounding background ridged plains (Figure 5c, between 4 and 5). High-resolution views of these latter deposits show them to be somewhat hummocky. Although the surface is cratered, there is no clear evidence for the presence of local volcanic source vents that might have been associated with the emplacement of these deposits.

On the basis of these modes of occurrence we believe that a significant portion of the low-brightness deposits in the marginal troughs is related to the local downslope movement of material from ridges in the background ridged plains, and from the steeper outer ridge slopes of the major ridges and bands (Figure 5a). We interpret this material to be largely of finer grain size than the rough blocks seen on the upper slopes.

The shading of the features and deposits located on wall slopes and in the marginal trough is very highly correlated with local slopes (steep slopes and highs, bright; shallow slopes and flat areas, dark) and can be readily interpreted as erosion and shedding of material of highs and steep slopes, its downslope movement, and its collection in local topography (e.g., between hummocks, in chutes, and behind terraces) and regional topography (e.g., at bases of extensive ridge slopes and in marginal troughs). Whether the brightness difference is due to compositional differences (e.g., dark material being shed off exposing fresher, brighter ice; or sublimation of water ice leaving a lag of silicates which moves downslope), grain-size differences (e.g., downslope movement of finer fragments exposing brighter slopes and bedrock), or some combination of these, is not obvious from these observations alone. In addi-
tion, in some cases the brightness of the background ridged plains, particularly in the marginal troughs, appears lower than in adjacent areas outside of the trough, even though there is no evidence for surface morphological modification at a scale that can be detected in these images. This, combined with evidence from Galileo SSI low-resolution color images that there are color variations in association with ridges and triple bands [e.g., Geissler et al., 1998a, c; Clark et al., 1998], indicates that, in addition to mass wasting, other processes might be operating to alter surface albedo. Although mass wasting of the ridge structure seems to explain many of the observed features, the process itself does not account for the formation of the ridges. Some hypotheses for the origin of ridges, specifically, volcanic ejecta hypotheses, call on fragmental accumulation and downslope movement as a primary factor in ridge formation [Greenberg et al., 1998a, 1999; Fagents et al., 1998; Kadel et al., 1998; see also Greeley et al., 1998b].

Previously, we pointed out that the most prominent of the ridges in the background ridged plains extend toward the top of the ridge crest in the study area (Figure 4). We mapped all ridges associated with background ridged plains that intersect the outer slope of the outer ridge in this area. Under half of these extend across the marginal trough and up onto the base of the outer slope, disappearing as they are draped and mantled by the intermediate-albedo slope deposits interpreted to be material mass wasting from the upslope terrace-scarp unit (Figure 4). Over half of these features can be traced, often in degraded form, halfway up the outer slope into the scarp-terrace area, where they are then lost in the junible of the rough-textured upper slope unit. Two of the most prominent of the ridges can be traced up the outer wall into the rough-textured upper slope to the vicinity of the crest of the outer ridge.

On the basis of these observations (summarized in Figure 5a) we conclude the following: First, the outer slopes of outer ridges were at one time composed of ridges and troughs of the background plains and since that time have been tilted upward and been modified by a range of processes. Second, these modification processes include (1) faulting and segmentation of all but the most prominent background ridges in the upper parts of the outer slope, (2) terrace and scarp formation in the medial parts of the outer slope, (3) talus and debris modification and burial in the lower parts of the slope and in parts of the surrounding plains, and (4) a process or processes causing brightness and color modifications (e.g., change in grain size and/or volatile mobilization and migration).

In addition, we have outlined a classification scheme for ridges and troughs on Europa that represents a sequence from simple to more complex structures [Pappalardo et al., 1998a; see also Greenberg et al., 1998a; Geissler et al., 1998c] (Figure 6). In this sequence, isolated linear troughs represent the simplest manifestation of linear features. Although there is some evidence of local raised rims, in general, the rim appears to be relatively level with the surrounding terrain (Figure 6 (1)). Some troughs are characterized by more well-developed marginal raised flanks (Figure 6 (2)). These features appear to be transitional to larger double ridges, in which the raised flanks become prominent double ridges (Figure 6 (3)). In some cases a median ridge is observed (Figure 6 (4)), forming a triple ridge, and sometimes, as in the example shown here, the median ridge has a median trough. Ridges that are wider and more complex often display a more prominent medial trough (Figure 6 (5)). Wider examples (complex ridges) are composed of multiple parallel ridges and troughs (Figure 6 (6)), often with a prominent medial trough. At each step in this sequence, features such as raised rims and medial ridges seem to be related or transitional, prompting the question: Does this classification scheme represent an evolutionary sequence? Or do the individual features form in independent and different ways?

4. Interpretation of the Formation and Evolution of Ridges and Triple Bands

Observations concerning ridges and triple bands that need to be explained by any hypothesis of origin include (1) their linearity, (2) their great lateral extent and along-strike consistency in morphologic form, (3) their positive topography, (4) the upbowing of some background ridged plains features in the formation of their outer ridges, (5) the formation of marginal troughs, (6) the formation of washboard texture and margin-parallel fractures, (7) the formation of inner ridges, (8) the detailed nature of their outer and inner slopes, (9) their continued formation with multiple, sequential orientations, (10) their color characteristics, (11) their relationships to other features,

![Figure 6](image)

Figure 6. A classification scheme of Europian ridges and troughs. After Pappalardo et al. [1998].
and (12) the potential significance of their arrangement in a classification scheme from simple troughs to complex ridges.

Are these observations consistent with an origin of ridges and triple bands by diapiric processes similar to those that have been hypothesized to be responsible for lenticulae (pits, spots, and domes) [Pappalardo et al., 1998a; Head et al., 1997h, 1998a, d, manuscript in preparation, 1999; Spaun et al., 1999] (Figure 2)? On Earth, numerous examples of linear diapirs are known in the geologic record, including many with fault- and fold-diapir associations [e.g., Jackson et al., 1990]. Commonly, regional anisotropic contractional tectonic stresses cause an initial linear instability to form, and material (usually evaporitic horizons) rises diapirically to form anticlines from 50 to 120 km long [e.g., Elston et al., 1962], with ascent related to buoyancy forces and subsequent differential loading. In other cases, anticlines form by diapirism in static or extensional environments through diapiric rise and ductile flow of evaporitic layers [e.g., van Berkel, 1989]. Indeed, Jackson and Vendeville [1994] showed that salt upwelling in 18 different salt-diapir provinces on Earth was linked to regional extension and that linear diapirs with lengths of many tens of kilometers were common. Jackson and Tilbott [1986] describe salt anticlines and fault-related diapirs up to 260 km in length in the northern Gulf of Mexico. On the basis of these types of examples, Vendeville and Jackson [1992] considered the rise of diapirs below extensional faults in a brittle overburden and showed that this environment was highly favorable to the formation of linear diapirs. In summary, in terrestrial examples of fold- and fault-diapir associations, most commonly in evaporite basins, regional fractures and faults commonly localize the upwelling of positively buoyant material [e.g., Jeryn, 1986] to produce linear diapiric structures tens to several hundred kilometers in length. Geologic structures and physical and numerical modeling show that structures typical of active diapirism are a central crustal graben flanked by relatively unstrained flaps that rotate upward and outward [e.g., Schultz-Ela et al., 1993].

In Figure 7 we present a conceptual model for the formation of linear ridges and triple bands by diapirism in a setting similar to that described for the thermal structure of layers involved in the formation of lenticulae [Pappalardo et al., 1998a]. We first envision a brittle layer overlying a more ductile layer [e.g., Golombek and Banerdt, 1990; Pappalardo et al., 1999; Pappalardo and Head, 1999] which deforms in response to stresses of regional to global scale. The most likely sources are diurnal tidal stresses or nonsynchronous rotation tidal stresses [e.g., Greenberg et al., 1998a, 1999; Geissler et al., 1998a, c], unlike those commonly related to deformation on Earth and producing longer and more regional to global fractures than observed in terrestrial environments characterized by diapirism [e.g., Jeryn, 1986; Jackson et al., 1990]. The strain rates associated with tidally induced regional to global fracturing may be sufficiently high to fracture not only the brittle layer but also the upper portions of the underlying ductile layer. This could form a preferentially strained and heated region in the ductile layer [Stevenson, 1996] just below the fracture in the brittle layer (Figure 7). Following the formation of a regional crack in the brittle layer, buoyant ductile material underlying the brittle layer begins to rise diapirically along the fracture and begins to upbow and modify the upper layer. The diapir would rise to a level related to a number of possible factors, including its initial density contrast, the strength of the brittle lid, and the rate of thermal equilibration with surrounding colder material. The ~16 kg m$^{-3}$ density difference between very "warm" ice (~260 K, 918 kg m$^{-3}$) and "cold" ice (~100 K, 934 kg m$^{-3}$) [Hobbs, 1974] may provide sufficient force to upwar a thin, weak brittle ice layer. In most cases of ridges that we have observed, we would interpret this upbowing to result in the formation of two parallel ridges with paired steep inward facing slopes, representing the separated sides of the fracture plane. Occasionally, a central ridge is observed (the inner ridge of a triple band; Figure 6 (4)), and in some cases its albedo and color are different than the outer ridges. We would interpret this inner ridge to be the surface manifestation of the upwelling ductile layer, analogous to a piercingment ridge in terrestrial diapirs [Jeryn, 1986].

Candidate processes for formation of the marginal troughs include (1) rim synclines caused by subsidence due to the lateral and vertical translation of ductile material into the rising diapir, a phenomenon common in terrestrial diapirs [Jeryn, 1986]; (2) folding resulting from lateral forces caused by initial opening of crack and intrusion of ductile material; (3) folding caused by lateral forces associated with the topography of the upraised ridge; and (4) subsidence caused by flexure related to the load of the newly formed ridge [e.g., Pappalardo and Coon, 1996; Greenberg et al., 1998a]. On the basis of our observations and interpretation of the formation mechanism, we favor the first option, but more quantitative analyses and comparison to multiple topographic profiles will be required to test these models further. We interpret the marginal fractures as forming on the outward margin of the zone of subsidence related to the rim syncline.

During the upward flexing and deformation of the ridge, a number of processes are operating on the outer and inner slopes. First, on the inner steeper slopes representing the separated walls of the initial fault, mass wasting and slumping occurs as they are pulled apart and rotated upward. Concurrent with this rotation, internal deformation takes place and the topographically highest and thus most translated parts of the ridge are fractured to produce the rough-textured upper slope deposits. The often linedate upper parts of the ridge (Figure 5c) are interpreted to represent the faulted upper part of the most displaced portion of the uplifted layer; the innermost parts may be topographically raised by reverse faulting as material is displaced from below preferentially adjacent to the original part of the initial fracture. In our interpretation the low brightness terraces and high-brightness scarps may represent the transition point to the more broadly folded and less intensely deformed background ridged plains forming the lower slopes and marginal trough. Superposed on these patterns and forming co-incident with them and subsequently are the multiplicity of features indicating mass wasting and downslope movement of material (Figure 5). Also predicted from this model are the consequences of warmer ice rising toward the surface. The thermal effects of such rising warm ice may cause thermal alteration (e.g., warming of surface ice could cause recrystallization and produce variations in grain size), thermal migration (e.g., heating and volatilizing portions of surface materials or burning off of surface frost), local melting or mobilization of low-melting-point materials such as brines [Head and Pappalardo, 1999], and possible volcanism.

5. Discussion and Conclusions

On the basis of our analysis, we conclude that an origin for ridges by cracking and linear diapirism offers a plausible alter-
1) REGIONAL CRACK FORMS DUE TO TIDAL DEFORMATION

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<tr>
<th>BRITTLE LAYER</th>
<th>DUCTILE LAYER</th>
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<td>CRACK FORMATION</td>
<td>HEATS LOCAL REGION</td>
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2) BUOYANT DUCTILE MATERIAL DIAPERICALLY RISES ALONG FRACTURE, BEGINS MODIFYING LAYER

<table>
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3) BRITTLE SURFACE LAYER FLEXES UPWARD, FOLDS, FAULTS

| RIM SYNCLINES |

Figure 7. Conceptual model for the formation of linear ridges and triple bands by diapirism. Step 1: Regional crack forms in brittle layer owing to tidal deformation. Step 2: Buoyant ductile material underlying brittle layer begins to rise diapirically along the fracture and begins to upbow and modify the brittle surface layer. Step 3: The brittle surface layer flexes upward and is deformed and faulted. At a the brittle layer is flexed upward along the fracture to produce parallel ridges. At b the linear diapir may reach the surface to produce a piercement ridge. At c, rim synclines form by subsidence following inward and upward migration of the diapir. At d, marginal fractures and washboard texture form in response to various forces, including compression, flexure, and subsidence. At e, deformation-related changes in slope, fracturing, cause a range of mass-wasting deposits. At f, thermal effects from the rising warm ice may cause thermal alteration, thermal migration, local melting, and, possibly, volcanism.

Native to other proposed origins [e.g., Sullivan et al., 1997; Greeley et al., 1998b; Greenberg et al., 1998a, 1999; Kadel et al., 1998; Turtle et al., 1998] (see review and assessment by Pappalardo et al. [1999]). For example, several hypotheses for the origin of ridges, classified as volcanic ejecta hypotheses, call on accumulation of pyroclastic fragments and downslope movement as a primary factor in ridge formation [Greenberg et al., 1998a, 1999; Fagents et al., 1998; Kadel et al., 1998, see also Greeley et al., 1998b]. Volcanic ejecta is often fragmental and nonwelded even in cryovolcanic environments [e.g., Wilson and Head, 1998], and thus mass-wasting processes and landforms may have many similarities to those related to volcanic ejecta. Linear volcanic vents, however, require migration of magma from source depths to shallower depths, where volatile formation and disruption of magma occurs, resulting in the emplacement of fragmental ejecta [e.g., Head and Wilson, 1987]. Typically, initial dike emplacement causes formation of a series of vents along the strike of, and above, the dike, and the “curtain of fire” stage of the event occurs, producing a series of irregular spatter cones. Conductive cooling along the narrow parts of the dike results in the localization of the eruption to a small number of vents, usually one, within a short period of time [Wilson and Head, 1988]. Ejecta is then emplaced in patterns dictated by the number of vents, the nature of the volatile exsolution process, the velocity of the pyroclasts, the radial variation in accumulation from the vent, pyroclastic accumulation rates, atmospheric effects, and surface temperatures [e.g., Wilson and Head, 1981]. This wide array of variables is responsible for the tremendous diversity of pyroclastic deposits observed on Earth and planetary surfaces [e.g., Wilson and Head, 1983; Head and Wilson, 1989]. The linear nature of the ridges over tens to hundreds of kilometers, their distinctive lateral regularity and continuity, and the linear continuity of faces along the sides of the ridge (Figures 3a and 5a) argue more for an origin through predominantly tectonic, rather than volcanic, processes. Even hypotheses which call on global tectonic deformation to produce long, linear fractures, followed by volcanic ejecta to produce the ridge topography and morphology [e.g., Greenberg et al., 1999], would seem to predict much more irregular along-strike and across-strike ridge formation.
and evolution than what is observed. In any case, the detailed observations on the characteristics of these ridges outlined in this contribution should provide a basis for further discussion and debate on the origin of these pervasive features on Europa.

On the basis of the observations and interpretations outlined here, we believe that a plausible case can be made for the formation of ridges and triple bands through linear diapirism. Once extremely linear tidally related fractures of great lateral extent are formed, our hypothesis accounts for the resulting ridges and their along-strike and across-strike morphological regularity; their positive topography, the upwelling of background ridged plains in the formation of their outer ridges, the formation of marginal troughs, the formation of margin-parallel fractures, the formation of inner ridges, the detailed nature of their outer and inner slopes, and their continued formation with multiple, sequential orientations. In addition, since the vast majority of deformation is vertical in this scenario, this mechanism minimizes the necessity for complementary compressional deformation in the initial stages of ridge formation. Finally, the classification scheme of ridges and troughs on Europa that represents a sequence from simple to more complex (Figure 6) may also represent a sequence of evolutionary steps in the formation of ridges and bands. In this sequence, isolated linear troughs might represent the first stage of cracking (step 1), followed by upwelling to produce troughs with raised flanks (step 2) and then by the doublet ridge (step 3) as the brittle layer upwells and cracks. Following this, a median ridge might form (step 4) as the ductile layer undergoes axial extrusion (forming a piercement structure). The more complex morphology suggests that there may be situations when the processes continue on to involve separation and infilling (step 5) and possibly even repeated separation (step 6). Presently unresolved is whether steps 1-4 might represent the sequence that all ridges go through or are related to variations in local thermal structure and other factors.

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