ORIGIN OF RIDGES AND BANDS ON EUROPA: MORPHOLOGIC CHARACTERISTICS AND EVIDENCE FOR LINEAR DIAPIRISM FROM GALILEO DATA.

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Introduction: Recent Galileo SSI images of Europa provide morphological evidence that supports the hypothesis that domes, pits and spots are of internal diapiric origin [1-4], leading to the questions: Could ridges and triple bands have originated through the same type of diapiric process? How would the process of linear diapirism work and are the characteristics of ridges and triple bands consistent with this hypothesis? Here we describe the nature of the ridges and bands and show their relationship to other background features in order to address these questions.

Nature of ridges and bands: The detailed examination of ridges at very high resolution (~20 m/pixel) in the E4 coverage shows a range of features (Fig. 1,2). The ridges themselves are linear features which consist of paired ridges, each with an outer and inner slope. Some ridges are characterized by a third inner ridge, whose crest is commonly at a lower elevation. Ridges and bands commonly cross-cut and are superposed on background ridged plains. Ridges and triple bands are sometimes flanked by marginal troughs, which are shallow lowlying linear depressions developed along the margins of the ridges at the base of their outer slopes, extending beyond the base of the outer ridge slope out to about one-half of the ridge width. Photoclinometric data (R. Kirk, pers. comm.) suggest that ridges may be up to about 200 meters in height, and that the depressions are typically a few tens of meters in depth relative to the surrounding plains [5]; maximum average slopes of the outer flanks of the ridge would be ~12 degrees.

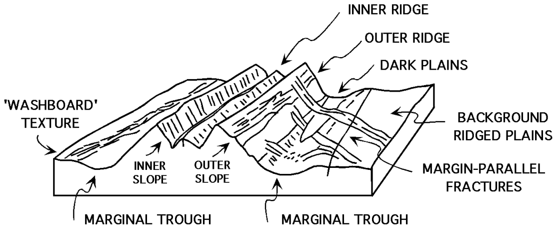

Fig. 1. Ridge morphology and nomenclature.

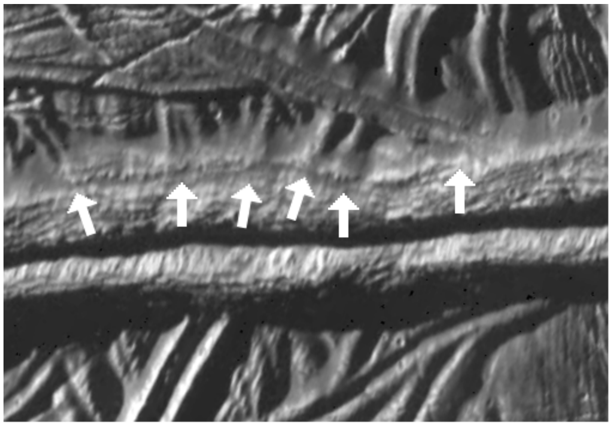

Fig. 2. Ridge structure; height of image is ~5 km.

Marginal troughs have a wide variety of surface textures: 1) they may simply reflect a depression in the lineated background plains; 2) in some cases lineated structures are apparently darkened, and sometimes appear to be mantled with dark material, subduing their morphology; 3) in some cases, the trough is occupied by dark plains that appear to embay, and indeed cover, pre-existing ridged plains. Marginal troughs also exhibit associated structural features apparently not related to the background ridged plains: 1) 'raked' texture is characterized by a set of narrow parallel ridges and troughs oriented parallel to the ridge, each ridge of the texture typically a few tens of meters across; 2) margin-parallel fractures characterized by fractures and narrow troughs several tens of meters wide superposed on the background ridged plains.

The upper 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 (Fig. 3) that are oriented more parallel to the ridge. 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 (Fig. 2). 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 (Fig. 1, arrows in 2), and in a few cases, the most prominent ridges extend up to the top of the outer ridge scarp. 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.

Detailed morphology of ridge inner and outer slopes: Inner slopes (Fig. 3) 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. These grooves appear to be 'talus chutes' by which material is moving off of ridges and downslope, accumulating in talus fans. 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 furrows 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. 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. We thus conclude that slumping and local faulting parallel to the ridge, followed by mass wasting, are important processes in inner wall formation.

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: Unit 1: rough-textured upper slope composed of topographic elements in the 50-150 m range; rectangular blocks oriented randomly, or aligned into somewhat linear ridges parallel or subparallel to the ridge. Unit 2: low-albedo terraces flanked downslope by higher albedo scarps (Fig. 3); 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. Unit 3: lower slope unit of intermediate albedo; distinguished by its uniform smooth texture and its uniform albedo and occurs just downslope of the high-albedo scarps; shows embayment relations with ridges and troughs in the background ridged plains. 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 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. Unit 4: hummocky low-albedo deposit, sometimes observed along the outer ridge at the base of the slope (Fig. 3) 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.

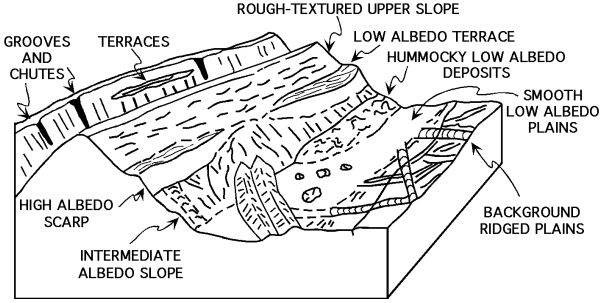

Fig. 3. Block diagram illustrating nomenclature of features and their distribution in relation to ridge topography.

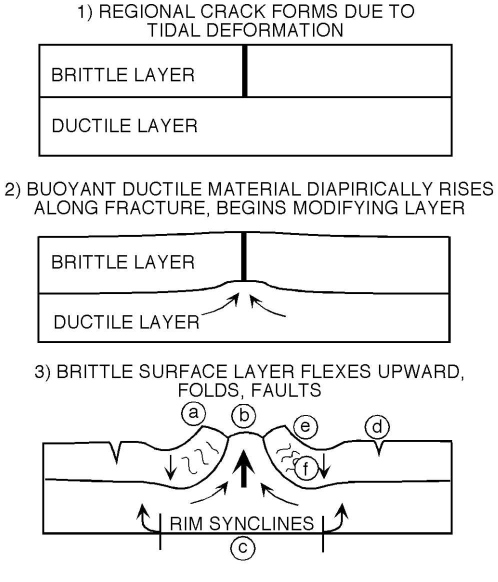

Fig. 4. Conceptual model for the formation of linear ridges and triple bands by diapirism. At a, the brittle layer is flexed upward along the fracture to produce parallel ridges. At b, the linear diapir may reach the surface to produce a piercement ridge. At c, rim synclines form by subsidence following inward and upward migration of the diapir. At d, marginal fractures and raked 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, and local melting and volcanism (?).

Relatively smooth low-albedo plains are observed in the marginal troughs in several forms (local deposits in lowlying areas between ridges; material from the slopes that grades laterally downslope; material that mantles ridges of background plains; and smooth material embaying and burying ridges and troughs of the surrounding background ridged plains). We thus believe that a significant portion of the low-albedo deposits in the marginal troughs are related to the local downslope movement of material from the steeper outer ridge slopes of the major ridges and bands, composed largely of finer grain-size than the rough blocks seen on the upper slopes. The albedo of the features and deposits located on wall slopes and in the marginal trough are 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 off highs and steep slopes, its downslope movement, and its collection in local and regional topography. This, combined with evidence from Galileo SSI color images that there are color variations in association with ridges and triple bands [6,7], indicates that additional processes might be operating to alter surface albedo [8].

On the basis of these observations (Fig. 2, 3) we conclude: 1) The outer slopes of outer ridges were at one time composed of ridges and troughs of background plains, and have since been tilted upward and modified by a range of processes which include: a) faulting and segmentation of all but the most prominent background ridges in the upper parts, b) terrace and scarp formation in the medial parts of the outer slope, c) talus and debris modification and burial in the lower slope and in parts of the surrounding plains, and d) a process possibly related to thermal effects causing albedo and color modifications (e.g., change in grain size and/or volatile mobilization and migration) without visible morphological variations in the marginal troughs and some nearby areas.

Comparison to linear diapirism model of ridge formation: On the basis of the characteristics and associated features of bands, we find that a a consistent explanation for the observed features is a process in which initial fracturing (most plausibly related to tidal deformation [9]) of a brittle layer overlying a buoyant ductile substrate causes linear diapriric upwelling. In this process, the upwelling linear diapir (Fig. 4, Step 1, 2) causes flexure of the region marginal to the fracture (Fig. 4, Step 3), the deformation and uplift of adjacent plains material and its pre-existing structures, 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 not destroy, the pre-existing structure of the adjacent plains. Specifically, this mechanism can account for the linearity of the ridges, their consistent and regular morphology over their great lateral extent, their positive topography, the presence of preexisting structure on the outer ridges (caused by upbowing of background ridged plains), the formation of marginal troughs (as diapiric 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 [9]). 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 [9]. Other processes [9,10] may also be important in the evoution of these ridges or in ridges outside the area examined in this study.

References: 1. J. Head et al., in review, Icarus. 2. R. Pappalardo et al, Nature, in press, 1998. 3. J. Head, GSA, A312, 1997. 4. J. Moreau et al., GSA, A312, 1997. 5. R. Sullivan et al., LPSC 28, 1395, 1997. 6. P. Geissler et al., Icarus, in review, 1997. 7. T. Denk et al., Europa Color, LPSC 28, 1998. 8. R. Pappalardo et al., LPSC 29, 1998. 9. R. Greenberg et al., Icarus, in review,1997. 10. R. Greeley et al., Icarus, in review, 1997.