TROUGH-BOUNDING RIDGE PAIRS ON EUROPA - CONSIDERATIONS FOR AN ENDOGENIC MODEL OF FORMATION. S. D. Kadel, S. A. Fagents, R. Greeley and the Galileo SSI Team, Arizona State University, Box 871404, Tempe, Arizona 85287-1404. E-mail: kadel@asu.edu.

Introduction

Recent high-resolution (up to 18 m/pixel) images obtained by the Galileo spacecraft Solid State Imaging (SSI) camera indicate that trough-bounding ridge pairs are very common surface features on Europa. Measurements of ridge dimensions and slope angles, in combination with observed morphologies, photometric data and theoretical considerations, support interpretation of these features as endogenic deposits produced by short-lived gas-driven fissure eruptions [1] of frost, ice, water (?) and some minor silicate fraction. Quantitative morphological results and a conceptual model of ridge formation are presented here.

Background

Evidence for the resurfacing of Europa by water, either in liquid, slush or vapor/snow phases has been suggested by studies indicative of frost-like properties of the surface [2,3], a relative paucity of impact craters [4,5] (possibly indicative of burial by endogenic processes [6]), and the gradual brightening of surface features with time [7,8]. Initial Voyager images of the surface of Europa showed numerous linear features, dubbed lineae and triple bands [4,9], criss-crossing its icy surface. Little relief was observed in association with these or other features on Europa from Voyager data, due to 1) image resolution of ≥2 km/pixel, 2) the relatively small amounts of relief typical for Europa (generally <300 m), and 3) the small number of low sun-angle images obtained.

Observations and Model Discussion

Recent high-resolution (up to 18 m/pixel) images obtained by Galileo indicate that trough-bounding ridge pairs are quite common (Figure 1). A pressure-ridge orig\in has been proposed for these ridges [10,11], but the inferred thickness (kilometers to tens of kilometers) of Europa's ice during ridge formation [7,10,12] suggests stresses predicted from available tidal and nonsynchronous rotational energy sources would be insufficient to cause compressional failure. However, failure of a kilometers-thick ice sheet could be induced by currently available tensional stresses [13,14]. Origins by viscous intrusion [15], viscous extrusion [3], and periodic compressionally forced liquid extrusion [16] have also been proposed. Here we further develop an alternative mechanism for the formation of trough-bounding ridges: the progressive build-up of "levees" of water ice and frost adjacent to tensional fractures. The fractures may have acted as conduits through which expanding water vapor and other exsolving gases (e.g., SO_2, CO_2), produced by exposure of liquid water at depth to the near vacuum surface conditions of Europa, rose and were erupted onto the surface of Europa.

The freezing of such vapor (and entrained material) plumes should lead to deposition of frost or snow-like deposits of water ice on the surface. Previous work [3,17,18] has assumed that water frost would be distributed widely, or in symmetrical plumes, without considering thickness variations approaching the "vent" location. Redistribution of water from the trailing to the leading hemisphere of Europa due to ion bombardment [19] would indeed act to distribute frost widely across the surface over time. However, expanding gas (and any liquid water, ice and silicate debris entrained with it) erupted from a crack that is very narrow with respect to its length and depth (e.g., perhaps a few meters wide, several kilometers or more deep, and tens of kilometers long) should produce deposits that thin rapidly outward from the fracture. Continued expansion of the vapor cloud will occur, but the distribution of frost and ice (+/- water and silicates) "fall-

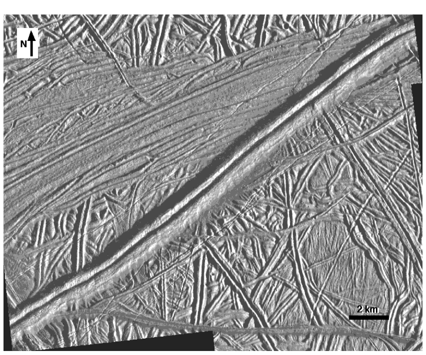
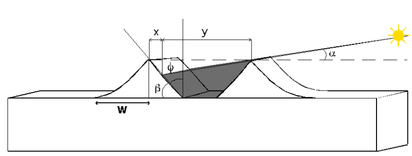


Figure 1.



$$\beta = \tan^{-1}[(y/x)(\tan\alpha)]$$

$$u = \sqrt{\frac{g\,w}{2\sin\phi\cos\phi}}$$

Figure 2.

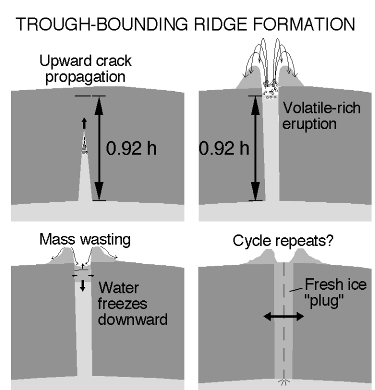


Figure 3.

out" should be greatest adjacent to the linear vent and should thin out to a feather-edge away from the fracture. To a first order, a ballistic trajectory may be assumed for erupted materials, with the resulting deposit widths controlled by the vent geometry and the particle velocities when leaving the fracture.

Data and Analysis

Over 60 individual measurements of ridge dimensions (height and width) and morphology (e.g., slope angles) have been made from high-resolution, low sun-angle images obtained of Europa by Galileo during the spacecraft's first twelve orbits around Jupiter. Here we assume a vent geometry consistent with measured average inner slope angles of ridge pairs, and assume ballistic trajectories from the fracture (Figure 2). Results indicate an average ridge width of ~340 m, an average ridge height of ~220 m, and average interior and exterior ridge slopes of 36.5° and 38°, respectively. These average slopes are similar to the expected ~34° angle of repose, but measured exterior slopes range up to 55° locally, suggesting at least partially consolidated materials. This is consistent with observed scarps on the exterior flanks of the ridges seen at very high resolutions (≤30 m/pixel). The relative warmth and possible entrained liquid in icy fall-out adjacent to the fractures could produce an effect not unlike welding of terrestrial tuff deposits, creating ridges able to support slopes significantly greater than 34°. Measured local slopes ~55°, and recent photometric observations [20] suggesting freshly exposed coarse-grained ice in ridges, are consistent with this process. Ridge heights are roughly proportional to their widths, with an average h/w ratio of 0.8. The eruption velocity necessary to reach a distance of 340 meters from the fracture with the given geometry is approximately 22 m/s, necessitating slight overpressure in the vent fracture.

Diffuse deposits distributed to widths greater than those associated with the ridges are also expected, and may be observed as thinly blanketed/infilled low-lying areas adjacent to ridges, and potentially as spectral signatures (e.g., those observed in Near-Infrared Mapping Spectrometer (NIMS) data for the Tyre Macula area ; [21]) or photometric phase function data indicative of cryovolcanic deposits with distinct compositions and/or grain size distributions in areas bilaterally symmetric about ridge pairs. With time, the exposed liquid water surface (after rising approximately 92% of the way to the surface) will freeze over again, with vaporization inhibited after formation of an approximately 0.5 m ice crust [22,23]. As the new ice shell is forming and growing to this thickness, which should take significantly less than ten days [24], the rate of vaporization and subsequent "eruption" of water vapor, other gases, and entrained liquid and solid components should decrease with time. As this rate decreases, the velocity with which these materials leave the fracture should similarly decrease, thus reducing the total height and distance from the fracture to which these materials are distributed. Hence, the resulting cryovolcanic deposits will be further thickened in areas proximal to the fracture, with the last materials being deposited in a manner and location not unlike the building of spatter ramparts by terrestrial fissure eruptions.

The endogenic model presented here for the formation of ridges adjacent to central fractures on Europa should lead to the observed bilaterally symmetric ridge geometries (Figure 3). The central trough between the ridges could represent either a reopening of the fracture (accompanied by further cryovolcanic deposition) or the result of mass wasting of the cryovolcanic deposits into a graben left above the newly formed ice surface at depth. The latter process almost certainly occurs, as evidenced by measured inner slope angles near 34°. As ice shell thickening continues within the fracture, a plug of ice should rise up until it essentially reaches the pre-existing ice surface. Continued mass wasting of the cryovolcanic materials should lead to a central trough depth that is slightly less than the height of the ridges above the surrounding plains. Before the ice plug has reached its full thickness, repeated reactivation of this fracture, accompanied by further gas-driven fissure eruptions, would be favored as long as the local stress regime remains relatively unchanged.

References

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