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Flanking fractures and the formation of double ridges on Europa

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ABSTRACT

Europa, a satellite of Jupiter, is one of the most intriguing worlds in the Solar System. Its dearth of impact craters and plethora of surface morphologies point to a dynamic evolution of its icy shell in geologically recent times. Double ridges are a common landform and appear to have formed over a significant fraction of the satellite's observed geologic history. Thus, understanding their formation is critical to unraveling Europa's history, and many models have been proposed to explain their creation. A clue to the formation of ridges may lie in evidence for flexure of the lithosphere in response to a load imposed by the ridge itself (marginal troughs and subparallel flanking fractures). When this flexure has been modeled, a simple elastic lithosphere has typically been assumed; however, the generally thin lithospheres suggested by these models require very high heat flows that are inconsistent with Europa's expected thermal budget (of order 1 W m^{-2} vs. of order 10 mW m^{-2}). Each of the proposed formational models, however, predicts a thermal anomaly that may facilitate the flexure of Europa's lithosphere. Here, we simulate this flexure in the presence of these anomalies, as a means to evaluate the different models of ridge formation. We find that nearly all models of double ridge formation are inconsistent with the observation of flexure (specifically the flanking fractures), except for a cryovolcanic model in which the growing ridge is underlain by a cryomagmatic sill that locally heats and thins the lithosphere.

1. Introduction

Europa, a satellite of Jupiter, is one of the most intriguing worlds in the Solar System. Only slightly smaller than the Moon, Europa possesses a metallic core and a rocky mantle surrounded by a shell of water/water ice ∼100 km thick (Anderson et al., 1998; Schubert et al., 2009). Its dearth of impact craters and plethora of surface morphologies point to a dynamic evolution of its icy shell in geologically recent times (e.g., Greeley et al., 2004; Schenk et al., 2009; Bierhaus et al., 2009). In addition, the preponderance of evidence points to a liquid water ocean beneath the ice shell (e.g., Pappalardo et al., 1999; Kivelson et al., 2000). Because liquid water is a necessary (but insufficient) biological requirement, Europa is one of the prime candidates for extraterrestrial life in the Solar System. This ice shell is of order 10 km thick (see Schenk and Turtle, 2009), but regardless of whether the shell is somewhat thinner or thicker, the heat flow coming out of Europa is likely greater than what can be supplied by radiogenic heating in the silicate portion (see, e.g., Schubert et al., 2004; Ruiz, 2005; Sotin et al., 2009). This fact implicates tidal dissipation as the engine that drives Europa's diverse (and ongoing?) activity.

Ridges are the most ubiquitous landform on Europa, with multiple generations of ridges cross-cutting each other (for reviews, see Pappalardo et al., 1999; Greeley et al., 2004; Prockter and Patterson, 2009). These features can run remarkably uniformly for more than 1000 km across the surface, a challenge for any model of their formation. A wide spectrum of morphologies has been classified as ridges on Europa, from isolated troughs to ridge complexes that display a series of subparallel features (Head et al., 1999). The most common form is known as the double ridge (Fig. 1); these features are generally ∼0.5–2 km wide, ∼100–300 m tall, and possess a central trough and outer flanks with slopes typically <20° (Head et al., 1999; Coulter et al., 2009; Coulter and Kattenhorn, 2010). These shallow angles on the outer flank are usually interpreted as less than the angle of repose, suggesting non-granular processes are at work. On the other hand, materials can display a wide range of repose angles, including down to ∼10°, depending on the size, shape, and stickiness of the particles (e.g., Zhou et al., 2002), as well as the gravity of the target body (Kleinhans et al., 2011). The outer flanks of double ridges appear to be dominated by mass-wasting processes. Head et al. (1999) reported that the terrain immediately peripheral to a ridge can be traced up the flank of the ridge, suggesting that the ridges represent upwarping of the pre-existing terrain. This interpretation, however, is not unique (Sullivan et al., 1998); if ridges formed by deposition of material on the surface, they would reflect to some degree the topography of the underlying terrain. Furthermore, some of the cracks that persist up the flanks could

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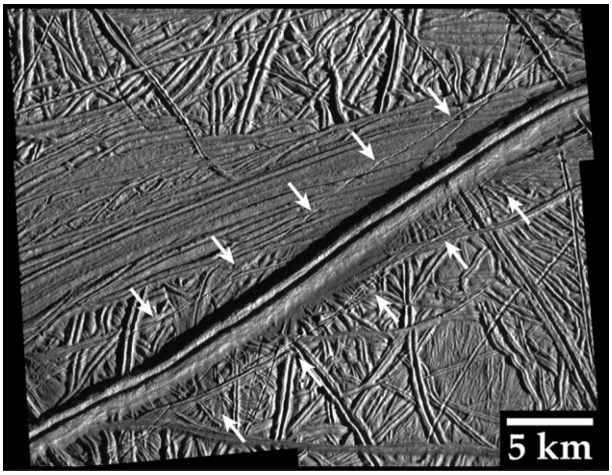

Fig. 1. This high-resolution view of the Androgeos Linea double ridge (14.7°N, 273.4°W) was taken by NASA's Galileo spacecraft during its E6 orbit. It is obvious that Androgeos Linea is but the latest in a long history of double-ridge formation in this area. The arrows mark the flanking, subparallel cracks.

be due to reactivation along pre-existing structures. A subtle marginal trough a few tens of meters deep is fairly common (see Hurford et al., 2005), and subparallel, presumably tensile fractures can sometimes be found near the outer reaches of these troughs (Fig. 1). Additionally, the marginal troughs can sometimes possess diffuse regions of lower albedo, suggesting burial or processing of the terrain.

Several models have been proposed for the formation of double ridges (to be reviewed in the next section). All of these models appeal to exploitation of a pre-existing crack in the ice shell of Europa. Addressing the source of the initial crack has been beyond the scope of these models (and continues to be so in this current work), but it is thought that the cracks form in response to externally applied stresses (Greeley et al., 2004; Kattenhorn and Hurford, 2009). As pointed out by Greeley et al. (2004), "each model has different implications for the presence and distribution of liquid water at the time of ridge formation." Given that ridges are the most ubiquitous landform, it is therefore critical to understand ridge formation in order to decipher Europa's unique history.

A clue to the formation of ridges may be provided by evidence for flexure of the lithosphere in response to a load imposed by the ridge itself. Several groups have interpreted the presence of marginal troughs and subparallel flanking fractures associated with ridges as characteristic of flexure (e.g., Pappalardo and Coon, 1996; Tufts, 1998; Billings and Kattenhorn, 2005; Hurford et al., 2005; Dombard et al., 2007). The addition of a ridge to the surface will cause the lithosphere to warp downward, producing marginal troughs and uplifting a flexural bulge peripheral to these troughs that may be detectible. Between the bulge and the trough, tensile flexural stresses peak and may produce subparallel fractures (arrows in Fig. 1). When this flexure is modeled, a simple elastic lithosphere has usually been assumed (see Turcotte and Schubert, 2002); however as we will discover below, the generally thin lithospheres indicate very high heat flows inconsistent with Europa's expected thermal budget, which implicates a localized thermal anomaly in the formation of the double ridges (cf. Dombard et al., 2007).

In this paper, we will evaluate models of double ridge formation by determining which ones are consistent with the observation of flexure. As we will discuss, ridges that display evidence of flexure (marginal bulges, troughs, and fractures) are common but not abundant, and those that possess evidence of flexure can provide important constraints. Because the bulge and trough topography is subtle, we will specifically look to see which models, and under what conditions, predict tensile stresses that peak at the right range of distances away from the central ridge axis, and thereby are able to reproduce the flanking fractures. In the next section, we review the various models that have been proposed and discuss the thermal anomalies that may be associated with each one. Then, we discuss a suite of measurements of double ridges, in order to determine the range of distances of the flanking fractures. We subsequently describe our thermal–mechanical finite element simulations, present our results, and discuss the implications.

2. Models of double ridge formation

Many of the proposed models for double ridge formation are summarized in Fig. 2. In the volcanic model of Kadel et al. (1998), a pre-existing crack provides a pathway for fissure eruptions that build the ridges cryoclastically (Fig. 2a). In the tidal squeezing model of Greenberg et al. (1998), daily tidal forces cause the crack to open and close, squeezing material onto the surface (Fig. 2b). A dike intrusion model (Turtle et al., 1998) posits that injection of melt into the subsurface can deform the lithosphere around the crack, uplifting the ridge. An ice wedging model (Melosh and Turtle, 2004; Han and Melosh, 2010) represents a hybrid between the tidal squeezing and dike intrusion models. Here, water fills a crack that opens during the tensile part of a tidal cycle but does not reach the surface because of enhanced cooling; the subsurface build-up of ice wedges open the crack and deforms the surface, producing the ridge. Head et al. (1999) proposed that the crack leads to formation of a wall diapir of warm ice that uplifts the ridge (Fig. 2c), while Sullivan et al. (1998) argued that the ridge represents a symmetric buckle of the lithosphere adjacent to the crack under a compressive stress state (Fig. 2d). A shear heating model (Gaidos and Nimmo, 2000; Nimmo and Gaidos, 2002; Han and Showman, 2008) has been proposed where cyclical strike-slip motion on a crack dissipates heat in the interior, resulting in the warmer, buoyant ice uplifting the ridge (Fig. 2e).

Last, Dombard et al. (2007) recently proposed a variant of the cryovolcanic model. In volcanic systems on Earth, the amount of subsurface magmatism generally exceeds the amount of surface volcanism, often by a large amount (Crisp, 1984). On an icy satellite, it is reasonable to expect this phenomenon to hold, especially since the cryomagma (water) is denser than the country rock (ice). Thus, we have proposed that while the ridge is being built on the surface effectively as a cryoclastic fissure eruption (Kadel et al., 1998), a cryomagmatic sill forms at a depth of ~1 km, at the level of neutral buoyancy of water in an ice shell (Fig. 3).

For the purposes of this work, these models may be assigned to different classes. Some of these models are not consistent with the presence of the flanking fractures. The dike intrusion model (Turtle et al., 1998), ice wedging model (Melosh and Turtle, 2004; Han and Melosh, 2010), and the compression model (Sullivan et al., 1998) predict local to regional compressive stresses immediately exterior to the ridge, which would inhibit the formation of the fractures; thus, we will not consider these models further. The cryovolcanic model of Kadel et al. (1998) and the tidal squeezing model (Greenberg et al., 1998) have liquid water arising solely along the pre-existing crack; we classify these mechanisms as "central conduit" models. Our cryovolcanic sill variant (cf. Dombard et al., 2007) adds the thermal effects of a sill to the central conduit models (Fig. 3). The wall diapir model (Head et al., 1999) is like the shear heating model (Gaidos and Nimmo, 2000; Nimmo and Gaidos, 2002; Han and Showman, 2008) in that the buoyancy that raises the ridge comes from thermal expansion due to heating along a