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Antarctic analog for dilational bands on Europa

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We would like to dedicate this work in memory of Dr. B. Randall 'Randy' Tufts (1948–2002)

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ABSTRACT

Europa's surface shows signs of extension, which is revealed as lithospheric dilation expressed along ridges, dilational bands and ridged bands. Ridges, the most common tectonic feature on Europa, comprise a central crack flanked by two raised banks a few hundred meters high on each side. Together these three classes may represent a continuum of formation. In Tufts' Dilational Model ridge formation is dominated by daily tidal cycling of a crack, which can be superimposed with regional secular dilation. The two sources of dilation can combine to form the various band morphologies observed. New GPS data along a rift on the Ross Ice Shelf, Antarctica is a suitable Earth analog to test the framework of Tufts' Dilational Model. As predicted by Tufts' Dilational Model, tensile failures in the Ross Ice Shelf exhibit secular dilation, upon which a tidal signal can be seen. From this analog we conclude that Tufts' Dilational Model for Europan ridges and bands may be credible and that the secular dilation is most likely from a regional source and not tidally driven.

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1. Introduction

Lineaments are pervasive on Europa's surface. The majority of these features have been interpreted to form as a result of tensile failure (McEwen, 1986; Leith and McKinnon, 1996). This interpretation is supported by the fact that ice has a low tensile strength that ranges between about 100 kPa and 2 MPa (Lee et al., 2005) and that Europa naturally experiences tension from diurnal tidal stress that can meet this failure threshold (Greenberg et al., 1998). Moreover, some lineaments display dilational separation indicating that large extensions of the ice shell have occurred. The tidal cycle alone would not predict net extension so the second source of extension on either a regional or global scale is needed.

The most common lineament morphology are ridges or double ridges (Fig. 1a). These features consist of a trough that is flanked by a ridge on either side. They may extend 1000 s of km across the surface and are typically a few km wide and a few 100 s of m tall. Ridges represent an advanced state of an evolutionary development process (Geissler et al., 1998; Head et al., 1999). In its early stage, ridges are thought to form as tensile failure of the surface, forming a trough with no ridges. Subsequent processing of the crack then can build the observed ridge edifices with time.

There are a number of models for subsequent ridge formation that have very different implications for fundamental processes on Europa. However, all assume the formation of the tensile fracture but then differ on the ridge building mechanism. Kadel et al. (1998) builds the ridges through fissure eruptions of material from the crack onto the surface adjacent to the fissure, while Head et al. (1999) describes upward bending of the surface due to a buoyant upwelling of ice intruding along the fissure. Turtle et al. (1998) incremental wedging model forms ridges from compression of material that gets trapped in the fissure and drives deformation on each flank. Finally, Greenberg et al. (1998) ridge model appeals directly to the working of the fissure by tidal stresses to expose, freeze and extrude material onto the surface as the fracture opens and closes daily.

While Greenberg et al. (1998) ridge formation model acknowledges the role of tidal processing in ridge formation, all the other models might also be linked to the cyclical tidal processes that are thought to work on active fractures on Europa (Prockter and Patterson, 2009). For example, fissure eruptions might be controlled by tidal stress (Hurford et al., 2007), tidal shear stress might provide a source of heat that drives buoyant upwelling ice (Gaidos and Nimmo, 2000) or tidal stress might open a crack allowing material to slump into the fissure, which later, when compressed by tidal stress forms wedge ridges. Therefore, the role of diurnal tidal stresses may be critical to the formation of ridges on Europa.

Apart from ridges, extensional features known as dilational bands are observed on Europa. Bands are widely distributed on Europa's surface and can be a few 10 s of km across, although this width may not always be uniform (e.g. wedged shaped bands) and

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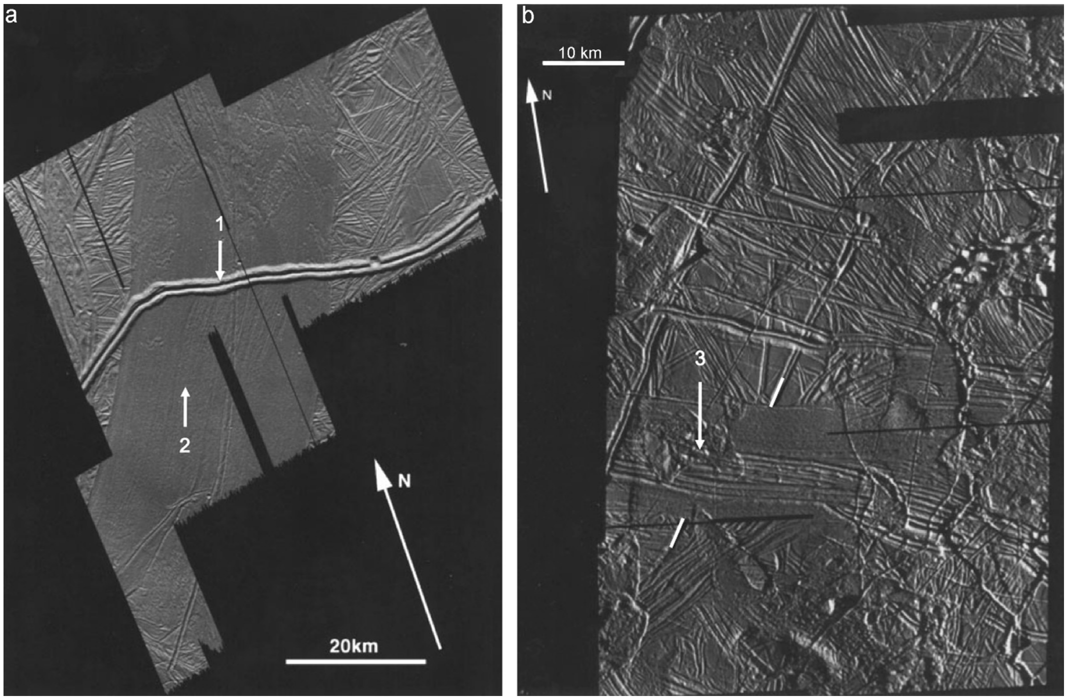

Fig. 1. a) A portion of Thynia Linea is shown as imaged by Galileo at 39 m/pixel resolution from the E17 orbit. Arrow 1 points to a prominent ridge, which is younger than the smooth dilational band of Thynia Linea (arrow 2). b) Galileo images at 32 m/pixel from orbit E11 show the complex geological history of Europa's surface. Arrow 3 points to a ridged band, which lies in the midst of a smooth band. The two bands may or may not have formed as part of the same dilational evolution of the surface. White lines on either edge of the band show piercing points for reconstruction purposes (cf. Tufts et al., 2000).

can extend 100 s of km in length. Evidence for the extensional nature of these bands comes from the fact that ridge terrain on either side of the band can be matched up with the removal of the band infill material in reconstructions (Schenk and McKinnon, 1989; Sullivan et al., 1998). This fact implies that band interiors are composed of new material relative to the surrounding terrain (Prockter et al., 2002). The interior structure of the bands can range from relatively smooth fine striae, aligned with the band's margins (Fig. 1b) or the more coarse structures (such as Ridged Bands), which resemble the edifices that comprise ridges (Fig. 1c).

Some dilational bands show evidence of raised flanks (see below), which implies that extension leading to the band exploited preexisting fractures in the crust. While the regional extensional stress needed for the dilational band may not necessarily be responsible for the initial failure of the surface nor participate in the ridge building process, this extension may be contemporaneous with daily diurnal tidal stresses, which participate in the ridge building process. Tufts et al. (2000) explored the interplay between regional extension and diurnal tidal process to define a morphological continuum of evolution from ridges to smooth dilational bands.

1.1. Tufts' Dilation Model

In Tufts' Dilation Model, ridges represent one end member of the formation continuum. In the model, diurnal tidal stresses work a fracture, slowly building ridges on its flanks. There is no regional dilation to affect this process (Fig. 2, case a). While Tufts et al. (2000) originally linked their model to Greenberg et al. (1998) ridge formation model, this is not a rigid constraint on Tufts' Dilation Model. In fact, any of the above ridge-formation models are valid with Tufts' Dilation Model as long as ridge building is mainly influenced by diurnal tidal stresses or motions.

Once the daily cycle of stress acting on a fracture experiences regional extension concurrent to the ridge building process, a dilational band will be formed. Its morphology will depend on the interplay between the ridge building process and the regional extension. This interplay depends on the "dilational quotient", which is defined as the ratio of the rate of the regional secular dilation to the cyclical diurnal tidal dilation. If the quotient is very low, ridges forms without much dilation. The formation of smooth bands is the other end member of Tufts' Dilation Model (high quotient), where dilation dominates over ridge growth. As long as the dilation quotient remains uniform over the timescale of band formation, a band with a smooth texture or fine striae will be formed (Fig. 2). However, the magnitude of the dilation quotient can affect the relief of the band infill material compared to the surrounding terrain. If the dilational quotient is low, the band is spreading out the ridge building process, leading to a smooth band whose infill terrain stands at the height of a typical ridge (Fig. 2, Case b). But if the dilational quotient is high, no ridge building can occur, leading to a smooth band whose infill terrain stands at the height of the background terrain or lower (Fig. 2, Case c).

More coarse dilational bands, such as ridged bands, may form from regional extension, which is nonuniform over the timescale of band formation. Ridged bands can form in Tufts' Dilation Model as a band dilates with episodes of no (or slow) secular dilation interspersed with times of high secular dilation. For example as shown in Fig. 3, a ridge may form along a crack during a period of no (or slow) secular dilation (a), but then rapid dilation can spread apart the ridge pair, creating a uniform floor (b) upon which, once dilation slows or ceases, a new ridge pair can form (c), until the next episode of rapid dilation. Thus, over time and cycles of slow and rapid dilation, a band of ridges can form (Fig. 3d).

Using Tufts' Dilational Model, examples of band formation on Europa can be described in terms of the processes of secular and tidal dilation. Fig. 4 shows the location of the roughly 10% of Europa's surface that has been mapped at about 250 m/pix resolution to study the geology on its surface. Within this region, the location of 10 examples of bands have been called out and insets of the bands themselves included. The formation of these bands can be described in the context of Tufts' Dilational Model.