Icarus 274 (2016) 297–313

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Fracturing and flow: Investigations on the formation of shallow water sills on Europa

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ARTICLE INFO

Article history:
Received 17 April 2015
Revised 30 December 2015
Accepted 5 January 2016
Available online 4 March 2016

Keywords:
Europa
Geophysics
Tectonics
Satellites
General

ABSTRACT

Double ridge tectonic features appear prominently and ubiquitously across the surface of Jupiter's icy moon Europa. Previous studies have interpreted flanking fractures observed along some of the ridges as indicators of stress resulting from the ridge loading and flexing of the ice shell above a shallow water body. Here, we investigate a shallow water sill emplacement process at a time when the shell is cooling and thickening and explore the conditions that would make such a system feasible on timescales of ridge formation. Results show that fracture initiation and transport of ocean water to shallow depths can realistically occur, although horizontal fracturing and sill lifetimes prove challenging. Finite element models demonstrate that mechanical layering or a fractured shell do not provide enough stress change to promote horizontal fracturing, but tidal forcing does result in a small amount of turn. Assuming it is possible for a shallow sill to form, a sill would convect internally and conduct heat out quickly, resulting in a short lifetime in comparison to an estimated flexure timeframe of 100 kyr suggested required for double ridge formation. Consideration of heat transfer and residence in the overlying ice, however, extends the flexure timeframe and multiple sill intrusions or replenishment with warm ocean water could prolong the effective sill lifetime. Though challenges still remain for sill formation at Europa, these analyses constrain the potential mechanisms for emplacement and indicate sills can act as viable options for supplying the heat needed for surface flexure. Further analyses and future missions to Europa will help to increase our understanding of these enigmatic processes.

1. Introduction

The jovian moon Europa sparks our curiosities with the promise of a vast, salty and thermally mixing ocean that may harbor life beneath its icy exterior (Vance and Goodman, 2009). Data returned by the Voyager and Galileo spacecrafts enabled the determination of the differentiation achieved within Europa. A vast water ocean topped with an icy shell overlies a rocky layer with a metallic core. Tectonic features cover the surface, suggesting a young and geologically active history. One prominent feature, the double ridge, is ubiquitous across Europa yet how it forms is still poorly constrained (Aydin, 2006; Prockter and Patterson, 2009). Here we explore a suggested double ridge formation mechanism and resulting implications for ice shell characteristics.

Composition and structural differences in Europa's rocky layer constrain the ice-water layer to between 105 and 160 km thick (Kuskov and Kronrod, 2005; Cammarano et al., 2006). Billings and Kattenhorn (2005) summarized model estimates for ice shell thickness based on thermal analyses, impact studies and mechanical calculations. Estimates for the total shell thickness ranged from ∼0.25 km (Tufts, 1998) to a few tens of kilometers (Schenk and McKinnon, 1989; Lucchitta and Soderblom, 1982; Rathbun et al., 1998; Sotin et al., 2004). Flexure models suggested an elastic thickness of the ice shell of ∼2 km (Williams and Greeley, 1998; Pappalardo, 1999).

Tectonic features cover Europa indicating a structurally active history that may have provided an avenue for deeper material to interact with the surface. Double ridge tectonic features appear prominently and ubiquitously across the surface (Prockter and Patterson, 2009; Kattenhorn and Hurford, 2009). A central trough, bordered by a ridge on each side, characterizes double ridges. The widths of double ridges range from about 200 m to more than 4 km and their lengths can extend up to around 1000 km (Greeley et al., 2000; Coulter et al., 2009). Although abundant, how ridges form remains unconstrained (Aydin, 2006; Prockter and Patterson, 2009). By increasing our understanding of possible ridge formation

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http://dx.doi.org/10.1016/j.icarus.2016.01.023
0019-1035/

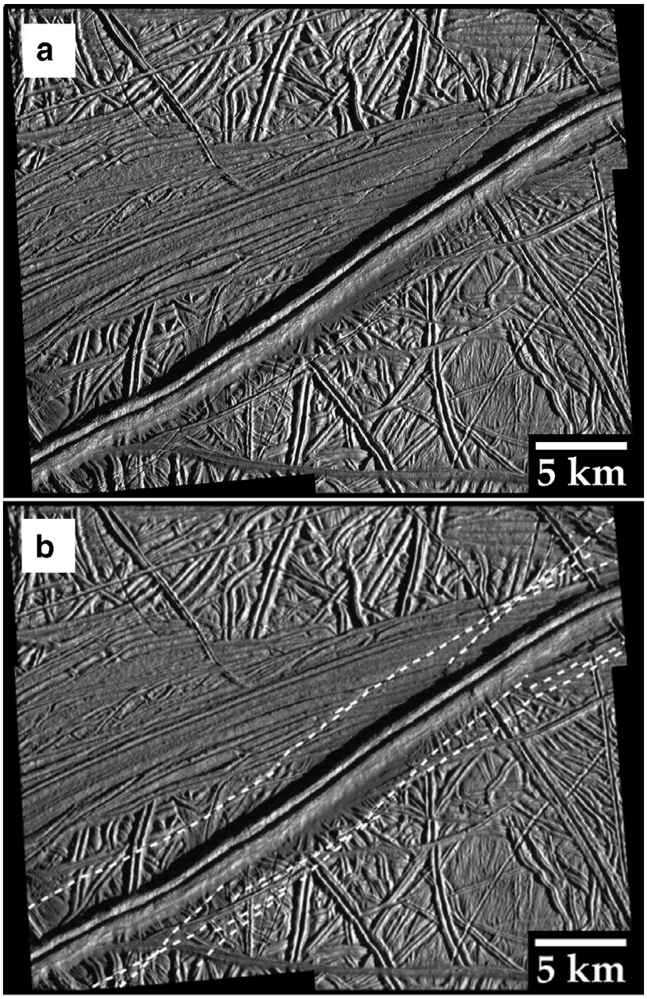

Fig. 1. (a, b) Image of the Androgeos Linea double ridge morphology on Europa's surface (14.7°N 273.4°W, E6ESBRTPLN02) shown together such that dotted lines in (b) indicate the locations of flanking, subparallel fractures, which are more easily viewed in (a).

processes, characterization of Europa's ice shell and ocean structures can occur.

Here, we explore how a shallow water body intrusion into the ice shell could occur beneath double ridges on Europa and contribute to flexure observed there. Two potentially diagnostic morphological features associated with some double ridges include subparallel flanking fractures (Greeley et al., 2004; Kattenhorn and Hurford, 2009) and marginal troughs (Hurford et al., 2005). The images presented in Fig. 1 of the double ridge, Androgeous Linea, show a prime example of flanking fractures though inadequate lighting does not allow discernment of the troughs. Hurford et al. (2005) profiled marginal troughs at many ridges using photoclinometry and the troughs do display similar shape to that shown in the ridge cross-section in Fig. 2. A study by Jones et al. (2008) characterized ridge flanking fractures across Europa's surface, although observations of these fractures require spatial resolutions smaller than about 200 m/pixel and current surface coverage at this resolution is sparse. Even though limited observations suggest that flanking fractures may not be present at all double ridges on Europa, the features can still provide crucial clues about how the ubiquitous double ridges form and evolve. Previous work has shown that the presence of marginal troughs and flanking fractures indicate flexure occurred in a generally thin elastic lithosphere, with a thickness estimated between a couple 100 m up to about 6 km (Billings and Kattenhorn, 2005; Hurford et al., 2005; Nimmo et al., 2003). As determined by Dombard et al, (2007, 2013), a thin elastic lithosphere of ~100 m–1 km requires a much higher heat flow of about 1 W/m^2 compared with the estimated heat flow for Europa of ~50 to 200 mW/m^2 (Pappalardo, 1999; Ruiz and Tejero, 1999, 2000). This discrepancy suggests the presence of a local, shallow heat source (cf. Dombard et al., 2007).

Several proposed ridge formation mechanisms employing subsurface liquid water associated with dikes, diapirs and/or frictional heating could provide a local subsurface thermal source and exhibit flanking fractures. Kadel et al. (1998) proposed ridge building by way of cryoclastic eruptions through a preexisting open fissure to the surface. Pappalardo and Coon (1996) suggested tidal forcing could squeeze material up through a crack, a model developed further by Greenberg et al. (1998) and Tufts et al. (2000). Fagents (2003) described the presence of volatiles or pressurization of a subsurface reservoir as a means to expel fluid on the surface. Dombard et al. (2007, 2013) also suggested a cryovolcanic mechanism but added formation of a water sill beneath the ridge. Sills form as fluid intrudes into the subsurface with a greater width, w, than height, l, resulting in an aspect ratio much greater than 1 ($w/l >> 1$). The sill may form a short third dimension, making a more circular shape when viewed from above, or long, forming a ribbon like intrusion. Conversely, a dike intrusion forms with a w/l aspect ratio $<<1$.

Additional ridge formation theories suggested a diapir mechanism (Head et al., 1999) or shear heating (Gaidos and Nimmo, 2000; Nimmo and Gaidos, 2002; Han and Showman, 2008) could cause ridges to rise up as a consequence of thermal expansion along a plane in the ductile region of the ice shell beneath a brittle region with a central preexisting crack. Most recently, another study by Johnston and Montési (2014) applied a simplified finite element model to investigate expansion of freezing water intrusions, both dikes and sills, in the shallow subsurface and their results suggested that expanding dike intrusions could form double ridge like morphology at the surface. The analyses of Dombard et al. (2013) concluded that, among these potential formation mechanisms for double ridges, only a shallow water sill intrusion ~1 to 2 km beneath the ridge could provide a thermal anomaly sufficient to account for the observation of flanking fractures associated with double ridges. Here, we explore if and how such a feature might form and evolve in Europa's icy shell.

2. Proposed sill emplacement process

Formation of a water sill at a shallow depth within Europa's ice shell would require several conditions. First, assuming the ice shell has thickened to at least several kilometers, a fracture would need to open to the ocean and enable water to move up to shallow depth. A build-up of stress that reaches a level greater than the strength of ice could initiate a fracture that would then either open a fracture at the surface for subsequent propagation down to the ocean (e.g. Lee et al., 2005), begin at the shell base and propagate upwards (e.g. Walker et al., 2014), or begin within the shell and propagate both up and downwards to the ocean (e.g. Manga and Wang, 2007). Stress buildup to initiate such a fracture could occur as Europa loses heat over time and the shell cools and thickens (Nimmo, 2004) and as tidal forces act on areas with high porosity (Lee et al., 2005). Once the ocean water reaches a shallow depth, a change in the direction of least compressive stress needs to occur to turn the preferred fracture propagation direction from vertical to horizontal for sill emplacement. Based on these required conditions, we propose a set of steps for sill emplacement, depicted in Fig. 3. We suggest that during a period of cooling and thickening, when Europa's ice shell reaches about 10 km thick, a fracture initiates at 1–2 km below the surface, where Nimmo (2004) predicted