Icarus 000 (2016) 1–9

Contents lists available at ScienceDirect

Icarus

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

Formation of lenticulae on Europa by saucer-shaped sills

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ARTICLE INFO

Article history:
Available online xxx

Keywords:
Chaos
Domes
Sills
Intrusions
Elastic flexure

ABSTRACT

Europa's surface contains numerous quasi-elliptical features called pits, domes, spots and small chaos. We propose that these features, collectively referred to as lenticulae, are the surface expression of saucer-shaped sills of liquid water in Europa's ice shell. In particular, the inclined sheets of water that surround a horizontal inner sill limit the lateral extent of intrusion, setting the lateral dimension of lenticulae. Furthermore, the inclined sheets disrupt the ice above the intrusion allowing the inner sill to thicken to produce the observed relief of lenticulae and to fracture the crust to form small chaos. Scaling relationships between sill depth and lateral extent imply that the hypothesized intrusions are, or were, 1–5 km below the surface. Liquid water is predicted to exist presently under pits and for a finite time under chaos and domes.

1. Introduction

Europa's surface is littered with approximately elliptical features ~10 km in diameter. They may have either negative (pits; Fig. 1a) or positive (domes; Fig. 1b) relief relative to their surroundings, they may have smooth surfaces (spots), and pre-existing terrain is sometimes broken into blocks (small chaos or micro chaos; Fig. 1c). Collectively these features are sometimes called lenticulae. Their similar sizes suggest that they may have a common origin and the different surface morphologies record different stages in the evolution of a single event within the ice shell (e.g., Pappalardo et al., 1998; Greenberg et al., 1999; Collins and Nimmo, 2009). Lenticulae and larger chaos features are abundant with large spatial variability in number density (Neish et al., 2012) and type (Culha and Manga, 2016), and they cover approximately 5% to 40% of the surface (Figueredo and Greeley, 2004; Riley et al., 2000). Lenticulae have attracted attention because their formation should provide insights into heat and mass transport processes within Europa's ice shell (e.g., Quick and Marsh, 2016), including possible liquid water transport from the underlying ocean to the surface and near-surface of the ice shell.

A variety of models for lenticulae formation have been proposed. Although an impact origin has been hypothesized (Cox et al., 2008), both the large number of lenticulae and their morphology compared to other impact features (e.g., Moore et al., 1998) suggest that lenticulae originate from geodynamic processes within the ice shell. Endogenic models range from those involving only solid-state processes such as thermal (e.g., Rathbun et al., 1998) and thermochemical (e.g., Han and Showman, 2005) convection in the ice shell, to processes involving liquid water produced within the ice shell (e.g., Collins et al., 2000; Sotin et al., 2002; Schmidt et al., 2011) or delivered from the ocean (e.g., Greenberg et al., 1999) that might form both lenticulae and larger chaos. The extent of resurfacing by lenticulae and chaos appears to have increased with time whereas tectonic resurfacing decreased with time, observations that Figueredo and Greeley (2004) attribute to a gradual thickening of the ice shell. Thickening promotes solid state convection (e.g., McKinnon, 1999), and also increases overpressure in the ocean (e.g., Manga and Wang, 2007), two processes that have been invoked to originate lenticulae.

The large relief of lenticulae, w_{max}~10^2 m (Greenberg et al., 2003; Schenk and McKinnon 2001; Singer et al., 2010), provides additional constraints on their origin. For isostatically compensated density anomalies $\Delta\rho$ of vertical thickness L, $w_{max} = \Delta\rho L/\rho$; vertical density anomalies as large as 10 km require a density anomaly of 1% to obtain w_{max} ~10^2 m and hence a temperature anomaly of 50 K, much larger than those produced by stagnant lid isochemical convection (McKinnon, 1999), and elastic flexure of cold near-surface ice will further reduce relief (e.g., Nimmo and Manga, 2002). The magnitude of relief is most easily explained if liquid water is present because of the large density difference between liquid water and water ice. The reorientation of blocks within large chaos is also most easily explained if liquid water or some other low viscosity material directly underlies the blocks (Collins et al., 2000) and the same may be true for small chaos. All these models have been reviewed and assessed in many

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http://dx.doi.org/10.1016/j.icarus.2016.10.009
0019-1035/

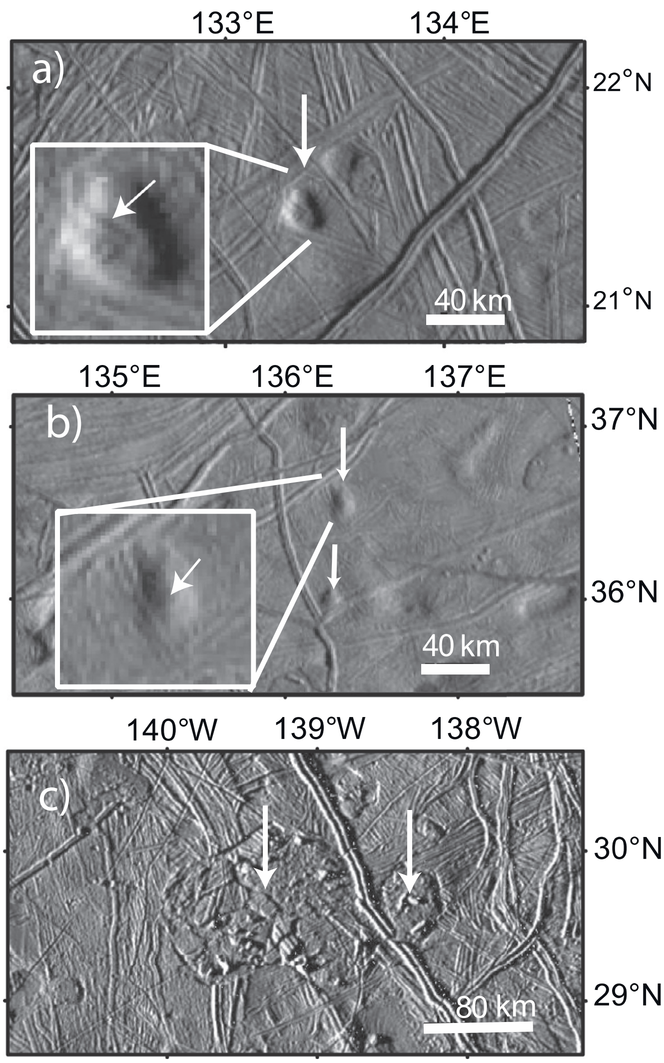

Fig. 1. Examples of a) pits, b) a dome, and c) small chaos from Galileo SSI images and modified from Culha and Manga (2016). Illumination directions from lower right, right, and lower left, respectively.

studies including Collins and Nimmo (2009) and more recently by Culha and Manga (2016) – at present, it remains uncertain what set of processes can explain the observations, although liquid water is likely to play a role. The key challenges for any successful model are to explain 1) the lateral dimension of lenticulae, $\sim 10^1$ km, 2) the large relief, 10^2 m (e.g., Schenk and Pappalardo, 2004), and 3) how pits, domes and small chaos might share a common origin (e.g., Pappalardo et al., 1998; Greenberg et al., 1999) if, in fact, they do.

Here we consider a mechanism for creating lenticulae through the formation of saucer-shaped sills and the subsequent freezing of water in the sill. Sills and dikes have also been implicated for the formation of ridges on Europa (Dombard et al., 2013; Johnston and Montesi, 2014; Craft et al., 2016). Saucer-shaped sills have two main regions, illustrated in Fig. 2a: the horizontal inner sill, and a surrounding steeply dipping inclined sheet. The inner sill follows bedding and the inclined sheet crosses bedding. The dip of inclined sheets is 20–60° (Polteau et al., 2008). There is sometimes an outer sill that follows the bedding, but at a more shallow depth than the inner sill. Saucer-shaped intrusions have been imaged seismically on Earth in sedimentary basins (e.g., Hansen and Cartwright, 2006) and exposed in outcrops (e.g., Chevallier and Woodford, 1999). The intruding material can be magma or injected sediment (e.g., Huuse and Mickelson, 2004). They have been made and studied in the lab (e.g., Galland et al., 2009). On Earth, saucer-shaped intrusions have been implicated in caldera formation and collapse (Andersson et al., 2013). The inclined sheets may feed dikes (e.g., Muirhead et al., 2014) and surface eruptions (Polteau et al., 2008).

2. Mechanics of intrusion

There are several possible sources of the water in sills, including melting above a rising diapir (e.g., Schmidt et al., 2011), water expelled from other bodies of liquid water in the ice shell (Fagents, 2003), or from an overpressured ocean under the ice shell (Manga and Wang, 2007). The relief of $\sim 10^2$ m for pits and domes (Schenk and McKinnon, 2001; Fagents, 2003; Greenberg et al., 2003) implies a vertical thickness of water bodies of $\sim 10^2$ m if the weight is entirely supported elastically and $\sim 10^3$ m if the water is close to isostatically compensated. Combined with the lateral extent of ~ 10 km, the dimensions of lenticulae thus require large volumes of water. Nimmo and Giese (2005) highlight the challenge of creating enough water in the cold ice above rising diapirs of warm ice. We thus assume for the remainder of the analysis, as have others (e.g., Craft et al., 2016), that the water originates in a large, deep reservoir (the ocean) but note that any process that can produce enough water might give rise to the intrusion dynamics we consider next.

We consider the evolution of a sill from 1) its initiation as a crack to 2) a laccolith in which intrusion is governed by the flexure of the overlying ice, culminating in 3) the disruption of this ice and 4) the final solidification of the water in the intrusion. The distinctions between these different stages are determined by the time scales over which key relevant processes operate and how thermophysical properties evolve in space and time. During the first stage when the sill is short in length relative to its depth the intrusion fractures at its front and propagates as if in an infinite medium (the crack stage). When the sill has spread far enough that the stress is affected by the deformation of Europa's surface, the free surface modulates the stress and the propagation of the sill (the laccolith stage). In particular, during the laccolith stage, the direction of maximum tensile stress rotates at the tip of the sill where fracturing occurs. The rotation of the stress causes the fracture to propagate upward, forming the inclined sheets. In the next sections we quantify the dimensions and processes that govern the initial intrusion, the transition from a horizontal sill to a saucer-shaped sill, and the consequences of freezing of water in the sills. The different stages are finally summarized in a cartoon illustrating the different stages of the model (Fig. 3).

2.1. Initial intrusion

Water rising vertically in a dike is arrested by either buoyancy or rheological contrasts that then favor horizontal spreading as a sill (e.g., Gudmundsson, 2011). There are two stages of intrusion: the "crack" stage (Fig. 3b) and the "laccolith" stage (Fig. 3c) with the distinction being whether the free-surface affects the stresses and the propagation of the intrusion. At the initiation of the horizontal crack its depth d is large compared to its radius R, $d \gg R$, and the crack has an elliptical shape with thickness $2w_c$ (Lister and Kerr, 1991),

$$w_c(r) = \frac{4\Delta P_e R\left(1-\nu^2\right)}{\pi E}\left(1-\left(\frac{r}{R}\right)^2\right)^{1/2}, \tag{1}$$

where r indicates the radial position, ΔP_e is the overpressure in the crack, and ν and E are the Poisson ratio and Young's modulus, respectively, of ice. As the crack grows, it maintains this shape until the free-surface affects the stresses and deformation (Pollard and Holzhausen, 1979; Fialko, 2001). The sill then becomes a laccolith whose thickness is now governed by the ability to flex