UC Berkeley

UC Berkeley Previously Published Works

Title

Formation of lenticulae on Europa by saucer-shaped sills

Permalink

<https://escholarship.org/uc/item/21b207sv>

Authors

Manga, M
Michaut, C

Publication Date

2017-04-01

DOI

10.1016/j.icarus.2016.10.009

Peer reviewed

Formation of lenticulae on Europa by saucer-shaped sills

Author links open overlay panel [Michael Manga](#)^a [Chloé Michaut](#)^b

Show more

<https://doi.org/10.1016/j.icarus.2016.10.009> Get rights and content

Highlights

-

Saucer shaped sills may create pits, domes, spots and small chaos on Europa.

-

Sills are predicted to be 1–5 km below Europa's surface.

-

Liquid water is predicted to exist presently under pits, and some domes and small chaos.

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.

- [**Previous** article in issue](#)
- [**Next** article in issue](#)

Keywords

Chaos

Domes

Sills

Intrusions

Elastic flexure

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.

1. [Download high-res image \(874KB\)](#)

2. [Download full-size image](#)

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.

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, $w_{max} \sim 10^2$ 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 $w_{max} \sim 10^2$ 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 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](#)).

1. [Download high-res image \(177KB\)](#)
2. [Download full-size image](#)

Fig. 2. Schematic cross-sections of the a) saucer-shaped sill identifying the horizontal inner sill and inclined sheets, and the b) crack and c) laccolith stage of intrusion.

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](#)).

1. [Download high-res image \(540KB\)](#)
2. [Download full-size image](#)

Fig. 3. Schematic illustration of the evolution of a saucer-shaped sill and its surface expression to create pits, domes or small chaos. The upward-pointing parts of the frozen sill represent intrusions produced by freezing and lead to surface disruption, or [extrusion](#) to make spots. Not to scale.

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](#)),

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

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 the overlying elastic layer of ice with thickness d (e.g., [Goult and Schofield, 2008](#))

$$(2) w_l(r) = 3\Delta P_e R^4 (1-\nu^2) 16 E d^3 (1-(r/R)^2)^2,$$

where w_l is the vertical uplift and we note that $w_{l0} = 3\Delta P_e R^4 (1-\nu^2) 16 E d^3$ is the thickness at $r = 0$. We assume that, over the timescale of inner sill propagation, the sill is at shallow enough depths in the elastic sheet that deformation is dominated by flexure of the overlying ice rather than the underlying ice. The pressure required to bend the overlying ice is given by

$$(3) \Delta P_e = E d^3 12 (1-\nu^2) \nabla^2 w_l.$$

Pressure decreases rapidly with increasing R , scaling with $\sim E d^3 w_l / 12 (1-\nu^2) R^4$ ([Michaut, 2011](#), [Thorey and Michaut, 2014](#)). We assume the layer of ice below the intrusion remains deformed as it was during the crack stage with a downward vertical displacement w_c .

In the laccolith stage, the bending of the overlying ice rotates the stress at the tip of the spreading intrusion and a critical transition occurs: it becomes easier for the crack to propagate towards the surface than to continue its horizontal propagation. Inclined sheets are expected to form at the sill front at the beginning of the laccolith stage, because in this stage the horizontal radial stress in the overlying elastic layer given by

$$(4) \sigma_{rr}(r) = E d^2 (1-\nu^2) (\partial^2 w_l / \partial r^2 + \nu r \partial w_l / \partial r),$$

is maximum in tension at the sill front ([Turcotte and Schubert, 1982](#)), and decreases as R increases. Replacing for w_l given by [Eq. \(2\)](#) in [Eq. \(4\)](#) we obtain

$$(5) \sigma_{rr}(R) = 4 E d (1-\nu^2) w_{l0} / R^2.$$

In the laccolith stage, under constant influx conditions, the maximum flow thickness w_{l0} increases with radius R following a power-law with an exponent that varies with the front

geometry and flow dynamics but is always less than 2. For a [viscous flow](#), the exponent relating the maximum thickness to the radius is close to one ([Michaut, 2011](#); [Lister et al., 2013](#)); it is large but still less than 2 in the case of a [turbulent flow](#) ([Michaut and Manga, 2014](#)). As a result, the radial stress given by (5) in the overlying layer decreases with radius R and fracturing of the overlying layer and formation of inclined sheets should occur at the transition between the crack stage and the laccolith stage, when the radial tensile stress is a maximum.

In order to determine the radius of the sill at which horizontal intrusion is no longer favored we determine the conditions at which spreading changes from the crack to the laccolith stage – which is when radial tensional stresses at the intrusion's tip will be greatest. As the shape and spreading change from that of a crack ([Eq. 1](#)) to that of a laccolith ([Eq. 2](#)), at a given radius R , the volume and pressure do not change

$$(6) \int_0^R 2\pi r w_c(r) dr = \int_0^R 2\pi r w_l(r) dr,$$

which, using [Eqs. \(1\)](#) and [\(2\)](#) for the intrusion thicknesses and integrating, gives

$$(7) 8\Delta P_e(1-\nu^2)E[-13(R^2-r^2)^{3/2}]_0^R = 3\pi\Delta P_e R^4(1-\nu^2)8Ed^3[r^2-r^4-2R^2+r^6R^4]_0^R.$$

Solving [Eq. \(7\)](#) and eliminating ΔP_e we obtain the radius R with the largest horizontal radial stresses in the overlying ice

$$R^3 = 128d^3/3\pi,$$

and hence

$$(8) R \approx 2.4d.$$

At this radius, the inclined sheets shown in [Fig. 2a](#) will form. The time scale for the intrusion to reach this radius is 10^3 – 10^4 s ([Michaut and Manga, 2014](#)).

Numerical simulations (e.g., [Malthe-Sorensen et al., 2004](#), [Fialko, 2001](#)), lab experiments (e.g., [Pollard and Johnson, 1973](#), [Galland et al., 2006](#), [Mathieu et al., 2008](#)) and observations on Earth (e.g., [Polteau, 2008](#)) are consistent with both an approximately linear scaling between R and d and the constant of proportionality in [Eq. \(8\)](#).

We can also evaluate the thickness of the intrusion at the time the inclined sheets initiate. Overpressures in an ocean produced by thickening of the ice shell can exceed 10^5 Pa ([Manga and Wang, 2007](#)). [Water pressure](#) in other reservoirs is unlikely to reach overpressures much greater than the [tensile strength](#) of ice, 1 – 3×10^6 Pa ([Schulson, 2006](#)). The overpressure in the source is then reduced by the overpressure necessary to compensate for the negative buoyancy of water over its ascent height, and hence $\Delta P_e < 10^6$ Pa. Using $E = 10^9$ Pa ([Nimmo, 2004](#)), $\nu = 0.33$ ([Shulson, 2001](#)), and $\Delta P_e = 10^5$ to 10^6 Pa, $2.3 \text{ m} < w_o < 23 \text{ m}$ for an intrusion with $R = 10 \text{ km}$. This thickness is too small to explain the $\sim 10^2 \text{ m}$ relief of lenticulae: additional thickening processes must occur.

If the radii of lenticulae do in fact reflect the radius of saucer-shaped sills governed by the scaling in [Eq. \(8\)](#), then typical diameters of 5–25 km (e.g., [Singer et al., 2010](#), [Culha and Manga, 2016](#)) imply depths of 1–5 km.

2.2. Intrusion thickening (domes)

Once the inclined sheets form, the overlying ice is fractured, and its elastic thickness decreases from d to a new value $\delta < d$. Bending of the overlying layer is facilitated ([Eq. 2](#)) and creates a maximum positive vertical relief of

$$(9) W_{\text{dome}} = \Delta P_e R^4 / (3(1-\nu^2)16E\delta^3).$$

Using the same parameters as in [section 2.1 \(Table 1\)](#), W_{dome} exceeds 100 m for $\delta < 1.2$ km.

Table 1. Variables and values.

Quantity	Symbol	Value	Reference
Young's modulus	E	10^9 Pa	Nimmo (2004)
poisson ratio	ν	0.33	Schulson (2001)
tensile strength		1–3 MPa	Schulson (2006)
water compressibility	β	$5 \times 10^{-10} \text{ Pa}^{-1}$	
temperature	T		
thermal conductivity	k	$567/T \text{ W m}^{-1} \text{ K}^{-1}$	Klinger (1980)
viscosity ice	η	equation (15)	Barr and Showman (2009)
sill radius	R		
sill depth	d		
flexural rigidity	D		
overpressure in sill	ΔP_e		
density water	ρ_w	1000 kg m^{-3}	
density ice	ρ_i	910 kg m^{-3}	

If the overlying ice is fractured to the point that the ice no longer has any elastic strength ($\delta \rightarrow 0$), the overpressure in the source is compensated by the weight of the water and leads to a positive relief

$$(10) w_{\text{dome}} = \Delta P_e \rho_w g$$

which gives a positive relief of 70 m to 700 m for the assumed range of overpressures.

At this stage in the evolution of the water body, [Walker and Schmidt \(2015\)](#) showed that the overlying ice may be broken into multiple blocks, with collapse more likely and widespread for greater R .

In order to create the relief given by [Eqs. \(9\)](#) or [\(10\)](#), water must continue to flow into the intrusion through the feeder dike before the dike freezes. For expected dike widths of 0.1–1 m, the freezing time is 10^6 – 10^8 s ([Appendix A](#)). Over this time period, [Michaut and Manga \(2014\)](#) show that sufficient water can flow into the intrusion for its thickness to reach values limited by either [Eqs. \(9\)](#) or [\(10\)](#).

2.3. Compensation of water weight (domes and pits)

Liquid water in the intrusion will solidify over a time that scales with its thickness squared, with only a minor dependence on the depth of intrusion for reasonable values (Figure 7 in [Michaut and Manga, 2014](#)). An intrusion 1 km thick takes about 5×10^{12} s to solidify.

If the overlying ice is broken, the weight of the water in the sill can be supported by the elastic flexure of the ice underneath the sill. The surface relief for elastically supported intrusions is determined by both the amount of water intruded and the flexural deformation of the underlying ice. We approximate the volume of intruded water as

$$(11) V = \pi R^2 w_{\text{dome}},$$

where R is the intrusion radius and we assume the overlying ice has been disrupted so that w_{dome} is given by [Eq. \(9\)](#). By assuming [\(10\)](#) we neglect the water stored by downward displacement of the underlying ice ([Michaut and Manga, 2014](#)).

The flexure h of the ice is computed from the flexure equation,

$$(12a) D \nabla^4 h = (p_w - p_i) g h - p_w g h(R_f) \text{ for } 0 < r < R_f$$

and

$$(12b) D \nabla^4 h = -p_i g h - p_w g h(R_f) \text{ for } R_f < r < R_i$$

for a negative relief $h(R_i)$ over a radius $R_i < R$, for a pit, or from

$$(13) D \nabla^4 h = (p_w - p_i) g h + p_w g w_f \text{ for } 0 < r < R$$

for a final positive relief w_f at the surface over the entire sill radius R . Both sets of equations are subject to the condition that the volume V of water is conserved;

and $D = E d^3 / 12(1 - \nu^2)$ is the flexural rigidity of the underlying ice with elastic thickness d . [Eqs. \(11–13\)](#) assume small [strains](#).

[Fig. 4](#) shows the surface relief as a function of elastic thickness for initial intrusion radii of 5 and 10 km and overpressure of 5×10^5 Pa, corresponding to a dome thickness of 378 m, [Eq. \(10\)](#). Negative relief of ~ 100 m requires thin elastic layers.

1. [Download high-res image \(425KB\)](#)
2. [Download full-size image](#)

Fig. 4. Topography above the center of the intrusion as a function of the thickness of the elastic layer d underlying the intrusion for two initial radii (5 or 10 km) of an assumed cylindrical intrusion. The inset figures show cross-sections through the ice shell to

illustrate the shape of the elastically supported water body and surface deformation for the two elastic thicknesses shown with the blue circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

If the ice underlying the intrusion is warm enough, the ice will not be able to support the weight of the intrusion by elastic flexure. Elastic support is possible provided the [relaxation time](#) of the ice is longer than the freezing time. Assuming a Maxwell viscoelastic model, stresses decay exponentially at a rate that scales with

$$(14) \tau_{\text{relax}} = \eta(T) E^{-1}$$

where T is the ice temperature, and we use a commonly adopted formulation for viscosity η

$$(15) \eta = \eta_0 \exp[A(T_m T - 1)]$$

with $A = 26.4$, $\eta_0 = 10^{14}$ Pas ([Barr and Showman, 2009](#)) and T_m is the melting temperature of ice. For the temperature of the ice shell we assume that a conductive lid with [thermal conductivity](#) $k = 567/T$ ([Klinger, 1980](#)) overlies a convecting [isothermal layer](#) with temperature 250 K ([Nimmo and Manga, 2002](#)). We use a [surface temperature](#) of 110 K. [Fig. 5](#) shows the depth below which the relaxation time (before intrusion) is less than freezing times between 10^{12} and 3×10^{13} s. These times and the assumed rheological parameters permit elastic support in roughly the upper half of the conductive part of the ice shell. This depth constraint, combined with an intrusion depth of 1–5 km inferred from the saucer-shaped sill scaling, requires that the conductive part of the ice shell is greater than 10 km thick if intrusions at depths of 5 km (the upper end of the depth range) are to be supported elastically. The total ice shell thickness, chosen as 15 km for illustrative purposes in [Fig. 5](#), does not affect the inferred thickness of the conductive part of the ice shell. We note that there is considerable uncertainty in both the viscosity and temperature structure of the ice shell. However, intrusion occurs in the conductive portion of the ice shell where the temperature distribution is much less uncertain. As relaxation time is proportional to viscosity, the two blue curves in [Fig. 5](#) provide a sense of how much the thickness of elastic layers change for a viscosity difference of a factor of 30, with elastic thickness increasing as viscosity increases. We have neglected the effects of downward conduction of heat from the intrusion in thinning the underlying elastic layer of ice because cooling times scale with thickness squared and the intrusion is a few times thinner than the conductive portion of the ice shell.

1. [Download high-res image \(172KB\)](#)
2. [Download full-size image](#)

Fig. 5. Bounds on the depth at which intrusions are expected to form (grey region), as a function of the conductive layer thickness and assuming the saucer-shaped scaling in [Eq. \(7\)](#) applies for lenticulae 5–25 km in diameter. The two blue curves show the depth above which ice will behave elastically and support the weight of the sill prior to freezing. The yellow line shows the deepest a sill could intrude and disrupt the overlying, rather than underlying, ice. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

If the underlying ice is too warm to support the water weight elastically, the intrusion should sink through the ice as a diapir.

2.4. Freezing (domes, spots and chaos)

If the water was sourced from an ocean under the ice shell so that there is a net addition of mass locally into the ice shell (rather than only vertical redistribution within the ice shell), and if part of the weight of the water was supported by elastic flexure of the ice shell, the volume expansion of the water as it freezes will raise the surface – making domes. The calculation for surface deformation in [Michaut and Manga \(2014\)](#) applies. If the water weight was isostatically compensated, freezing will lead to near-zero surface topography. Domes and chaos underlain by frozen intrusions will be

supported by the elastic strength of the ice shell, though on $> 10^6$ year timescales, only the upper third of the conductive part of the ice shell will behave elastically.

The pressure of liquid water trapped in the sill will increase as it freezes (e.g., [Fagents, 2003](#)). Overpressures become sufficient to create additional cracks, $> 10^6$ Pa, possibly to move blocks of ice, and allow liquid water to flow to the surface – processes that collectively disrupt the surface. Overpressure may drop to zero after every new episode of crack formation, but overpressures sufficient to create new cracks will occur repeatedly as the water freezes ([Appendix B](#)), providing opportunities to create new fractures and blocks. The progressive inward migration of freezing and hence decreasing radius of the region with liquid water, will lead to failure at progressively smaller radial distances from the center of the intrusion.

Overpressures in the freezing intrusions sufficient to squeeze liquid water onto the surface may flood the surface to create the smooth surface of spots or the smooth, dark surfaces seen adjacent to some lenticulae (e.g., [Fagents, 2003](#)). The low [albedo](#) of spots may arise from differences in [grain size](#) or composition, though the spatial correlation of low-albedo and non-ice materials suggests compositional differences, plausibly hydrated salts (e.g., [McCord et al., 1999](#)). If spots are produced by water in sills being extruded onto the surface, then the water in sills is likely salty, though this does not distinguish between water generated within the ice shell (e.g., [Head and Pappalardo, 1999](#)) or water from the ocean.

3. Discussion

The saucer-shaped sill model addresses two challenges with previous models for lenticulae formed by intrusions. First, the formation of inclined sheets provides a scale for the lateral extent of intrusion. In particular, we predict a (possibly testable) relationship between the depth of intrusion and the lateral dimension of lenticulae. Previous explanations for the lateral arrest of intrusions invoked the [fracture toughness](#) of ice ([Michaut and Manga, 2014](#), [Craft et al., 2016](#)). Second, the inclined sheets may disrupt the overlying ice, a layer that would otherwise have an elastic thickness too great to permit large surface deformation, allowing small chaos to form and large $\sim 10^2$ m relief to develop ([section 2.2](#)).

Any model for lenticulae should explain their lateral dimensions and relief. Here we briefly summarize observations, and how our model can or cannot explain the observations. We note that observations are based on mapping a small fraction of Europa's surface and hence that mapped and reported attributes of lenticulae may not be representative.

(1)

Pits and domes have similar sizes (but pits have smaller mean radii)

Based on the similar dimensions of domes, pits, spots and small chaos, it is reasonable to assume they may share a common origin (e.g., [Pappalardo et al., 1998](#), [Greenberg et al., 1999](#)) hence our attempt to relate all features to different stages in the evolution of one event: intrusion and then solidification of liquid water. The scaling relationship, [Eq. \(8\)](#), makes the testable prediction that the inner sill should be 1–5 km below Europa's surface, given the diameters of pits, domes and small chaos of 5 to 25 km ([Culha and Manga, 2016](#)). Large chaos, many 10 s of km across, such as Thera Macula and Conamara, may have a different origin although they have been also proposed to originate from large laccoliths of warm or slushy ice (e.g., [Mevel and Mercier, 2007](#)).

Owing to the downward flexure of ice underneath the intrusion, the lateral extent of the intrusion decreases and its thickness increases. To create negative relief, the intrusion's lateral extent decreases a few tens of percent ([Fig. 4](#)). Pits do in fact have smaller mean diameters, 6.6 ± 2.8 km, than domes, 9.5 ± 5.5 km ([Culha and Manga, 2016](#)).

(2)

Domes are more numerous than pits

Once the intrusion has frozen, provided the water weight was not isostatically compensated, positive relief will be preserved from a combination of the water added into the ice shell and its expansion after it freezes. Pits are only expected to form if the underlying ice has a thin elastic thickness and while the intrusion is liquid ([Fig. 4](#)). If the intrusion model is correct, the implication of the much greater number of domes and small chaos than pits ([Culha and Manga, 2016](#)) is that the ice has a large enough elastic thickness to support the weight of most intrusions, greater than 10^2 m ([Michaut and Manga, 2014](#)).

(3)

Pits are clustered in space

Of all the classes of lenticulae, pits are the only features with a statistically significant clustering, occurring in only a few locations ([Culha and Manga, 2016](#)). One interpretation of this observation, if robust given the limited fraction of the surface that has been mapped, is that there are spatial variations in properties of the ice shell that allow pits to form. In our model, this would be a thin enough

lithosphere to allow downward flexure or even sinking and water diapirs ([Michaut and Manga, 2014](#)). That is, features that evolve into pits form where the [heat flow](#) is high and the lithosphere is thin. Our model requires that liquid water is present beneath pits and hence that pits are geologically young (younger than the freezing time of 10^{12} – 10^{13} s) and hence that the thin lithosphere and high heat flow would be current conditions. We speculate that regionally thinned lithosphere might be a consequence of repeated intrusions that locally warm the ice shell.

Large-scale spatial variations of ~ 1 – 2 km in the thickness of the lithosphere can arise from tidal dissipation within the ice shell ([Tobie et al., 2003](#)). The two regions with pits at about -90° W, 40° S and -230° W, 40° N ([Culha and Manga, 2016](#)) do in fact correspond approximately to two of the four regions with the thinnest predicted lithosphere ([Tobie et al., 2003](#)). However, we strongly caution against over-interpretation because of the small fraction of Europa's surface that has been mapped.

(4)

Small chaos are larger than other lenticulae

Large water bodies allow the overlying ice to more readily break apart ([Walker and Schmidt, 2015](#)). The saucer-shaped sill model predicts that larger lenticulae have deeper intrusions, which in turn would lead to larger blocks and more pronounced disruption ([Collins et al., 2000](#)). Large chaos regions such as Thera Macula and Conamara may have a fundamentally different origin than small or micro chaos, or may be produced by multiple intrusions. Saucer-shaped sills on Earth are clustered and form sill complexes (e.g., [Bell and Butcher, 2002](#), [Coetzee and Kisters, 2016](#)); large chaos may be the surface expression of a large number of smaller intrusions that collectively disrupt a large surface area.

4. Hypothesis tests

The implied evolutionary sequence summarized in [Fig. 5](#) has liquid water present under all features at some point in their history. However, all pits are predicted to be underlain by liquid water at present. Ice penetrating radar should be able to identify the water-ice interface at the predicted depths provided that the ice is not too attenuating ([Blankenship et al., 2009](#)). The absence of liquid-filled lenses underneath pits would rule out the model. Using radar to identify solidified intrusions underneath uplifted features,

both the horizontal inner sills and inclined sheets, would require [dielectric property](#) differences between the ice in the solidified intrusion and its surroundings. The shear failure that accompanies the formation of inclined sheets will produce Europaquakes whose waves could be used for imaging if recorded by a [seismometer](#) on a lander. If failure propagates from the intrusion to the near-surface, a distance of ~ 1 km, seismic events should be energetic enough to exceed [background noise](#) ([Lee et al., 2003](#)). [Seismic reflections](#) of waves from local Europaquakes (possibly induced by tidal deformation, analogous to moonquakes) from the surface of water lenses might also be imaged with high frequency or broadband instruments ([Pappalardo et al., 2013](#)).

5. Summary

The horizontal intrusion of water within the ice shell will cause fractures to extend towards the surface once the radial extent of the intrusion reaches ~ 2.4 times its depth. The transition, [Eq. \(8\)](#), occurs when the stresses at the tip of the horizontally spreading sill are both at their maximum values and have rotated so that it becomes easier for cracks to propagate to the surface. The formation of inclined faults may thus govern the lateral extent of lenticulae. At the same time, inclined faults disrupt the overlying ice, allowing the intrusion to thicken, without further lateral spreading, and lift up the surface producing the observed relief of domes and chaos. On time scales much longer than intrusion times, but prior to solidification, if the elastic thickness of the underlying ice is thin enough, the weight of the water may allow sufficient downward flexure of the underlying ice to produce pits. This model predicts that pits, but only some domes and small chaos, are currently underlain by liquid water.

Acknowledgements

The authors thank the editor and two reviewers for detailed and constructive comments. The authors thank IPGP for hosting a visit by MM to Paris. Work supported by PNP/INSU (CM) and NSF (MM).

Appendix A. Timescale for the dike to remain open and transmit water to the sill

The width of the [dike](#) supplying water to the sill is governed by the balance of [elastic deformation](#) of the ice surrounding the dike and [overpressure](#) in the water. Using the scalings in [Rubin \(1995\)](#), and overpressures of $5 \times 10^4 - 5 \times 10^5$ Pa ([Manga and Wang, 2007](#)), the dike width will likely be in the range of 0.1 to 1 m ([Michaut and Manga,](#)

2014). [Craft et al. \(2016\)](#) apply similar physics to infer fracture widths, but obtain 10–100 m by invoking much larger stress differences. Our smaller value is based on assuming that the deviatoric stress at the bottom of the ice shell will have relaxed by viscous deformation over the long time scales that govern [thermal evolution](#) of the ice shell ([Nimmo, 2004](#), [Rudolph and Manga, 2009](#)).

We assume that the dike remains open until cooling and solidification close the dike. Using the scaling in [Rubin \(1993\)](#), this time scale is $4 \times 10^5 - 4 \times 10^7$ s ([Michaut and Manga, 2014](#)). On this time scale most of the part of the ice shell through which heat is transferred by conduction will behave elastically.

Appendix B. Solidification and further disruption of the ice shell by freezing

When water freezes, its density decreases 9%. The consequent volume expansion in an enclosed body of water will pressurize the remaining, unfrozen water. While the sill remains connected to its water source the pressure change will be small if the water source is large (e.g., an ocean). After the sill is intruded, and the connection to its source seals, e.g., by some combination of solidification and viscous deformation of the ice around the feeder [dike](#), large pressures will develop in the sill as it freezes.

The change in volume upon freezing will be accommodated by compression of the remaining water, which increases pressure, and [elastic deformation](#) of the surrounding ice, which relieves some of this pressure. The [overpressure](#) in the water creates stresses around the sill that, as we show next, are large enough to create fractures and disrupt the overlying ice.

The change in volume ΔV of a sill with volume V is

$$(B1) \Delta V = [f(p_w/p_i - 1) - \beta \Delta P] V$$

where f is the fraction of the sill that freezes, β is the compressibility of water, and ΔP is the increase in pressure in the remaining water. The first and second terms of [Eq. \(B1\)](#) account for the volume expansion of ice and the compression of water, respectively. The increase of P will produce elastic deformation of the surrounding ice; the solution of [Eshelby \(1957\)](#) for an oblate ellipsoidal cavity with radius R_0 and thickness w_0 embedded in a spatially infinite [elastic medium](#), in the limit of $R_0 \gg w_0$ is ([Amoruso and Crescentini, 2009](#))

$$(B2) \Delta V = V \Delta P (1 - 2\nu) E [4R_0(1 - \nu^2)\pi w_0(1 - 2\nu) - 3] \approx 4V \Delta P R_0(1 - \nu^2)\pi E w_0.$$

Equating the volume changes in [\(B1\)](#) and [\(B2\)](#) we obtain a relationship between the fraction of the sill that solidifies, its geometry, and the pressure change,

$$(B3) f = \rho_i p_w - \rho_i [\beta \Delta P + 4 \Delta P R_0(1 - \nu^2)\pi E w_0].$$

The maximum [tensile stress](#) generated in the overpressured sill is ([Gudmundsson, 2011](#), chapter 6)

$$\sigma_{\max} = \Delta P [4R_0 w_0 - 1].$$

If $\sigma_{\max}$ exceeds the [tensile strength](#) of ice, about 10^6 Pa ([Petrovic, 2003](#), [Schulson, 2006](#), [Litwin et al., 2012](#)), then fractures will form and disrupt the ice shell.

For $R_0 w_0 \gg 1$, failure will occur if

$$(B_4) f_{\text{fail}} > (1 - \nu^2) \pi E (\rho_w / \rho_i - 1) \sigma_{\max} \approx 3 \times 10^{-3}.$$

This solution ([B4](#)) neglects the effects of the finite thickness of the elastic layer, which would lower the overpressure generated by freezing and increase the value of f needed to disrupt the ice shell. Regardless, only small amounts of freezing are needed to create fractures in the surrounding ice, and this type of disruption should occur repeatedly as the entire sill freezes.

References

[Anoruso and Crescentini, 2009](#)

A. Anoruso, L. Crescentini **shape and volume change of pressurized ellipsoidal cavities from deformation and seismic data**

J. Geophys. Res., 114 (2009), p. B02210, [10.1029/2008JB005946](#)

[Andersson et al., 2013](#)

M Andersson, A. Malehmir, V.R. Troll, M. Dehghannejad, C. Juhlin, M. Ask **Carbonatite ring-complexes explained by caldera-style volcanism**

Sci. Rep., 3 (2013), p. 1677, [10.1038/srep01677](#)

[View Record in Scopus](#)

[Barr and Showman, 2009](#)

A.C. Barr, A.P. Showman **Heat transfer in Europa's icy shell**

University of Arizona Press (2009), pp. 405-430

[View Record in Scopus](#)

[Bell and Butcher, 2002](#)

B. Bell, H. Butcher **On the emplacement of sill complexes: evidence from the faroe-shetland basin**

D.W. Jolley, B.R. Bell (Eds.), The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes, 197, Geological Society of London, Special Publications (2002), pp. 307-329

[CrossRef](#)[View Record in Scopus](#)

[Blankenship et al., 2009](#)

D.D. Blankenship, D.A. Young, W.B. Moore, J.C. Moore **Radar Sounding of Europa's Subsurface Properties and Processes: The View From Earth**

University of Arizona Press (2009), pp. 631-654

[View Record in Scopus](#)

[Chevalier and Woodford, 1999](#)

L. Chevalier, A.C. Woodford **Morpho-tectonics and mechanism of emplacement of the dolerite rings and sills of western Karoo, South Africa**

South African J. Geology, 102 (1999), pp. 43-54

[Coetzee and Kisters, 2016](#)

A. Coetzee, A. Kisters **The 3D geometry of regional-scale dolerite saucer complexes and their feeders in the secunda Complex, karoo basin**

J. Volcanol. Geothermal Res., 317 (2016), pp. 66-79

[ArticleDownload PDFView Record in Scopus](#)

[Collins and Nimmo, 2009](#)

G.C. Collins, F. Nimmo **Chaos on Europa**

University of Arizona Press (2009), pp. 259-282

[View Record in Scopus](#)

[Collins et al., 2000](#)

G.C. Collins, J.W. Head III, R.T. Pappalardo, N.A. Spaun **Evaluation of models for the formation of chaotic terrain on Europa**

J. Geophys. Res., 105 (2000), pp. 1709-1716

[CrossRefView Record in Scopus](#)

[Cox et al., 2008](#)

R. Cox, L.C. Fong, M. Arakawa, K.C. Schneider **Impact penetration of Europa's ice crust as a mechanism for formation of chaos terrain**

Meteoritics. Planet. Sci., 43 (2008), pp. 2027-2048

[CrossRefView Record in Scopus](#)

[Craft et al., 2016](#)

K.L. Craft, G.W. Patterson, R.P. Lowell, L. Germanovich **Fracturing and flow: investigations on the formation of shallow water sills on Europa**

Icarus (2016), [10.1016/j.icarus.2016.01.023](#)

[Culha and](#)

[Manga, 2016](#)

C. Culha, M. Manga **Geometry and spatial distribution of lenticulae on Europa**

Icarus, 271 (2016), pp. 49-56

[ArticleDownload PDFView Record in Scopus](#)

[Dombard et al.,](#)

[2013](#)

A.J. Dombard, G.W. Patterson, A.P. Lederer, L.M. Prockter **Flanking fractures and the formation of double ridges on Europa**

Icarus, 223 (2013), pp. 74-81

[ArticleDownload PDFView Record in Scopus](#)

[Eshelby, 1957](#)

J.D. Eshelby**The determination of the elastic field of an ellipsoidal inclusion, and related problems**

Proce. R. Soc. A, 241 (1957), pp. 376-396

[CrossRefView Record in Scopus](#)

[Fagents, 2003](#)

S.A. Fagents**Considerations for effusive cryovolcanism on Europa: the post-Galileo perspective**

J. Geophys. Res., 108 (2003), [10.1029/2003JE002128](#)

[Fialko, 2001](#)

Y. Fialko**On origin of near-axis volcanism and faulting at fast spreading mid-ocean ridges**

Earth Planet. Sci. Lett., 190 (2001), pp. 31-39

[ArticleDownload PDFView Record in Scopus](#)

[Figueredo and Greeley, 2004](#)

P. Figueredo, R. Greeley**Resurfacing history of Europa from pole-to-pole geologic mapping**

Icarus, 167 (2004), pp. 287-312

[ArticleDownload PDFView Record in Scopus](#)

[Galland et al., 2006](#)

O. Galland, P.R. Cobbold, E. Hallot, L. de Bremond d'Ars, G. Delavau**Use of vegetable oil and silica powder for scale modeling of magmatic intrusion in a deforming brittle crust**

Earth Planet. Sci. Lett., 243 (2006), pp. 786-804

[ArticleDownload PDFView Record in Scopus](#)

[Galland et al., 2006](#)

O. Galland, S. Planke, E.-R. Neumann, A. Malthes-Soressen **Experimental modeling of shallow magma emplacement: application to saucer-shaped intrusions**

Earth Planet. Sci. Lett., 277 (2009), pp. 373-383

[ArticleDownload](#) [PDFView](#) [Record in Scopus](#)

[Goulty and Schofield](#)

N.R. Goulty, N. Schofield **Implications of simple flexure theory for the formation of saucer-shaped sills**

J. Struct. Geol., 30 (2008), pp. 812-817

[ArticleDownload](#) [PDFView](#) [Record in Scopus](#)

[Greenberg et al.](#)

R. Greenberg, G.V. Hoppa, B.R. Tufts, P. Geissler, J. Riley **Chaos on Europa**

Icarus, 141 (1999), pp. 263-286

[ArticleDownload](#) [PDFView](#) [Record in Scopus](#)

[Greenberg et al.](#)

R. Greenberg, M.A. Leake, G.V. Hoppa **Pits and uplifts on Europa**

Icarus, 161 (2003), pp. 102-126

[ArticleDownload](#) [PDFView](#) [Record in Scopus](#)

[Gudmundsson, 2001](#)

A. Gudmundsson **Rock Fractures in Geological Processes**

University of Cambridge Press (2011), p. 591

[Han and Showman](#)

L. Han, A.P. Showman **Thermo-compositional convection in Europa's icy shell with salinity**

Geophys. Res. Lett., 32 (2005), [10.1029/2005GL023979](#)

[Hansen and Carter](#)

D.M. Hansen, J.A. Cartwright **Saucer-shaped sill with lobate morphology revealed by 3D seismic data: implications for resolving a shallow-level sill emplacement mechanism**

J. Geol. Soc. London, 163 (2006), pp. 509-523

[CrossRefView](#) [Record in Scopus](#)

[Head and Pappalardo](#)

J.W. Head, R.T. Pappalardo **Brine mobilization during lithospheric heating on Europa: implication for the formation of chaos terrain, lenticula texture and color variations**

J. Geophys. Res., 104 (1999)

27,143–27,155

[Huuse and Mickelson](#)

M. Huuse, M. Mickelson **Oceanic sandstone intrusions in the tampen spur area (Norwegian north sea quad 34) imaged by 3D seismic data**

Mar. Pet. Geol., 21 (2004), pp. 141-155

[ArticleDownload](#) [PDFView](#) [Record in Scopus](#)

[Johnston and Moore](#)

S.A. Johnston, L.G.J. Montesi **Formation of ridges on Europa above crystallizing water bodies inside the ice shell**

Icarus, 237 (2014), pp. 190-201

[ArticleDownload PDFView Record in Scopus](#)

[Klinger, 1980](#)

J. Klinger **Influence of a phase transition of ice on the heat and mass balance of comets**

Science, 209 (1980), pp. 271-272

[View Record in Scopus](#)

[Lee et al., 2003](#)

S.W. Lee, M. Zanolin, A.M. Thode, R.T. Pappalardo, N.C. Makris **Probing Europa's interior with natural sound sources**

Icarus, 165 (2003), pp. 144-167

[ArticleDownload PDFView Record in Scopus](#)

[Lister and Kerr, 1991](#)

J.R. Lister, R.C. Kerr **Fluid-mechanical models of crack propagation and their application to magma transport in dykes**

J. Geophys. Res., 96 (1991), pp. 10049-10077

[CrossRef](#)

[Lister et al., 2013](#)

J.R. Lister, G.G. Peng, J.A. Neufeld **Viscous control of peeling an elastic sheet by bending and pulling**

Phys. Rev. Lett., 111 (2013), p. 154501

[CrossRef](#)

[Litwin et al., 2012](#)

K.L. Litwin, B.R. Zygielbaum, P.J. Polito, L.S. Sklar, G.C. Collins **Influence of temperature, composition and grain size on the tensile failure of water: implications for erosion on Titan**

J. Geophys. Res., 117 (2012), p. E08013, [10.1029/2012JE004101](#)

[Manga and Wang, 2007](#)

M. Manga, C.-Y. Wang **Pressurized oceans and the eruption of liquid water on Europa and Enceladus**

Geophys. Res. Lett., 34 (2007), p. L07202, [10.1029/2007GL029297](#)

[Mathieu et al., 2008](#)

L. Mathieu, B. van Wyk de Vries, E.P. Holohan, V.R. Troll **Dykes, cups, saucers, and sills: analogue experiments on magma intrusion in brittle rocks**

Earth Planet. Sci. Lett., 271 (2008), pp. 1-13

[ArticleDownload PDFView Record in Scopus](#)

[Malthe-Sørenssen et al., 2008](#)

A. Malthe-Sørenssen, S. Planek, H. Svensen, B. Jamtveit **Formation of saucer-shaped sills**

C. Breitzkreuz, N. Petford (Eds.), *Physical Geology and High-Level Magmatic Systems*, vol. 234, Geological Society of London (2004), pp. 215-227

[CrossRefView Record in Scopus](#)

[McCord et al., 1999](#)

T.B. McCord, *et al.* **Hydrated salt minerals on Europa's surface from the Galileo near-infrared mapping spectrometer (NIMS) investigation**

J. Geophys. Res., 104 (1999)

11,827–11,851

[McKinnon, 1999](#)

W.B. McKinnon **Convective instability in Europa's floating ice shell**

Geophys. Res. Lett., 26 (1999), pp. 951-954

[CrossRefView Record in Scopus](#)

[Mevel and Mercier, 2007](#)

L. Mevel, E. Mercier **Large-scale doming on Europa: a model for the formation of the macula**

Planet. Space Sci., 55 (2007), pp. 915-927

[ArticleDownload PDFView Record in Scopus](#)

[Michaut, 2011](#)

C. Michaut **Dynamics of magmatic intrusions in the upper crust: theory and applications to laccoliths on Earth and the Moon**

J. Geophys. Res., 116 (2011), p. B05205, [10.1029/2010JB008108](#)

[View Record in Scopus](#)

[Michaut and Manga, 2014](#)

C. Michaut, M. Manga **Domes, pits, and small chaos on Europa produced by water sills**

J. Geophys. Res., 119 (2014), pp. 550-573

[CrossRefView Record in Scopus](#)

[Moore et al., 1998](#)

J.M. Moore, E. Asphaug, R.J. Sullivan, *et al.* **Large impact features on Europa: results of the Galileo nominal mission**

Icarus, 135 (1998), pp. 127-145

[ArticleDownload PDFView Record in Scopus](#)

[Muirhead et al., 2014](#)

J.D. Muirhead, G. Airoidi, J.D. White, J.V. Rowland **Cracking the lid: Sill-fed dikes are the likely feeders of flood basalt eruptions**

Earth Planet. Sci. Lett., 406 (2014), pp. 187-197

[ArticleDownload PDFView Record in Scopus](#)

[Neish et al., 2011](#)

C.D. Neish, L.M. Prockter, G.W. Patterson **Observational constraints on the identification and distribution of chaotic terrain on icy satellites**

Icarus, 221 (2012), pp. 72-79

[ArticleDownload PDFView Record in Scopus](#)

[Nimmo, 2004](#)

F. Nimmo**Stresses generated in cooling viscoelastic ice shells: applications to Europa**

J. Geophys. Res., 109 (2004), p. E12001, [10.1029/2004JE002347](#)

[Nimmo and Man](#)

F. Nimmo, M. Manga**Causes, characteristics and consequences of convective diapirism on Europa**

Geophys. Res. Lett., 29 (2002), p. 2109, [10.1029/2002GL015754](#)

[Nimmo and Giese, 2005](#)

F. Nimmo, B. Giese**Thermal and topographic tests of Europa chaos formation models from galileo E15 observations**

Icarus, 177 (2005), pp. 327-340

[ArticleDownload PDFView Record in Scopus](#)

[Pappalardo et al., 1998](#)

R.T. Pappalardo, et al.**Geological evidence for solid-state convection in Europa's ice shell**

Nature, 391 (1998), pp. 365-368

[CrossRefView Record in Scopus](#)

[Pappalardo et al., 2013](#)

R.T. Pappalardo, et al.**Science potential from a Europa lander**

Astrobiology, 13 (2013), pp. 740-773

[CrossRefView Record in Scopus](#)

[Petrovic, 2003](#)

J.J. Petrovic**Mechanical properties of ice and snow**

J. Mater. Sci., 38 (2003), pp. 1-6

[CrossRefView Record in Scopus](#)

[Pollard and Holzhausen, 1979](#)

D.D. Pollard, G. Holzhausen**On the mechanical interaction between a fluid-filled fracture and the earth's surface**

Tectonophysics, 53 (1979), pp. 27-57

[ArticleDownload PDFView Record in Scopus](#)

[Pollard and Johnson, 1973](#)

D.D. Pollard, A.M. Johnson**Mechanics of growth of some laccolithic intrusions in the Henry Mountains, Utah, II. Bending and failure of overburden layers and sill formation**

Tectonophysics, 18 (1973), pp. 311-354

[ArticleDownload PDFView Record in Scopus](#)

[Polteau et al., 2008](#)

S. Polteau, A. Mazzini, O. Galland, S. Planke, A. Malthe-Sorensen**Saucer-shaped intrusions: Occurrences, emplacement and implications**

Earth Planet. Sci. Lett., 266 (2008), pp. 195-204

[ArticleDownload PDFView Record in Scopus](#)

[Quick and Marsh, 2016](#)

L.C. Quick, B.D. Marsh **Heat transfer of ascending cryomagma on Europa**

J. Volcanol. Geothermal Res., 319 (2016), pp. 66-77

[ArticleDownload PDFView Record in Scopus](#)

[Rathbun et al., 1998](#)

J.A. Rathbun, G.S. Musser, S.W. Squyres **Ice diapirs on Europa: implications for liquid water**

Geophys. Res. Lett., 25 (1998), pp. 4157-4160

[CrossRefView Record in Scopus](#)

[Riley et al., 2000](#)

J. Riley, G.V. Hoppa, R. Greenberg, et al. **Distribution of chaotic terrain on Europa**

J. Geophys. Res., 105 (2000), pp. 22599-22615

[CrossRefView Record in Scopus](#)

[Rubin, 1993](#)

A.M. Rubin **On the thermal viability of dikes leaving magma chambers**

Geophys. Res. Lett., 20 (1993), pp. 257-260

[CrossRefView Record in Scopus](#)

[Rubin, 1995](#)

A.M. Rubin **Propagation of magma-filled cracks**

Ann. Rev. Earth Planet. Sci., 23 (1995), pp. 287-336

[CrossRefView Record in Scopus](#)

[Rudolph and Manga, 2009](#)

M.L. Rudolph, M. Manga **Fracture penetration in planetary ice shells**

Icarus, 199 (2009), pp. 536-541

[ArticleDownload PDFView Record in Scopus](#)

[Schenk and McKinnon, 2001](#)

Schenk, P.M. and W.B. McKinnon (2001) Topographic variability of Europa from galileo stereo images. LPSC 32 abstract 2078.

[Schenk and Pappalardo, 2004](#)

P.M. Schenk, R.T. Pappalardo **Topographic variations in chaos on Europa: implications for diapiric formation**

Geophys. Res. Lett., 31 (2004), [10.1029/2004GL019978](#)

[Schmidt et al., 2011](#)

B. Schmidt, D. Blankenship, G. Patterson, P. Schenk **Active formation of chaos terrain over shallow subsurface water on Europa**

Nature, 479 (2011), pp. 502-505

[CrossRefView Record in Scopus](#)

[Schulson, 2001](#)

E.M. Schulson **Brittle failure of ice**

Eng. Fract. Mech., 68 (2001), pp. 1839-1887

[ArticleDownload PDFView Record in Scopus](#)

[Schulson, 2006](#)

E.M. Schulson **The fracture of water ice Ih: a short overview**

Meteoritics Planet. Sci., 41 (2006), pp. 1497-1508

[CrossRefView Record in Scopus](#)

[Singer et al., 2010](#)

Singer, K.N., W.B. McKinnon and P.M. Schenk (2010) Pits, spots, uplifts, and small chaos regions on Europa: evidence for diapiric upwelling from morphology and morphometry. LPSC 39 abstract 2195.

[Sotin et al., 2002](#)

C. Sotin, J.W. Head, G. Tobie **Europa: tidal heating of upwelling thermal plumes and the origin of lenticulae and chaos melting**

Geophys. Res. Lett., 29 (2002), pp. 741-744

[Thorey and Michaut, 2014](#)

C. Thorey, C. Michaut **A model for the dynamics of crater-centered intrusions: application to lunar floor-fractured craters**

J. Geophys. Res., 119 (2014), [10.1002/2013JE004467](#)

[Tobie et al., 2003](#)

G. Tobie, G. Choblet, C. Sotin **Tidally heat convection: constraints on Europa's ice shell thickness**

J. Geophys. Res., 108 (2003), p. 5124, [10.1029/2003JE002099](#)

[View Record in Scopus](#)

[Turcotte and Schubert, 1982](#)

D.L. Turcotte, G. Schubert **Geodynamics: Applications of Continuum Physics to Geological Problems**

John Wiley, New York (1982)

[Walker and Schmidt, 2015](#)

C.C. Walker, B.E. Schmidt **Ice collapse over trapped water bodies on Enceladus and Europa**

Geophys. Res. Lett., 42 (2015), pp. 712-719

[CrossRefView Record in Scopus](#)