Sill Emplacement in Europa's Ice Shell as a Driving Mechanism for Double Ridge Formation

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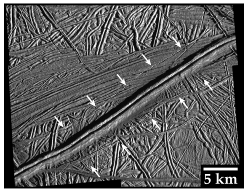
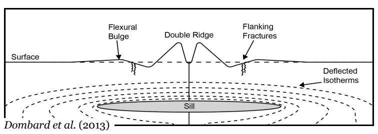
Introduction

A wide range of tectonic features cover the icy surface of the Jovian moon Europa. The prominent ***double ridge*** morphology (shown at right) displays two raised ridges and flexural bulges. Flanking fractures observed at a number of double ridges (arrows at right) led *Dombard et al.* (2013) to propose a formation mechanism that employs heat transfer from a shallow subsurface water sill (figure below):



Androgeos Linea double ridge (14.7N, 273.4W). Arrows locate the flanking, subparallel cracks (*Dombard et al., 2013*)

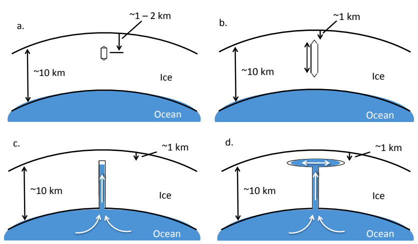


Dombard et al. (2013)

The question remains in this scenario of how sill emplacement would occur at shallow depths. Here we suggest a possible emplacement sequence involving stress growth and fracture propagation within a cooling, thickening ice shell. We assess the viability of sill emplacement through calculations of heat transfer for crack and sill lifetimes and the fracture mechanics of sill growth.

Objective: Investigate conditions under which a shallow sill (~ 1 to 3 km deep) could form in a cooling, thickening ice shell.

Sill Emplacement Overview



a. Stress grows in cooling, thickening ice shell and crack initiates; **b.** Vertical fracture propagation; **c.** Fracture reaches ocean and water flows up to ~ 1 km depth; **d.** Sill grows horizontally

Investigations and Methods

1. Will fluid freeze before reaching depth needed?
   → Calculate ***fluid flow velocities*** into fracture
2. Can a horizontal fracture form? Why would it turn horizontally and not continue upwards propagation?
   → Apply finite element program, Franc2d (*Wawrzynek and Ingraffea*, 1987), to consider ***stress field*** and conditions under which a ***horizontal fracture*** (sill) could grow
3. Will sill last long enough to provide heat for flexure that *Dombard et al.* (2013)'s model requires?
   → Calculate ***sill lifetime***

1. Vertical Fluid Flow Velocity

Ocean to shallow subsurface

- Navier stokes equations and scale analysis result in relationship for pressure contrast when fracture reaches ocean:

$$\frac{\rho_{water} u^2}{w} \approx \nabla P$$

where ρ_{water}= 1000 kg/m³ and ρ_{ice} = 900 kg/m³, u = fluid velocity, w= fracture width, ∇P= pressure gradient

- Solving for u, and replacing ∇P with $\rho_{ice} gH/H$ =>

$$u = \sqrt{\frac{w}{\rho_{water}} \rho_{ice} g}$$

where g=Europa's acceleration due to gravity and H = height of fracture (~shell thickness = 10 km)

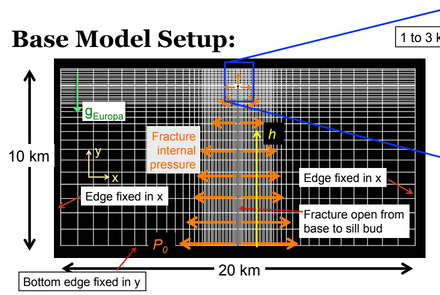
⇒ u = **3 m/s** for 10 m wide fracture → **50 min to flow up** to ~ 1 km depth

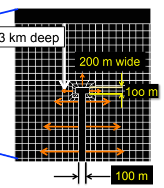
– sufficient time to reach shallow depth before freezing according to conductive time scale ~ w^2/a where a is the thermal diffusivity of water

2. Horizontal Fracture Investigations

- Can a horizontal fracture form in shallow subsurface? Franc2d finite element models are used to determine the σ_y stress field and direction of fracture propagation.
- Model begins with a vertical fracture and sill bud pressurized with liquid water. The hydrostatic load decreases with distance above base, h, as: P_o- ρ_{water}*g*h

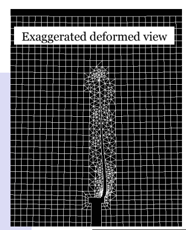
Base Model Setup:





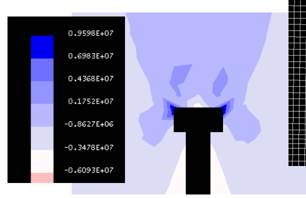
	Nominal values
E	5 x 10^9 Pa
nu	0.3
ρ_{ice}	900 kg/m³
ρ_{water}	1000 kg/m³
sill depth	1 km or 3 km
sill bud geometry	small bud (200m wide)

* **No excess pressure at 1-km depth (neutral bouyancy)** - models at 3-km allow for driving pressure



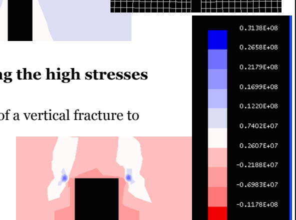
3-km Deep Sill Bud

- Initial σ_y stress field shows highest tensile stresses at upper corners
- Crack propagates up until ~ 1 km depth
- Curves towards center slightly



Are the corners of initial fracture causing the high stresses there?

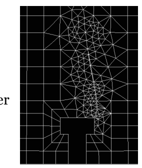
- Emplaced two small horizontal cracks at corners of a vertical fracture to "remove" corners
- Analysis results show high σ_y tensile stresses remain at crack tips and upward propagation is the preferred direction



2. Model Variations

Material characteristics varied to determine model sensitivity

- Young's Modulus set to lower bound E = **6 x 10⁷ Pa** (*Williams and Greeley*, 1998) → **no change to σ_y stress field or crack propagation direction**
- Poisson's ratio set to upper bound, ν=**.35** (*Hillier and Squyres*, 1991)
  → **small decrease in σ_y** stress field (~3 MPa decrease at max stress location) but **no change to crack propagation direction**



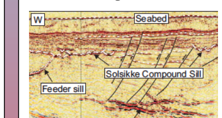
High Density Contrast

- ρ_{water}= 1208 kg/m³ (represents briny fluid (*Chuang et al.*, 2001; *Figueredo et al.*, 2002) and ρ_{ice} = 900 kg/m³
- Pressure inside vertical fracture and sill bud are lower due to higher ρ_{water} in P_o-$\rho_{water}gh$

→**lower (~7 MPa) overall stress** field; **upward propagation** direction; fracture only propagates to ~2500 m depth

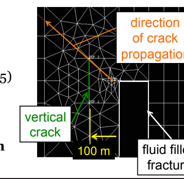
How can we promote horizontal propagation?

- Multiple **fractures in shallow subsurface** could induce stress field such that horizontal fracturing is preferred – similar to suggested terrestrial Solsikke sill emplacement (*Hansen and Cartwright*, 2006) and dike and sill emplacements at mid-ocean ridges (*Gudmundsson*, 1990)



from *Hansen and Cartwright* (2006)

- **Fractures** calculated to propagate to depths **>1 km on Europa** (*Lee et al.*, 2005)
- Our initial models of a vertical crack near the fluid filled fracture show crack propagation **deviates from vertical**



3. Sill Lifetime

- Rayleigh number calculation shows 10 to 100 m thick sill will **convect** for a 1°C ΔT:

$$Ra = \frac{g\rho_{water}\alpha d^3 \Delta T}{\mu a} \approx 10^{11}$$

$$q = \frac{k\Delta T}{d} Ra^{1/3} \Rightarrow \quad \tau = \frac{\rho L d}{q}$$

d= sill thickness, α= thermal expansion coeff., ΔT= temperature difference, μ=dynamic viscosity, a=thermal diffusivity, k=thermal conductivity, L = latent heat

=> τ ~ a few to 10s of yrs

***Much lower lifetime* than the 1000s of years needed** by *Dombard et al.* (2013) to form flanking fractures on double ridges

→ **Need replenishment** from ocean to supply warm water

- Solidification processes of terrestrial magmatic dikes (i.e. *Delaney and Pollard*, 1982)

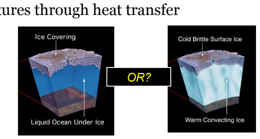
Also will consider – would freezing water cause **sill** to **migrate deeper** with time?

Summary

- Fluid **velocity adequate** to reach shallow depth **before freezing**
- Even though density of water is greater than ice, the **stress field encourages upward** rather than downward **propagation**
- **Shallow fractures show promise for enabling horizontal fracture**
- A 10-100 m thick convecting **sill only lasts ~a few to 10s of yrs** – not long enough to form double ridge flanking fractures through heat transfer

Europa Clipper Mission Data Needed!

Data could verify presence of shallow water bodies and determine the ice shell thickness



References

Chuang et al. (2001) Proc. *Lunar Sci. Conf. 32*,. Abstract 1848; Dombard personal communication (2012); *Delaney and Pollard* (1982) *Amer. J. Sci.*; Dombard et al (2013), *Icarus*; Figueredo et al. (2002), *JGR*; Gudmundsson (1990), *Tectonophysics*; Hansen and Cartwright (2006), *J. Geolog. Soc. London*; Hillier and Squyres (1991), *JGR*; *Lee et al.* (2005), *Icarus*; Wawrzynek and Ingraffea (1987), *Theoretical and Applied Fracture Mechanics*; Williams and Greeley (1998), *GRL*.