SILL EMPLACEMENT IN EUROPA'S ICE SHELL AS A DRIVING MECHANISM FOR DOUBLE RIDGE FORMATION

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Introduction: Double ridges are ubiquitous on Europa, though their formation process is still incompletely understood. A variety of mechanisms have been proposed to explain their formation [1-3]. Recent work suggests that specific morphological characteristics of double ridges are best explained by the presence of a shallow sill of liquid water [4]. The question remains, however, of how the sill becomes emplaced. Here we explore the viability of a possible emplacement mechanism that involves fracturing and pressure-driven ascent of ocean water in a thickening ice shell.

Sill Emplacement Overview: Previous studies proposed that subsurface liquid water associated with dikes, diapirs and/or frictional heating could explain certain morphological characteristics of double ridges [6,7]. More recent work has shown that the presence of marginal troughs and flanking fractures associated with some double ridges require local heat flow distributions that can only be produced by a shallow sill [4]. Following on these works we suggest a possible sequence of events for sill emplacement in the shallow subsurface of a thickening ice shell.

As Europa's ice shell cools and thickens, stresses accumulate and peak at certain depths. For an ~10 km thick shell, maximum tensile stresses of ~3-5 MPa occur at a depth of 1 - 2 km [8]. The model by [8] assumes a global, uniform ice shell thickening. In reality faults may occur during thickening that could alter the stress field and change fracture initiation location. The stresses estimated by [8] are more than sufficient to initiate a fracture [9] (Figure 1a). If a fracture does form, it will quickly propagate up until the induced stress load balances overburden pressure and down until it reaches the ocean [8,9] (Figure 1b.). The pressure released during opening of a fracture at the base of the ice-ocean interface will then drive water vertically through the ice shell until reaching the neutral buoyancy level or top of fracture (~ 1 km depth) [9,10] (Figure 1c.). Finally, a sill is emplaced through horizontal movement of water by local melting and/or by the propagation of horizontal fractures in a zone of weakness within the shell (Figure 1d.).

Discussion and Results: This investigation concentrates on fluid flow characteristics, fracturing for sill emplacement and sill lifetime. Flow velocity up the fracture is important in order to determine if the water will reach the shallow subsurface before freezing. The next step of sill emplacement requires that either the driving pressure would fracture or melting would carve out a horizontal space in the ice. Last, sill lifetime is calculated and compared to estimates of ~ 10-100 kyrs required for formation of the double ridge troughs and fractures [5].

Fluid inflow velocity: Assuming a typical width to height crack aspect ratio of ~ 10^{-3} [11], a 10 km vertical fracture would have a width of 10 m. Flow calculations show the velocity of ocean water upwards would be turbulent. Using a scale analysis with the Navier-Stokes equations, the following relationship results:

$$\frac{\rho_w u^2}{d} \approx \nabla P \tag{1}$$

where ρ_w is the density of water, d is the fracture width, u is the flow velocity and ∇P is the pressure gradient driving the flow ($\nabla P = \rho_i g h / h$). ρ_i is the density

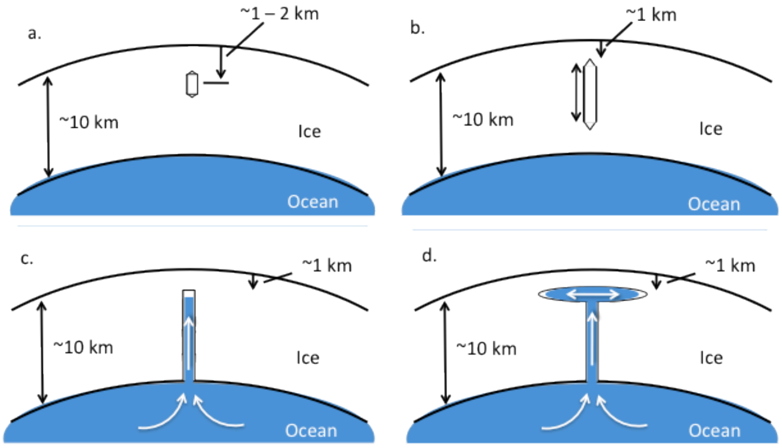

Figure 1. Sill emplacement steps: a. Stress grows in cooling, thickening ice shell and crack initiates; b. Vertical fracture propagation; c. Fracture reaches ocean and water flows up to ~ 1 km depth; d. Sill grows horizontally

of ice, g is acceleration due to gravity and h is the height of the fracture (~10 km). Solving equation (1) for u and replacing ∇P gives:

$$u = \sqrt{\frac{d}{\rho_w}\rho_i g} \tag{2}$$

For the assumed ~10 km thick ice shell and 10 m wide fracture, the turbulent flow would occur at about 3 m/s and take around 50 minutes to reach ~1 km depth. This is sufficiently quick to discard freezing concerns as the fluid would take on the order of a few to 10s of years to lose its heat according to the conductive timescale, $\tau \sim d^2/a$, where a is the thermal diffusivity of water.

Sill formation: The ocean water is assumed to be only slightly above freezing and therefore would not melt much ice before freezing itself. Fracture mechanics theory dictates that a fracture will initiate if an applied stress overcomes the strength of a material and will propagate along a plane of weakness or perpendicular to the least principle stress. For the described model, according to the stress intensity factor, K_I, equation:

$$K_I = 2\sqrt{\frac{r}{\pi}}\left(P_{ex} - P_{lith}\right) \tag{3}$$

the overburden, P_{lith}, always overrides the driving pressure, P_{ex}, for depths of 1 to 3 km, making it difficult to initiate a fracture (r is radius of the crack tip). Therefore, a mechanism that would promote the formation of a horizontal plane of weakness would be necessary.

Two potential mechanisms of altering the strength of the ice at depth include: (1) the presence of multiple fractures/faults in close proximity to one another; (2) radial stresses resulting from the volume expansion and thermal contraction of a cooling ice shell that peak at shallow depths [8]. A terrestrial analogue for multiple fractures affecting the formation of sills can be found at mid-ocean ridge systems (e.g., the Solsikke sill – Figure 2) [12,13]. On Europa, stresses and torques imparted by diurnal tides, nonsynchronous rotation, true polar wander, libration, and obliquity could induce faulting at the surface that would propagate to depths sufficient to make this mechanism viable [e.g. 2,14]. Radially variable stresses within the cooling and thickening ice shell could also promote the formation of a zone of weakness at depth.

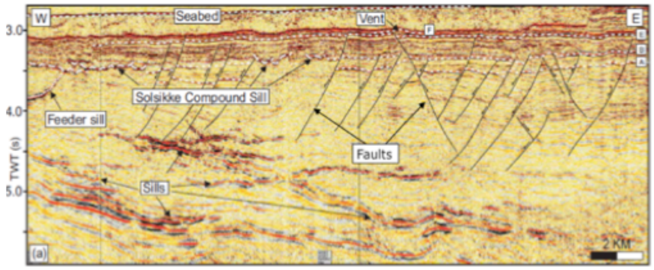

Figure 2. East-west trending, 3D seismic section depicting the Solsikke sill (modified from [13])

Sill lifetime: Assuming the sill horizontal fracturing challenges can be overcome, we consider whether the sill could last long enough to deform the surface and cause fractures observed at the ridges. Following the typical Rayleigh number calculation ($Ra \sim \rho g \alpha \Delta T d^3/\mu\kappa$) for a fluid body, a 10 to 100 m thick sill has a high Ra ~ 10^{11} for a 1°C ΔT. The sill will therefore convect and lifetime calculations show that that the sill will cool over a few years to 10s of years, far shorter than the 10-100 kyrs required for ridge trough and fracture formation [5]. In order to keep a sill active for this length of time, the sill would need to be replenished. Terrestrial dike intrusion solidification, as described by [15], provides a means to analyze sill replenishment. An additional concern about sill lifetime includes that any ice during cooling would float upwards and the sill roof would essentially migrate downwards over time. Further investigation of these processes is ongoing.

Summary: Recent work has suggested that shallow water sills are necessary to cause the troughs and fractures observed around some double ridges [4]. Our review of previous studies confirms that initiation and propagation of a fracture from the shallow subsurface to the ocean can occur from stress buildup in the cooling shell [8,9] followed by pressure driven fluid flow to a shallow depth of ~ 1 km [9]. Further, our investigations find that external forces and shell cooling could cause shallow subsurface faulting and/or radial stresses that can decrease ice strength and enable a horizontal fracture to propagate and emplace a sill. Concerns exist about the short lifetime of the sill at ~10s years compared to the thousands needed and that the water would likely migrate deeper in the ice shell over time. Overall, our study shows sill emplacement may be difficult on Europa, yet mechanisms exist that with further investigation may overcome the obstacles.

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