ICE THICKNESS, UPWELLING, AND TOPOGRAPHY IN BANDS ON EUROPA.

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Introduction: The outer ice shell of Europa, a Galilean satellite of Jupiter, displays clear evidence for tectonic extension along tabular "bands" [Figure 1]. The margins of some bands fit closely if the band itself is removed [1-3], and morphologies of the terrain inside these bands bear similiarities to terrestrial mid-ocean ridges (MORs) [4]. Like MORs, bands often feature subparallel ridges that have been interpreted as normal fault scarps related to tectonic resurfacing. Because bands form as the result of ice shell divergence, the geodynamics of their formation depends on the upwelling of thermally or compositionally buoyant ice beneath the diverging ice shell [4].

One constraint on band geodynamics comes from stereo photography, which shows typical band elevations 100 to 150 m above surrounding terrain [4, 5, Figure 1]. One explanation is that warm ice from the base of the ice shell is drawn up toward colder ice underneath the band, decreasing the density and increasing elevation. However, higher ice shell temperatures may also induce melting, limiting ice shell thickness and elevation. To understand this balance, we analytically derive the steady-state elevation and temperature structure of bands for a range of opening rates.

Our results show that, when active, bands should be at a lower elevation than the surrounding regions. Thus, observations of elevated bands are most easily explained by a compositional difference between the ice beneath the band, which may be pristine ice crystallized during and especially after band activity, and the surrounding, older, materials.

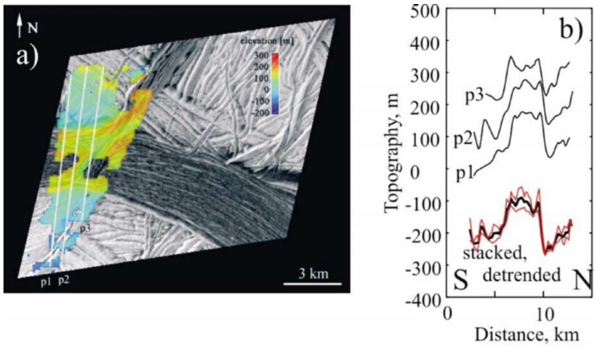

Figure 1: From Nimmo et al., 2003, a) Galileo image centered at 18°S, 163°E, of a dark band, with topography derived from stereo imagery; b) topographic profiles across the band

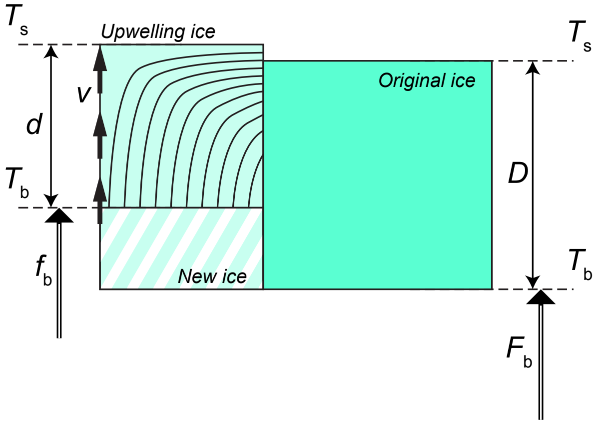

Figure 2 : Schematic diagram of the model. We solve for the equilibrium thickness of ice in th band, assuming a uniform upwelling velocity V, and outside the band (no upwelling). The elevation of the band may be due to a higher ice density outside the band due to impurities.

Analysis: We derive an analytical solution for the conductive temperature structure of upwelling ice I. Conservation of energy, assuming the ice is moving vertically at velocity V, leads to

$$dF/dz - WF - H = 0\,,$$

where $F = -k\, dT/dz$ is the heat flux, k is the thermal conductivity, κ is the thermal diffusivity, T is the temperature, z is the depth (positive-up), H is the volumetric tidal heat production, assumed to be dissipated uniformly within the shell, and $W \equiv V/\kappa$.

We integrate this equation and impose a heat flux, f_b, at the base of the ice shell, $z = d$. That solution is then integrated, assuming $T = T_b$ at $z = d$ to give the temperature profile:

$$T = T_b + \frac{1}{\kappa W}\left(\frac{f_b}{k} + \frac{H}{w}\right)\{1 - \exp[W(z-d)]\} + \frac{H}{KW}(z-d)\,.$$

Finally, ice thickness is solution to the transcendental equation obtained by setting $T = T_s$ at the surface

$$\Delta T + \frac{1}{\kappa W}\left(\frac{f_b}{k} + \frac{H}{w}\right)[1 - \exp(-Wd)] - \frac{Hd}{KW} = 0\,,$$

Here, $\Delta T = T_b - T_s$.

We assume that V is constant, as is appropriate for mid-ocean type upwelling governed by corner flow theory [6; Figure 2].

If the ice is static ($V = 0$) and the basal heat flux is F_b, the ice thickness and temperature are respectively

$$D = \frac{F_b}{H}\left[1 - \sqrt{1 + \frac{2k\Delta T H}{Fb^2}}\right],$$

$$T = T_b - \frac{F_b}{k}(z - D) - \frac{H}{2k}(D - z)^2 .$$

The basal heat flux F_b is controlled by dissipation in the rocky core of the satellite and in the ocean. However, when the ice is upwelling, the ice-water interface must migrate downwards at velocity $-V$ at steady state. The associated ice crystallization liberates heat, so that $f_b = F_b + \rho L V$, where L is the latent heat of crystallization of the ice.

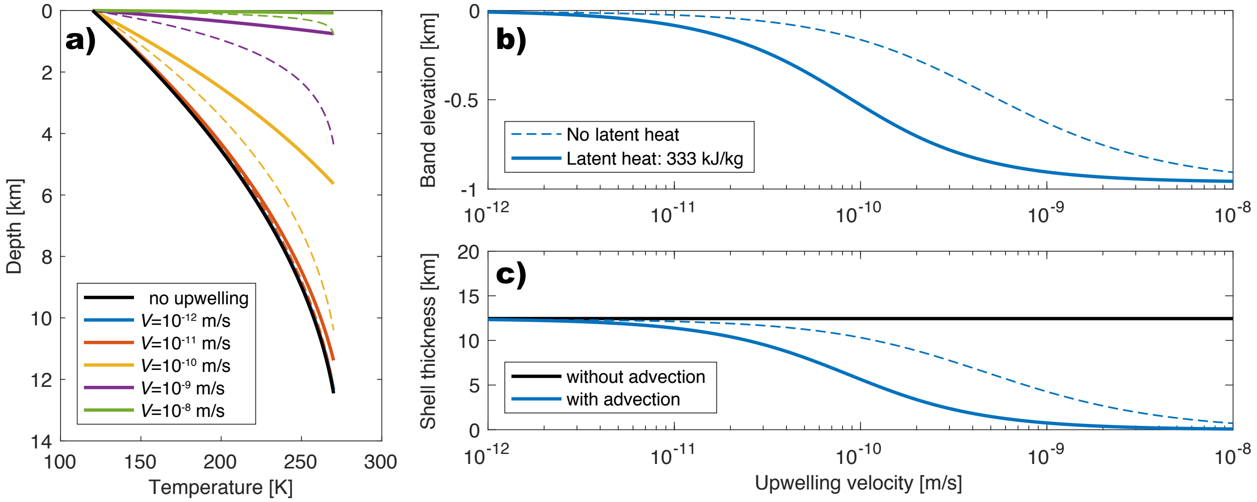

Figure 3: a) Steady-state temperature profile in a conductive ice shell for various upwelling rates and b) band elevation and c) shell thickness assuming the same intrinsic density inside and outside the band. The band is always at lower elevation than the surrounding ice. Solid lines include the effect of latent heat of crystallization of the ice, and the dashed lines do not.

Results: Figure 3 shows ice shell temperature profiles and equilibrium ice thickness for various upwelling velocities. For slower upwelling velocities, the ice conductively cools faster than it is advected, producing no change in thermal structure. A residual ice thickness of ~14 km may support the relief of ridges. When $V \sim \kappa / D > 10^{-10}$ m/s (3 mm/yr) ice thickness decreases and becomes negligible at upwelling velocities 100 times larger than this critical value. This thinner ice is isostatically compensated at a lower elevation than the surroundings, despite the higher band temperature and lower density.

We propose that the water underneath the thinned ice crystallizes into pristine ice after the band stops opening. This accreting ice excludes densifying salts preferentially into the melt, producing a lower density band. Salt contents as high as 20% have been proposed for the Europan ice shell [7, 8]

Because this accretion ice must be less dense than the underlying water, the upwelling velocity is limited to less than $4{\times}10^{-10}$m/s (~ 10 mm/yr), similar to that of slow mid-ocean ridges on Earth (Figure 4).

References: [1] Schenk, P. M. and McKinnon W. B. (1989) *Icarus, 79,* 75-100. [2] Pappalardo, R. T. and Sullivan R. J. (1996) *Icarus, 123,* 557-567. [3] Tufts B. R. et al. (2000) *Icarus, 146,* 75-97. [4] Prockter L. M. et al. (2002) *JGR, 107,* 5028, doi 10.1029/2000JE001458; [5] Nimmo F. et al. (2003) *Icarus, 166,* 21-32; [6] McKenzie D. P. (1969) *GJI, 18,* 1-32 [7] Johnson B. C. et al. (2017) *JGR 122*, doi: 10.1002/2017JE005370. [8] Kargel F. (2000) *Icarus, 148,* 226-265.

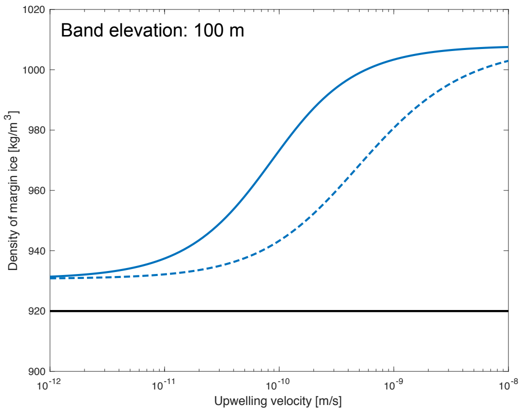

Figure 4: Density of the ice surrounding the band required so that the band stands 100 m higher than it surroundings.