STRAIN HISTORY OF THE ICE SHELLS OF THE GALILEAN SATELLITES FROM RADAR SOUNDING. Amy C. Barr, Department of Space Studies, Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder CO 80302, USA (amy@boulder.swri.edu).

Background & Motivation: Orbital radar sounding has been suggested as a means of determining the subsurface physical and thermal structure of the ice I shells of the Galilean satellites [1]; a radar sounder is a likely choice of instrument on the forthcoming Europa/Jupiter System Mission. The dielectric permittivity of ice is strongly affected by temperature and salinity [5,6,7,8]. Much attention has been paid to the temperature and salt distributions expected within the satellites' shells [7,8].

However, the orientation of the ice crystal lattice also affects the permittivity. At radar frequencies, the dielectric permittivity of polycrystalline ice is anisotropic [2], with the permittivity in a direction parallel to the crystallographic *c*-axis ~ 1% higher than the perpendicular direction. The anisotropy of ice has allowed the inference of crystal orientation fabric (COF), indicative of strain history, from terrestrial ice-penetrating radar surveys of the Antarctic ice sheet [e.g., 3]. Changes in COF can cause reflections of -50 to -80 dB [2], within the nominal -60 dB dynamic range of an orbiting radar sounder [1].

On Earth, large strains ($\varepsilon >>1$) in ice with grain sizes d~1 mm and T>240 K [3,4], lead to the formation of regions with crystal orientations dictated by the local strain field (referred to as "fabric"). These conditions are similar to conditions expected in a convecting ice shell on the Galilean satellites. Because COF is preserved after deformation stops, reflections due to changes in COF could be used to deduce the strain history of the ice shells of the Galilean satellites from an orbiting radar sounder.

Here, I use simulations of solid-state convection to show that COF can form in cold downwellings in a convecting ice shell on the Galilean satellites. COF can also form in the warm convecting sublayer of the ice shells if d>1 mm. Reflections from changes in COF provide a means of testing the hypothesis that resurfacing on the icy satellites is driven by ductile flow of warm solid ice [18; 19].

Fabric Formation on Earth: Deformation in polycrystalline ice can change the size and orientation of the crystal lattice of individual ice grains [4]. When a stress is applied, grains deform by basal slip and their crystallographic *c*-axes rotate toward the axis of compression [4]. Large strains at high temperatures create regions wherein the lattices of adjacent crystal are co-aligned. Deformation by anisotropic creep mechanisms such as dislocation creep or grain boundary sliding coupled with basal slip is required to form COF; flow by diffusion creep, an isotropic deformation mechanism, destroys COF.

Predicting Locations of Fabric Formation in the Galilean Satellites: Here, I simulate solid-state convection in the satellites' ice shells to determine where COF may form [9].

The total strain rate in ice, $\dot{\varepsilon}$, is equal to the sum of strain rates from dislocation creep (disl), grain size-sensitive creep (grain boundary sliding "gbs"/basal slip "bs"), and diffusion creep (diff) [10],

$$\dot{\varepsilon} = \dot{\varepsilon}_{disl} + \left(\dot{\varepsilon}_{gbs}^{-1} + \dot{\varepsilon}_{bs}^{-1}\right)^{-1} + \dot{\varepsilon}_{diff} \qquad (1)$$

where the effective viscosity (η) from each deformation mechanism is related to temperature (T), stress (σ), and grain size (d), $\eta=(d^p/2A)\sigma^{1-n}\exp(Q^*/R_GT)$, with $\eta=\sigma/2\dot{\varepsilon}$, grain size exponent p, stress exponent n, pre-exponential constant A, gas constant R_G=8.314 J/mol-K, and activation energy Q^*. Values for these parameters for each flow law are listed in Table 1.

Rheology	A ($m^p\ Pa^{-n}\ s^{-1}$)	n	p	Q^* (kJ/mol)
Volume Diffusion	1.16×10^{-10}	0	2.0	59.4
GBS	6.2×10^{-14}	1.8	1.4	49
BS	2.2×10^{-7}	2.0	0	60
Dislocation	4.0×10^{-19}	4.0	0	60

Table 1. Rheological parameters for water ice I after Goldsby & Kohlstedt (2001).

A composite rheology [11, 12, 13],

$$\frac{1}{\eta_{tot}} = \frac{1}{\eta_{disl}} + \left[\eta_{GBS} + \eta_{BS}\right]^{-1} + \frac{1}{\eta_{diff}} \qquad (2)$$

is used to account for contributions to the ice viscosity from each deformation mechanism. I assume that the ice shell has a uniform grain size 0.1 mm < d < 30 mm, appropriate for low-temperature fabric formation without concomitant recrystallization [4], and an ice shell whose grain sizes are kept constant by grain boundary pinning from silicate microparticles [14, 15].

CITCOM [16] is used to simulate convection for a range of grain size and shell thickness values appropriate for the Galilean satellites. First, I perform a series of 2-dimensional simulations in a 1x1 Cartesian box to determine how the locations of COF formation change as a function of grain size. Then I perform three-dimensional Cartesian simulations in a 4x4x1 box to illustrate the pattern of COF formation and its relationship to the convection pattern [9].

The surface is kept constant at T_s=110 K, and the bottom of the ice shell is basally heated to maintain T_b=260 K. Free-slip boundary conditions are imposed on the vertical sides of the box. The Rayleigh number is,

$$Ra_o = \frac{\rho g \alpha \Delta T D^3}{\kappa \eta_o} \quad (3)$$

with reference viscosity $\eta_o = \eta_{diff}(T_b)$, ice density ρ=920 kg/m^3, gravity (mean value approximately valid for Europa, Ganymede, and Callisto) g=1.3 m^2/s, coefficient of thermal expansion $\alpha=10^{-4}$ K^{-1}, $\Delta T=(T_b-T_s)$, and thermal diffusivity $\kappa=10^{-6}$ m^2/s. The viscosity of ice is expressed as $\eta=(1/\beta)\sigma'^{1-n}\exp(E(1-T'))$ for each term [17], where $E=(Q^*\Delta T/R_G T_b^2)$, and $\beta=(2\eta_o)^n \dot{\varepsilon}_o^{\,n-1} A d^p \exp(-Q^*/R_G T_b)$, where $\sigma'=\sigma/2\eta_o \dot{\varepsilon}_o$, $\dot{\varepsilon}_o=\kappa/D^2$, and $T'=(T-T_s)/\Delta T$.

Strain in the ice shell is estimated as $\varepsilon \sim \dot{\varepsilon}(D^2/\kappa)$, by assuming that strain accumulates over at least one thermal diffusion time scale. COF forms where the ratio of strain due to dislocation + GSS creep,

$$R = \frac{\varepsilon_{disl} + \varepsilon_{GSS}}{\varepsilon_{diff}} \quad (4)$$

is greater than 1, and where T>240 K.

Results: *Convection.* Simulations of convection in ice shells with 20 km < D < 100 km and 0.1 mm < d < 30 mm show that COF can form in the cold convective downwellings, regardless of ice grain size or shell thickness [9]. For grain sizes d> 1 mm, COF-forming regions encompass the entire ice shell. Figure 1 illustrates the temperature and R values in a 30 km-thick ice shell with d=0.3 mm. The diameter of regions with R>1 is about 25 km, similar to the thickness of the ice shell. An instrument that could spatially resolve convective upwellings would be able to detect reflections off the edges of the downwellings. Past convection could be detected by looking for a layer of relict crystal fabric within a conductive ice shell. Future work should address how shallow [24] and deep tidal heating [25] in Europa's ice shell could affect the sites of COF formation.

Resurfacing. Because warm ice and large strains have been suggested as a means of forming surface features on Europa and Ganymede, reflections from COF can shed light on the satellites' modes of resurfacing. If Europa's bands form in a manner similar to a terrestrial mid-ocean ridge [20], I predict that COF will form beneath bands. Modeling of band formation suggests ε>>1, flow during extension accommodated by dislocation creep, and T~260 only a few km below the surface [21]. COF will likely form beneath Ganymede's grooved terrain, where strains ~0.5 to 2 are recorded by ancient impact craters [22], flow in the subsurface is accommodated by dislocation creep, and high thermal gradients near the surface lead to T>240 K at a depth of a few km [23].

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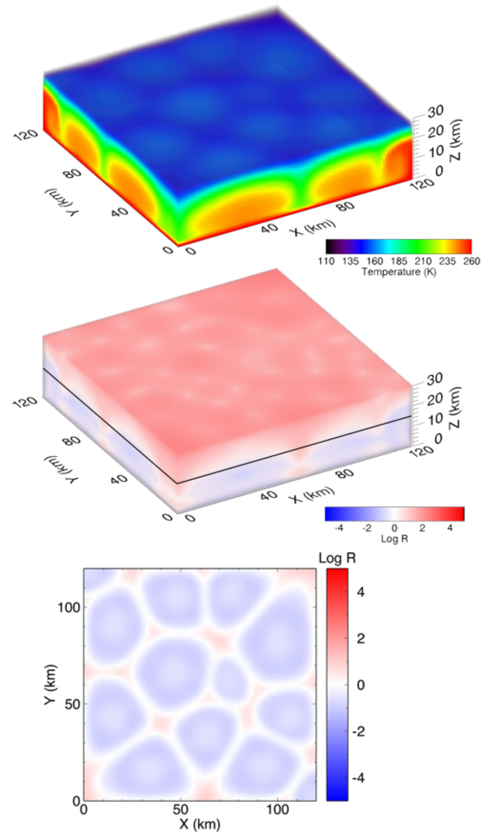

Figure 1. Temperature (top), R (middle), and slice of R values at the depth where the horizontally averaged T=240 K for a 120x120x30 km section of the ice I shell of a Galilean satellite with d=0.3 mm (Ra_o=1.4x10^6). In the bottom two panels, red areas within convective downwellings are locations where COF is created. Blue areas show locations where strain is accommodated by volume diffusion, which destroys COF.

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