GRAIN SIZE CONTROLLING PROCESSES WITHIN EUROPA'S ICE SHELL G. Tobie, P. Duval and C. Sotin [1]LPG (UMR CNRS-6112) Univ. Nantes, , 2, rue de la Houssinière, BP 92208, 44322 Nantes cedex 03, France, [2]LGGE (UMR-CNRS 5138), Domaine Universitaire, 54 rue Molière, BP 96, 38402 S^t Martin d'Hères, France (corresponding author : gabriel.tobie@univ-nantes.fr)

Introduction: Magnetic data gathered by the Galileo spacecraft [1] as well as images of the tectonically active surface [2,3] provide circumstantial evidence that a soft, probably liquid, layer may exist few kilometers to few tens beneath the cold icy surface of Europa. However, the thickness and the thermal state of the icy crust still remain poorly constrained. Uncertainties mainly results from our misunderstanding of ice rheology at low stresses relevant for both convective and tidal deformations [4]. Several laboratory studies and field data analysis indicate that the flow law for deviatoric stresses lower than 0.1 MPa is associated with a stress exponent of 2 and is grain-size sensitive [5,6]. These results can be questioned because of the long time needed to obtain reliable data. However, a clear indication of the decrease of the stress exponent ($n<2$) below 0.1 MPa is also found from the analysis of Earth's polar ice sheet field data [7].

Following the experimental works of [5], it has been commonly argued that the grain size within Europa's ice I shell should be small (less than 1 mm) for the ice shell to be convective [8, 9, 10]. However, such small grain sizes are incompatible with grain size measurements along ice cores on Earth's polar cap [11, 7, 12], which experience stress and temperature conditions similar to ice within Europa's convective ice shell [4]. In order to accurately assess the grain size distribution within Europa's ice Ih shell, we propose to use the model of Montagnat and Duval [7], developed to interpret grain size distribution along Arctic and Antarctic ice cores. The grain size distribution within the convective ice layer is computed from the temperature and strain rate fields obtained from numerical simulations of the tidally heated convective ice layer [4].

Grain size controlling processes: Depending on temperature and the stored energy within grains, several processes can control grain size in Europa's ice shell. During normal grain growth, the microstructure exhibits a uniform increase of size. The driving force arises from a reduction in the grain boundary free energy. In polar ice sheets, the driving force is typically between 100 and 10 J.m^{-3} with grain sizes in the range of 1 to 10 mm [13]. It is worth noting that crystals with a size larger than 100 mm were found in the deepest parts of East Antarctica [14]. The grain boundary migration rate is less than 10^{-14} m^2.s^{-1} below -10^{o}C; but, it can reach a value of about 10^{-8} m^2.s^{-1} at the melting point [15]. During deformation, grain size is generally controlled by dynamic recrystallization [16]. During continuous (or rotation) recrystallization, high-angle boundaries develop with the progressive misorientation of sub-boundaries produced by recovery processes [17]. With this recrystallization process, grain boundaries migrate in the same low-velocity regime as the one associated with grain growth. The growth of grains is balanced by the formation of new grain boundaries [7]. This recrystallization regime is the main controlling grain size process in polar ice sheets [14], and it is adopted here.

Within Europa's ice Ih shell, both tidal deformation and convection contribute to the total strain of ice Ih. However, though tidal strain rate is about two orders of magnitude above the convective strain rate [4], it is applied on short timescales, so that the cumulative strain on a half tidal cycle never exceeds 2.10^{-5}. Cyclic loading mechanical tests [18, 19] show that no dislocation generation is observed for such a low strain, at least for frequency higher than 10^{-4} s^{-1}. Nevertheless, even though the viscoelastic response of ice to tidal forcing does not modify the population of dislocations, it is highly sensitive to the density of existing dislocations within the ice crystal lattice. Like in the primary (or transient) creep [e. g., 20], the evolution of stress within cyclically loaded ice Ih is related to the storage of strain energy in the internal energy of the polycrystals by rearranging the local field of stress around each grain [15]. During the first quarter of tidal cycle, the strain energy is progressively stored as the compressive stress increases, and then, during the second quarter, it is returned once the compressive stress decreases. The same process operates during the other half period, when the stress is tensile. The energy storage and recovery are associated with the dislocation motions mainly on the basal plan, which explain the heterogeneity of the local stress field and its subsequent rearrangement [15]. Dissipation within the ice Ih is thus related to the mobility of dislocations and their friction with the crystal lattice during their short-range displacement created by the alternative compression and tension. These back and forth motions are unlikely to induce accumulation of dislocations within the crystal, whereas the slow motions of dislocation related to convective strain should progressively accumulate dislocations, leading to the polygonization of the grains.

Simulated grain size distribution: The temperature and strain rate fields are computed with the 2D numerical code used and described in [4], from which the time evolution of grain size distribution is computed using the physical model of [7]. Contrary to [4] where the Frank-Kamenetskii approximation was applied, here we adopt an Arrhenius law with possible variations of the activation energy close to the melting point in order to take into account the creep enhancement owing to premelting [5,6]. It provides a better description of the viscosity variation in both hot and cold thermal boundary layers (TBL), which is essential to correctly assess the effective strain rate. The viscosity of ice is assumed to be Newtonian and no grain size dependence is taken into account. The activation energy E_a is set to 50 kJ.mol^{-1}, except for T>255K where it is set to 190 kJ.mol^{-1} if premelting effect is considered [5, 6].

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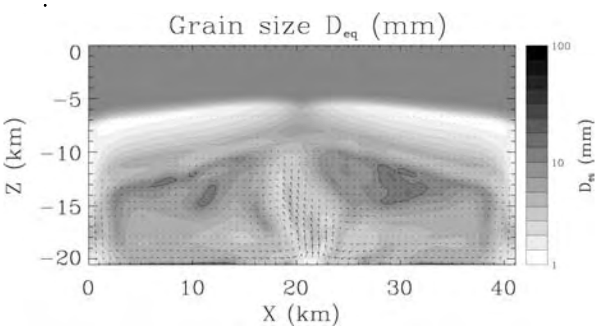

Figure 1: Average grain size field obtained for the slower grain boundary migration rate as defined by [14] and when creep enhancement is considered at T>255 K.

Fig. 1 represents a snapshot of the average grain size field, in the case where creep enhancement at T>255 K is taken into account, for a 20.5 km ice shell and a reference viscosity of 1.4x10^{14} Pa.s at T=255K, and an initial grain size of 10 mm. It shows that the grain size distribution is heterogeneous, reflecting a mixing of the strain rate and temperature distributions. The minimum average grain size (1 mm) is found in the cold TBL where the downwellings initiate. The average grain size also reaches a few millimeters at the base of the central hot plume, but can exceed few centimeters in the wings of the plume. Note that the grain size is not affected by thermal instabilities in the conductive stagnant lid.

Fig. 2 shows the corresponding mean profile (solid black curve) as well as other profiles obtained for different assumption on viscosity and grain boundary migration (GBM). Two extreme assumptions on grain boundary migration rate as defined by [14] have been used. Variations of these values modify the mean grain size value, but do significantly the lateral and depth variations. On the other hand, when the creep enhancement at high temperature is not considered, the effective strain rate strongly reduces in the hot plume, resulting in an increase of grain size above 4-5 mm. Alternatively, the grain size in the cold TBL remains identical, being even a little bit smaller due to a slight enhancement of the effective strain rate there.

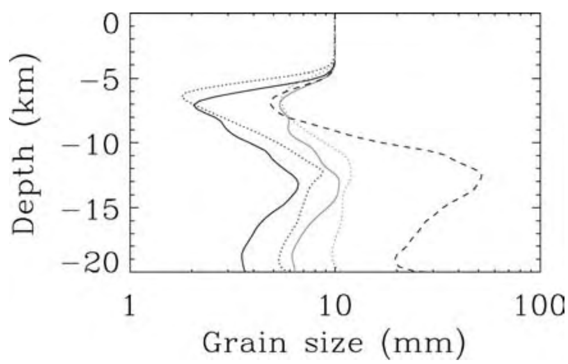

Figure 2: Horizontally averaged grain size profile obtained for slow (solid) or rapid (dashed) GBM rate and with (black) or without (grey) creep enhancement at T>255 K.

Conclusions: Our simulations demonstrate that the grain size distribution in Europa's ice shell is strongly heterogeneous with values ranging from 1 mm to several centimeters. The smaller grain sizes are usually found at the base of the conductive lid where cold downwellings initiate and at the center of hot plumes. Even though the incorporation of impurities (salt minerals, dust etc.), which are not taken into account here, could slightly modified our present conclusion, extended areas with grain size smaller than 1 mm within Europa's ice shell is physically unrealistic. Our derived grain size distribution is in agreement with grain size distribution along terrestrial ice cores. As for polar ice on Earth, this supports the assumption of the preponderance of intracrystalline slip, accommodated by grain boundary migration associated with normal grain growth or rotation recrystallization.

References:[1] Kivelson et al. 1998; Science 89, 1340 [2] Greenberg et al 1998 Icarus 135, 64; [3] Pappalardo et al. 1999 JGR ; [4] Tobie et al. 2003 ; JGR 108(E11) [5] Goldsby and Kohlstedt, 2001 JGR 106, 11017; [6] Durham et al., 2001 JGR 106, 11036 [7] Montagnat and Duval 2000, EPSL 183, 179 [8] McKinnon 1999 GRL 26, 951 [9] Nimmo and Manga 2002, 29 [10] Ruiz and Tejero 2003; Icarus 162, 362 [11] Cuffey et al. 2000 JGR 105; 27889 [12] Duval and Montagnat 2002 JGR 107(B4); [13] Duval and Castelnau, 1995 JGR J. Phys. 5, 197; [14] Durand et al., 2005; JGR in press [15] Duval et al., 1983 J. Chem. Phys. 87, 4006 [16] De la Chapelle et al., 1998 JGR 103, 5091; [17] Poirier, 1985; [18] Tatitbouet 1987 PhD thesis Univ Lyon Fr., [19] Cole et al. 1998, JGR 103(C10) ; [20] Jacka 1984 CRST 8(3), 261.