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Recrystallization Processes in Granular Ice

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Abstract: Recrystallization mechanisms are known to accommodate the deformation as observed along ice cores. The three main processes are classically described as being, successively from the top of the cores, normal grain growth, rotation dynamic recrystallization and migration dynamic recrystallization. Recent observations on local mechanisms at the grain scale tend to question this description.

This paper aims at presenting the basic knowledge about dynamic recrystallization processes in materials, with focus on the corresponding mechanisms occuring during deformation of granular ice, more particularly along ice cores. We stress the significance of the scale to consider when analysing the mechanisms, depending on the applications. In particular, we will demonstrate that dislocation substructures can develop locally, due to strong strain heterogeneities, without challenging the classical description that explains the evolution of average grain size and fabrics along ice cores.

Keywords: Dynamic recrystallization. Ice sheets. Microstructures. Fabrics.

1 Introduction

Ice cores are an important source of information on past climates [1, 2, 3, 4]. However, paleoclimatic interpretations are dependant on the relation between the depth of a layer and its age. This link is established by annual layer counting for high accumulation rate sites (mostly Greenland) and by inversion of simplified flow models, which are unable to reproduce the observed flow heterogeneities [5, 6]. The ice rheology has a strong impact on the flow and must be correctly taken into account in ice flow models to better understand the dynamics of ice sheets [7, 8, 9]. Regarding material science, ice extracted from ice cores contains a unique set of data which provides valuable observations on deformation controling processes. Therefore, understanding the processes which drive the deformation of ice, is of primary interest.

Ice is a polycrystalline material with hexagonal structure. The orientation of each crystal can be specified by its c and a axes. Deformation occurs mainly by dislocation glide along basal planes confering an important viscoplastic anisotropy to the crystal [10]. Such an anisotropy at the crystal scale induces the development of strong internal stresses during deformation of the polycrystal, associated with the mismatch of dislocation slip between neighboring grains.

It is now well demonstrated that plasticity of ice single- and poly-crystal is strongly heterogeneous, with dislocation motion highly intermittent in space and time [11, 12]. This means that deformation takes place through isolated "bursts" (dislocation avalanches) in which the instantaneous strain rate may exceed the average strain rate by several orders of magnitude [13]. In ice polycrystals, grain boundaries appear to act as barriers to the dynamic propagation of avalanches but also to transmit internal stresses [11]. Recently Louchet et al. [14] questioned the impact of such self-organised critical dynamics on the deformation in the ice core conditions. Field data suggest that grains contain a very low number of dislocation moving at a time but that strong back-stresses are present, corresponding to a significant density of potentially mobile dislocations [15]. These findings are consistent with critical dislocation dynamic, in which collective motion events occur for a short time, followed by long periods of inactivity during which grain growth, rotation recrystallization and other recovery processes contribute to the reduction of the long range internal stress field [14].

In most parts of ice sheets, due to intracrystalline dislocation slip, c axes rotate during deformation toward the compression directions and away from tensional ones [16], while they center around an axis perpendicular to the shear plane, in areas where simple shear is dominant. Then, c axes distribution (referred to as fabric in what follows) is a consequence of the strain-history experienced by the ice layer from the ice-sheet surface. The spatial variability of the observed fabrics, from a single maximum fabrics [6, 17] to girdle type fabrics [18], indicates the strong coupling existing between the fabric and the local flow conditions. The fabric formation confers a strain induced anisotropy to the polycrystal which influences further flow [7, 19, 8]. At some stage, it is a chance, because ice-sheets can be seen as a huge database containing fabric evolution experiments for a very large range of strain-history and temperature conditions. On

the other hand, the very small amount of data (few ice cores) regarding the ice-sheets typical size renders the exploitation of all these data very difficult.
Deformation in ice sheets occurs at very low strain rate (from 10^{-12} s^{-1} to 10^{-10} s^{-1}) and under deviatoric stresses estimated to be lower than 0.1MPa. The average temperature ranges between roughly -50°C and the pressure melting point, from the top to the bottom of the ice sheet. Due to these extreme deformation conditions, recovery processes are very active. Alley et al. [20] described the grain growth mechanism which theoretically explains the increase in grain size in the first hundred meters of the cores. Further down, with increasing total strain, dynamic recrystallization mechanisms occur. Beside the rotation of c axes due to strain, it is commonly agreed that recrystallization processes affect the texture of ice (*i.e.*, the fabric as well as the topological arrangement of grains), and thus the effective viscosity of the polycrystal [21, 22].
Recent results [23, 24] have questioned the classical description of the deformation accommodating processes along the core, by suggesting that dynamic recrystallization processes impact the deformation much earlier than commonly expected. The aim of the present paper is to build a state of the art of what we actually know about recrystallization processes as occurring in ice sheets, thanks to ice core texture measurements. We will first recall the basic knowledge of recrystallization mechanisms in materials, then what is known and observed for ice from laboratory tests and from ice cores. The commonly known mechanisms will be questioned regarding new results and assumptions.

2 Recrystallization processes in materials

Recrystallization and related annealing phenomena have been most widely studied in metals. Therefore, most of the description and terminology used further for the description in rock and natural materials have been taken from metallurgical research, and some were adapted to fit the natural deformation conditions.
Recrystallization mechanisms that we will describe in this paper are the ones relevant to ice deformation conditions. They only occur during deformation and are then called "dynamic recrystallization" eventhough the term "dynamic" will sometimes be omitted. On the contrary, in metals, most of the recrystallisation processes widely studied so far are "static" recrystallization mechanisms, *i.e.* occurring after deformation is over.

2.1 Normal grain growth

In polycrystalline materials, the *normal grain growth* is driven by the decrease of the total grain boundary energy within the polycrystal. Normal grain growth mainly occurs after primary recrystallization, or during deformation when the strain stored energy is low compared with the total grain boundary energy.
The driving pressure on a boundary of energy γ_{gb} arises from its curvature. The driving pressure P is given by :

$$P = \gamma_{gb}\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \tag{1}$$

where R_1 and R_2 are the principal radii of curvature of a boundary of energy γ_{gb}.
Assuming that the grain boundary is a part of a sphere of radius R, the driving pressure can be expressed as [25].

$$P = \frac{2\gamma_{gb}}{R} \tag{2}$$

By assuming that γ_{gb} is the same for all the boundaries and the radius R is proportional to the mean radius $< R >$, the boundary velocity is given by:

$$\frac{d < R >}{dt} = M\frac{\alpha\gamma_{gb}}{< R >} \tag{3}$$

with α a constant and M the grain boundary mobility. Already note that γ_{gb} increases with misorientation up to about 15° and is then roughly constant except for coincidence orientations where it is lower. The kinetics of normal grain growth is then expressed by:

$$\langle R\rangle^m = \langle R_0\rangle^m + Kt \tag{4}$$

where $\langle R\rangle$ is the mean grain radius, $\langle R_0\rangle$ is the initial mean grain radius, K an Arrhenius temperature dependant constant which can be considered as the grain boundary migration rate, and $m = 2$. The parabolic law was derived from mean field approximations which consider the behavior of a single grain embedded in an environment which is some average representation of the whole assembly [26]. Other approaches, like Monte Carlo simulations [27] or vertex modeling [28] give similar grain growth law exponents for the mean grain radius evolution of an assemblage of grains. Normal grain growth can be affected by temperature, by solutes and particles or by the fabric. Indeed, as a highly clustered fabric contains a large proportion of low angle grain boundaries, there is therefore a reduced driving force for grain growth.
In the regime of normal grain growth, the distribution of normalized grain sizes $R/\langle R\rangle$ remains unchanged, unimodal, and is generally well fitted by a log-normal distribution [29, 30]. Note however that this log-normal fit has not so far received theoretical support.
An extensive description of the theory of *normal grain growth* can be found in [29] and with particular emphasis on normal grain growth in polar ice in [20, 31, 32].

2.2 Dynamic rotation and migration recrystallization

From Humphreys and Haterly [29] it is well established that in minerals, and thus in ice, two types of dynamic recrystallization occur. At high temperature and high stresses, a discontinuous form of dynamic recrystallization similar to recrystallization during hot working in metals occurs, and is referred, in the geological literature as "migration recrystallization". However, at lower temperatures and stresses there is often a transition toward a mechanism called "rotation recrystallization" similar to what is called "dynamic recrystallization by progressive lattice rotation", with a discontinuity in the grain boundary migration rate at the transition.

Rotation (or continuous) recrystallization

From Humphreys and Haterly [29], in many materials, new grains with high angle boundaries may be formed during straining, by the progressive rotation of subgrains with little accompanying boundary migration. This is a strain-induced phenomenon which should not be confused with the subgrain rotation which occurs during static annealing.

This mechanism was first found in minerals. It involves subgrains, adjacent to pre-existing grain boundaries, which progressively rotate as dislocations are accumulated with strain. A gradient of misorientation is developed in the grain, from the centre to the edges, where dislocations are piled-up, and at high strains, high angle boundaries may develop.

This mechanism is then likely associated with inhomogeneous plasticity and accelerated dynamic recovery in the grain boundary regions.

Considering the heterogeneous nature of dislocation slip processes [33] and evidence for intermittent nature of creep deformation [34, 35, 36, 37], we can wonder whether this mechanism is progressive or occurs as a burst-type mechanism. To our knowledge, there exist no studies relating the intermittent dislocation behavior to the dynamic recrystallization mechanisms. What we call "progressive" structure evolution might rather be a threshold type of mechanisms evolving rapidly with time [38]. Traditionnal post-deformation observations can only capture a final state and are not able to characterize the intermittent nature of such mechanisms. Observations were made during in-situ deformation of pure copper under X-ray diffraction where dislocation structures showed intermittent dynamics, appearing and disappearing with proceeding deformation [39].

At the local scale, there is a threshold value of dislocation density up to which a subgrain is energetically more favorable than an isolated dislocation structure. The energy of a subgrain with a misorientation θ is given by [38]:

$$E(\theta) = E_0\theta\,(A - ln\theta) \tag{5}$$

$$E_0 = \frac{bG}{4\pi(1-\nu)} \tag{6}$$

$$A = 1 + ln\frac{b}{2\pi r_0} \tag{7}$$

where b is the norm of the Burgers vector, G is the shear modulus, ν is the Poisson ratio, and r_0 is the dislocation radius.

The energy of a density ρ of isolated dislocations is:

$$E = \frac{\mu b^2 \rho}{2} \tag{8}$$

with μ the shear modulus. In ice, for $r_0 = b$ the subgrain energy is smaller than the isolated dislocation energy for a misorientation θ equal to about $1°$corresponding to a dislocation density of about 5×10^7 m^{-2}, a value that would correspond to the initial state in a non deformed crystal [40, 15].

At the polycrystal scale, the effect of rotation recrystallization is a decrease in the average grain size and the creation of some correlations between the orientation lattice of neighbouring grains [41, 42, 24].

Migration (or discontinuous) recrystallization

As was shown for instance for NaCl [43] and ice [44], there exist a clear boundary between rotation and migration recrystallization domains. The first occurring at low stresses and temperature, the second at high stresses and temperature. The transition is characterized by a jump in the grain boundary mobility. For a strain larger than a critical strain and if the temperature is high enough, the intrinsic mobility of the grain boundary (linked to the temperature and the misorientation angle) may be high enough for migration recrystallization to occur.

Humphreys and Haterly [29] provide an accurate simplified description of the mechanism which is as follows. New grains are created at the old grain boundaries, but due to deformation going on, the new grains accumulate dislocations, thus reducing the driving force for their further growth. Therefore, a critical deformation is necessary in order to initiate dynamic migration recrystallization. For grain boundary migration, the driving force is due to the difference in strain energy between deformed grains and dislocation-free areas. For very low strain rates and large initial grain size, intragranular nucleation becomes more important. The driving force for dynamic migration recrystallization increases with applied stress and the intrinsic boundary mobility is a function of temperature. The created new grain structure, which may or may not involve the migration of grain boundaries, eventually becomes independant on strain [29, 45].

Humphreys and Haterly [29] compiled data from a large variety of materials providing the evolution of the dynamically recrystallized grain size as a function of stress at high temperature. The empirical relationship is given by:

$$\sigma = KD^{-m} \tag{9}$$

where m<1 and K is a constant that does not depend on temperature. Such measurements were performed on ice by Jacka and Li [46], and will be presented in paragraph 3.1.

The obtained steady state is coming from the balance between nucleation of new small grains and migration of existing boundaries. Derby and Ashby [47] have developed an analysis based on the characteristic time taken for a moving boundary to sweep out a volume equivalent to the mean steady state grain size. This time is supposed to be equivalent to the one required for a nucleus to be formed in the growing volume. The difficulty with this approach is to estimate a realistic value of the nucleation

rate.
Criterium based on the bulging mechanisms, together with dislocation density as a main parameter was suggested by Roberts and Ahlblom [48] and more recently by Bréchet et al. [49]. Both approaches predict that dynamic recrystallization is favoured for high values of mobility and stress, and low values of strain rate.

3 Dynamic recrystallization processes in ice

The above described recrystallization mechanisms are observed in ice. But, due to the very low strain rates and stresses in ice sheets, processes observed in the field are very different from those observed in the laboratory. The first can not yet be reproduced in the laboratory and there exist no obvious matching between recrystallization observed in laboratory tests and most of the recrystallization processes measured along ice cores.

3.1 Migration recrystallization in laboratory deformed ice

We will focus on the mechanical behaviour of "granular" ice, which is the closest to glacier ice. Most of the tests performed in the laboratory have been creep tests, performed under constant applied stress, for applied shear stresses lower than 1MPa.
A sketch of a typical creep curve is shown in Figure 1 giving, on log scale, the strain rate as a function of strain. Three creep stages are observed [50, 40, 51]. Following the first instantaneous elastic strain, there is a primary or transient creep during which the creep rate decreases continuously. This primary creep occurs to about 1% strain, and is followed by a secondary creep corresponding to a minimun creep rate between 1 and 2% strain. This secondary creep corresponds to the transition between the decelerating primary creep and the accelerating tertiary creep. During the tertiary creep, and beyond about 10% of strain, a steady state is reached which is associated with stable fabrics and steady state grain size due to dynamic migration recrystallization [10, 51].

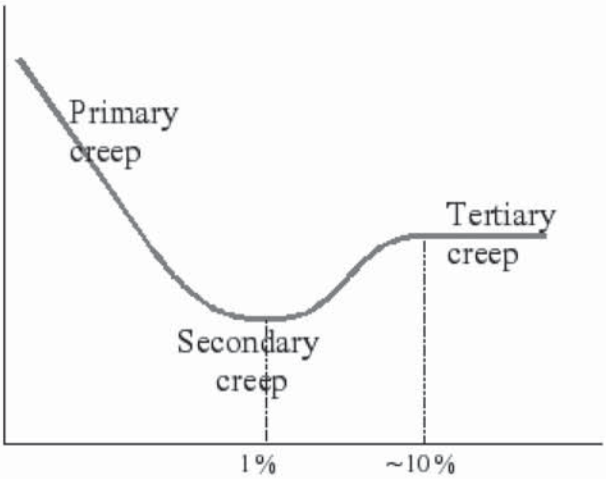

Figure 1: *A typical creep curve, strain rate as a function of strain, for a constant applied stress on isotropic granular ice.*

During primary creep, strong internal stresses are built due to the mismatch of dislocation slip between grains. Dislocations are accumulated at grain boundaries, but the accumulated strain is too low to induce any fabric development. When the stored energy is high enough, the internal stresses are relaxed via dynamic migration recrystallization during tertiary creep and lead to the steady state just described.
Jacka and Li [52] performed uniaxial compression creep tests on laboratory prepared samples, with initially randomly oriented crystals. The tests covered the temperature range of -10°C to -45°C for stresses ranging between 0.1 to 0.8 MPa.
The minimum creep rate was systematically obtained for strain close to 1%. At -15°C, for stresses higher than 0.1 MPa, the three creep regimes are observed. The tertiary creep is always characterized by a steady-state strain rate which decreases with the stress. The fabric pattern associated with this tertiary creep is well characterized by a small circle girdle at around 30°from the compression axis. This girdle tends to weaken with decreasing temperature and stresses. From that, the authors conclude that migration recrystallization is the dominant mechanism controlling flow rate at higher stresses and temperature. Assuming that this recrystallization mechanism is still active at lower stresses and temperature, the processes are too slow to reach a steady state fabric and microstructure within the duration of the experiments.
Jacka and Li [46] show that during tertiary creep, not only a stable preferred crystal orientation developed but also a steady-state grain size resultes from deformation to large strains (> 10%) following Equation 9. Equilibrium crystal size does not depend on temperature and decreases with increasing applied stress. It is considered as a "balance" between crystal growth due to grain boundary migration and small new grain nucleation due to accumulated dislocation substructures during deformation.
Duval et al. [10] showed some microstructures after migration recrystallization under compression and torsion which reveal some interlocking microstructures with large irregular grains surrounded by smaller grains. Similar microstructures were observed by Jacka and Maccagnan [53] for tests performed in compression at strain higher than 5%, with girdle-like fabric around 30°from the compression axis.

In summary, during laboratory experiments, tertiary creep is associated with a steady state due to dynamic migration recrystallization occurring after a few % strain. This dynamic recrystallization provides a constant grain size at a given deviatoric stress, a microstructure characterized by large interlocked grain surrounded by smaller grains. Fabrics formed by such strain-induced recrystallization processes are characterized by orientations favorable to the basal slip which can adjust rapidly to a change in applied stress.

3.2 Dynamic recrystallization in polar ice sheets

So far, it has commonly been accepted that recrystallization mechanisms accommodating deformation along ice cores were, successively, normal grain growth, rotation dynamic recrystallization in the main part of the cores, followed by migration recrystallization in the bottom part of some cores where temperature becomes higher than -10°C, and accumulated stress is sufficient [18, 54, 17, 22, 55, 6].

All the described processes occurs during deformation. This has to be emphasized when describing "normal grain growth" along ice cores.

Recent results tend to show that there exists strong overlaps between these recovery mechanism areas of dominance, with processes that can locally occurs at the grain scale. To distinguish the relevant scale of analysis is then of main importance when trying to model the basic mechanisms associated with recrystallization or to represent the average evolution of the textures and microstructures.

Figure 2 presents the evolution of grain size along the GRIP (Greenland) [17], EPICA Dome C [56] and Byrd (Antarctica) [57] ice cores. Please note that the measurement techniques are different and can introduce bias in the absolute values [58].

Normal grain growth

Created by the progressive densification of snow and firn, ice in ice cores has small grain size in the upper layers (about 1 mm). Grain growth is already occurring in firn [59, 60], and probably in snow as the densification processes take place over more than 2000 years in some cold places (Antarctic plateau). Deformation processes being very slow, the surface energy is reduced by a mechanism similar to the "metallurgical" normal grain growth described in paragraph 2.1 while deformation is going on. At the interface between ice and air, the local stresses can be very high and dislocation pile-ups are expected.

Alley et al. [31], Arnaud et al. [61] and, more recently, Durand et al. [32] have shown that average grain size evolution with depth in bubbly ice and firn (first hundred meters of the core) was very well represented by classical modeling of normal grain growth in dense materials. This was also true for the microstructure evolution, topography and size distribution. In particular, Weiss et al. [62] has shown that, up to 580 m depth along the EPICA Dome C ice core, the distributions of normalized grain sizes are well fitted by log-normal distributions, as expected when normal grain growth is dominating. The two independent parameters characterizing the log-normal distribution, i.e. the average and the standard deviation, are slightly evolving with depth, which could be interpreted as a transient regime.

As already mentioned, normal grain growth driven by the free energy of grain boundary is observed along polar ice cores where deformation processes are active. At the transition where the grain size becomes constant along the Byrd and GRIP ice core (see Figure 2), an upper bound for average dislocation density accumulated by deformation is estimated by Montagnat et al. [15] of 10^{11} m^{-2}. This corresponds to a driving force due to deformation stored energy of about 30 Jm^{-3}. From the top of the core to this transition zone, grain size ranges between about 1 and 5 mm. With $\gamma_{gb} = 0.065$ Jm^{-2}, the driving pressure P for normal grain growth (Equation 1) then decreases from about 130 to 30 Jm^{-3}. On average, then, the driving force for normal grain growth is always higher than the upper bound driving force associated with dislocations up to this transition in grain size, where dislocation induced recrystallization can dominate. However, locally near grain boundaries, dislocation density can be higher than the average value, which can explain some departure from the exact "normal grain growth" process, with the existence of local dislocation substructures.

The evolution with time of the mean grain size is given by Equation 4. The range of K between -50°C and -10°C is roughly between 10^{-17} and 5×10^{-15} m^2s^{-1} [10]. From data of grain growth in firn and shallow ice in Greenland and Antarctica, the activation energy is about 50 $kJ.mol^{-1}$ [59]. A much higher value is found above -10°C [46].

The exponent $m = 2$ in Equation 4 is a lower bound derived from mean field approximations as explained in paragraph 2.1. The profile of grain growth in the first 400 m of the GRIP core is well reproduced with $m = 2.5$ [17]. A value of 3.2 was found between 100 and 400 m depth along the EPICA Dome C ice core [62]. Departure from $m = 2$ has been associated with solute drag [63], interaction with microparticules, effect of texture [30]. From Durand et al. [32], the departure from the theoretical parabolic law along the EPICA Dome C ice core is likely to result from bubble pinning, assuming that the grain boundary mobility is significantly higher than the mobility of bubbles. Considering the new observations of dislocation substructures from firn and the early ice [23, 24] (presented in the next paragraph), a very plausible explanation for the value of $m > 2$ in deep ice cores is the progressive occurring of rotation recrystallization, with polygonization progressively influencing the grain size distribution.

A consequence of normal grain growth is clearly visible on Figure 2, for the Byrd and GRIP ice core. The stop in grain size increase is associated with the dominating impact of rotation recrystallization, in an area where the temperature remains constant along the core. On the contrary, along the EPICA Dome C ice core, such an abrupt change in grain size evolution is not evidenced, which is attributed to the continuous temperature increase along the core.

In glacial ice, grain growth rate is significantly lower than for interglacial periods [57, 64, 18, 65, 17, 66]. Significant variations in the particle and impurity contents are found in the Antarctic and Greenland ice sheets, most of them well correlated with climate [67, 68]. Several explanations were given for the correlation between climate and grain size, including impurity drag [31] and the pinning of grain boundaries by microparticles [66, 32]. The drag of soluble impurities segregated at grain boundaries could also reduce the grain boundary mobility [20, 31].

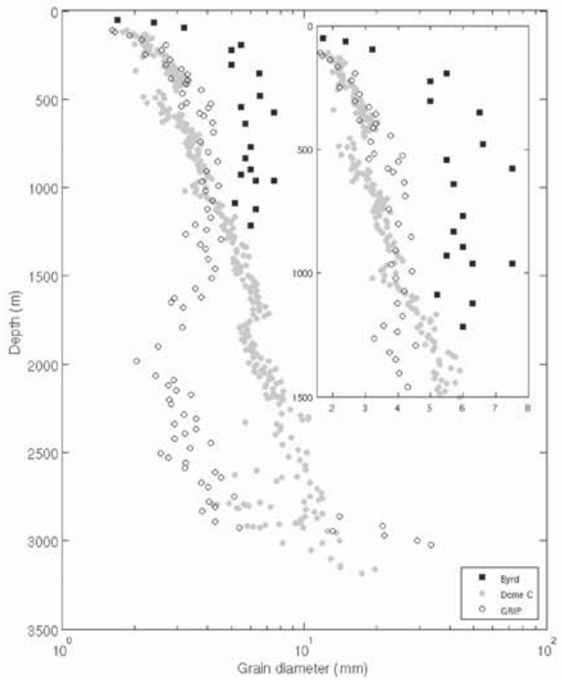

Figure 2: *Evolution of grain size along the EPICA Dome C (full circles), the GRIP (empty circles) and the Byrd (full squares) ice cores. Inner panel: focus on the first 1500 m*

Rotation recrystallization

Rotation recrystallization mechanisms appear to extensively occur in polar ice sheets. For the Byrd ice core, Alley et al. [41] indicate that polygonization processes associated with this recrystallization counteract further grain growth below 400 m depth. The same explanation was given by Castelnau et al. [21] for the constant grain size between 650 and 1625 m along the GRIP ice core. At Vostok and Dome C, due to the continuous increase in temperature from the surface, the transition from grain growth to rotation recrystallization is hard to determine from the grain size profile [22]. But Lipenkov [personal communication, 2000] observed the first sub-boundaries under polarized light below 700 m. Durand et al. [32] modeled the different mechanisms such as normal grain growth, rotation recrystallization as well as pinning effect of dust particles, bubbles and clathrates and showed that rotation recrystallization had to be taken into account in order to reproduce accurately the grain size profile along the EPICA Dome C ice core.

Obbard and Baker [69] did Electron Back Scattered Diffraction (EBSD) experiments on samples from the Vostok ice core to measure the complete fabric, including $\boldsymbol{c}$ and $\boldsymbol{a}$ axes in individual grains. The full orientation relations between grains and subgrains allow to distinguish the impact of rotation recrystallization [70]. They suggest that polygonization associated with rotation recrystallization takes place, demonstrated by the high number of low-angle grain boundaries (1-10°) in the misorientation distribution histograms from 1200 to 3329 m depth.

Durand et al. [24] investigated the relationships between neighbouring grains and applied it to the textures measured along the 900 m of the NorthGRIP ice core. Based on the assumption that the splitting of grains increases the number of neighbouring grains with a small angle of misorientation [41] they observed that rotation recrystallization occurred in the upper part of the ice sheet, and that the fractionation rate appeared to be constant. Rotation recrystallization appears as isotropic, independant of the c-axis orientation which evolves along the core. Furthermore, Kipfstuhl et al. [23], have observed lattice substructures inside grains in firn. These observations show that locally, subgrains can appear from the very beginning of the deformation process in the core. Both observations are coherent with the fact that normal grain growth, as occurs in ice core, is associated with deformation, and dislocations inhomogeneously accumulated can locally induce some lattice substructures which can evolve into sub-boundaries. In particular, such observations highlight the fact that, locally, several mechanisms compete.

De La Chapelle et al. [22] provides a model for the evolution of the stored energy along the GRIP and the Vostok ice cores. The evolution of the dislocation density is obtained by a balance between the generation due to deformation, and a reduction by the moving boundaries during grain boundary migration. Assuming average dislocation density in grains, the highest dislocation density obtained along the GRIP core is about 1.8×10^{11} m^{-2} and about 1.3×10^{11} m^{-2} along the Vostok core. From about 1500 m along the GRIP ice core, the average stored energy from dislocations becomes higher than the driving force for grain growth. We can thus assume that, when considering a higher dislocation density close to grain boundaries, such a condition is reached at a higher depth locally near grain boundaries. On the contrary, this condition is never reached on average along the Vostok ice core where the driving force for grain growth remains higher than the dislocation stored energy.

To summarize, due to the high viscoplastic anisotropy of the ice crystal, strong deformation incompatibilities develop which introduce strong heterogeneities of deformation inside the grains and between grains. That these heterogeneities are strong enough, even in firn, to locally induce strong lattice distortions up to subgrain structures is not surprising, considering that subgrains are appearing as early as 1% strain in the laboratory. Nevertheless, the deformation in ice core is so slow that grain boundary migration driven by the reduction in surface energy of grains is a very efficient process to reduce the local internal stresses and dominates in the upper part of the core. Then, this is not a contradiction to develop phenomenologic models, with average variables that consider only the dominating mechanism at a given depth [20, 31, 22, 15, 32]. Such models well reproduce the observed grain size evolution, and allow a prediction of the average dislocation density along the cores [22, 15].

Dynamic migration recrystallization

Migration recrystallization, as described in paragraph 2.2 and more specifically for laboratory deformed ice in paragraph 3.1 has not been clearly observed along ice cores. The driving force for migration recrystallization is the deformation stored energy through dislocations. For grain boundaries to migrate fast enough, it is necessary to provide a good balance between stored energy and grain boundary mobility, which was shown to increase by about 2 orders of magnitude when temperature becomes higher than -10°C [10].

Gow and Williamson [57] observed a rapid transformation to coarse-grained ice with multiple-maxima fabrics below 1810 m depth along the Byrd ice core (in the bottom 350 m). This was attributed to a rapidly increasing temperature from -15°C at 1810 m to -1.7°C at 2164 m favouring migration recrystallization mechanisms.

The same abrupt change is observed in the last 150 m of the 1000 m long Siple Dome ice core [71] where the obtained texture is close to typical "dynamic migration recrystallization" textures observed during laboratory experiments, with dispersed or multi-maxima fabrics. The temperature of the ice at 804 m is about -9°C.

In the last 240 m of the GRIP ice core, abrupt changes in grain size and fabrics appears, consistant with a temperature increase close to -10°C [17, 72]. Textures are characterized by large interlocking grains, and opened fabrics. The presence of large interlocking grains is explained by migration recrystallization but the change in fabrics evolution at the bottom of the core is linked [17] to a change in stress condition, evolving toward tensional stress.

At the bottom of the EPICA Dome C ice core, the temperature increases from -13°C at 2800 m to -2°C at 3250m. The ice is then warm enough for migration recrystallization to occur. Durand et al. [this issue] found a highly fluctuating fabric (measured by second order orientation tensor) in this part of the core, that can not be clearly correlated to climate or chemical components. But microstructures do not show any large interlocking grain. The authors observe some very small grains in between larger grains below 2846 m indicating that nucleation associated with migration recrystallization can occur locally, close to grain boundaries.

On the contrary (to rotation recrystallization), migration recrystallization induces fabrics which are different from strain-induced fabrics. As observed in Alpine glaciers [73, 74], during lab experiments [75, 53, 52] or at the bottom of the Byrd ice core [57], the c-axes rotate toward the direction of easy glide, between 30° and 45° from the vertical axis. Such a fabric provides orientations that favour the imposed compressive strain. The formed fabrics are either imposed by the nucleation of so-called *well* oriented grain, and/or the favoured growth of such grains. The fabric is then controlled by the stress state within the polycrystal [75]. Due to the fabric resulting from migration recrystallization, and the softening associated with this recovery process, the viscosity of the ice layers can become very low. Such an induced softening of the polycrystal behaviour in the bottom part of the core can have a non-negligible impact on the global flow around the core, and should then be accurately understood to be taken into account in flow modeling.

4 Conclusion

Thanks to the observations performed along polar ice cores we have a clear overview of dynamic recrystallization mechanisms accommodating the deformation in ice sheets. The data such as textures and microstructures that are measured along the cores remain "average" data, at the polycrystal scale. Recently, researchers have become involved in trying to understand the local mechanisms associated with grain growth, polygonization and nucleation which characterize recrystallization processes along ice cores. In doing so, the anisotropic nature of deformation of ice appears to have a strong influence on the local mechanisms, at the crystal scale, by inducing high local stress and strain heterogeneities near grain boundaries. Then, locally, recrystallization mechanisms can overlap each other, with evidence of local polygonization in areas where normal grain growth dominates the polycrystal behavior, and observation of small nucleus at some grain boundaries where rotation recrystallization is energetically the most favorable. Such observations stress the interest of a precise definition of the scale at which the observations are done, and their purpose.

The aim of this paper was to describe precisely the mechanisms as they have been defined in material science. "Normal grain growth" in ice core occurs with deformation, but in the upper part of the cores, the driving force due to dislocation storage remains low, at least on average, and the parabolic growth law provides a good representation of grain size distribution measurements.

Furthermore, we have very few clues concerning the occurrence of dynamic migration recrystallization along ice cores, while the process is clearly dominating the deformation of ice in the laboratory.

Considering the time scale of deformation as observed along ice cores, the question remains opened as regards the existence of a stationary state. The viscoplasticity in ice is an intermittent process and is competiting with grain boundary migration which is a very slow temperature dependant mechanism along the main part of ice cores. More observations need to be done to understand the interaction between recrystallization processes and the intermittency nature of deformation associated with dislocation glide. New technics such as EBSD characterization, microstructural observations or X-ray diffraction will be of good help to better understand the processes at the local scale.

References

[1] J.R. Petit, J. Jouzel, D. Raynaud, N. I. Barkov, J. M. Barnola, I. Basile, M. Bender, J. Chappellaz, M. Davis, G. Delaygue, M. Delmotte, V. M. Kotlyakov, M. Legrand, V. Y. Lipenkov, C. Lorius, L. Pépin, C. Ritz, E. Saltzman, and M. Stievenard. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature*, 399:429–436, 1999.

[2] EPICA Community members. Eight glacial cycles from an Antarctic ice core. *Nature*, 429:623–628, 2004.

[3] North Greenland Ice Core Project members. High resolution record of northern hemisphere climate extending into the last interglacial period. *Nature*, 431:147–151, 2004.

[4] EPICA Community members. One-to-one coupling of glacial climate variability in Greenland and Antarctica. *Nature*, 444:195–198, 2006.

[5] F. Parrenin, G. Dreyfus, G. Durand, S. Fujita, O. Gagliardini, F. Gillet, J. jouzel, K. Kawamura, N. Lhomme, V. Masson-Delmotte, C. Ritz, J. Schwander, H. Shoji, R. Uemura, N. Yoshida, O. Watanabe, and E. Wolff. 1D ice flow modelling at EPICA dome C and dome Fuji, East Antarctica. *Clim. Past*, 3:243–259, 2007.

[6] G. Durand, F. Gillet-Chaulet, A. Svensson, O. Gagliardini, S. Kipfstuhl, J. Meyssonnier, F. Parrenin, P. Duval, D. Dahl-Jensen, and N. Azuma. Change of the ice rheology with climatic transitions. Implication on ice flow modelling and dating of the EPICA Dome C core. *Climates of the Past*, 3:155–167, 2007.

[7] A. Mangeney, F. Califano, and K. Hutter. A numerical study of anisotropic, low Reynolds number, free surface flow of ice sheet modeling. *J. Geophys. Res.*, 102(B10):22,749–22,764, 1997.

[8] F. Gillet-Chaulet. *Modélisation de l'écoulement de la glace polaire anisotrope et premières applications au forage de Dôme C.* PhD thesis, Thèse de Doctorat de l'Université Joseph Fourier-Grenoble I, 2006.

[9] E. C. Pettit, T. Thorsteinsson, P. Jacobson, and E. D. Waddington. The role of crystal fabric in flow near an ice divide. *J. Glaciol.*, 53(181):277–288, 2007.

[10] P. Duval, M. F. Ashby, and I. Anderman. Rate-controlling processes in the creep of polycrystalline ice. *J. of Phys. Chem.*, 87(21):4066–4074, 1983.

[11] T. Richeton, J. Weiss, and F. Louchet. Dislocation avalanches: role of temperature, grain size and strain hardening. *Acta Materiala*, 53:4463–4471, 2005.

[12] M. Montagnat, J. Weiss, J. Chevy, P. Duval, H. Brunjail, P. Bastie, and J Gil Sevillano. The heterogeneous nature of slip in ice single crystals deformed under torsion. *Philosophical Magazine*, 86(27):4259–4270, 2006.

[13] M. Zaiser and A Seeger. *Long-range internal stress, dislocation patterning and work-hardening in crystal plasticity*, volume 56. Amsterdam: Elsevier, 2002.

[14] F. Louchet, P. Duval, and M. Montagnat. Are self-organised critical dislocation dynamics relevant to ice sheet flow? In T. Hondoh, editor, *Physics of Ice Core Records*. Hokkaido University Press, Sapporo, in press.

[15] Maurine Montagnat and Paul Duval. Rate controlling processes in the creep of polar ice, influence of grain boundary migration associated with recrystallization. *Earth Planet. Sci.*, 183:179–186, 2000.

[16] N. Azuma and A. Higashi. Formation processes of ice fabric pattern in ice sheets. *Ann. Glaciol.*, 6:130–134, 1985.

[17] T. Thorsteinsson, J. Kipfstuhl, and H. Miller. Textures and fabrics in the GRIP ice core. *J. Geophys. Res.*, 102(C12):26,583–26,600, 1997.

[18] V. Ya. Lipenkov, N. I. Barkov, P. Duval, and P. Pimienta. Crystalline texture of the 2083m ice core at Vostok Station, Antarctica. *J. Glaciol.*, 35(121):392–398, 1989.

[19] T. Thorsteinsson, E. D. Waddington, K. C. Taylor, R. B. Alley, and D. D. Blankenship. Strain rate enhancement at Dye 3, Greenland. *J. Glaciol.*, 45(150):338–345, 1999.

[20] R. B. Alley, J. H. Perepezko, and C. R. Bentley. Grain growth in polar ice: I. theory. *J. Glaciol.*, 32(112):415–424, 1986.

[21] O. Castelnau, Th. Thorsteinsson, J. Kipfstuhl, P. Duval, and G. R. Canova. Modelling fabric development along the GRIP ice core, central Greenland. *Ann. Glaciol.*, 23:194–201, 1996.

[22] S. de La Chapelle, O. Castelnau, V.Ya. Lipenkov, and P. Duval. Dynamic recrystallization and texture development in ice as revealed by the study of deep ice cores in Antarctica and Greenland. *J. Geophys. Res.*, 103(B3):5091–5105, 1998.

[23] S. Kipfstuhl, I. Hamann, A. Lambrecht, J. Freitag, S.H. Faria, D. Grigoriev, and N. Azuma. Microstructure mapping: a new method for imaging

deformation induced microstructural features of ice on the grain scale. *J. Glaciol.*, 52(178):398–406, 2006.

[24] G. Durand, A. Persson, D. Samyn, and A. Svensson. Relation between neighbouring grains in the upper part of the NorthGRIP ice core - Implications for rotation recrystallization. *Earth and Planet. Sc. Let.*, 265:666–671, 2008.

[25] J. E. Burke and D. Turnbull. Recrystallization and grain growth. *Progress in Metal Physics*, 3:220–292, 1952.

[26] M. Hillert. On the theory of normal and abnormal grain growth. *Acta Met.*, 13:227–238, 1965.

[27] M. P. Anderson, G. S. Grest, and D. J. Srolovitz. Computer simulation of normal grain growth in three dimensions. *Philos. Mag. B*, 59(3):293–329, 1989.

[28] D. Weygand, Y. Bréchet, J. Lépinoux, and W. Gust. Three dimensionnal grain growth: a vertex dynamics simulation. *Phil. Mag. B.*, 79(5):703–716, 1998.

[29] F. J. Humphreys and M. Haterly. *Recrystallization and related annealing phenomena*. Pergamon, 1996.

[30] B. Ralph. Grain growth. *Materials Science and Technology*, 6:1139–1144, 1990.

[31] R. B. Alley, J. H. Perepezko, and C. R. Bentley. Grain growth in polar ice: II. application. *J. Glaciol.*, 32(112):425–433, 1986.

[32] G. Durand, J. Weiss, V. Lipenkov, JM Barnola, G. Krinner, F. Parrenin, B. Delmonte, C. Ritz, P. Duval, R. Röthlisberger, and M. Bigler. Effect of impurities on grain growth in cold ice sheets. *J. Geophys. Res.*, 111:F01015, 2006.

[33] H. Neuhauser. Slip-line formation and collective dislocation motion. In *Dislocations in solids*, page 319. F. R. N. Nabarro, Amsterdam, 1983.

[34] J. Weiss, F. Lahaie, and J-R. Grasso. Statistical analysis of dislocation dynamics during viscoplastic deformation from acoustic emission. *J. Geophys. Res.*, 105(B1):433–442, 2000.

[35] T. Richeton, J. Weiss, and F. Louchet. Breakdown of avalanche critical behaviour in polycrystalline plasticity. *Nature Materials*, 4:465–469, 2005.

[36] M. Zaiser and E. C. Aifantis. Randomness and slip avalanches in gradient plasticity. *Int. J. Plasticity*, 22:1432–1455, 2006.

[37] T. Richeton, , P. Dobron, F. Chmelik, J. Weiss, and F. Louchet. On the critical character of plasticity in metallic single crystals. *Mat. Sc. Eng. A*, 424:190–195, 2006.

[38] J-P. Poirier. *Creep of crystals*. Cambridge Univ. Press, 1985.

[39] B. Jakobsen, H. F. Poulsen, U. Lienert, J. Almer, S. D. Shastri, H. O. Sorensen, C. Gundlach, and W. Pantleon. Formation and subdivision of deformation structures during plastic deformation. *Science*, 312:889–892, 2006.

[40] M. F. Ashby and P. Duval. the creep of polycrystalline ice. *Cold Reg. Sc. Tech.*, 11:285–300, 1985.

[41] R. B. Alley, A. J. Gow, and D. A. Meese. Mapping c-axis fabrics to study physical processes in ice. *J. Glaciol.*, 41(137), 1995.

[42] J. Wheeler, D. J. Prior, Z. Jiang, R. Spiess, and P. W. Trimby. The petrological significance of misorientations between grains. *Contrib Mineral Petrol*, 141:109–124, 2001.

[43] M. Guillopé and J.P. Poirier. Dynamic recrystallization during creep of single-crystalline halite: an experimental study. *J. Geophys. Res.*, 84:5557–5567, 1979.

[44] P. Duval and O. Castelnau. Dynamic recrystallization of ice in polar ice sheets. *J. Physique IV (suppl. J. Phys. III), C3*, 5:197–205, 1995.

[45] M. R. Barnett. A practical condition for migration dynamic recrystallization. *Acta Mater.*, 55:3271–3278, 2007.

[46] T. H. Jacka and J. Li. The steady-state crystal size of deforming ice. *Ann. Glaciol.*, 20:13–18, 1994.

[47] B. Derby and M.F. Ashby. On dynamic recrystallization. *Scr. Metall.*, 21(6):879–884, 1987.

[48] W. Roberts and B. Ahlblom. A nucleation criterion for dynamic recrystallization during hot working. *Acta Metallurgica*, 26:801–813, 1978.

[49] Y. Bréchet, Y. Estrin, and F. Reusch. A dynamic recrystallization criterion: DRX map. *Scripta Materiala*, 39(9):1191–1197, 1998.

[50] R. LeB. Hooke, M. Mellor, W.F. Budd, J.W. Glen, A. Higashi, T.H. Jacka, S.J. Jones, R.C. Lile, R.T. Martin, M.F. Meier, D.S. Russel-Head, and J. Weertman. Mechanical properties of polycrystalline ice: an assessment of current knowledge and priorities for research. *Cold Reg. Sci. Technol.*, 3(4):263–275, 1980.

[51] W.F. Budd and T.H. Jacka. A review of ice rheology for ice sheet modelling. *Cold Reg. Sci. Technol*, 16:107–144, 1989.

[52] T. H. Jacka and J. Li. Flow rates and crystal orientation fabrics in compression of polycrystalline ice at low temperatures and stresses. In T. Hondoh, editor, *Physics of Ice Core Records*, pages 83–102. Hokkaido University Press, Sapporo, 2000.

[53] T. H. Jacka and M. Maccagnan. Ice crystallographic and strain rate changes with strain in compression and extension. *Cold Reg. Sci. Technol.*, 8:269–286, 1984.

[54] R. B. Alley. Flow-law hypotheses for ice-sheet modeling. *J. Glaciol.*, 38(129):245–256, 1992.

[55] N. Azuma, Y. Wang, Y. Yoshida, H. Narita, T. Hondoh, H. Shoji, and O. Watanabe. Crystallographic analysis of the Dome Fudji ice core. In T. Hondoh, editor, *Physics of Ice Core Records*, pages 45–61. Hokkaido University Press, Sapporo, 2000.

[56] G. Durand, A. Svensson, A. Persson, O. Gagliardini, F. Gillet-Chaulet, J. Sjolte, M. Montagnat, and D. Dahl-Jensen. Evolution of the texture along the epica dome c ice core. In *Physics of ice core records II*, in press.

[57] A. J. Gow and T. C. Williamson. Rheological implications of the internal structure and crystal fabrics of the West Antarctic ice sheet as revealed by deep core drilling at Byrd station. *Geol. Soc. Am. Bull.*, 87(12):1665–1677, 1976.

[58] M. Gay and J. Weiss. Automatic reconstruction of polycrystalline ice microstructure from image analysis: application to the EPICA ice core at Dome Concordia, Antarctica. *J. Glaciol.*, 45(151):547–554, 1999.

[59] A.J. Gow. On the rate of growth of grains and crystals in south polar firn. *J. Glaciol.*, 8:241–252, 1969.

[60] A. J. Gow, D. A. Meese, and R. W. Bialas. Accumulation variability, density profiles and crystal growth trends in ITASE firn and ice cores from West Antarctica. *Ann. Glaciol*, 39:101–109, 2004.

[61] L. Arnaud, V. Lipenkov, J.M. Barnola, M. Gay, and P. Duval. Modelling of the densification of polar firn: charcterization of the snow-firn transition. *Ann. Glaciol.*, 26:39–44, 1998.

[62] J. Weiss, J. Vidot, L. Arnaud, P. Duval, and J.R. Petit. Dome Concordia ice microstructure: impurities effect on grain growth. *Ann. Glaciol.*, 35:552–558, 2002.

[63] D. Fan, S.P. Chen, and L.Q. Chen. Computer simulation of grain growth kinetics with solute drag. . *Mater. Res.*, 14:1113–1123, 1999.

[64] P. Duval and C. Lorius. Crystal size and climatic record down to the last ice age from Antarctic ice. *Earth Planet. Sci. Lett.*, 48(1):59–64, 1980.

[65] W. S. B. Paterson. Why ice-age ice is sometimes soft. *Cold Regions Science and Technology*, 20(1):75–98, 1991.

[66] A. J. Gow, D. A. Meese, R. B. Alley, J. J. Fitzpatrick, S. Anandakrishnan, G. A. Woods, and B. C. Elder. Physical and structural properties of the Greenland Ice Sheet Project 2 ice core: A review. *J. Geophys. Res.*, 102(C12):26,559–26,575, 1997.

[67] M. Legrand and P. Mayewski. Glaciochemistry of polar ice cores: a review. *Rev. Geophys.*, 35(3):219–243, 1997.

[68] B. Delmonte, J.R. Petit, and V. Maggi. Glacial to Holocene implications of the new 27,000-year dust record from the EPICA Dome C ice core. *Clim. Dyn.*, 18:647–660, 2002.

[69] R. Obbard and I. Baker. The microstructure of meteoric ice from Vostok, Antarctica. *Journal of Glaciology*, 53(180):41–62, 2007.

[70] R. Obbard, I. Baker, and K. Sieg. Using electron backscatter diffraction patterns to examine recrystallization in polar ice sheets. *Journal of Glaciology*, 52(179):546–557, 2006.

[71] A. J. Gow and D. A. Meese. Physical properties, crystalline textures and c-axis fabrics of the Siple Dome (Antarctic) ice core. *J. Glaciol*, 53(183):573–584, 2007.

[72] S. J. Johnsen, D. Dahl-Jensen, W. Dansgaard, and N. Gundestrup. Greenland paleotemperatures derived from GRIP bore hole temperature and ice core isotope profiles. *Tellus B*, 47:624–629, 1995.

[73] M. Vallon, J.-R. Petit, and B. Fabre. Study of an ice core to the bedrock in the accumulation zone of an alpine glacier. *J. Glaciol.*, 17(75):13–28, 1976.

[74] L. Lliboutry and P. Duval. Various isotropic and anisotropic ices found in glacier and polar ice caps and their corresponding rheologies. *Annales Geophysicae*, 3(2):207–224, 1985.

[75] P. Duval. Creep and fabrics of polycrystalline ice under shear and compression. *J. Glaciol.*, 27(95):129–140, 1981.