A MIGRATION RECRYSTALLIZATION MODEL FOR POLAR ICE

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Ice core samples drilled from depth in a polar ice sheet reveal strong anisotropic fabrics, shown by significant re-alignment of initially randomly oriented individual ice crystals (Gow *el al.* [1], Thorsteinsson *et al.* [2]). Progressive re-orientation of crystal c-axes (the axes of crystal hexagonal symmetry), taking place in the material in its response to current local strain and stress situations as ice particles descend from the free surface to depth, gives rise to considerable changes in ice macroscopic viscosities on different shear planes. The main micro-process that is responsible for the development of the oriented structure of the polar ice is the crystal lattice rotation due to the dislocation glide on the crystal basal planes. This process, present throughout the whole descent of the ice from the free surface to depth, but the effects of which are most pronounced in the upper half of a glacier, leads—in the absence of other micro-mechanisms—to very strong fabrics, with the majority of the crystal c-axes clustered along the vertical.

Beside the above lattice rotation mechanism, polar ice is also subject to recrystallization processes which have, or may have, effect on the directional properties of the material. One such a mechanism, the so-called normal crystal growth process, has no influence on the macroscopic anisotropy of ice. The other mechanism, known as the *rotational recrystallization* (or polygonization), is most active in the middle part of an ice sheet, and leads to the nucleation of new grains, the orientations of which are very close to those of existing grains (the latter do not disappear). Therefore, the macroscopic result of this mechanism is only a slight modification of the anisotropic properties of ice. As ice particles, during their descent, enter the bottom part of a glacier and approach its base, another recrystallization process becomes increasingly active, due to which the structure of ice changes dramatically, as evidenced by multi-maxima fabrics, with very coarse and interlocking grains, found near the glacier base (Duval and Castelnau [3], De La Chapelle [4]). Such a process, known as the *migration recrystallization*, is caused by rapid migration of grain boundaries between deformed and dislocation-free crystals, and leads to the nucleation of new grains at the expense of old ones (which ultimately disappear). Not all the factors which initiate and control the migration recrystallization mechanism have been identified yet, but it seems that the most important among them are: high, i.e. near-melting temperature, high strains, strain-rates and stresses, with some role also played by the bed topography. The macroscopic outcome of the above process is a significant weakening, and sometimes a complete destruction, of the strong anisotropy that has developed at earlier stages of the ice descent through a glacier. Thus, this process has a crucial effect on the overall flow of polar ice sheets, since the latter deform mainly by shearing in near-base regions.

To date only few theoretical attempts have been made to describe the process of migration recrystallization. These include a discrete-grain model by Van der Veen and Whillans [5], a cellular automata model by Ktitarev *et al.* [6], a phenomenological model by Staroszczyk and Morland [7], and a formulation by Morland [8] in which the process is described by means of a temperature-dependent critical lattice-distortion parameter.

In this paper a discrete-grain model is constructed, in which the phenomenon of migration recrystallization is modelled by extending an earlier theory by Staroszczyk [9]. In that theory, based on the Taylor-Voigt approximation of a uniform velocity gradient within a polycrystalline aggregate, the macroscopic behaviour of ice is derived by a simple average of the responses of a finite number of discrete grains representing the polycrystal. A single crystal of ice is treated as a transversely isotropic and incompressible body, the behaviour of which is assumed to be viscous. The response of a crystal is described by a constitutive law that involves three viscosity parameters defining different shear resistances in different glide directions.

Now the model is extended by incorporating into it the migration recrystallization mechanism. It is assumed that recrystallized are those crystals in an aggregate which are most stressed. Hence, a parameter is introduced to define a critical level of the deviatoric stress invariant, and it is supposed that a given crystal starts to recrystallize once the critical magnitude of this invariant has been reached in the crystal. A new grain is nucleated from that undergoing recrystallization in a smooth manner (in existing models it is usually assumed that the process occurs abruptly), and the orientation of this new grain is chosen in a way that is most favourable for its microscopic deformation by creep (that is, a newly formed grain is least stressed in a current macroscopic stress/strain configuration).

The model predictions are illustrated by the results of numerical simulations carried out for sustained uniaxial compression and simple shear, showing the evolution of the oriented structure of the material. Further, the variation of instantaneous macroscopic viscosities with increasing strains for different magnitudes of the critical stresses triggering the process of migration recrystallization is illustrated, displaying such features as the occurrence of *recrystallization waves*, or showing an example in which the viscosity in uni-axial compression becomes, due to the recrystallization, less than that of an isotropic sample (without the recrystallization involved the axial viscosity increases with the deformation). The latter feature has been known from experiments, but has not been predicted yet by any of the theoretical recrystallization models available so far.

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