Geophysical Research Abstracts
Vol. 16, EGU2014-12881-2, 2014
EGU General Assembly 2014

Application of composite flow laws to grain size distributions derived from polar ice cores

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Apart from evaluating the crystallographic orientation, focus of microstructural analysis of natural ice during the last decades has been to create depth-profiles of mean grain size. Several ice flow models incorporated mean grain size as a variable. Although such a mean value may coincide well with the size of a large proportion of the grains, smaller/larger grains are effectively ignored. These smaller/larger grains, however, may affect the ice flow modeling. Variability in grain size is observed on centimeter, meter and kilometer scale along deep polar ice cores. Composite flow laws allow considering the effect of this variability on rheology, by weighing the contribution of grain-size-sensitive (GSS, diffusion/grain boundary sliding) and grain-size-insensitive (GSI, dislocation) creep mechanisms taking the full grain size distribution into account [1]. Extraction of hundreds of grain size distributions for different depths along an ice core has become relatively easy by automatic image processing techniques [2].

The shallow ice approximation is widely adopted in ice sheet modeling and approaches the full-Stokes solution for small ratios of vertical to horizontal characteristic dimensions. In this approximation shear stress in the vertical plain dominates the strain. This assumption is not applicable at ice divides or dome structures, where most deep ice core drilling sites are located. Within the upper two thirds of the ice column longitudinal stresses are not negligible and ice deformation is dominated by vertical strain. The Dansgaard-Johnsen model [3] predicts a dominating, constant vertical strain rate for the upper two thirds of the ice sheet, whereas in the lower ice column vertical shear becomes the main driver for ice deformation. We derived vertical strain rates from the upper NEEM ice core (North-West Greenland) and compared them to classical estimates of strain rates at the NEEM site. Assuming intervals of constant accumulation rates, we found a variation of vertical strain rates by a factor 2-3 in the upper ice column.

We discuss the current applicability of composite flow laws to grain size distributions extracted from ice cores drilled at sites where the flow direction rotates by 90 degrees with depth (i.e. ice divide). An interesting finding is that a transition to a glacial period in future would be associated with a decrease in vertical strain rate (due to a reduced accumulation rate) and an increase of the frequency of small grains (due to an enhanced impurity content). Composite flow laws assign an enhanced contribution of GSS creep to this transition. It is currently unclear which factor would have a greater influence.

[1] Herwegh et al., 2005, J. Struct. Geol., 27, 503-521
[2] T. Binder et al., 2013, J. Microsc., 250, 130-141
[3] W. Dansgaard & S.J. Johnsen, 1969, J. Glaciol., 8, 215-223