Dynamic recrystallisation and its effect on ice deformation: the future depends on understanding this!

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The flow rate of polar ice sheet ice, from the land to the sea, will be the most important control on global sea level change over the coming decades and centuries. Ice flow rates will increase in response to rising global temperatures and will also increase locally in response to more dramatic changes in ice sheet configuration, that alter the driving stresses for flow; most particularly the collapse of floating ice shelves. Ice flow comprises a component of ice deformation and a component of sliding at the base of the ice sheet. It is likely that both components will increase in a warming world.

This presentation will focus on our understanding of ice deformation and its application to ice sheets. Terrestrial ice sheet temperatures are all above $0.8T_m$ (T_m = melt temperature) and the majority of ice sheet ice is above $0.9T_m$ (-30°C is $0.89T_m$). Overburden pressures supress fracture (crevassing) within the top 40 to 70m so that the bulk of the ice sheet (from hundreds of metres up to 4km thick) acts as a high homologous temperature metamorphic rock. Deformation occurs by “high temperature” creep mechanisms that can occur without significant dilatation. Mechanical behaviour is described by a power-law creep equation (strain rate is proportional to stress raised to a power n: the stress exponent) with Arrhenius temperature dependence. All natural glacial ice samples and all ice samples deformed in the laboratory have a crystallographic preferred orientation (CPO) and have microstructures indicative of the operation of recrystallisation processes. Experiments show us that ice rheology evolves with strain and empirically we link this to the changes in CPO and grain size that occur as ice deforms; changes that are intimately linked to dynamic recrystallisation.

Ice strength (the flow law), CPO and microstructure are controlled by a rate balance of different deformation and recrystallisation mechanisms. Experimental data show us that the CPO and microstructure, as well as strength, vary as a function of temperature, strain rate and strain (Qi et al., 2017). Furthermore CPO and strength evolve differently for different deformation kinematics; axial shortening versus shear for example (Treverrow et al., 2012). Our interpretation is that the CPO and microstructural changes depend on the balance of the rate of lattice rotation (dislocation glide, subgrain formation/rotation and grain boundary sliding) and strain induced grain boundary migration (Qi et al., 2017). Rotation becomes more significant at lower temperatures, higher strain rates and higher strain. Changes in strength relates to the CPO evolution, as individual ice crystals are very anisotropic, and changes in microstructure, as finer grains will increase the strain rate contribution of grain size sensitive deformation mechanisms.

The convention in ice sheet modelling is to use an ice flow law that is based on the mechanical data (stress and strain rate) at very low strain (~1%), sometimes with a linear adjustment (an enhancement factor) for the weakening that occurs between 1% and 10 - 20% strain. Because the microstructural and mechanical changes that occur as a function of strain are also controlled by strain rate (or stress) this approach presents problems. Experimental data sets where mechanical behaviour at 1% strain and at higher strains can be compared all show an increase in the stress exponent n from the 1% strain data to the higher strain data (Bons et al., 2018; Qi et al., 2017; Treverrow et al., 2012). Typical 1% n values are around 3, whereas those at higher strain are around 4, and this alone makes a huge difference to large scale model outputs (Bons et al., 2018). It is clear that natural ice has been deformed to high strain: generally much higher than has been achieved in the laboratory. The challenge now is to develop robust high-strain flow laws that can applied robustly to ice sheet models.

One aspect of ice deformation behaviour that is poorly captured in the experimental literature is the effect of chemical impurities. Ice sheets contain very small (up to ~10 ppm) proportions of particulate and/or solute impurities that come from atmospheric dust and aerosols. Although impurity levels are low, the limited data we have shows that the additional chemistry has a significant effect on mechanical behaviour (Hammonds and Baker, 2016, 2018) and on microstructural evolution (Craw, 2017; Weikusat et al., 2017). The effect is probably related to the impurity effect on grain boundary mobility (Weikusat et al., 2017) and the impact this then has on recrystallisation processes. The vast majority of laboratory ice deformation experiments use pure water ice. Probably the most important change we need to make to experimental programmes to understand ice mechanics is to use the “impure” ice chemistries characteristic of the Earth’s ice sheets. Implementing this will not be easy.

Deformation of ice to significant strain in the laboratory is restricted to strain rates at least two orders of magnitude slower than the fastest rates that occur in nature. CPO and microstructure can be quantified in experimentally and naturally deformed ice and similarity of experimental and natural CPOs provides some confidence that processes in the laboratory and nature are equivalent and the extrapolation of laboratory derived flow laws to natural systems is reasonable. However, whatever we do in the laboratory, validating the up-scaling, from small samples deformed quickly in the laboratory to large ice masses deforming slowly, is one of the most crucial activities in developing our ability to predict future ice flow contributions to sea level change. I will report on new attempts to use ice sheet scenarios to provide data for comparison with the extrapolations of laboratory mechanical data.

References *(not comprehensive: just some relatively new outputs)*

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