The effect of melt on the seismic anisotropy of ice polycrystalline aggregates

Maria-Gema Llorens¹, Albert Griera², Enrique Gomez-Rivas³, Paul D. Bons⁴, Ilka Weikusat^{4,5}, David Prior⁶ and Ricardo Lebensohn⁷

¹ICTJA-CSIC; ²Autonomous Univ. Barcelona; ³Univ. Barcelona; ⁴Univ. Tübingen; ⁵AWI; ⁶Univ. Otago; ⁷Los Alamos National Lab.







- Observations of P-wave (Vp) and S-wave (Vs) velocities in ice sheets reveal a strong decrease of ~25% of Vs with depth, while Vp remains approximately constant
- The low Vs may be due to the presence of unfrozen liquids resulting from pre-melting at grain joints and/or melting of chemical solutions buried in ice (Wittlinger and Farra, 2015)

Although previous studies of two-phase rocks (including melt and water) show that seismic velocities depend on both CPO and water content, studies on the effect of melt on polar ice seismic velocity are scarce

Aim \rightarrow Analyse polycrystalline ice with different melt fractions (temperate ice) through numerical simulations to:

- Understand how melt influences the development of microstructures
- Link the developed microstructures to the changes in P- and faster Swave velocities during ice deformation

Ice deformation mechanisms and rheology

Ice is **highly anisotropic**: the critical resolved shear stress required to activate slip systems (CRSS) for non basal vs basal slip systems is A>60

Deformation is mainly accommodated by **dislocation creep.** Preferential glide on the **basal plane** and along the <1120> direction



Viscoplastic deformation increases dislocation density and produces an **increment of the internal strain energy**. It can be reduced by:

- Recovery (annihilation of opposite dislocations and poligonisation)
- Recrystallisation (reduction of boundary energy and dislocation density)

Objective: Simulate temperate ice deformation in simple shear using VPFFT (Full Field crystal plasticity code) + dynamic recrystallisation (*DRX*) processes (recovery, recrystallisation and polygonisation) in order to investigate the **evolution of the microstructure and seismic velocity anisotropy during deformation**

Simulation approach: ELLE is an open-source numerical simulation platform used to simulate the development of microstructures during tectonic and/or metamorphic processes.





DBJECTIVE AND SIMULATION APPROACH

VPFFT (Viscoplastic full-field algorithm) solves the mechanical problem by finding the strain rate and stress field that minimize the average local work-rate. Viscoplastic deformation is accommodated by **dislocation glide**





Identifies the high angle grain boundaries (HAGB) and updates the grain boundary network

Llorens et al. (2017)

Ice with 3 different melt fractions of 0%, 5% and 15% located at triple grain junctions

- Initial random distribution of c-axis orientation (bulk isotropic)
- Ice: A=60 (CRSS basal vs non-basal slip systems) and n=3 and melt A=1 and n=3
- Dextral simple shear increments of 0.02 shear strain up to 8
- Dynamic recrystallisation applied in a substep sequence repeated 10 times after deformation





Crystal Preferred Orientation evolution



- Regardless the melt percentage (ϕ), all simulations evolve from a random fabric to a caxis preferred orientation (CPO) approximately perpendicular to the shear plane.
- When melt is present (columns II and III), the developed CPO is less intense than the pure ice simulation (I)

Calculation of P-wave and S-wave velocities

Using the AEH-EBSD Analysis Toolbox (Vel et al., 2016)



For zero melt (ϕ =0%), the highest Vp quickly aligns with the maximum c-axis orientation. At the same time, the maximum caxis development reduces Vs in this orientation

When water is present (ϕ >0%) the developed maximum c-axis is less intense, which results in both Vp and Vs being lower than in the case of purely solid ice. At high percentage of water (ϕ =15%), Vp is not aligned with the maximum c-axis, but follow the orientation of the grain elongation

For all simulations the anisotropy of Vp and Vs increases up to $\gamma=2$. Higher anisotropies are observed in S-wave velocities. When water in present, the anisotropy of both Vp and Vs is reduced, as the developed maximum c-axis is less intense

EXPERIMENTAL RESULTS

Calculation of P-wave and S-wave velocities



Table 1. Predicted Vp and Vs assuming the water bulk modulus for the melt phase.

The temperature dependence of the ice elastic parameters, together with the increment of Vp and decrease of Vs along the c-axis direction is due to the CPO development, but cannot explain itself the strong decrease of 25% in the Vs in the lower part of the ice-sheets

The presence of unfrozen liquids has been proposed as the cause of the low Vs found in the lower ice layer. But, even if melting occurs in a microstructure with a strong CPO, Vp would get proportionally reduced by the presence of water (Table 1)

Calculation of P-wave and S-wave velocities

Ice conditions	T⁰			
		V _p	V _s	V_p / V_s
Purely-solid isotropic ice	-30ºC	-	-	-
(standard)				
Purely-solid anisotropic ice	-1ºC	-	-	-
Anisotropic ice + 5% water	-1ºC	3.84	1.77	2.17
Anisotropic ice + 10%	-1ºC	3.83	1.66	2.31
water				
Anisotropic ice + 15%	-1ºC	3.80	1.54	2.46
water				

Table 2. Predicted Vp and Vs assuming ice bulk modulus at -1°C for both ice and melt phase.

The presented simulations are located at the transition between the deformation- and the recrystallisation-controlled regime, where **water is located in isolated pockets and not forming water pocket networks**. At this undrained conditions the bulk modulus of the water and ice aggregate must tend to the ice bulk modulus. **If we assume this condition, Vs is significantly reduced proportionally to the presence of water, while Vp is only slightly reduced (Table 2).** That would correspond to a thermomechanical regime of warm-based ice-sheet but with a thin temperate layer, where most of the deformation is internal and can be described by a standard power law flow law.

However, if we consider that the dynamic conditions in the lower part of the ice sheets correspond to the deformation-dominated regime, recrystallisation is too slow to counteract the shearing of water pockets and pockets get stretched continuously. **Melt films located on grain boundaries will modify and even overprint the CPO-dependent orientation and magnitude seismic anisotropy.**