Ultrasonic velocity experiments on ice cores to complement fabric measurements

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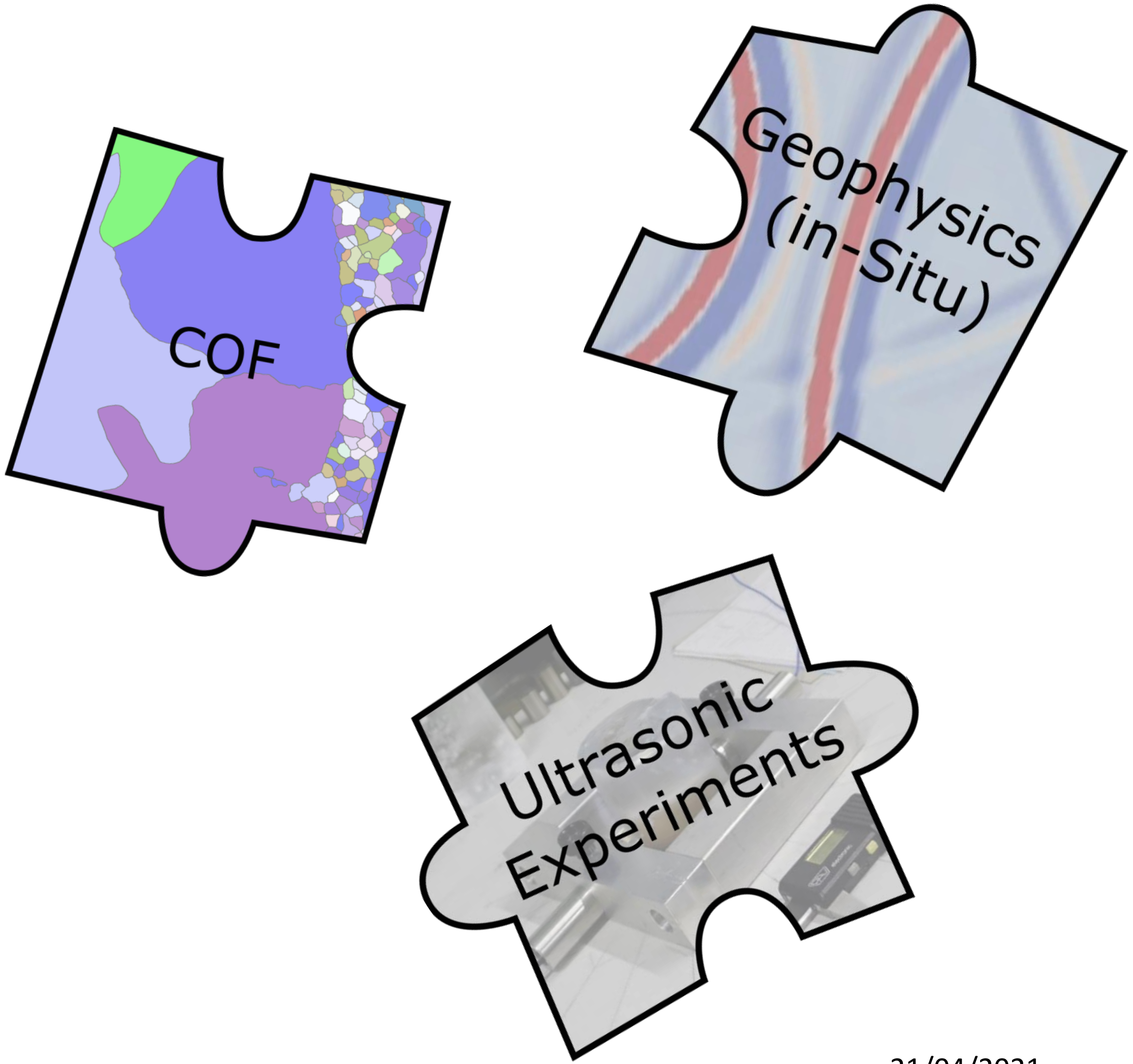
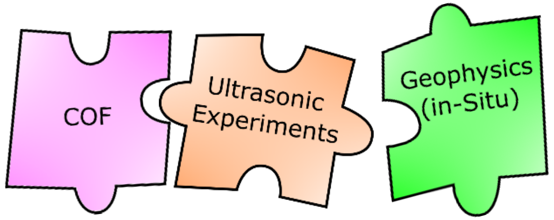
Currently under discussion in TCD

Outline

- Introduction
- Ultrasonic Experiments
- Comparison COF-US
- Summary & Outlook



Introduction

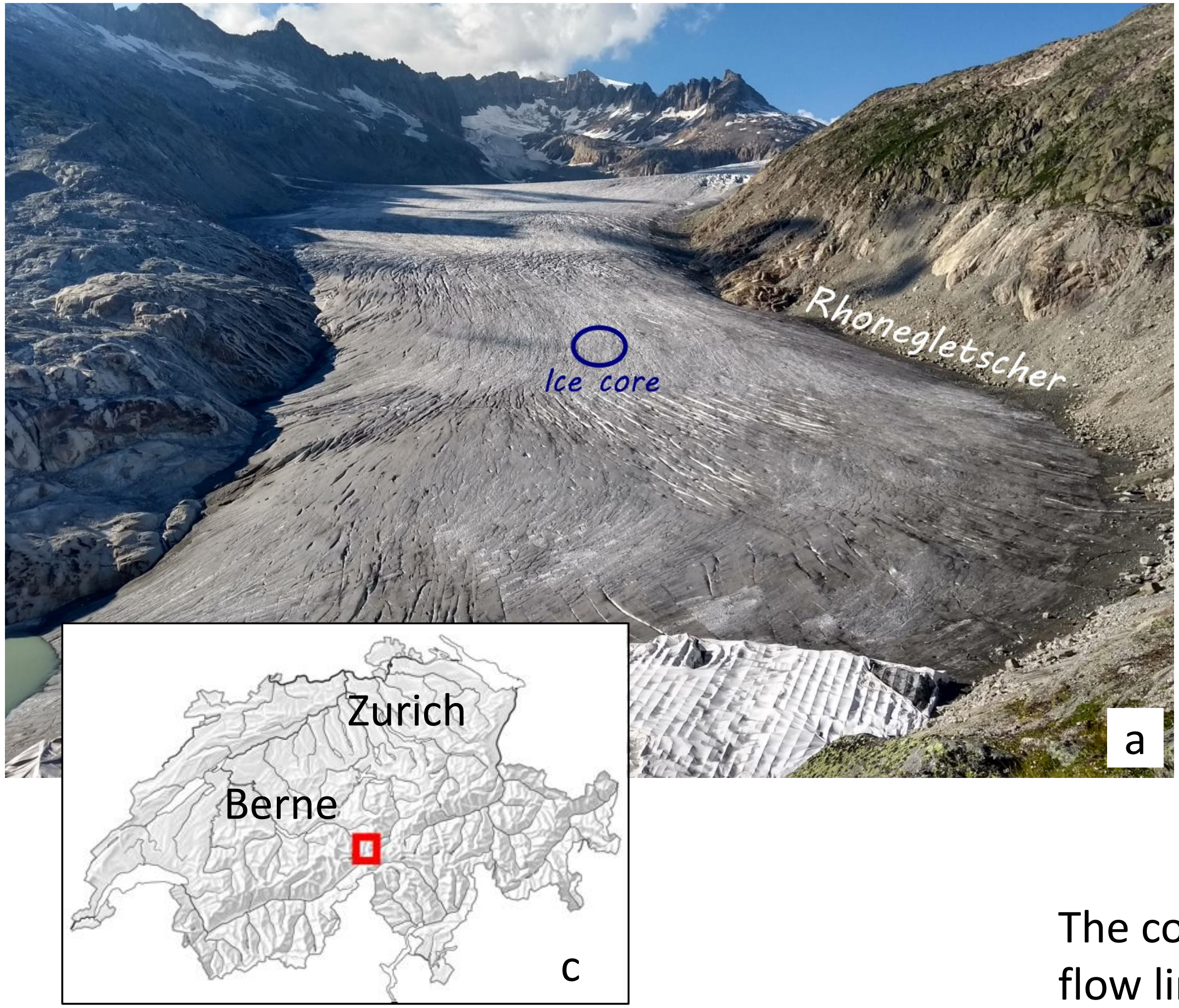


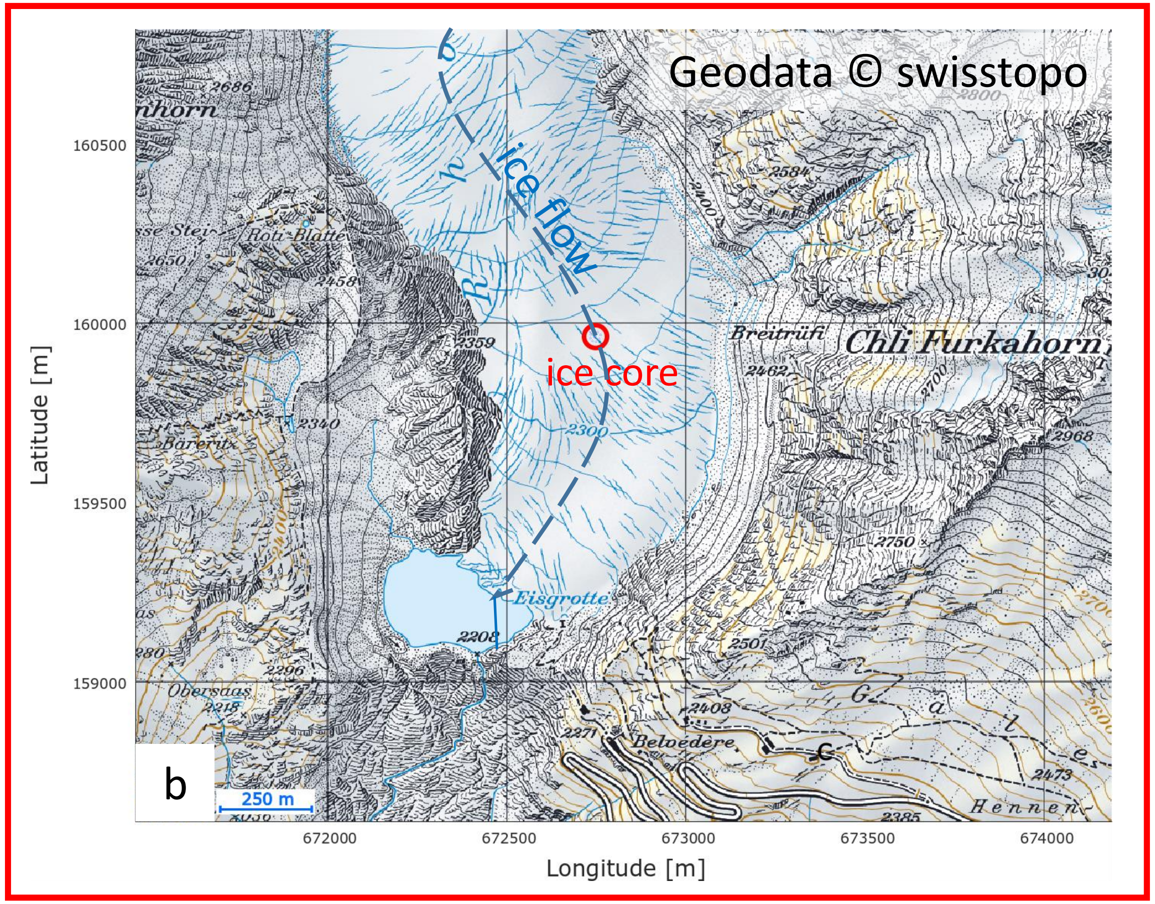
Aim of this study

We are investigating…

- … whether we can use ultrasonic measurements to detect the crystal-orientation fabrics (COF) within a temperate ice core
- … how ice properties (e.g. ice grain size or air bubble content) affect these geophysical measurements
- ✓ This study contributes to better understanding the effect of COF-induced anisotropy on geophysical measurements (e.g. cross-borehole seismics) in order to distinguish between macro- and microstructural anisotropy effects

For these purposes, we drilled a temperate ice core on Rhonegletscher, Swiss Alps in 2017. In a first step, the COF was analysed with respect to depth and glacier flow direction (core orientation preserved).

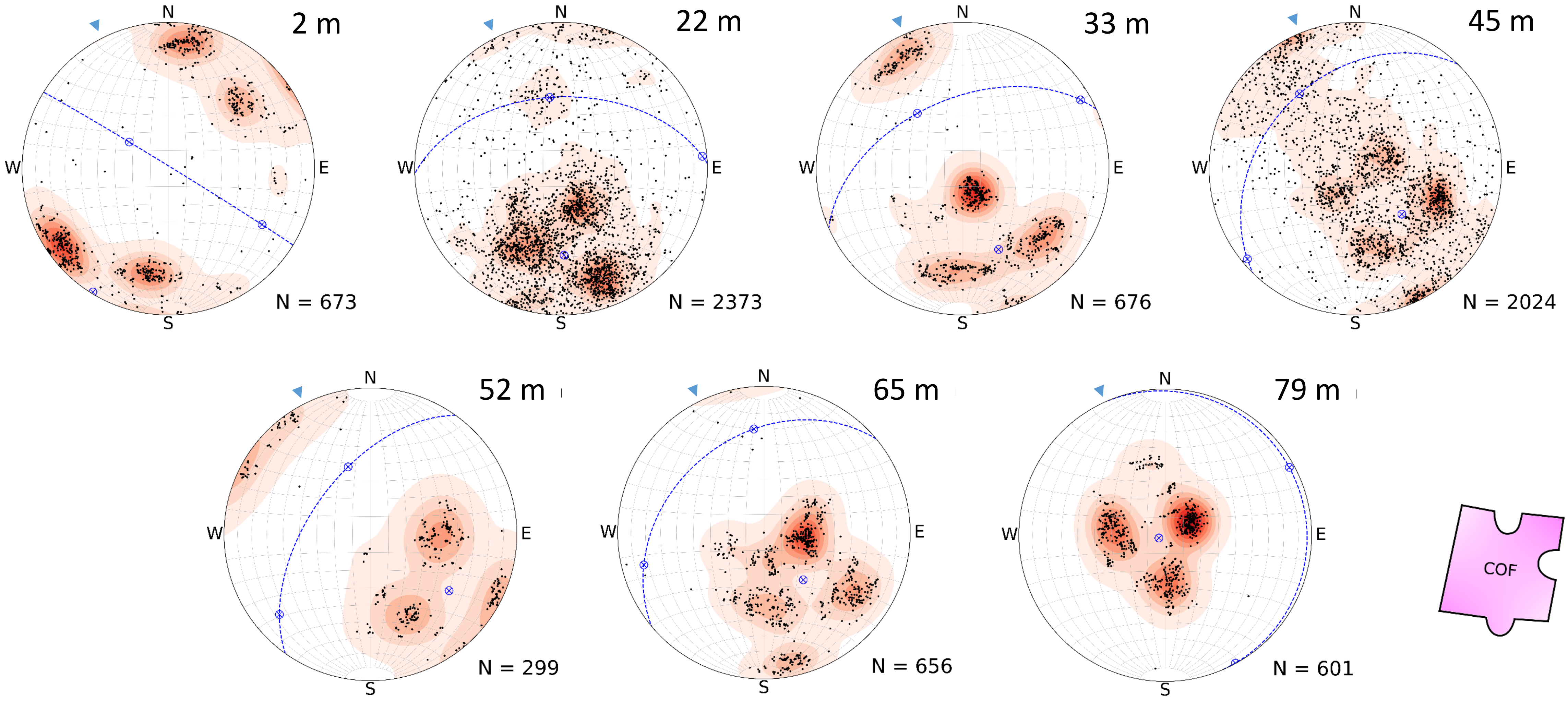




The core was taken 500 m north of the terminus in the central flow line of the glacier. The mean ice flow is NW-SE directed.

Introduction

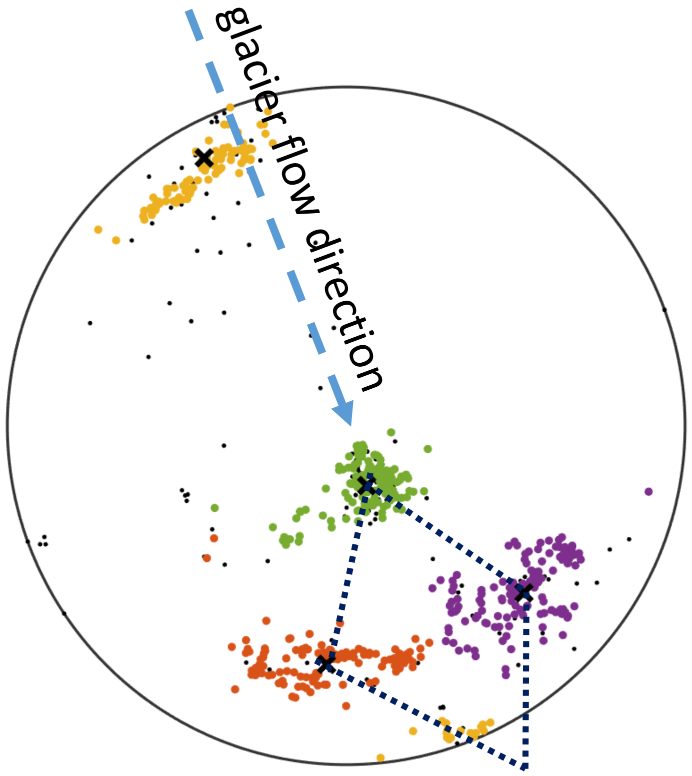
We conducted a crystal-orientation fabric (COF) analysis on 7 samples along the ice core. For each sample 50 cm of ice (in total 77 thin sections of $10 \times 6\ cm^2$) were analysed and the results are stitched together. Each black dot symbolises an ice grain. A four-maxima pattern is found in all depths.

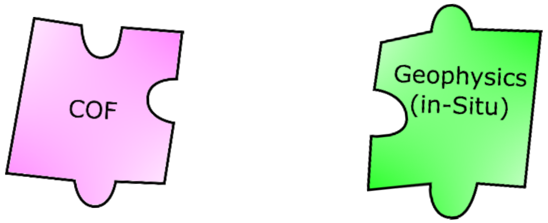


COF

Key findings of COF analysis

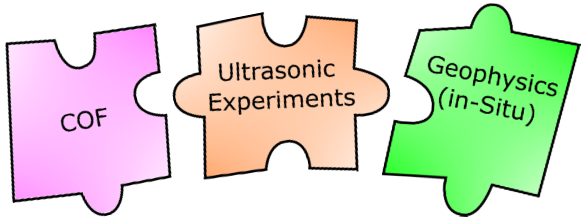
- Samples from **all depths clearly show a "diamond-shape"** COF
- Such a pattern has been observed in earlier studies (1950-1980) of temperate glacier ice (Rigsby, 1960; Budd et al. 1972) and also in deepest parts of polar ice (Gow&Williamson, 1976)
- It is most likely a result of strain-induced boundary migration (SIBM-N) with formation of new ice crystal nuclei (Faria et al., 2014) within the framework of principal stresses (Hellmann et al., 2021)
- The colatitude angle of the pattern changes from 90° to 0° with increasing depth (see previous slide).
- The azimuth of the cluster is aligned with the ice flow direction (with an exception in 2 m depth)





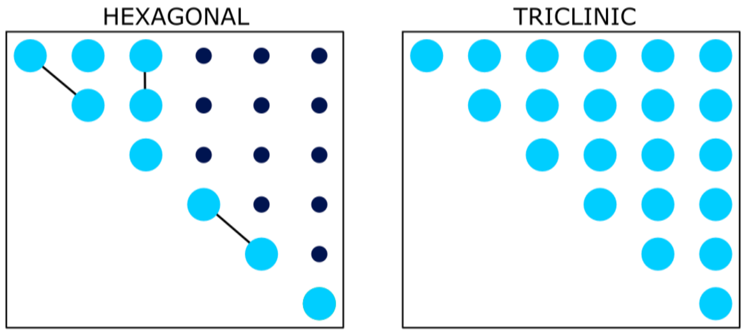
Open issues and next steps…

- the COF analysis is time consuming and only a few samples can be analysed in a reasonable amount of time (e.g. 77 sections → 23 days)
- we only have information from a single spot → can we employ geophysical methods to acquire more data from the entire glacier?
- We need to compare the calculated seismic velocity of such a COF pattern with geophysical measurements
- However, geophysical measurements are affected by microstructural but also macrostructural anisotropy (e.g. water drainage network, crevasses, pockets)
  → therefore we should consider to setup a method that serves as link between COF and geophysics



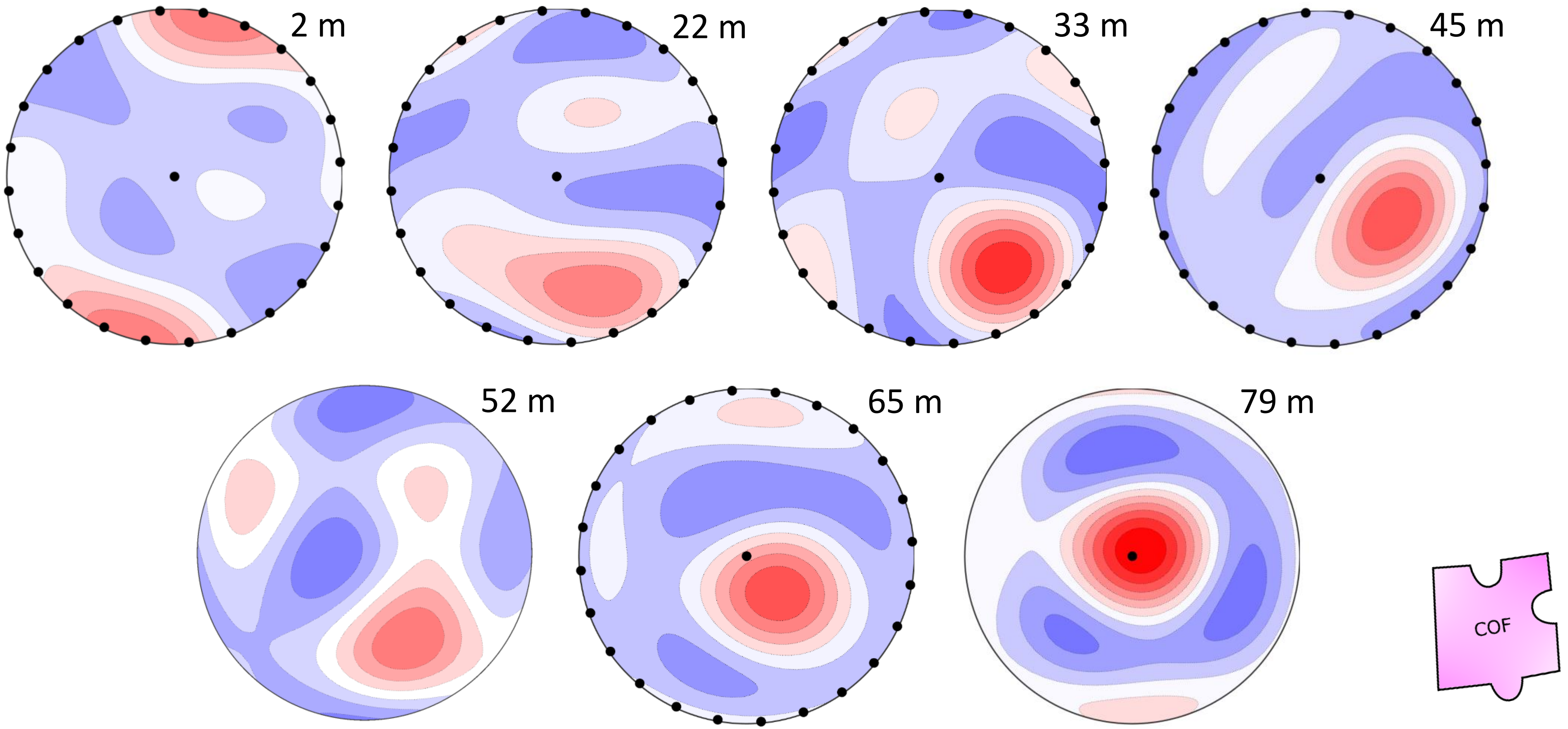
Calculated seismic velocities

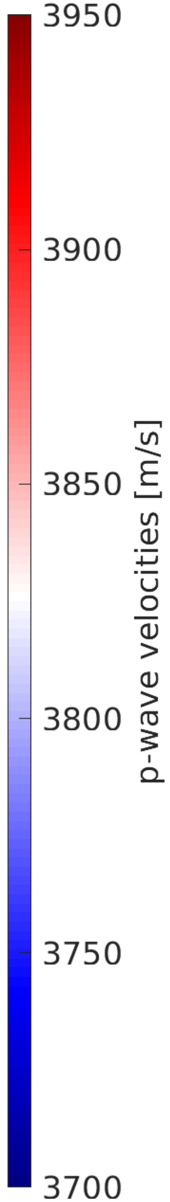
- Experiments on the ice core to link theoretically calculated velocities with actual measurements
- Theoretically calculated acoustic velocities from COF (Kerch et al., 2018):
  1. use a monocrystal elasticity tensor → transform it to azimuth/colatitude of the actual c-axis for each single grain = transformed monocrystal tensor
  2. sum over all transformed monocrystal tensors (superposition) = arbitrary polycrystal tensor (not hexagonal anymore)
  3. calculate the seismic velocities from this *triclinic* tensor by solving the elastodynamic wave equation with a harmonic steady-state plane wave (i.e. solve the Christoffel Equation)



(single crystal) (polycrystal)

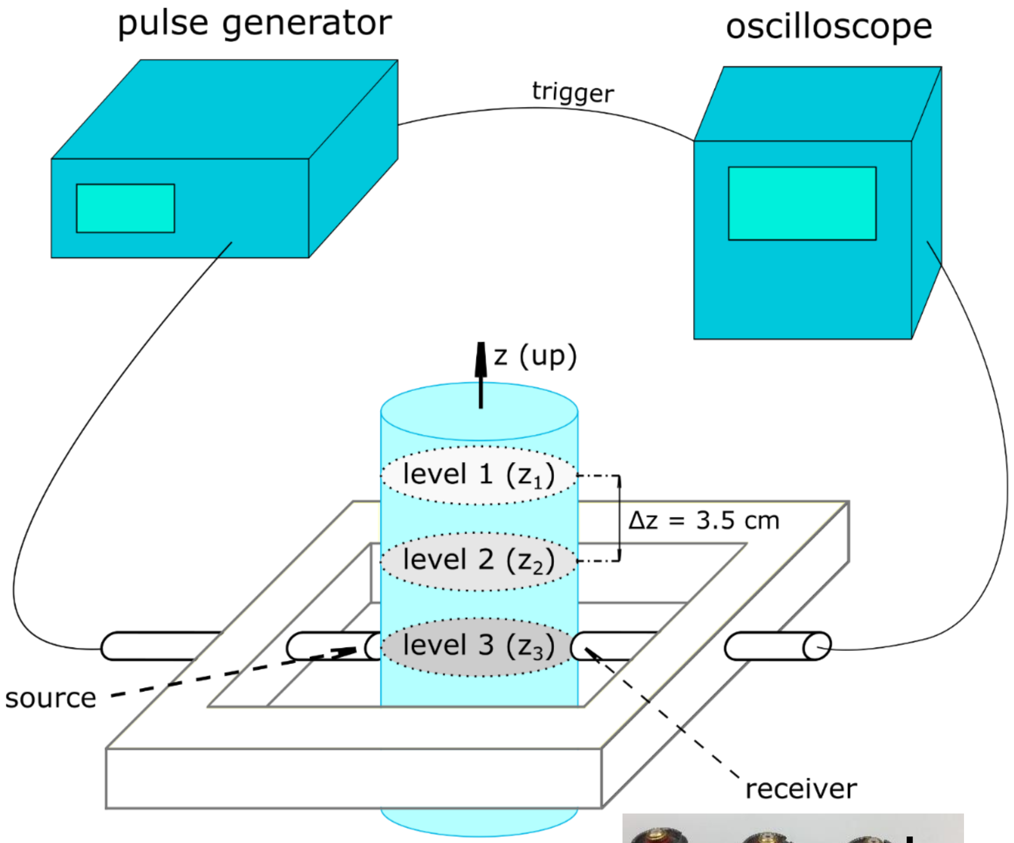
Seismic velocities





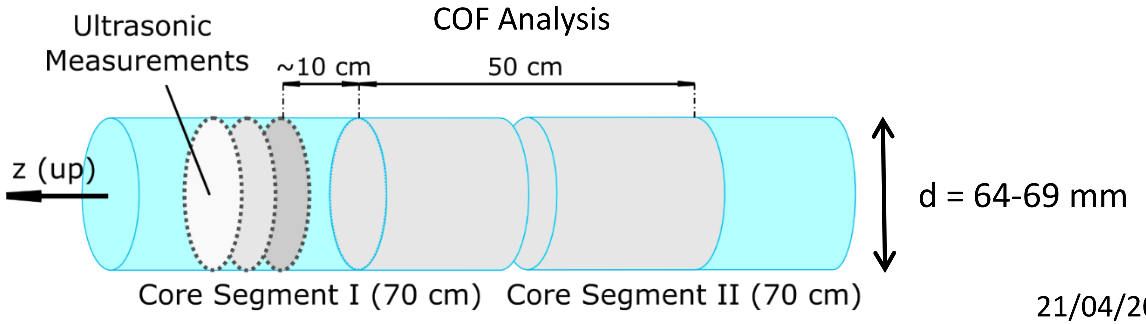
These are the *calculated* seismic p-wave velocities from COF for all 7 sampling depths and any incident and azimuth angle of a seismic wave. The maximum anisotropy is found for 79 m with 2.3%. The centre of the diamond-shape cluster represents the direction of maximum velocity, the minimum velocity is found around this maximum with an offset of about 45-50°.
We compare these velocities with ultrasonic velocities acquired at selected azimuths (black dots).

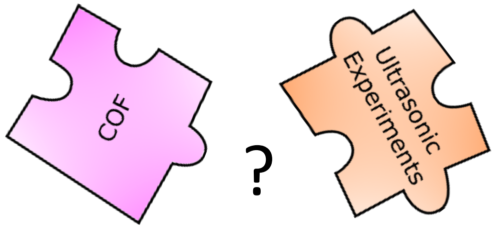
Measurement setup



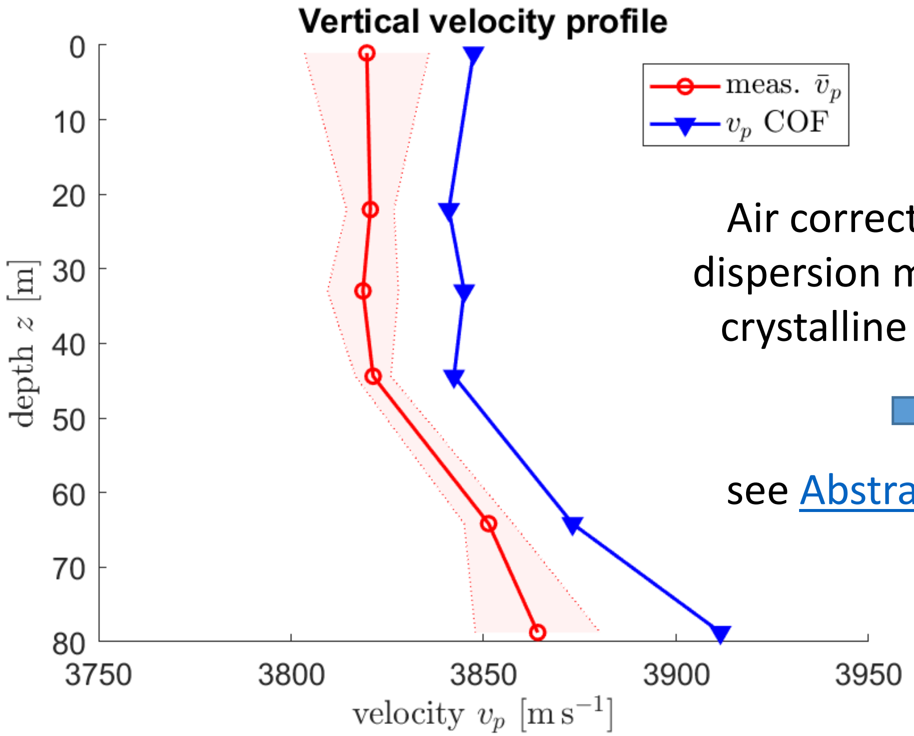
after Hellmann et al. (2021), in review

- Source/Receiver: Point contact transducers with main frequency 1 MHz (λ = 3.8 mm)
- Calibration measurements with steel cylinders (time-zero)
- 15° azimuthal resolution
- Only 0/90° colatitude angle
- Time resolution (sampling rate): 4 ns
- 20-40 stacks of waveform for noise reduction
- Coupling sometimes quite difficult (varying strength), with significant improvements after lathing the ice core
- Ice core diameter measured indirectly for each individual measurement, mean value ~67 mm



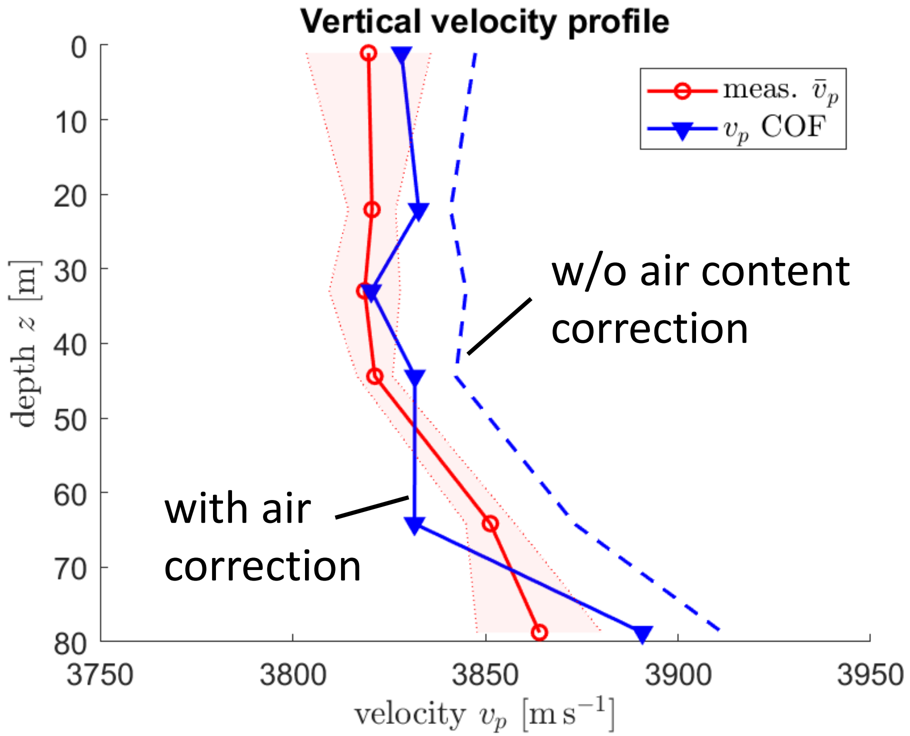


Air content correction



Air correction: we use a dilute dispersion model for porous poly-crystalline ice (Torquato, 2002)

see Abstract* of Sundu&Löwe

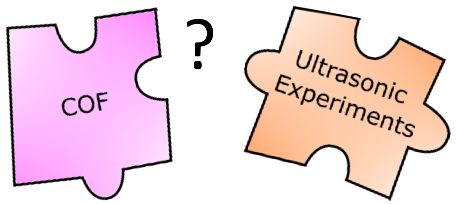


A direct comparison between calculated and measured velocities reveal a significant offset between both profiles, which can partly be explained by air bubbles in the core samples.

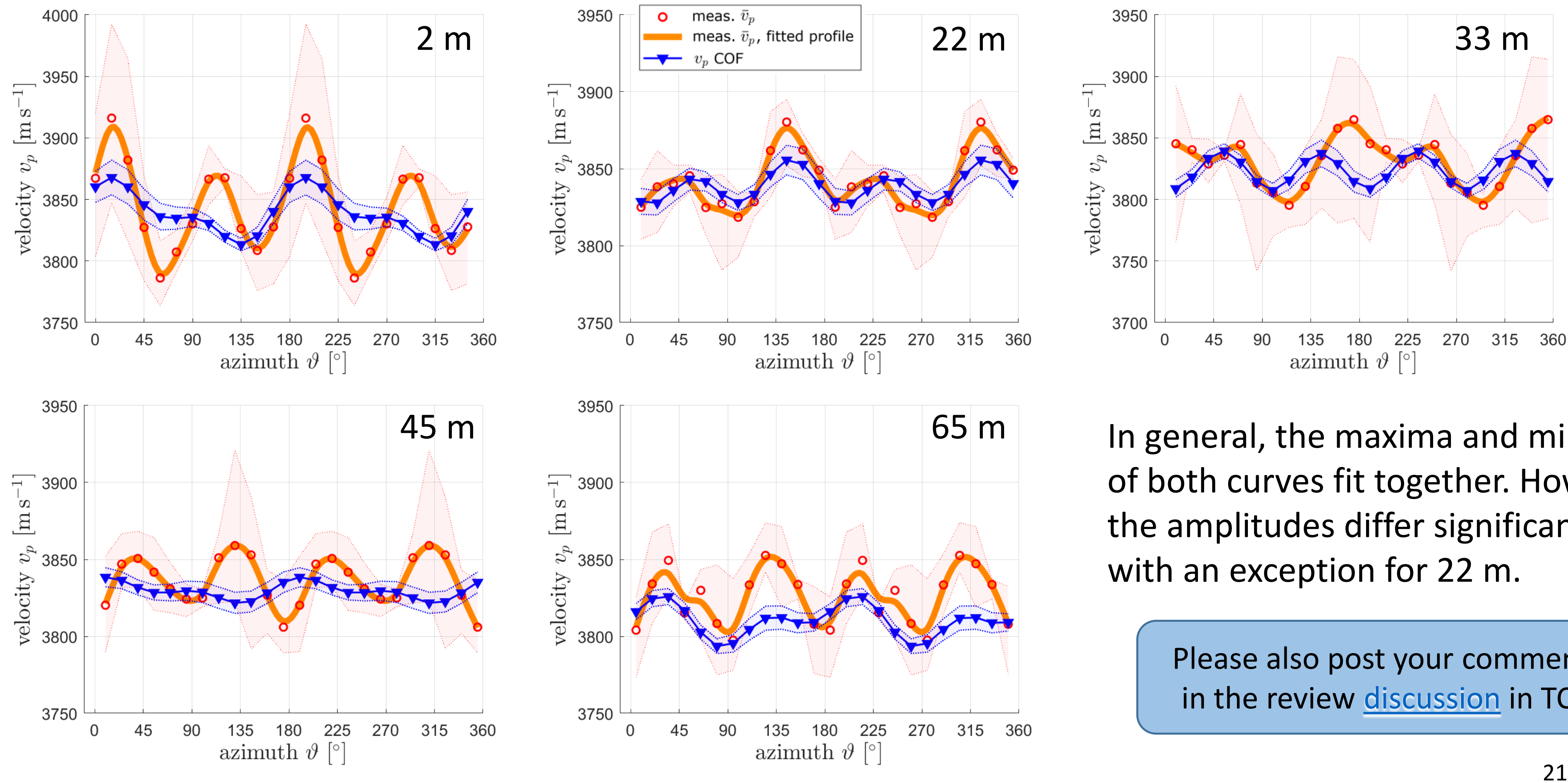
Porosity for air content correction from CT measurements

depth [m]	2	22	33	45	65	mean
porosity (CT) [%]	0.63	0.27	0.81	0.35	1.35	0.682

**https://doi.org/10.5194/egusphere-egu21-2129*



Measurement results and comparison



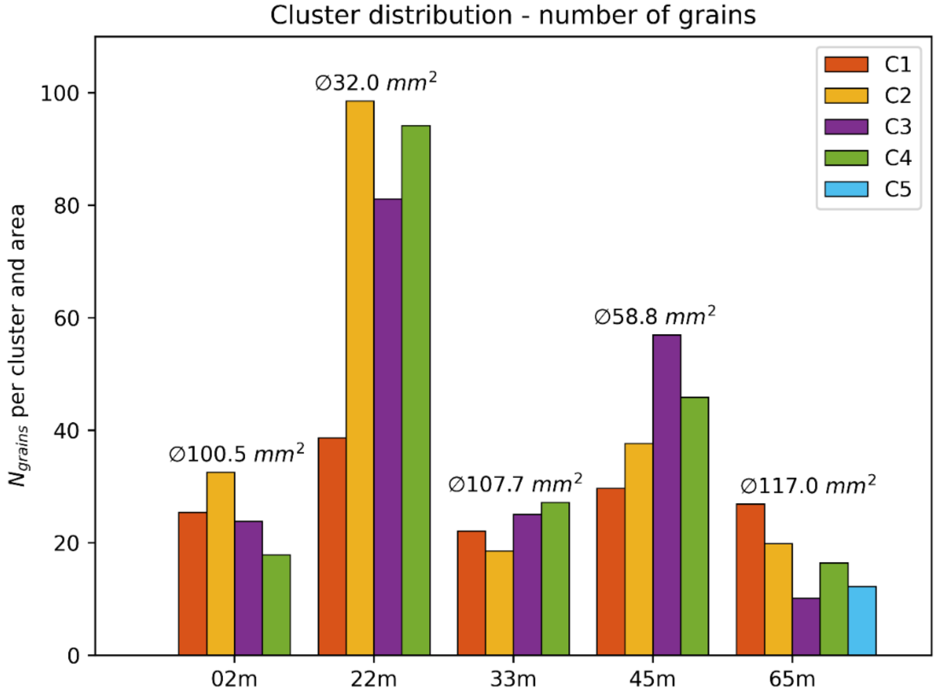
In general, the maxima and minima of both curves fit together. However, the amplitudes differ significantly, with an exception for 22 m.

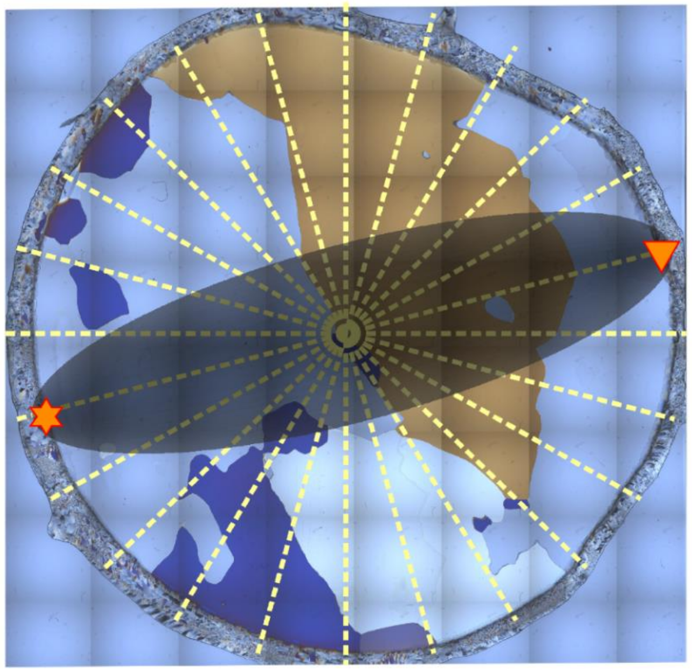
Please also post your comments in the review discussion in TCD

Corrections and Limitations

Grain size effects

This discrepancy is most likely a result of the extremely large ice grains. The presence of such large grains in a limited volume that is covered by the ultrasonic measurements cause an overrepresentation of the respective clusters. A representative example is shown in the right image: The dark area represents the Fresnel Volume. Only those grains within this volume affect the ultrasonic waves. The smallest grains are found in 22 m depth (left img.) with the best fit between calculated and measured velocities (see pevious slide)

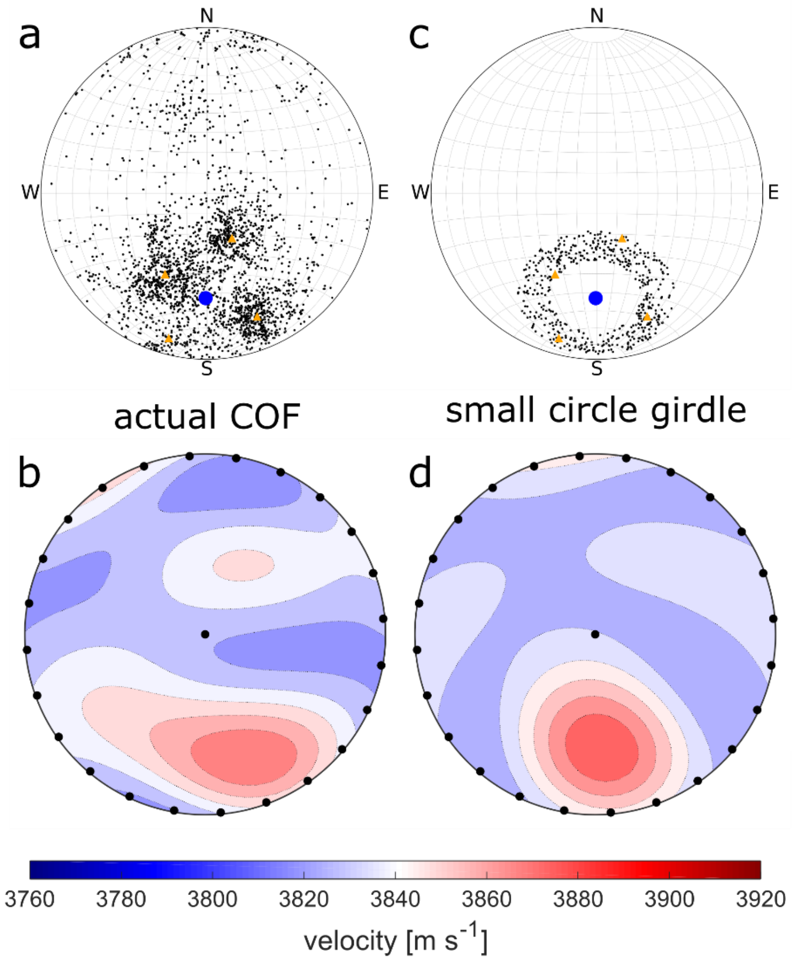




This grain size effect is highly important for temperate ice with extremely large ice grains relative to the limited volume of an ice core.

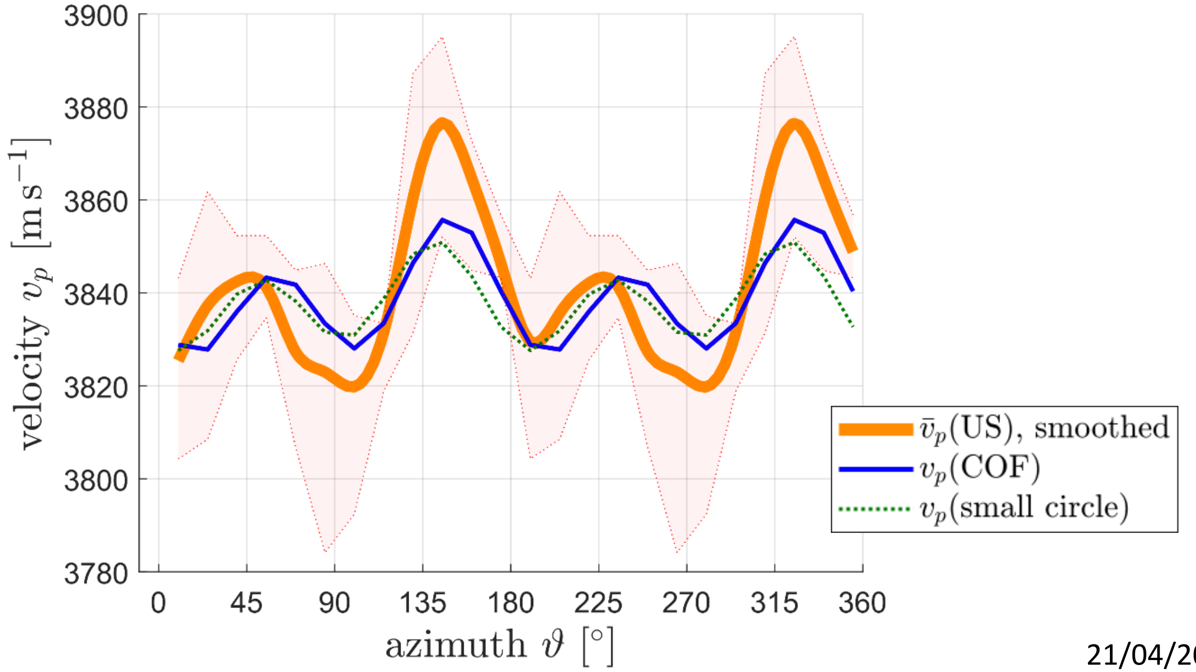
COF | Ultrasonic Experiments

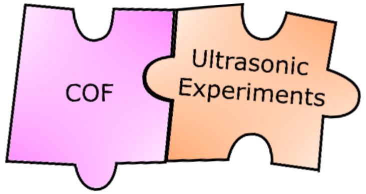
Ambiguities for similar COF’s



after Hellmann et al. (2021), in review

When we only consider horizontal (+ the 1 vertical) measurements (dots in Fig. b+d), we are NOT able to unambiguously distinguish between very similar COF’s such as small circle girdle and a multi-maxima pattern. Thus, we need to consider more directions and further combine information derived from COF and ultrasonic data.



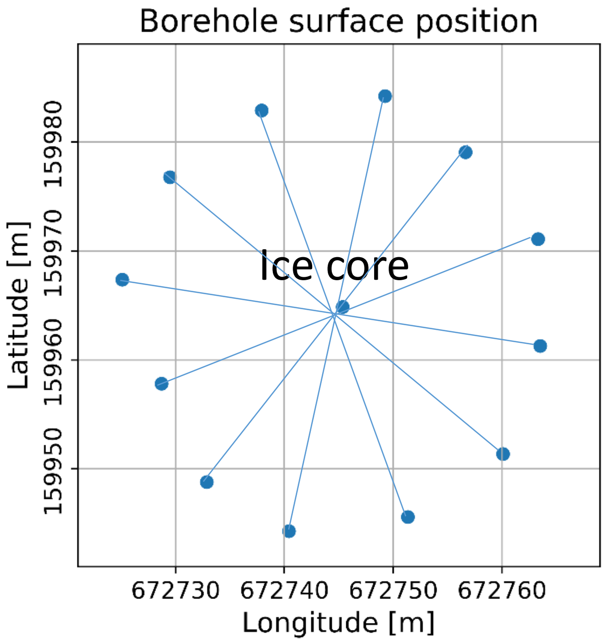


Summary

- Changes in COF are visible in the velocity patterns, i.e. ultrasonic measurements can be employed to detect changes in the COF along an ice core
- We can state at least for temperate ice cores:
  - Large grains limit these experiments as the complex diamond-shape pattern and the limited statistical averaging over a few large grains within a measurement plane reduce the clarity/enhance the ambiguity of the measured velocity pattern
  - Ultrasonic measurements cannot unambiguously distinguish between all kinds of COF and thus cannot fully replace the COF analysis, but might be used to support the extensive analysis, e.g. to fill the gaps between COF data points or detect sudden changes in the COF along an ice core

Outlook

- Ultrasonic experiments are a non-destructive method that is capable of tracing changes in COF
  - ➢ Potential for applications similar to DEP along a freshly drilled ice core that can be correlated with a few COF measurements later on
- For cold ice (smaller grains) this method may provide more conclusive results, but needs to be tested
- As a next step for this project, the measured velocities are going to be correlated with in-situ cross-borehole experiments
  - ➢ We need to analyse which parts of the cross-borehole velocity profile correlate with the ultrasonic velocity profile and hence are based on COF-related effects.



Potential measurement geometry for cross-borehole measurements

Summary & Outlook

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