Comparison of seismic velocities derived from crystal orientation fabrics and ultrasonic measurements on an ice core

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Outline

- Introduction
  - Aim of this study
  - Investigation area Rhonegletscher
  - Results from Crystal orientation fabric (COF) analysis

- Seismic velocities as proxy for COF?
  - Calculated velocities from COF
  - Measured velocities on ice core samples
  - Comparison between both types of velocities

- Summary and Outlook

Aim of this study

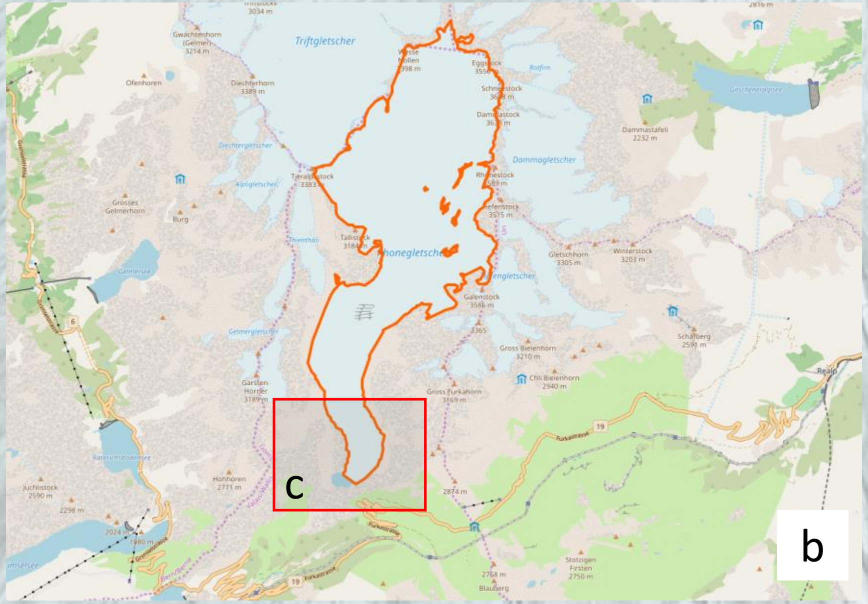
We try to investigate…

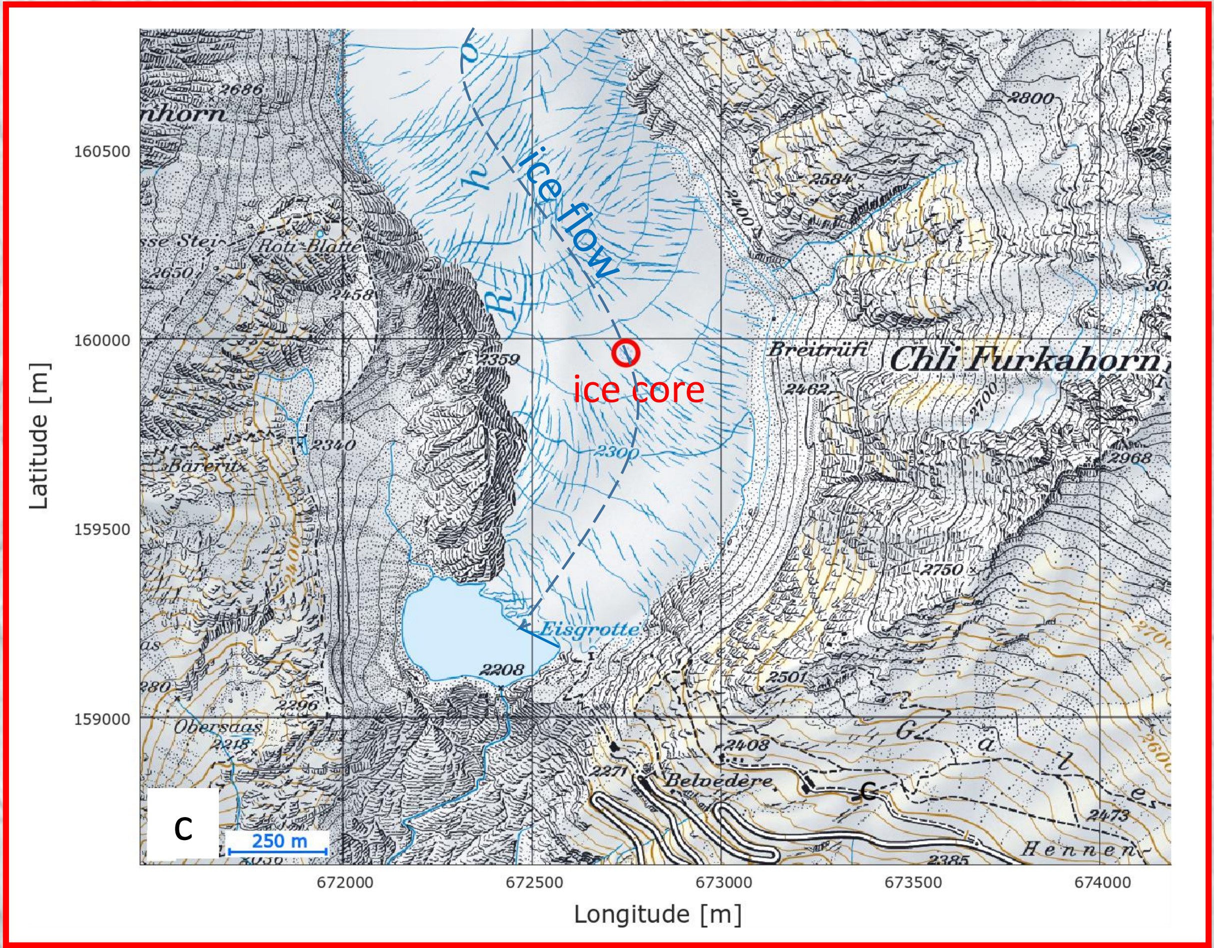
- … whether we can employ ultrasonic measurements to detect the COF within a temperate ice core
- … how the particular grain sizes and COF patterns, typical for temperate ice, affect the measurements?

✓ This study contributes to understanding the effect of COF-induced anisotropy on geophysical measurements (e.g. cross-borehole seismic data)

Introduction

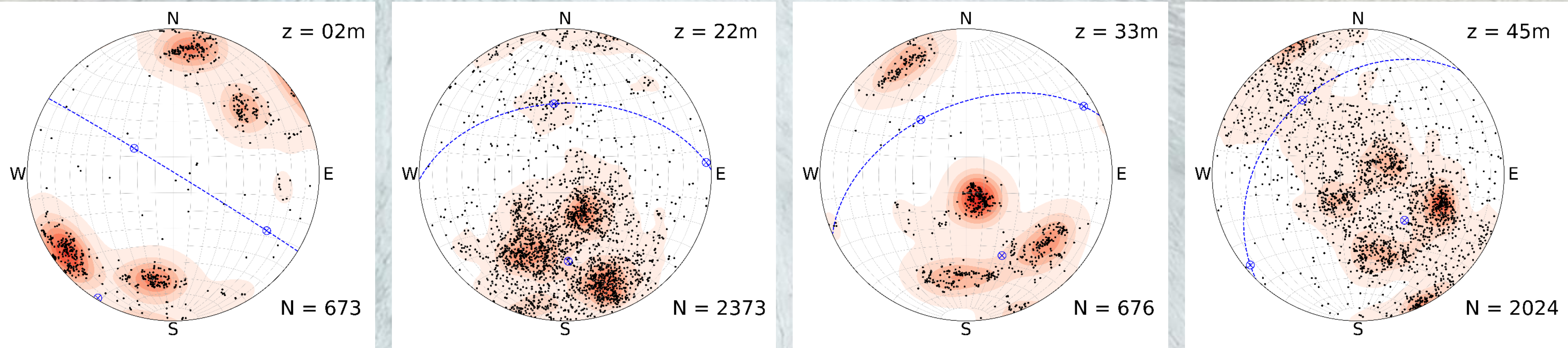
For these purposes, we drilled a temperate ice core on Rhonegletscher, Swiss Alps in 2017. In a first step, the COF was analysed with respect to the glacier flow direction (core orientation preserved).



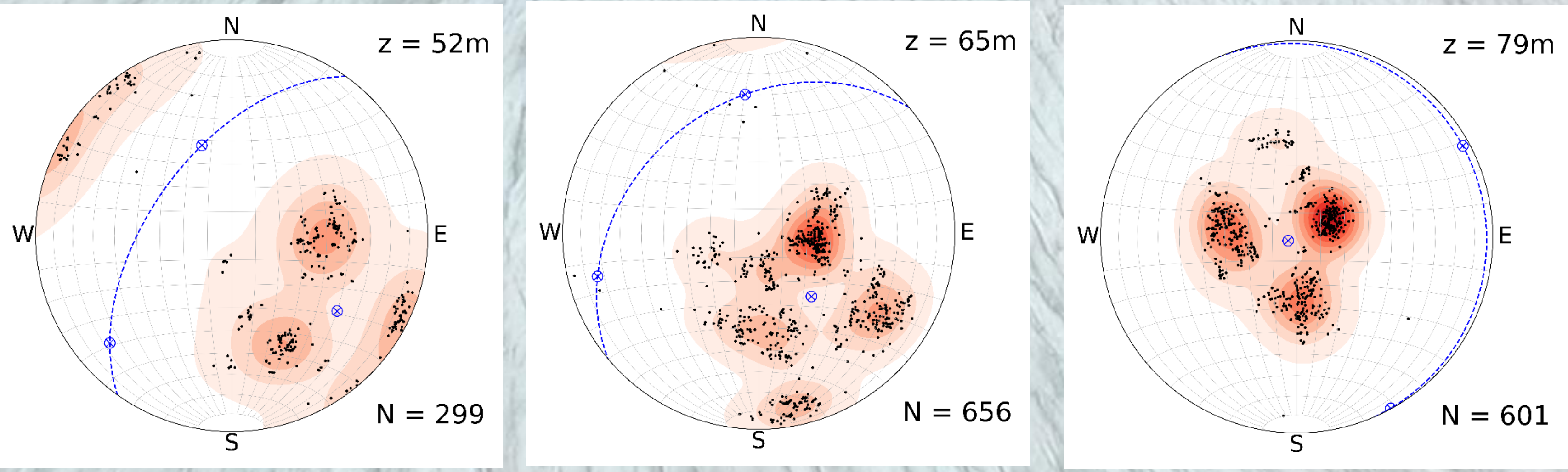


The core is taken 500 m north of the terminus. The mean ice flow in NW-SE directed.

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 ≈10x6 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.



The colatitude angle of the pattern changes from 90° to 0° with increasing depth.
The azimuth is aligned with the ice flow (ex. 2 m)

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) about temperate glacier ice (Rigsby, 1960; Budd et al. 1972) and also in deepest parts of polar ice (Gow&Williamson, 1976)

However…

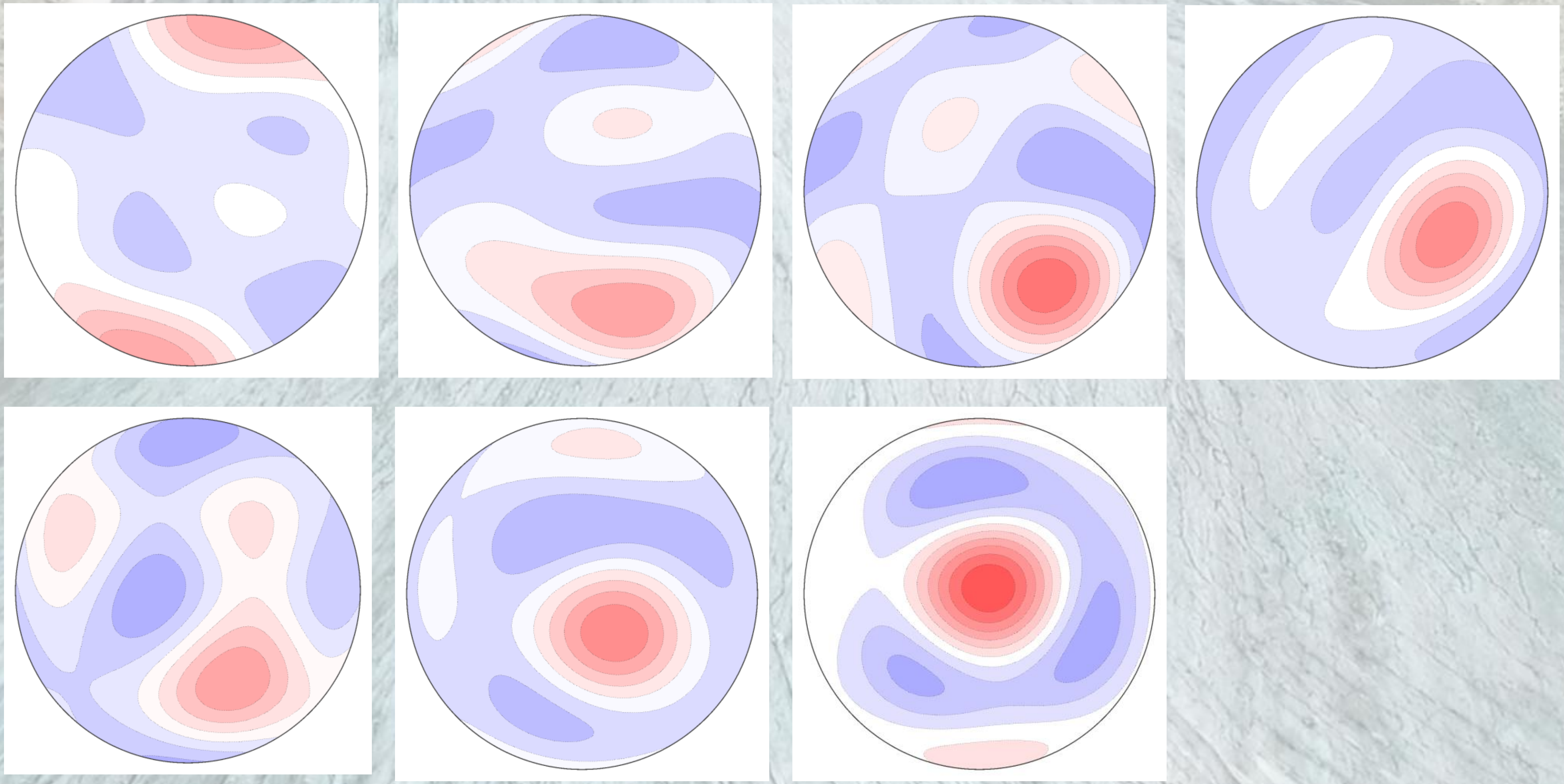
- the COF analysis is time consuming and only a few samples can be analysed in a reasonable amount of time (e.g. 77 sections → 23 days)
- Can we use seismic methods to support the COF analysis?
  - In turn: to what degree of velocity anisotropy leads such a diamond-shape pattern?

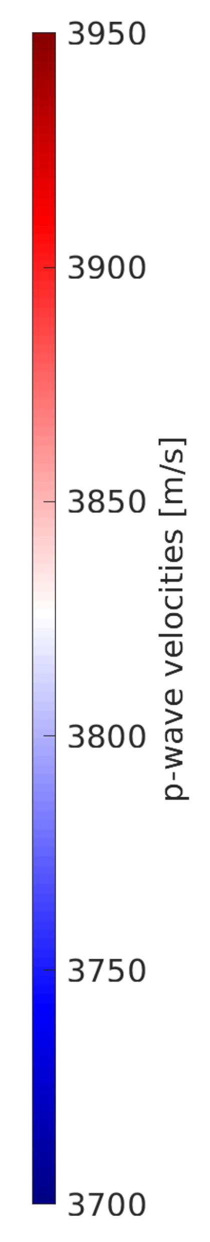
Introduction

Next steps…

- Calculate the seismic velocity of such a COF pattern
  - Kerch et al (2018) used an approach to calculate seismic velocities from a given COF:
    - Crystallographic hexagonal structure → velocities for ice monocrystal using the monocrystal elasticity tensor and the Christoffel equations
    - For polycrystalline ice: need a polycrystal tensor
      - ✓ use a monocrystal tensor → transform it to azimuth/colatitude of the actual c-axis for each single grain
        = transformed monocrystal tensor
      - ✓ sum over all transformed monocrystal tensors (superposition)
        = arbitrary polycrystal tensor (not hexagonal anymore)
      - ✓ calculate the seismic velocities from this *triclinic* tensor
- Obtain ultrasonic measurements and compare them with the calculated velocities

Seismic velocities



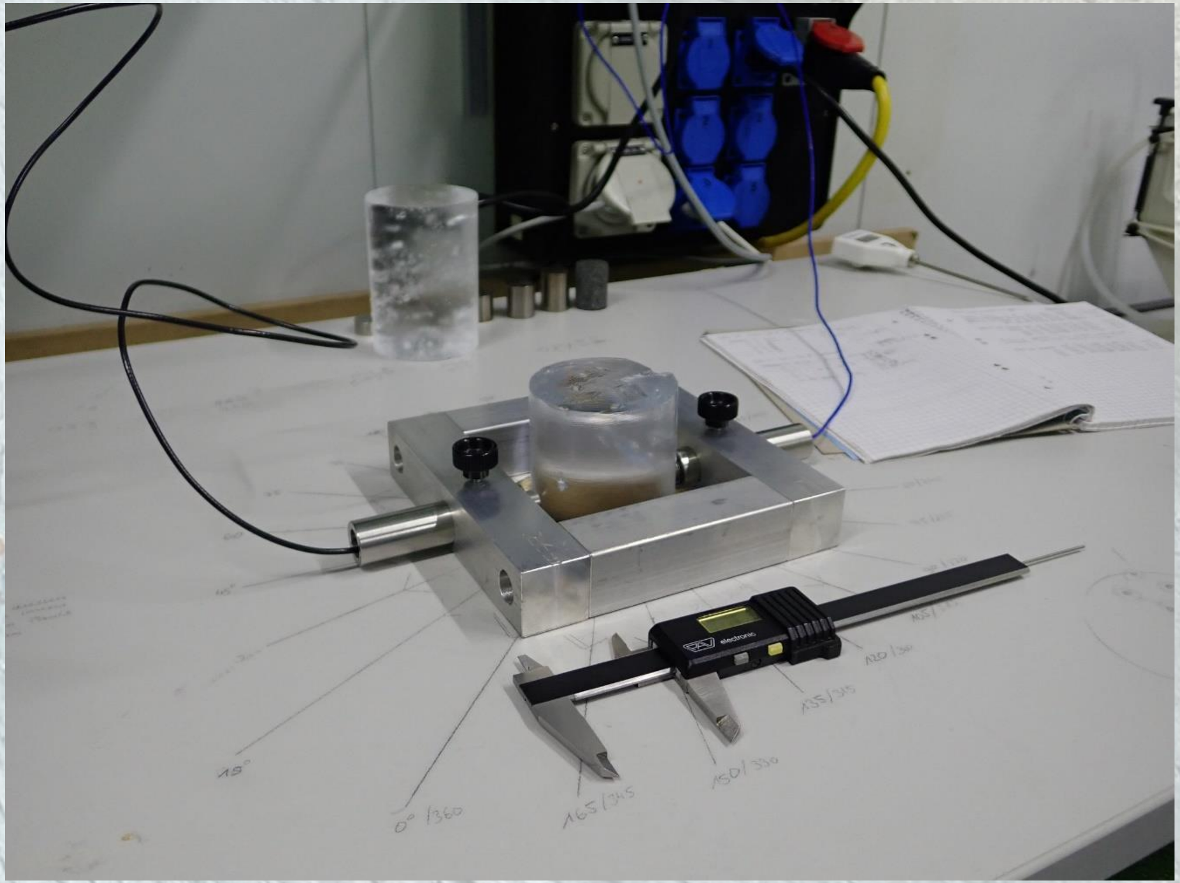


These are the seismic p-wave velocities for all 7 sampling depths and any incident and azimuth angle of a seismic wave. The maximum anisotropy is found for 79 m with 2.3%. The centre of the diamond-shape cluster represents the direction of maximum velocity, the minimum velocity is found around this maximum with an offset of about 45-50°.

Seismic velocities

Can we compare these calculated velocities with velocities measured on-ice?

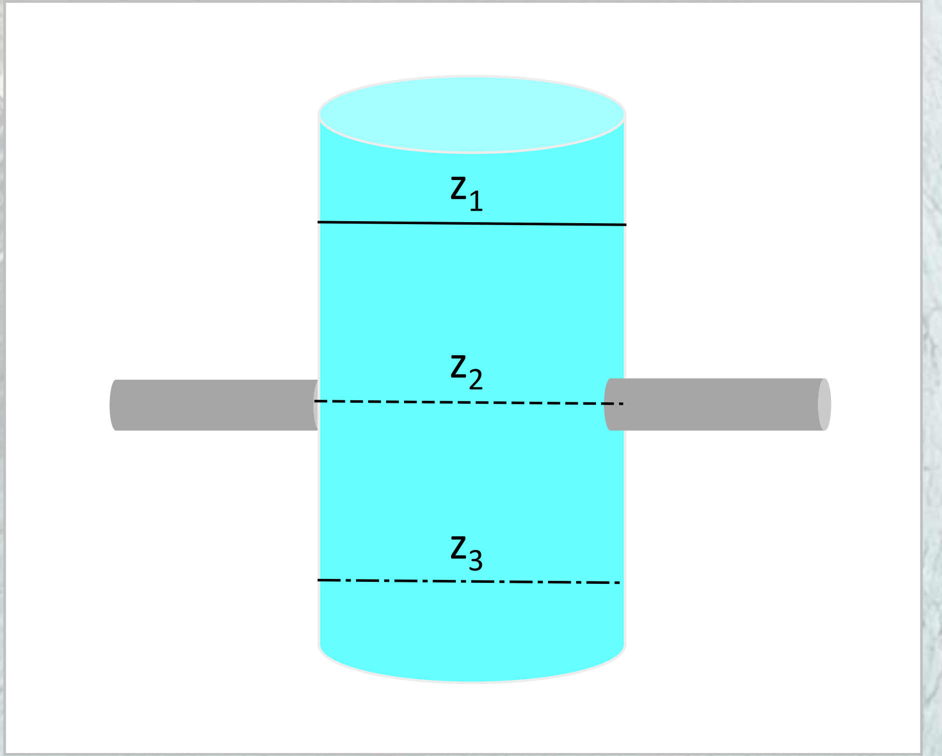
… and can we determine the COF from the velocity trend?

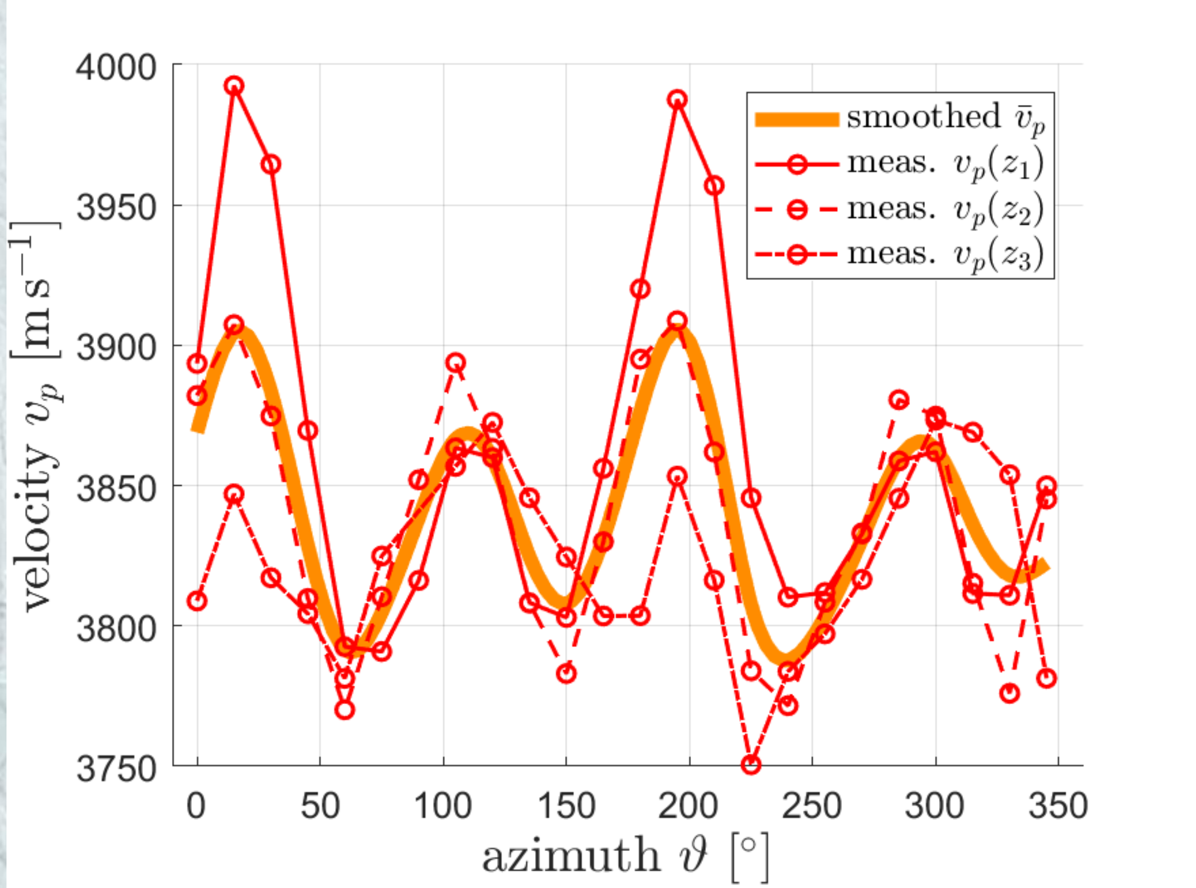


Experimental setup:

- **Ultrasonic experiments with piezoelectric transducers**
- **1 MHz signal frequency (→ $\lambda \approx 3.8$ mm)**
- **Core diameter of 64-69 mm**
- **Horizontal+vertical measurements (no diagonal traces), azimuthal resolution = 15°**
- **5 samples (2, 22, 33, 45, 65 m)**
- **3 measurements within 8 cm for statistical averaging**

Seismic velocities



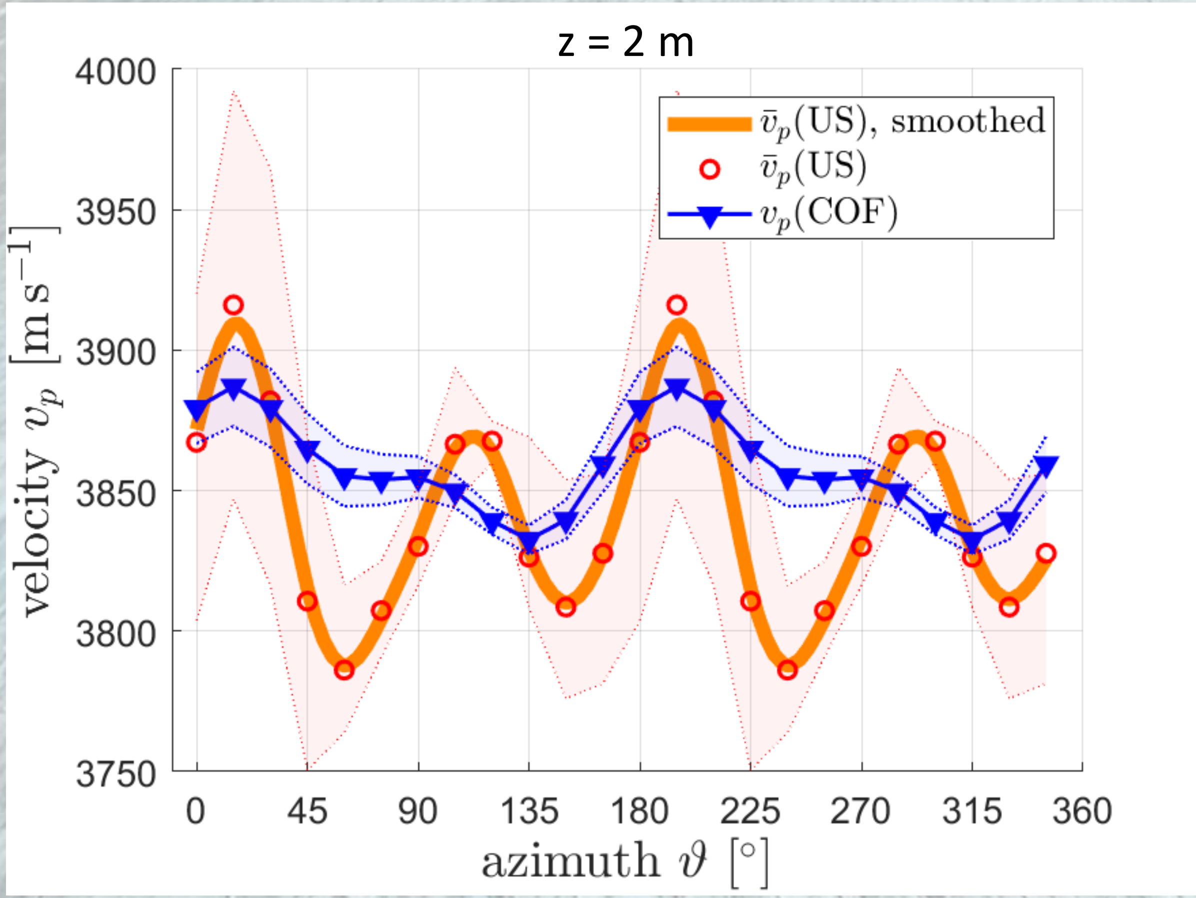


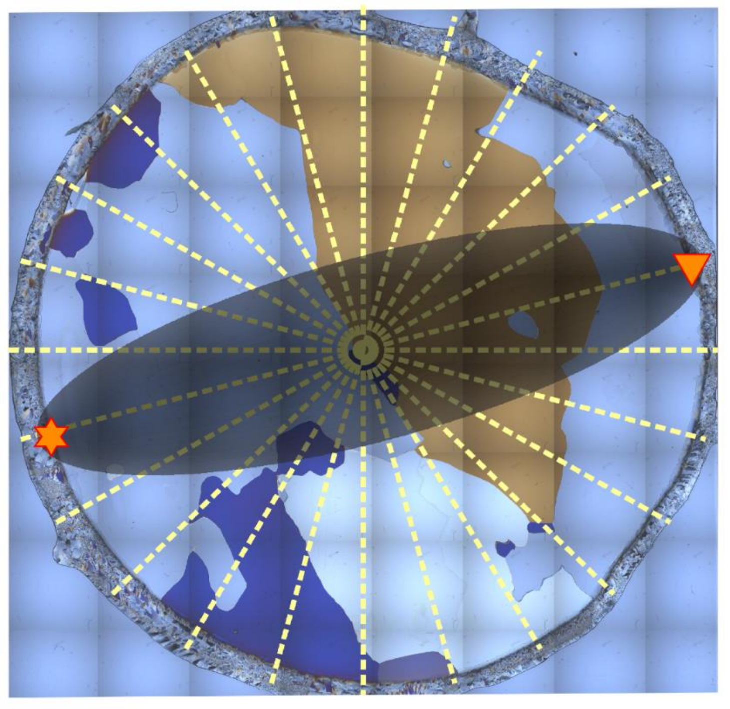
We obtained 3 measurements along a 10 cm long ice sample with an azimuthal resolution of 15°.

These results of the individual planes were averaged to calculate a mean value for the velocity. This mean velocity is comparable with the velocity derived from COF as both are averages over a few centimetres of ice.

Seismic velocities

A direct comparison between calculated and measured velocities reveals a discrepancy especially for max/min values.

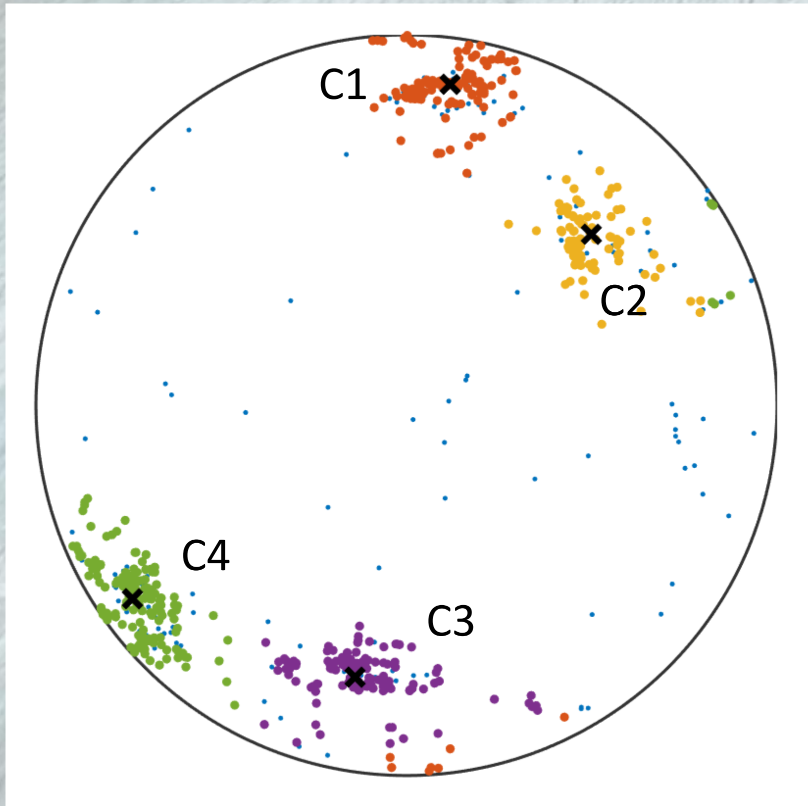


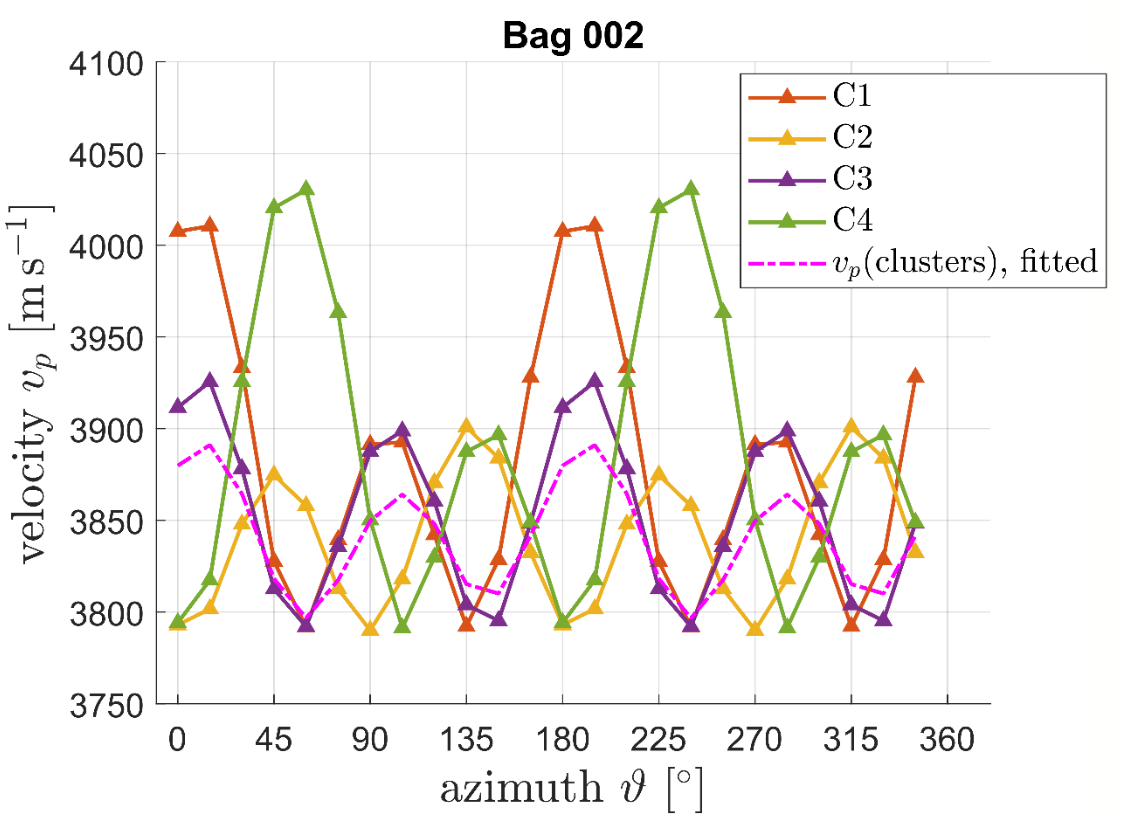


This discrepancy is most likely a result of the extremely large ice grains. Some dominate the measured velocity and others may not be present (example shown above with grains in different colours)

Seismic velocities

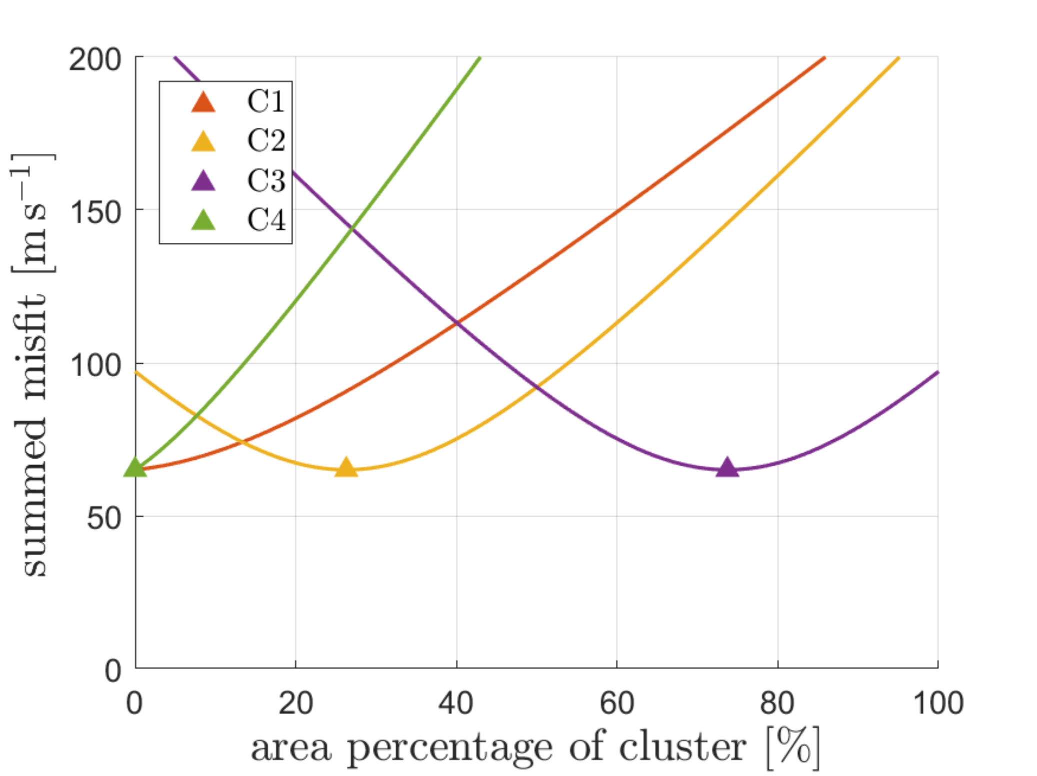
In a first step we analysed the contribution of each cluster to the obtained measured data – can we explain the measured curve with a weighted combination of the 4 clusters?

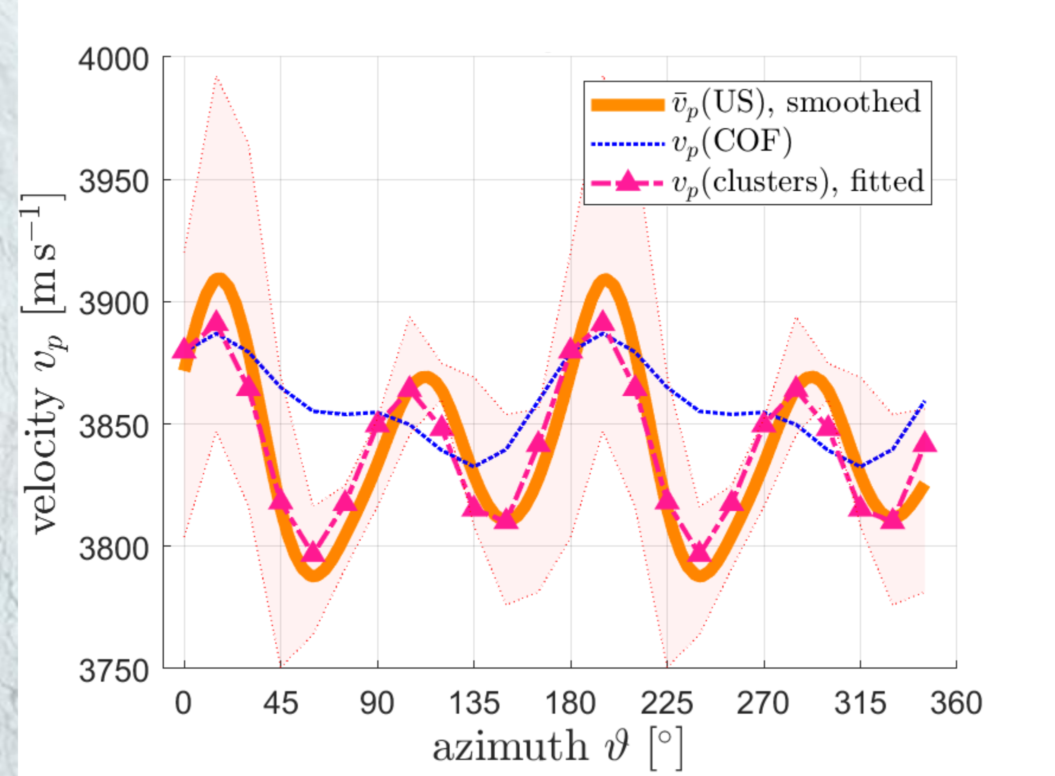




A few large grains dominate the measurement and thus this particular cluster has a larger influence on the obtained seismic velocity profile (dashed line).

Seismic velocities

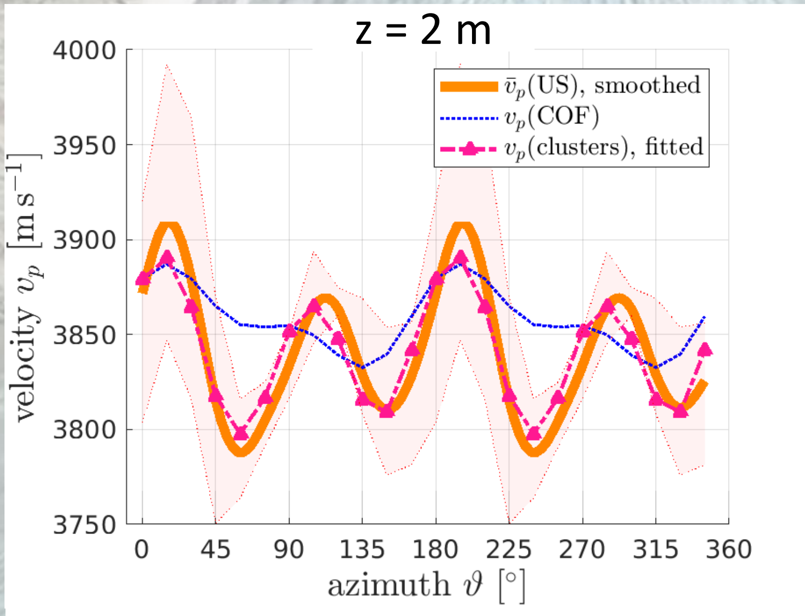


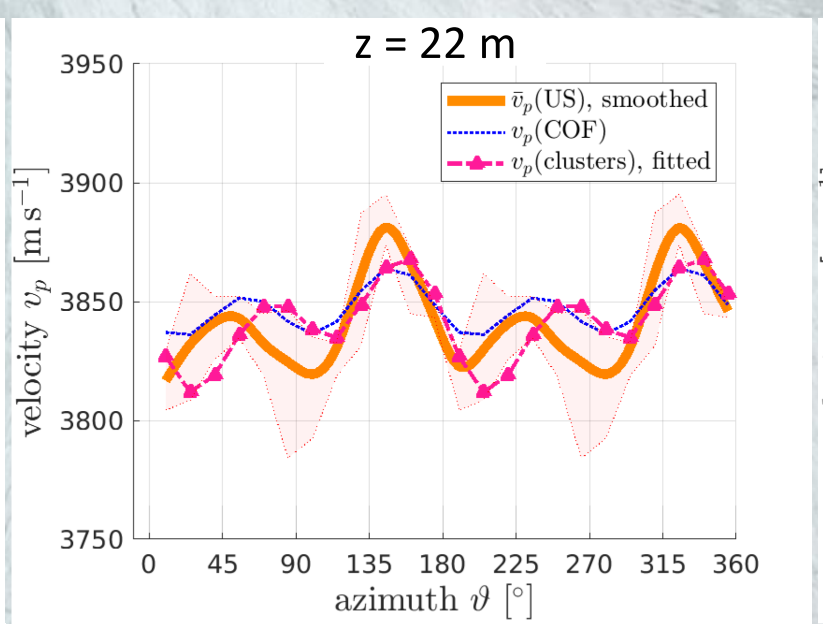


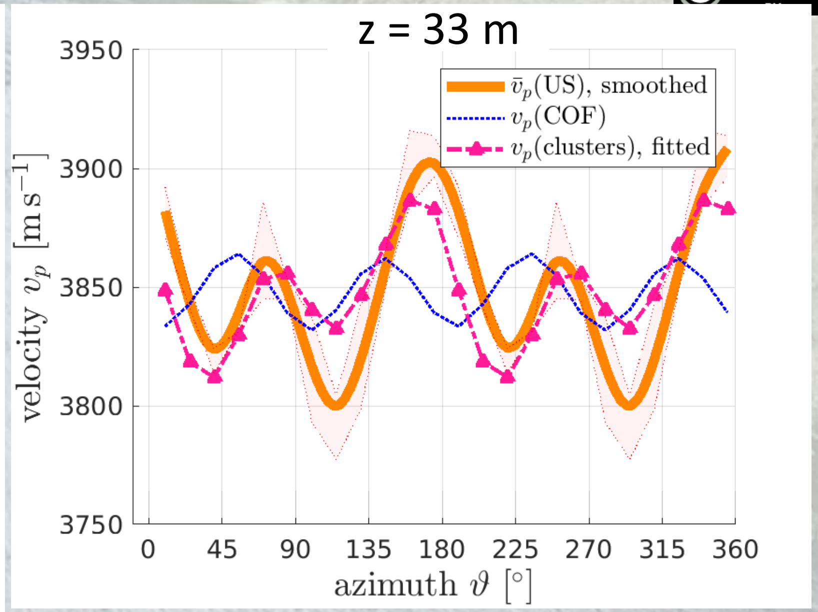
By analysing the summed misfit between measured and calculated curve, the contribution of each cluster to the measured curve is analysed. Clearly, C3 contributes most, C1+C4 do not contribute much.

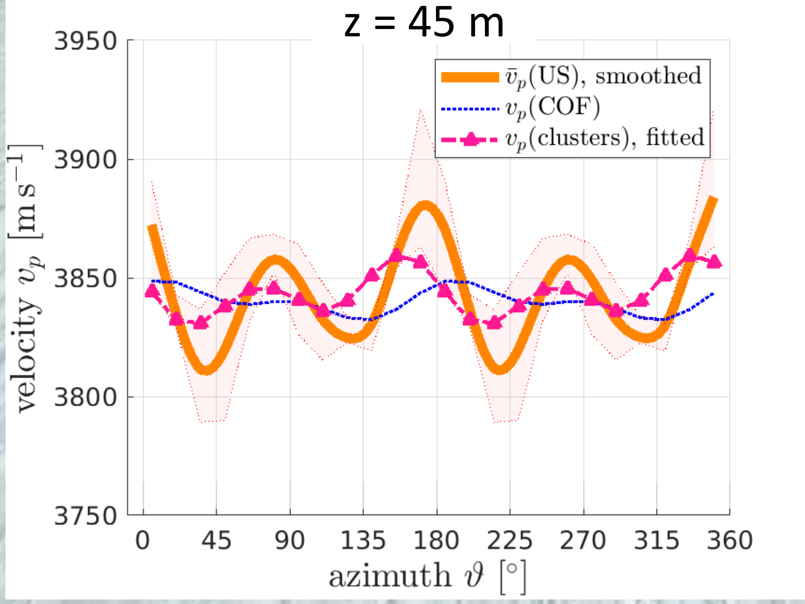
The measured, COF-derived and fitted velocity curves, are displayed in the figure to the right. Clearly, the curve of measured velocities can be explained by a combination of the known maxima. However, this also indicates that a certain a priory knowledge is required. Gradual changes should be traceable.

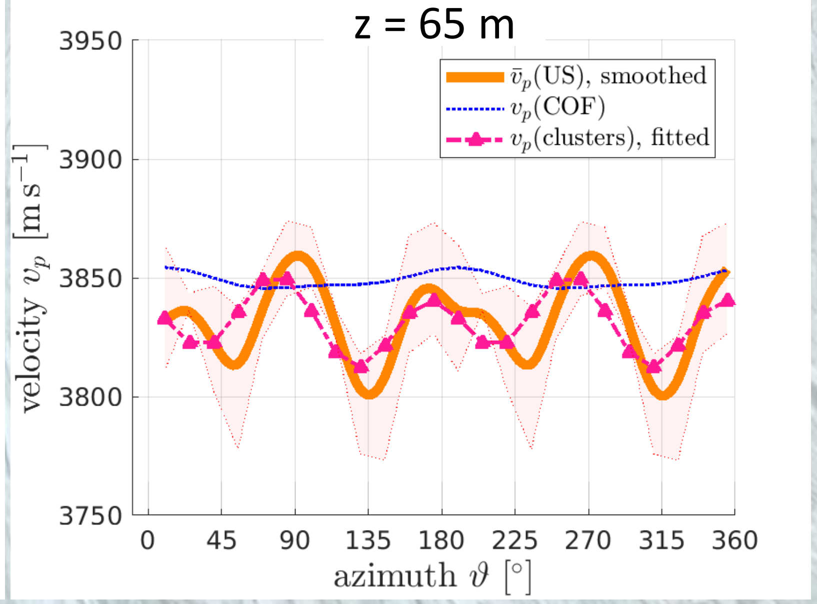
Seismic velocities











This processing scheme was repeated for all 5 samples along the ice core. The results of measured (orange), COF-derived (blue), and the fitted curve, calculated by varying the proportions of the individual clusters (purple) are presented here.

Key findings of velocity analysis

- For 2+22 m the analysis shows promising results
  - centroid of COF is close to horizontal
- For 45 and 65 m, the more horizontal clusters are overrepresented in the measurements, which may indicate that horizontal measurements are not sufficient enough to examine the COF
  - Here measurements with different azimuths and additionally a variety of colatitude angles is expected to improve the data quality.
  - Due to the broad angular sensitivity of point-contact transducers those experiments might be feasible.
- The 4-maxima COF pattern and the resulting low anisotropy (max. 2.3%) exacer-bate a fit between measured and calculated velocities for this temperate ice core

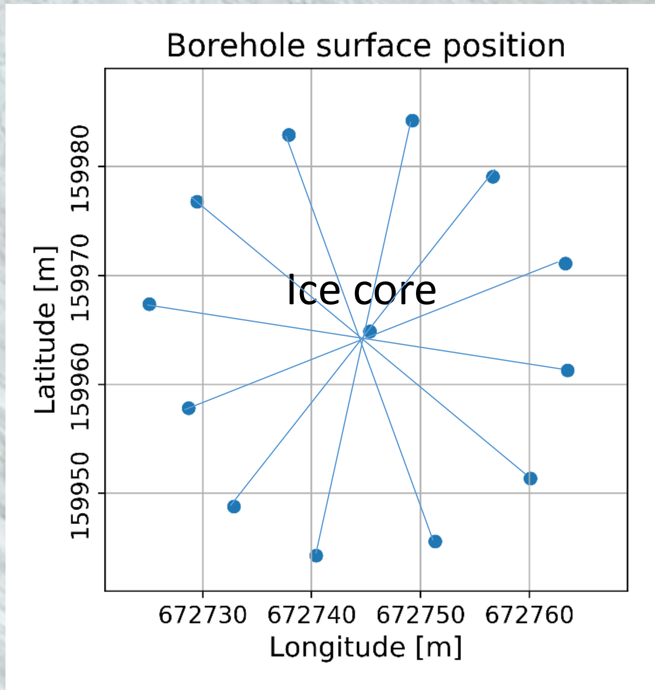
Summary

- Changes in COF are visible in the velocity patterns
- Diagonal measurements presumably enhance the data quality and interpretation by reducing ambiguity
- We can state at least for temperate ice cores:
  - ➢ Large grains limits 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
  - ➢ Measurements along the ice core cannot fully replace the COF analysis, but might be used to support the extensive analysis, e.g. to fill the gaps between data points

Summary & Outlook

Outlook

- A non-destructive method that is capable to trace changes in COF
  - ➢ There might be 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
- For this project the measured velocities can be correlated with in-situ cross-borehole experiments



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