ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR- UND MEERESFORSCHUNG

Investigation of crystal anisotropy using seismic data from Kohnen Station, Antarctica

Anja Diez[1,2], Olaf Eisen[1], Ilka Weikusat[1], Astrid Lambrecht[3], Christoph Mayer[3], Coen Hofstede[1], Thomas Bohlen[2], Heinrich Miller[1]
Contact: Anja.Diez@awi.de

Introduction

The flow behavior of glaciers and ice sheets is influenced by a preferred orientation of the anisotropic ice crystals. Knowledge about crystal anisotropy is mainly provided by crystal orientation fabric (COF) data from ice cores. To gain a broader understanding about the distribution of crystal anisotropy in ice sheets and glaciers we use seismic measurements, i.e., a surface based method.
Effects of crystal anisotropy on seismic data:
(i) the anisotropic fabric induces an angle dependency on the seismic velocities and, thus, traveltimes,
(ii) sudden changes in COF lead to englacial reflections.

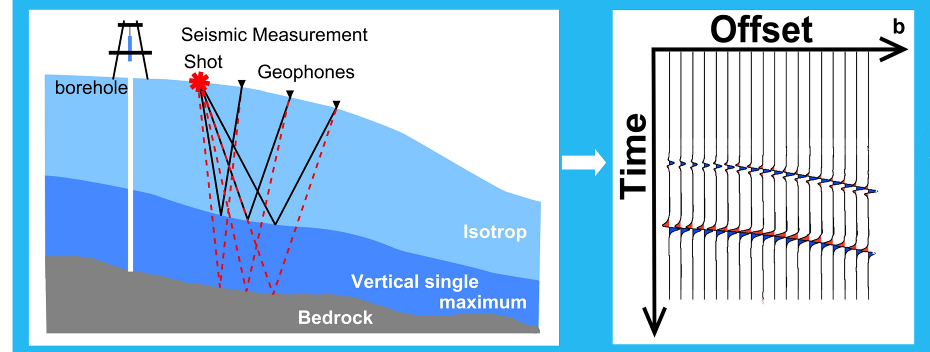


Fig. 1: (a) Sketch of seismic survey on ice with changing crystal orientation fabric (COF) over depth. (b) Reflections are expected form englacial and ice-bed boundary layers. Hence, the traveltime and reflection signature can be analysed to determine the COF.

Outline

(1) Data
(2) COF eigenvalues → Elasticity tensor
- Connection of COF eigenvalues with elasticity tensor.
- Calculation of seismic velocities from elasticity tensor.

(3) Vertical seismic profiling (VSP)
- Dervation of seismic velocity profile from VSP survey.
- Comparison with velocities calculated from COF eigenvalues.

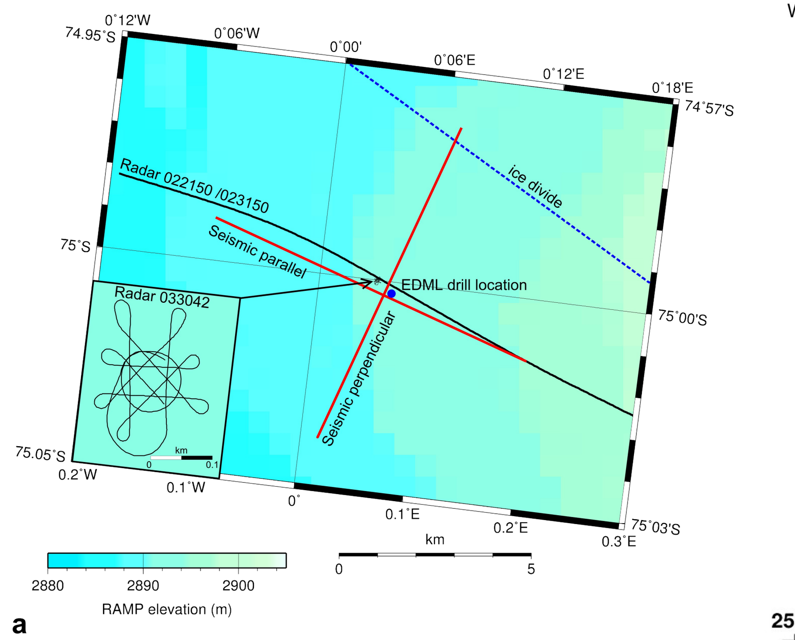
(4) Comparison of ice-core, seismic and radar data
- Investigation of COF induced reflections.

Survey location

- Kohnen Station, Dronning Maud Land, Antarctica
- EDML ice-core (length 2774 m)
- Ice thickness 2782 ± 5 m
- Data:
  - COF eigenvalues
  - Seismics: VSP, wideangle survey
  - Radar: 60 ns, 600 ns pulse

(1) Alfred Wegener Institute, Bremerhaven, Germany; (2) Geophysical Institute, Karlsruhe Institute of Technology, Germay; (3) Comission for Glaciology, Bavarian Academy of Sciences and Humanitites, Germany

(1) Data



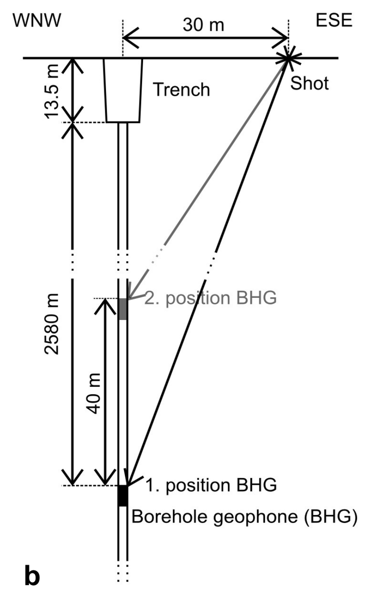
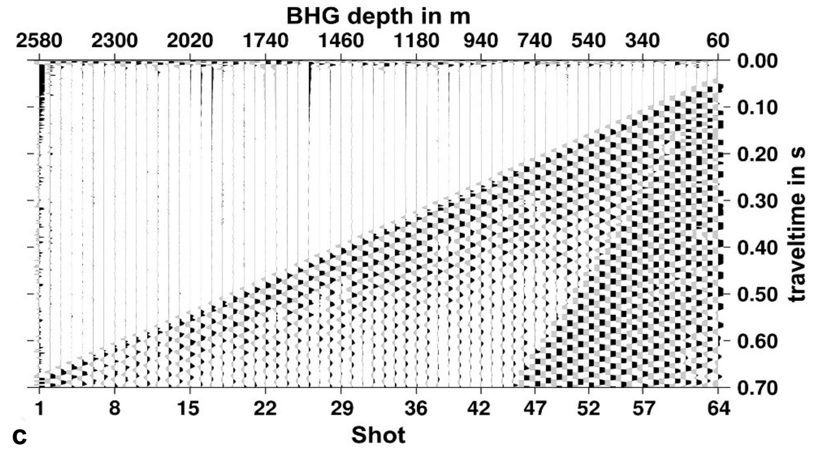


Fig. 2: (a) Surveys carried out at Kohnen station include seismic surveys (red), radar surveys (black) and the drilled ice-core EDML. (b) Sketch of the vertical seismic profiling measurement, carried out within the borehole of the EDML ice core. (c) Seismic data from the VSP measurement To calculate interval velocities the traveltimes were picked from the direct wave, that is well visible.



Data sets:

- Ice-core EDML (blue dot)
  - COF eigenvalues
- Seismics
  - Vertical seismic profiling (blue dot & Fig. 2b)
  - Wideangle survey (red lines)
- Radar (black lines)
  - Profile with 60 ns (022150) and 600 ns pulse (023150)
  - Polarization profile with 60 ns pulse (033042)

VSP survey:

- Source: detonation cord
- Reciever: borehole geophone
- Reciever position: 2580 m – 60 m depth
- Reciever interval: 40 m
- Analysed: traveltimes direct wave

(2) COF eigenvalues → Elasticity tensor

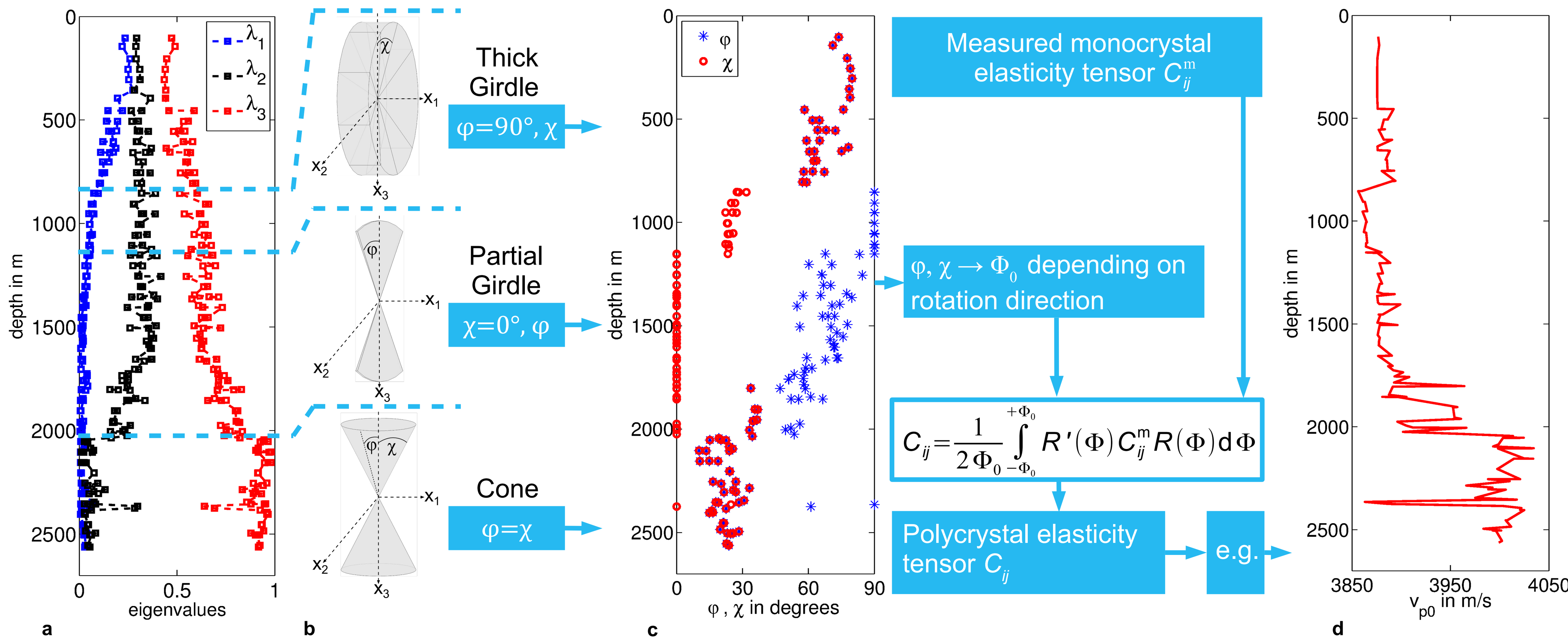
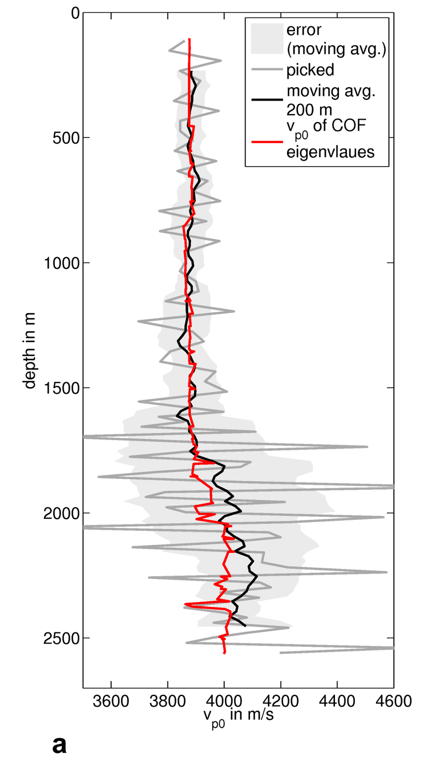


Fig.3 : (a) COF eigenvalues of EDML ice core, (b) enveloping of different c-axes distributions, thick girdle, partial girdle, cone fabric, (c) derived angels for the different fabrics form the COF eigenvalues, (d) zero-offset P-wave velocity calculated from the elasticity tensor derived from the COF eigenvalues. Calculation of the elasticity tensor using the rotation matrix R(Φ) and its transposed R'(Φ).

Calculation of elasticity tensor:

Connecting the micro with the macro scale, the COF eigenvalue with the elasticity tensor to be able to investigate the seismic wave propagation in anisotropic ice.
1. Distinguishing fabric – cone, partial girdle, thick girdle.
2. Deriving opening angle.
3. Integration of measured monocrystal elasticity tensor, using the opening angels φ and χ.
→ Calculation of velocities or reflection coefficients.

(3) Vertical Seismic Profiling



VSP velocities (a):

Picked traveltimes were used to calculate interval velocities over depth (gray line). To see the main velocity trend over depth a 200 m moving average (black line) was calculated:

- surface – 1800 m → ~ 3850 m/s
- 1800 m – 2030 m → velocity increase
- 2030 m – bed → ~ 4030 m/s

Measured elasticity tensors (b):

We use the monocrystal elasticity tensors measured by different authors to calculate the polycrystal elasticity tensor (Fig. 3). Best agreement between measured and calculated velocities can be found using the elasticity tensor by Gammon et al. (1983), Jona and Scherrer (1952) or Bennett (1968).

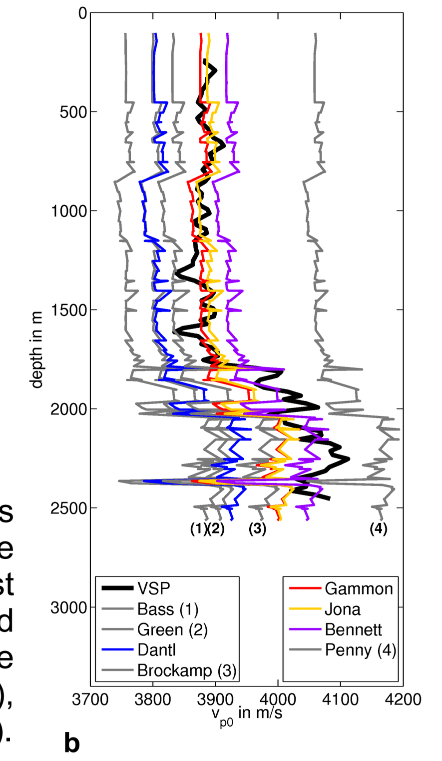


Fig. 5: (a) Interval velocities (gray line) calculated from the picked traveltimes of the VSP survey, with a 200 m moving average (black line) to see the main trend and its RMS error (gray area). For comparison the interval velocity profile calculated from the COF eigenvalues using the measured elasticity tensor of Gammon et al. (1983) is shown (red line). (b) comparison of velocity profiles calculated from monocrystal elasticity tensors measured by different authors in comparison to the VSP interval velocities (black line).

Comparison VSP/COF velocities

Good agreement can be found between the interval velocities from the VSP survey (black) and the COF eigenvalues (red). The main velocity trend is the same in both profiles, with a good agreement of the absolute velocity values.

Frequency dependency?

Ultrasonic sounding (28 kHz) experiment of Gusmeroli et al. (2012) showed good results using the elasticity tensor derived by Dantl (1968). Our VSP velocities (~100 Hz) show poor agreement with these derived velocities (blue).
→ Frequency dependency of seismic waves in ice!?

(4) Comparison ice-core, seismic, radar data

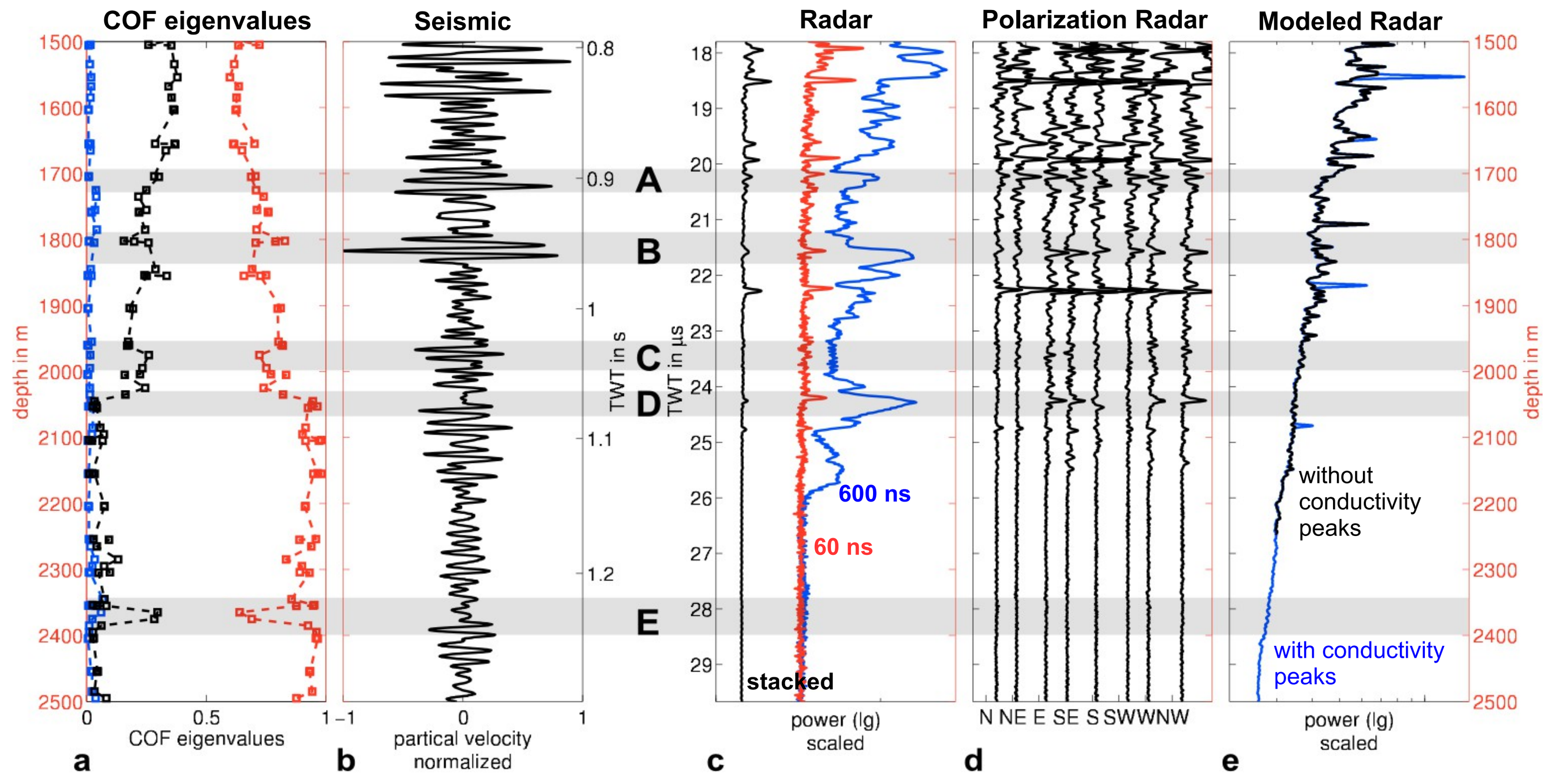


Fig. 6: (a) COF eigenvalues of EDML ice-core, (b) seismic trace, stack of 60 traces to enhance signal-to-noise ratio, (c) radar traces, in blue 600 ns pulse (023150), in red 60 ns pulse (022150), in black stack of all traces of the survey 033042 (60 ns pulse), (d) stack of traces belonging to one air plane direction of the survey 033042 (60 ns pulse), (e) modeled radar trace with (blue) and without (black) conductivity peaks (Eisen et al., 2007).

Challenges:

- Seismics:
  Identifying weak COF-induced reflections in coherent noise from, e.g., surface or diving waves.
- Radar:
  Distinguish between COF-induced and conductivity-induced reflections

Identification of reflection origin by comparison of different data sets:

Different events in seismic and radar data are interpreted to arise from an abrupt change in COF. A strong conductivity-induced reflector in the radar data at ~1870 m shows no corresponding signal in the seismic data.
- Event A:
  Seismic signal and corresponding signals in the radar traces. No corresponding jump in the COF eigenvalues.
- Event B:
  Seismic signal and corresponding signals in the radar traces. The jump in the COF eigenvalues seams to be to weak to cause such strong reflections.
- Event C:
  Rather quite zone in radar data corresponds to reflection signal in seismic data and a jump in the COF eigenvalues.
- Event D:
  Radar reflectors were already linked to the change in COF (Eisen et al., 2007). Seismic traces shows a quite zone followed by a distinct signal.
- Event E:
  Region of layer of developed girdle fabric. Seismic reflection visible in the depth region of the transition back from girdle to the narrow cone fabric.

Conclusions

COF eigenvalues → elasticity tensor

- Framework to calculate elasticity tensor from COF eigenvalues.
- Calculation for cone, thick girdle and partial girdle fabric.
- Elasticity tensor provides opportunity to calculate ,e.g., velocities or reflection coefficients
- Elasticity tensor offers possibility to carry out full waveform forward modeling as step towards full waveform inversion.

Vertical seismic profiling

- VSP interval velocities were compared to interval velocities derived from COF eigenvalues.
- Good agreement of main trend of COF eigenvalue and VSP velocity profiles.
- Best agreement with absolute values using elasticity tensor of Gammon et al. (1983), Jona and Scherrer (1952) and Bennett (1968).
- Result in contrast to results of Gusmeroli et al. (2012). Possible reason: Frequency dependency, dispersion of seismic waves in ice.

Comparison ice-core, seismic, radar data

- Common reflections in seismic and radar data identifiable by comparison of traces.
- Common reflections interpreted as arising from an abrupt change in the COF.
- COF eigenvalue data does not necessarily show corresponding change in COF.
- Is resolution of COF measurements sufficient?

References:
Bennett, H. F. (1986). An investigation into velocity anisotropy through measurements of ultrasonic wave velocities in snow and ice core from Greenland and Antarcitca. PhD thesis, University of Wisconsin-Madison.
Dantl, G. (1968). Die elastischen Modulen von Eis-Einkristallen. Phys. Kondens. Materie, 7:390 – 397.
Eisen, O., I. Hamann, S. Kipfstuhl, D. Steinhage, F. Wilhelms (2007). Direct evidence for continuous radar reflector origniating from changes in crystal orientation fabric. The Cryosphere, 1(1):1 – 10.
Gammon, P. H., H. Kiefte, M. J. Clouter and W. W. Denner (1983). Elastic constant of artificial and natural ice samples by brillouin spectroscopy. J. Glaciol., 29(103):433 – 460.
Gusmeroli, A., E. C. Pettit, J. H. Kennedy and C. Ritz (2012). The crystal fabric of ice from full-waveform borehole sonic logging. J. Geophys. Res., 117:F03021.
Jona, F. And P. Scherrer (1952). Die elastischen Konstanten von Eis-Einkristallen. Helvetica Physica Acta, 25(1 – 2):35 – 54.

Diez, A. (2013). Effects of cold glacier ice crystal anisotropy on seismic data. PhD thesis, Karlsruhe institute of technology, urn:nbn:de:swb:90-379840.

B901