Determination of crystal orientation fabric from seismic wide-angle data

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Introduction:

It is known from ice core analyses that the crystal orientation fabric (COF) of ice sheets is anisotropic and changes over depth. A better understanding of these anisotropies as well as their remote detection is important to optimize flow models for ice. Here, we show how seismic wide-angle measurements can be used to determine the COF remotely. We demonstrate the principle formalism how observed seismic travel times can be related to COF properties by a forward model and then apply the formalism to field data.
The eigenvalues that describe the ice fabric of the ice core EDML (Dronning Maud Land, Antarctca) are set into a relationship with the elasticity tensor. From the elasticity tensor, the expected seismic velocities and reflection coefficients are calculated. Additionally, we calculate the value η from the Thomsen-parameters ε and δ. The value η gives a measure of the anisotropy of vertical transverse isotropic (VTI)-media and is an important tool for the NMO-correction of anisotropic data. The approximation of reflection horizons as hyperbolas is not valid anymore in anisotropic media. The calculation of the moveout is therefore performed by a 4th-order NMO-correction with the RMS-velocity and the effective η value as variables.
This approach is applied to data from a wide-angle survey shot at Halvfarryggen, Dronning Maud Land, Antarctica. From this data, we derived RMS-velocities and effective η values. These values were than recalculated to interval velocities and interval η values to give a hint on the measure of anisotropy of the different layers. The results give first insight into the anisotropies at Halvfarryggen.

Conclusion:

- The elasticity tensors were derived from eigenvalues of the ice core EDML.
- The Halvfarryggen wide-angle data was processed, internal refelctors became visible.
- A 4th-order NMO-correction was carried out and the value η was derived from the wide-angle data.
- From the results for the interval η-values the anisotropy for single layers could be derived.

Outlook:

- Analyses of the wide-angle data from seismic survey at Kohnen (January 2012).
- Comparison of seismic and ice core results (from Kohnen).
- Connection of seismic, radar and ice core data for a better understanding of ice properties.

Acknowledgment to Rick, Sverrir, Yngve as well as the DFG.

Literature:
Gammon, P.H., H. Kiefte, M.J. Clouter, W.M. Denner, 1983. Elastic constant of artifical and natural ice samples by brillouin spectroscopy, J. Glaciol., 29(103), 433-460.
Nanthikesan, S., S. Shyam Sunder, 1994. Anisotropic elasticity of polycrystalline ice in Ih, Cold regions Science and Technology, 22, 149-169.

Eigenvalues ice core EDML

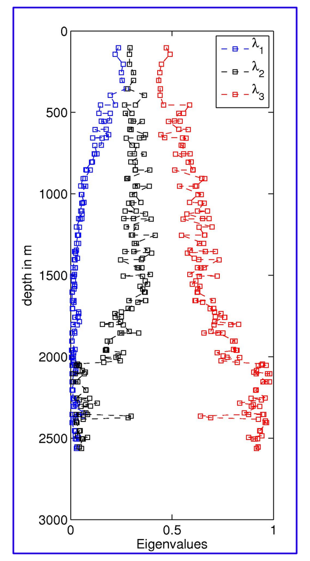

Figure 1: Eigenvalues measured on the ice core EDML at Kohnen station.

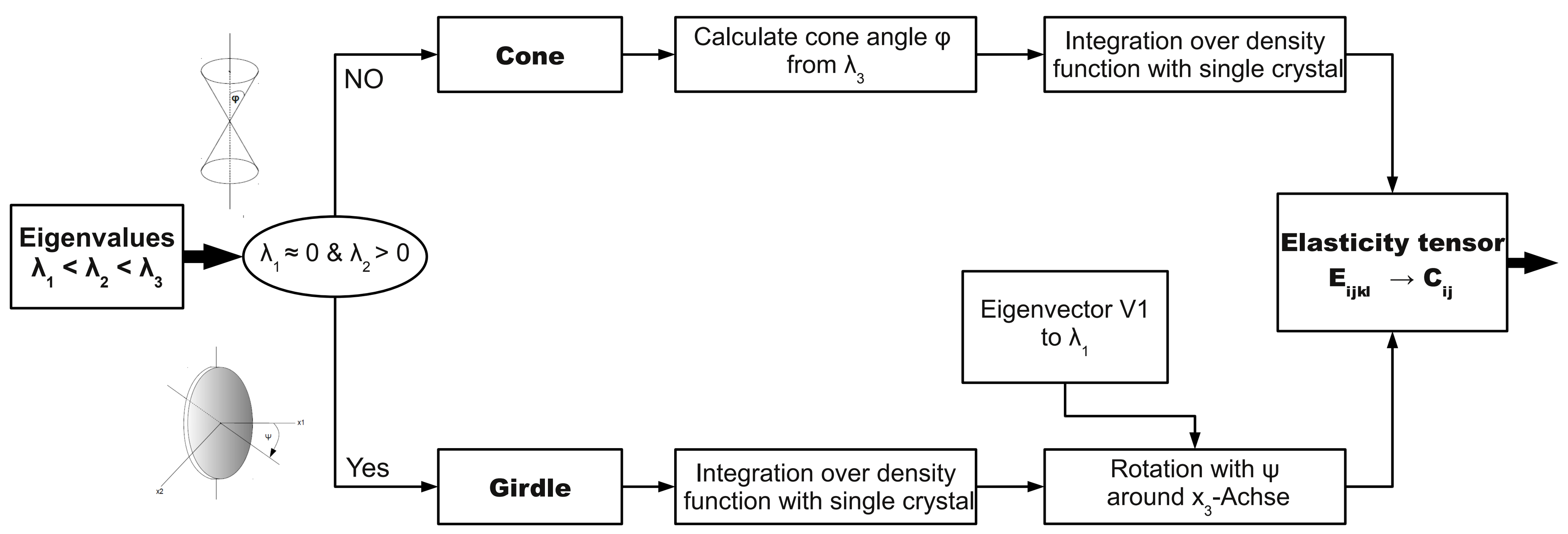

Figure 2: Flow diagram on how to derive the elasticity tensor from the eigenvalues of an ice core that describe the ice fabric.

Kohnen

- East Antarctica
- 750 km southeast of Neumayer III
- Ice core EDML
  - Drilled: 2001-2006
  - Length: ~2770 m
  - Age: 150 ka
  - Measured COF

To be able to **compare measurements of COF** from ice core data **with seismic data**, we need a connection betwen the description of the COF by eigenvalues (Fig. 1) and the elasticity tensor. From the elasticity tensor E_{ijkl} seismic velocities (P-, SV- and SH-wave) can be calculated as well as reflection coefficients. For these calculations, we use the compressed Voigt Notation C_{ij} as description of the elasticity tensor.

From the eigenvalues, we distinguish between girdle and cone fabric (Fig. 2). Afterwards C_{ij} of a single crystal (measured by Gammon, 1983) is used to calculate the elasticity tensor of the fabric by integration over a density function (Nanthikesan, 1994). Thus, the **elasticity tensor for different fabrics** is obtained.

Fabric

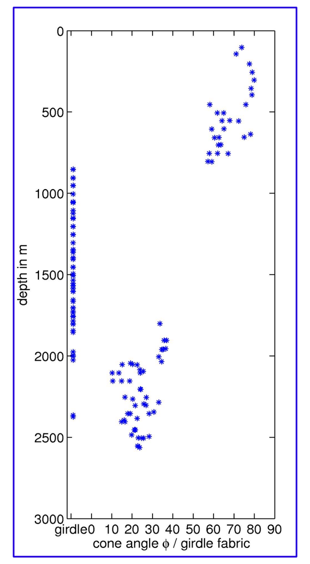

Figure 3: Cone or girdle fabric derived from the eigenvalues of ice core EDML.. The cone angle was derived from λ_3.

Velocity

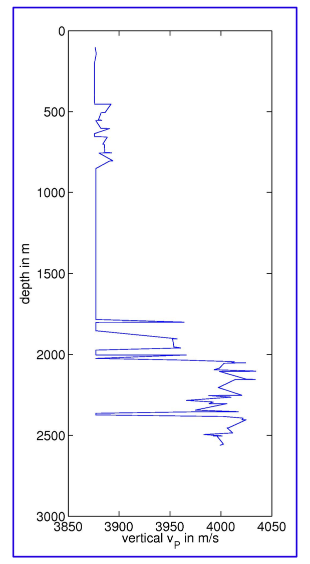

Figure 4: Vertical P-wave velocity calculated from the elasticity tensors derived from eigenvalues of the ice core EDML..

- **Fabric** (cone angle, girdle fabric) derived from eigenvalues (Fig. 3).
- **P-, SV- and SH-wave velocities** can be calculated from elasticity tensor.

Example: Figure 4 show the vertical P-wave velocity, this velocity is needed for the calculation of the RMS-velocity for the NMO-correction.

Thomsen parameter

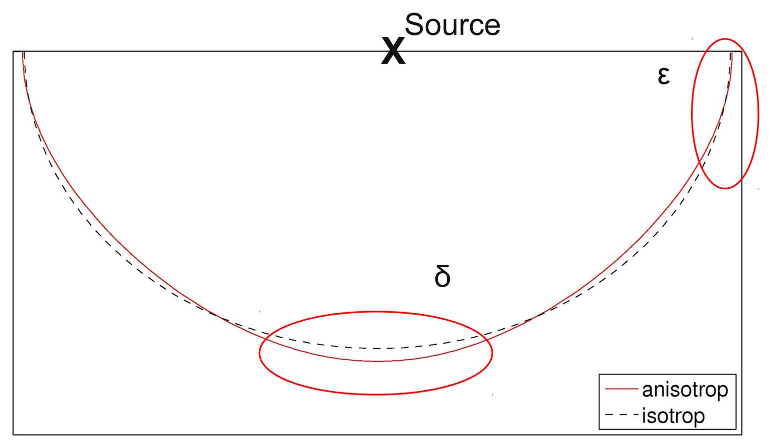

Figure 5: An isotropic and an anisotropic wavefront is shown. The anisotropic wavefront was calculated from the elasticity tensor for a single ice crystal, measured by Gammon (1983). The region of sensitivity of the Thomsen parameter δ and ε is marked.

Thomsen parameter for weak anisotropy:
- Vertical transversely isotropic material (**VTI**)
- With adjustments horizontal vertical transversely material (**HTI**)
- Calculation from the elasticity tensor C_{ij}

→ Approximate seismic velocities, reflection coefficients
- *δ*: angular dependence of v_P for vertical incidence
- *ε*: difference between horizontal and vertical for v_P
- ***η***: calculated from *δ* and *ε*, **measure for ansiotropy**

$$\eta=\frac{\epsilon-\delta}{1+2\delta}$$

→ *η* is needed for the NMO-correction of 4th-order in anisotropic material.

η-value

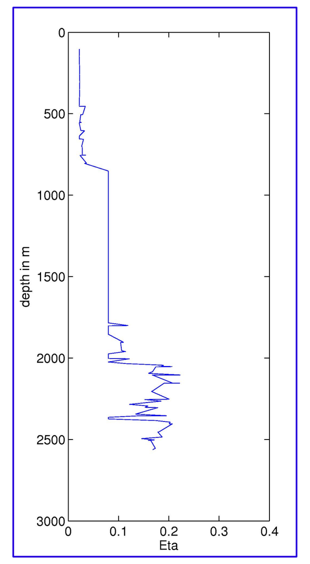

Figure 6: Value η calculated from the elasticity tensors derived from the eigenvalues of EDML..

- *η* calculated from the elasticity tensors.
- Analyses of seismic data with help of **4th-order NMO-correction**

→ **Result will be *η***

Ice core (COF) **Kohnen** → **Seismic**

Ice core (COF) ← **Halvfarryggen** **Seismic**

Halvfarryggen

- Antarctica, Dronning Maud Land
- Southeast of Neumayer III
- Catchment area of Ekströmisen
- Local dome, divide triple point
- Anisotropic ice, known from radar data
- Possible drill location within IPICS

Wide-angle Survey 2010

- Snowstreamer 60 channels (each channel: 8 geophone)
- Channel distance 12.5 m
- 18 shots
- Borehole distance 375 m
- 2 shots per hole
- Streamer increment 375 m

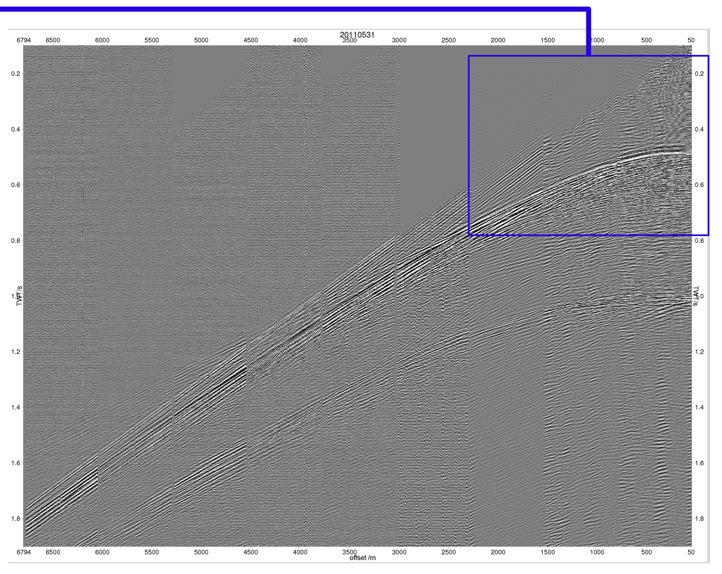

Figure 7: Wide-angle survey at Halvfarryggen, Dronning Maud Land, Antarctica. In total, 18 shots were placed with an total offset of 6794 m.

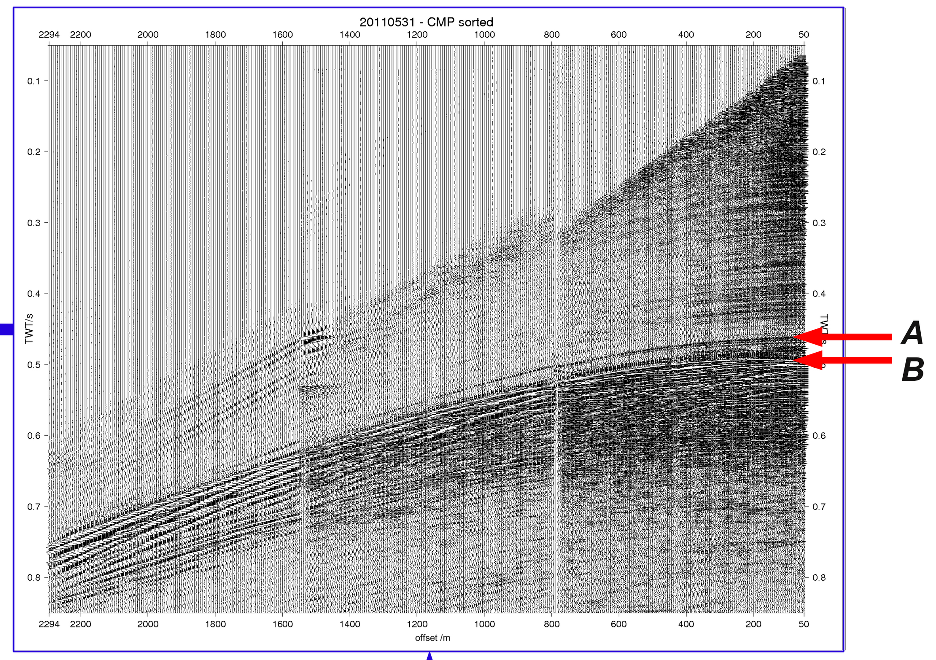

Figure 8: Zoom of the wide-angle survey, containing the first 6 shots and a total offset of 2294 m .

Seismic section

- Total offset 2294 m
- Two strong reflectors
  - *A:* strongest internal reflector within the ice
  - *B:* bed reflection
- Correction for bending of the reflection

→ **Normal moveout correction** (NMO)
- Travel time calculation for NMO-correction :

$$t_x^2=C_0(t_0)+C_1(v_{rms},t_0)x^2+C_2(\eta_{nmo},v_{rms},t_0)x^4...$$

t two way travel time, v_{rms} root-mean-square velocity, η_{nmo} effective η-value

- Usually, first two terms (2nd-order) are used to calculate moveout hyperbola.

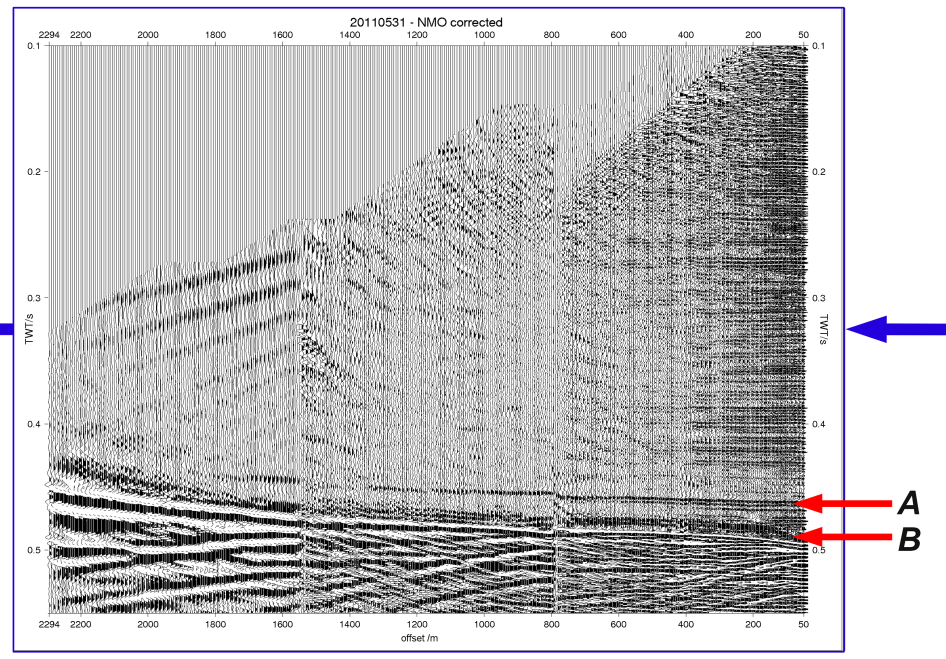

Figure 9: 2nd-order NMO-corrected section. For the small offsets up to 800 m the correction worked well. The bed reflector B and the internal reflector A are not flat for the bigger offsets.

NMO-correction

- NMO-correction of **2nd-order fails**!

$$t_x^2=t_0^2+\frac{x^2}{v_{rms}^2}$$

- Reflections for the first 800 m offset are leveld off.
- Internal reflector *A* and bed reflector *B* are bended upwards for bigger offsets.

→ Due to the anisotropy of the ice the wavefront is no longer a sphere, the approximation of the reflections by hyperbolas is no longer valid.

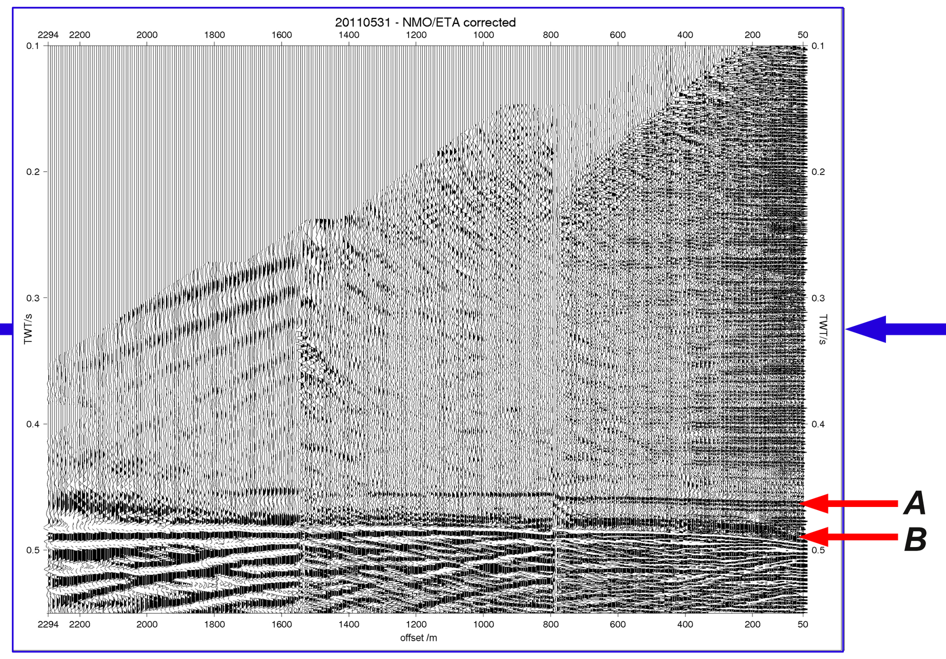

Figure 10: η-NMO-corrected section. Due to the correction for the anisotropy the internal reflector A and the bed reflector B are flat also for the far offsets.

4th-order NMO-correction

- **Correcting for the anisotropies** of the ice

→ Use of **x^4-term**
- Adding η inserts anisotropy in calculation of travel times

$$t_x^2=t_0^2+\frac{x^2}{v_{rms}^2}-\frac{2\eta_{nmo}x^4}{v_{rms}^2(t_0^2v_{rms}^2(1+2\eta_{nmo})x^2)}$$

→ Reflections for bigger offsets are leveld off
- NMO-correction of 2nd-order gives **RMS-velocity v_{rms}**
- NMO-correction of 4th-order gives **effective η-value η_{nmo}**

→ Derive corresponding interval values
→ Derive the anisotropy of the material

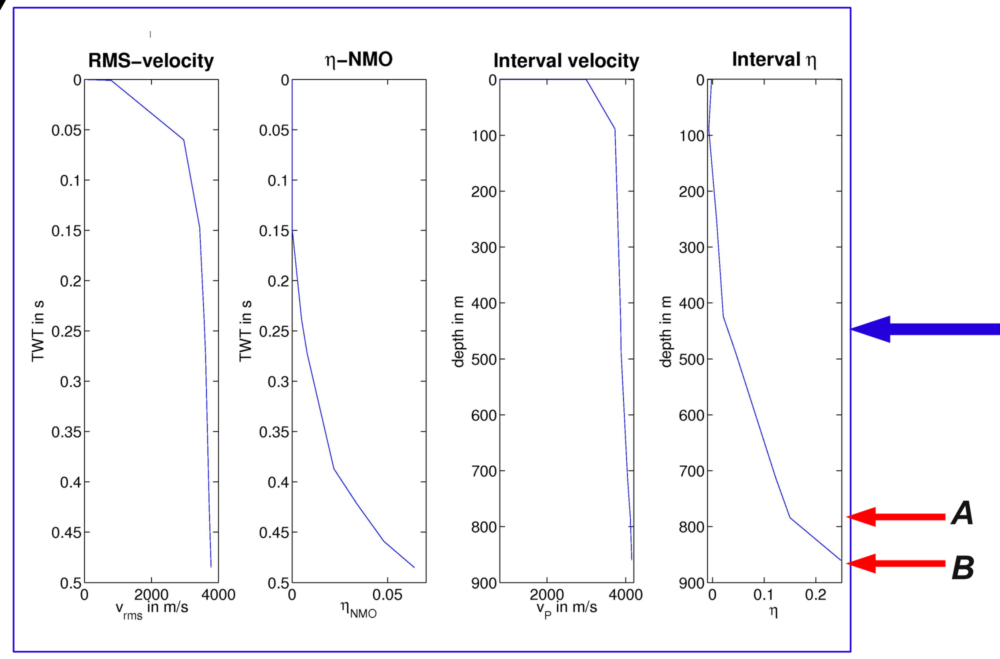

Figure 11: Interval velocity and interval η-value are calculated from RMS-velocity and η-NMO-value.

η-values

Calculation of interval values for velocity and *η*
- RMS-velocity → Interval velocity
- η-NMO-value → Interval *η*

Comparison with calculated values gives hint about anisotropy of layers:

Layer above internal reflector *A*:
***η* = 0.15 → cone angle *φ* ≈ 30°**
Layer above bed *B*:
***η* = 0.25 → cone angle *φ* ≈ 0°**

Desirable: Comparison to ice core data, but at Halvfarryggen no deep ice core exists yet.