Stress dependent dynamic anisotropy in shales

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Introduction

- Rocks typically exhibits elastic anisotropic behaviour:
  - Intrinsic anisotropy (layering, grain orientation etc.)
  - Induced anisotropy (stress)
- Layered materials, like shales, are often assumed to have an isotropic behaviour in the bedding plane (Transverse Isotropy)
- Elastic properties of the rock is closely linked to wave velocities
- Importance
  - Seismic interpretation (exploration and time-lapse) and modelling
  - Borehole sonic logging

Introduction

- Measurement of the dynamic properties on a cylindrical core with TI properties requires 5 independent measurements

$$\begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{pmatrix} = \begin{pmatrix} C_{11} & C_{11}-2C_{66} & C_{13} & 0 & 0 & 0 \\ C_{11}-2C_{66} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix} \begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ 2\Gamma_{yz} \\ 2\Gamma_{xz} \\ 2\Gamma_{xy} \end{pmatrix}$$

- The TI anisotropy can be described by the Thomsen parameters:

$$\varepsilon \equiv \frac{C_{11}-C_{33}}{2C_{33}}$$

$$\gamma \equiv \frac{C_{66}-C_{44}}{2C_{44}}$$

$$\delta \equiv \frac{1}{2C_{33}^2}\left[2\left(C_{13}+C_{44}\right)^2-\left(C_{33}-C_{44}\right)\left(C_{11}+C_{33}-2C_{44}\right)\right]$$

Thomsen, 1986

Introduction

- Assumptions
  - Transverse Isotropy
  - Homogeneous
  - Cylinder axis is parallel to the bedding plane normal
- The elastic (dynamic) moduli:

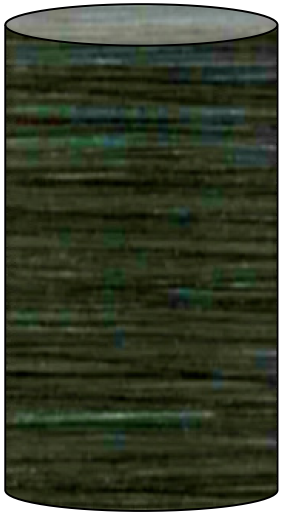
$$C_{11} = \rho V^2_{p,horizontal}$$

$$C_{33} = \rho V^2_{p,axial}$$

$$C_{44} = \rho V^2_{s,vertical(hor.)}$$

$$C_{66} = \rho V^2_{s,horizontal(hor.)}$$

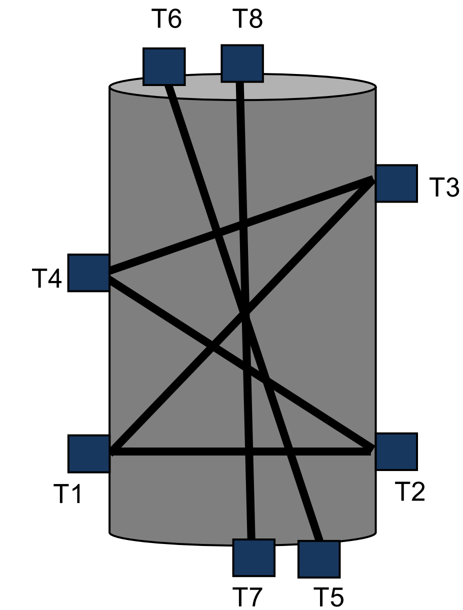
$$C_{13} = ?$$



- Estimate C_{13} from Thomsen theory and oblique measurements of P-wave velocities

P-wave measurements

- Setup of 8 P-wave transducers:
  - Measurements in both principal directions
  - Four measurements in oblique directions
- Sleeve transducer specifications:
  - 3.5 mm outside diameter
  - Curved front
  - 1.3 MHz resonant frequency
  - Crystal diameter 2 mm
- P-wave velocities at the following inclinations: 0° (vertical), 18°, 37°, 47, 69° and 90° (horizontal)

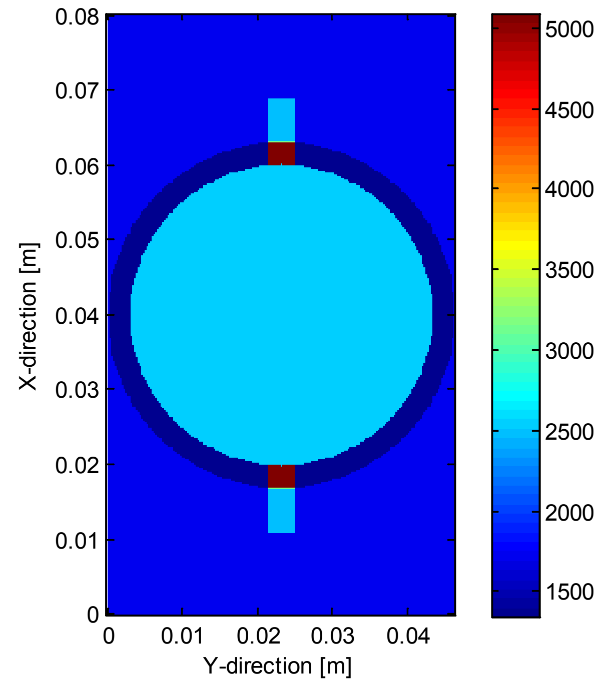


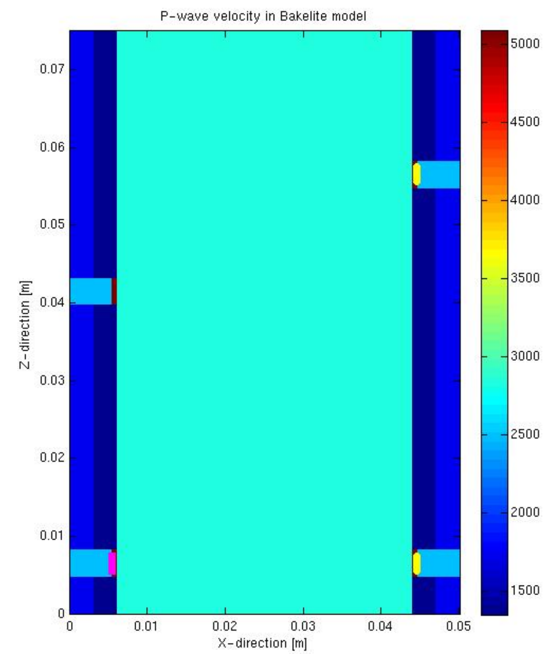
Validation

- Group or phase velocities for oblique waves?
  - FD simulations
  - Synthetic materials
    - measurements at ambient conditions
    - measurement under stress on cylindrical samples

FD model

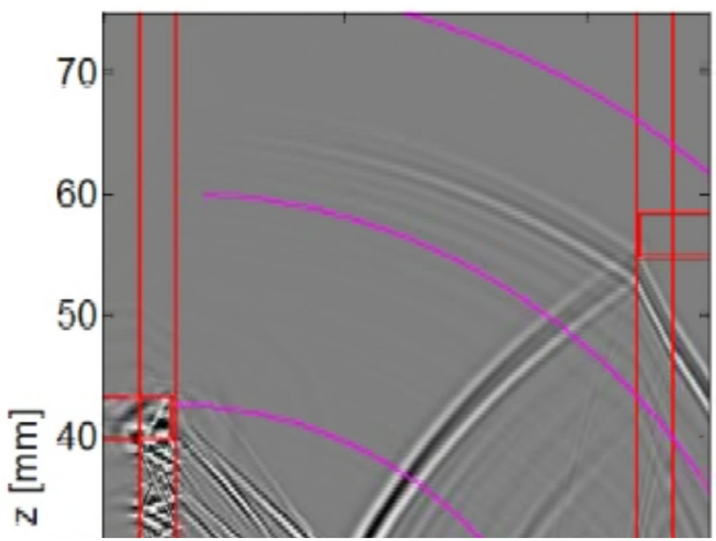
- Model with realistic geometries:
  - Transducers in the sleeve
    - 3.5 mm diameter
    - The source is simulated as a disk with 2 mm diameter and 0.075 mm thickness
    - ~0.4 mm titanium front piece
  - Oblique transducers in the piston
    - The source is a disk with 3.5 mm diameter and 0.075 mm thickness
    - ~0.4 mm steel front piece
- Spatial resolution is 0.075 mm
- Source signal is a Ricker wavelet with centre frequency of 1 MHz.

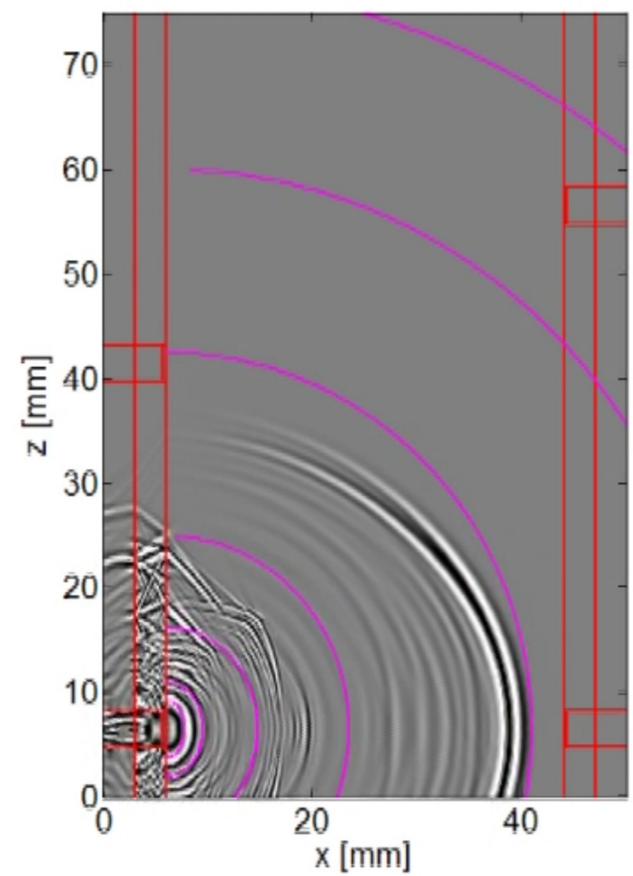




FD model simulations

- Material with TI properties:
  - Non-spherical wavefront
  - Wavefront normal oblique to transducer normal

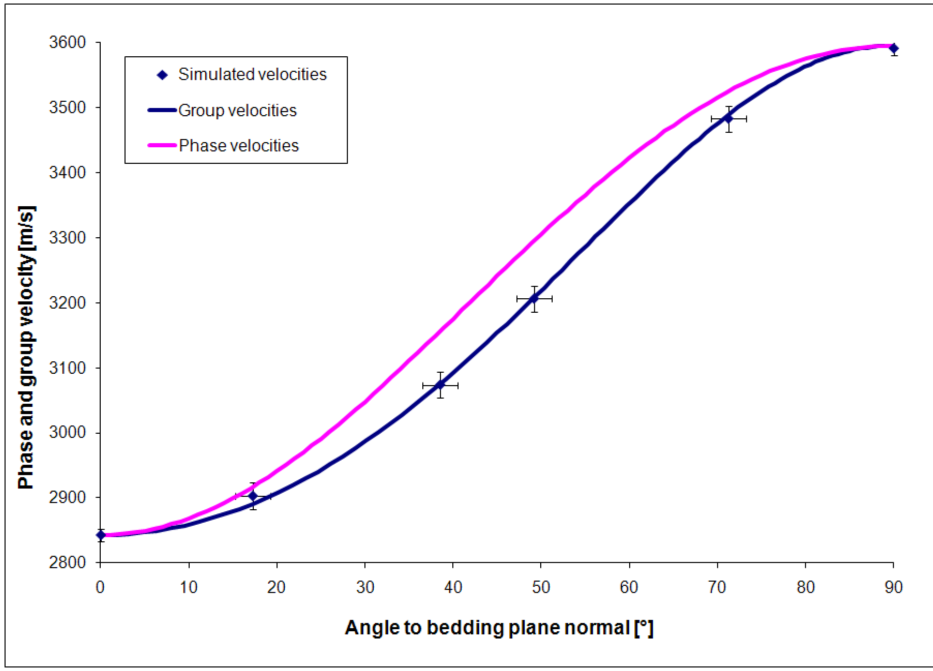




Cross section of density model

Simulation results

- Velocities picked from wavefront arrival for two materials:
  - Weak TI (ε=0.14, δ=0.04, γ=0.28)
  - Strong TI (ε=0.3, δ=0.3, γ=0.07)
- Both simulations showed that the picked velocities fall on the line for the theoretical group velocity for the material



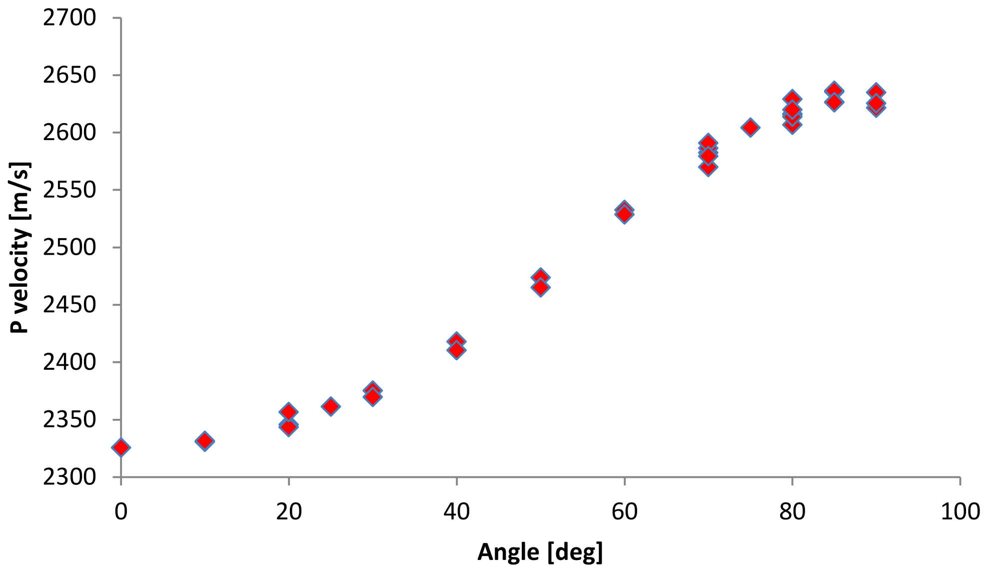
Thomsen parameters from strong TI model
10-20 m/s uncertainty in velocities
0-2 degrees uncertainty in angle

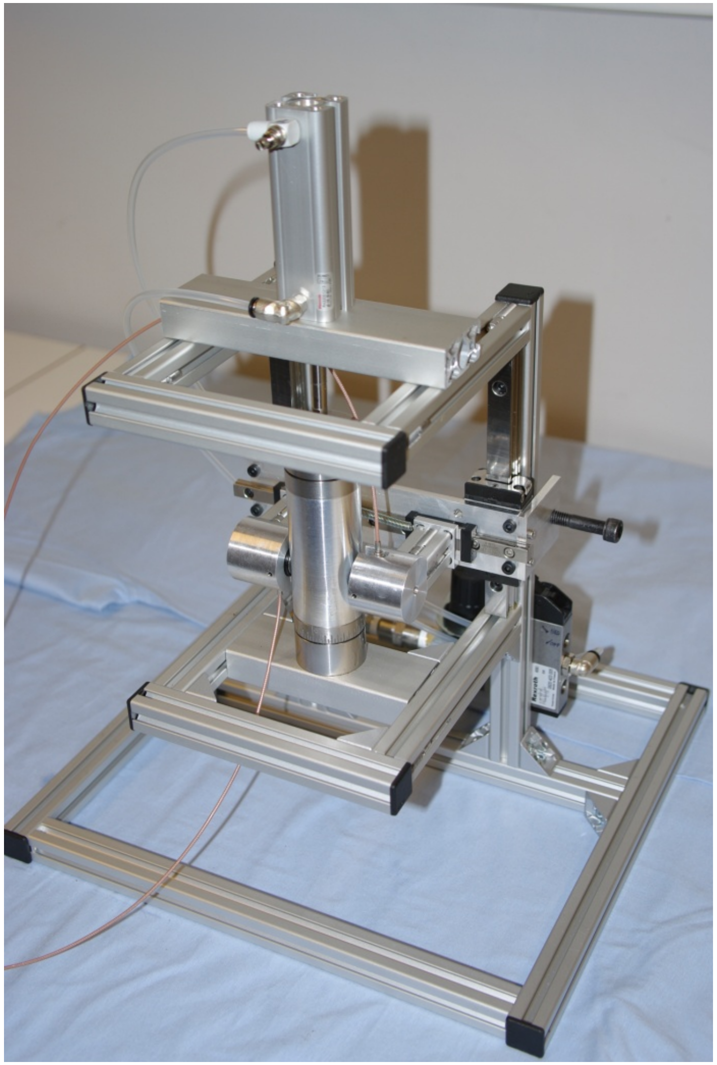
Materials

- Peek (used for calibration)
  - Isotropic
  - VP0 = 2564m/s
  - VS0 = 1129 m/s
  - Density = 1.305 g/cm^3
- Bakelite (strong TI)
  - Anisotropic (quasi-TI)
- Pierre shale (weak TI)
  - Anisotropic (quasi-TI)

Bench setup for radial P wave measurements

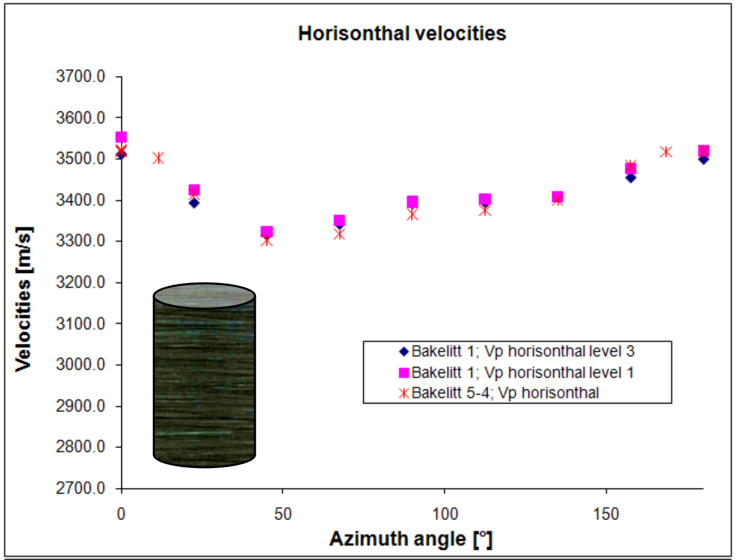
- Sample characterization prior to triaxial testing
- Measurements done on both vertical and horizontal samples

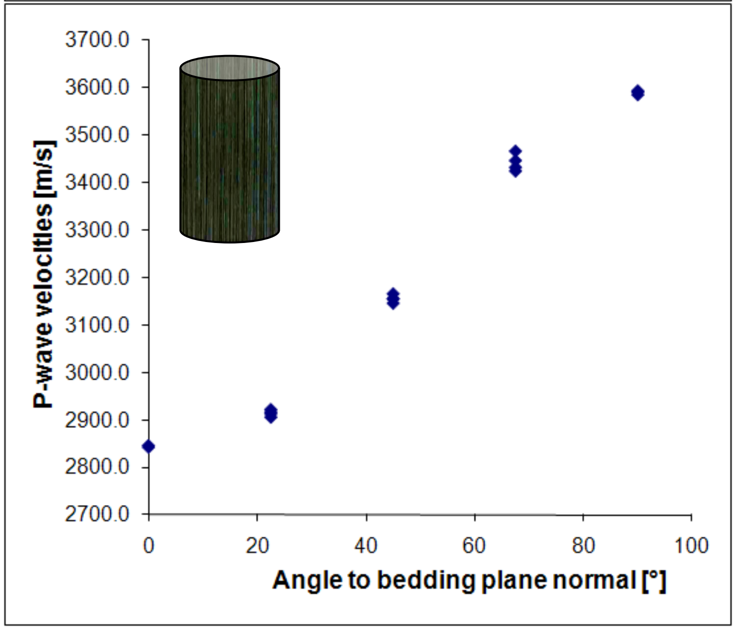




Strong TI material

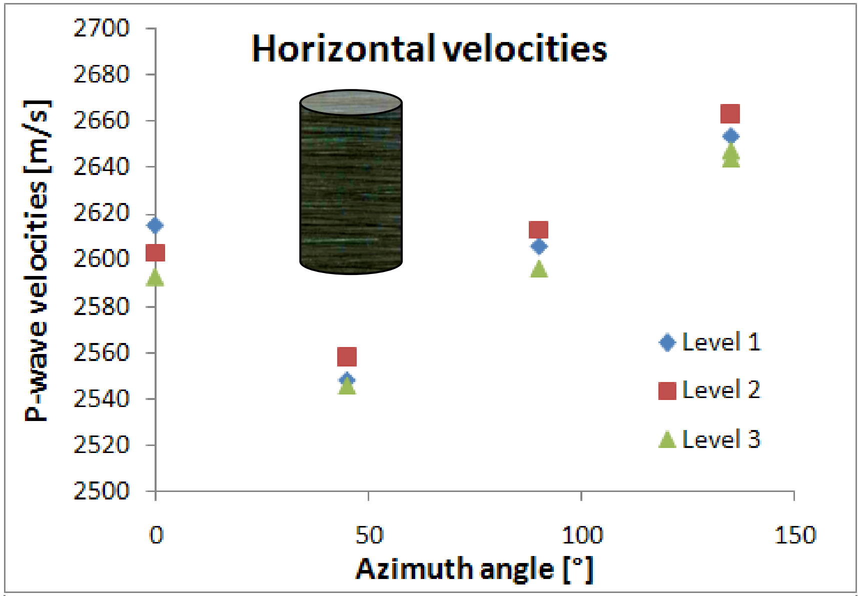
- Bakelite Cotton Phenolic (Etronax MF)
  - Density of 1371 kg/m^3
  - VP (axial) = 2843 m/s
  - VS (axial) = 1533 m/s
  - Layered media
  - Weak anisotropy observed in horizontal plane
  - Homogeneous sample (repeatable measurements)
  - Measurement along the fastest horizontal plane direction gives:
    - Thomsen ε = 0.30
    - Thomsen δ = 0.30
    - Thomsen $\gamma \approx$ 0.075 (not perfect TI-media)

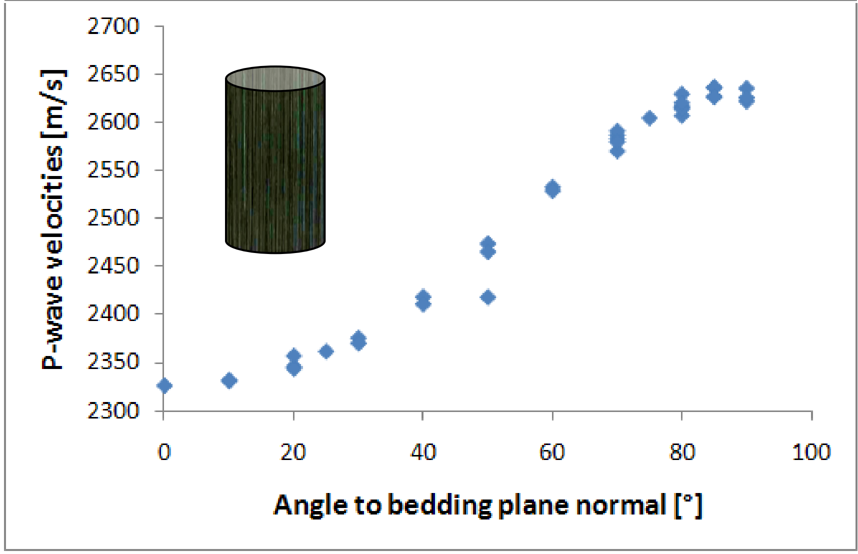




Weak TI material

- Pierre shale
  - Density of 2360 kg/m^3
  - VP (axial) = 2325 m/s
  - VS (axial) = 878 m/s
  - Layered media
  - Weak anisotropy observed in horizontal plane
  - Homogeneous sample (repeatable measurements)
  - Measurement along the fastest horizontal plane direction gives:
    - Thomsen $\varepsilon = 0.14$
    - Thomsen $\delta = 0.04$
    - Thomsen $\gamma \approx 0.28$ (not perfect TI-media)

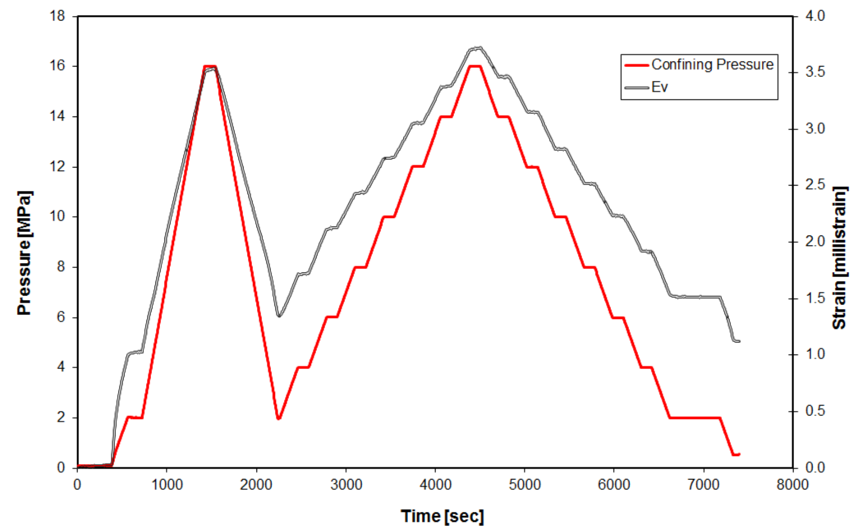


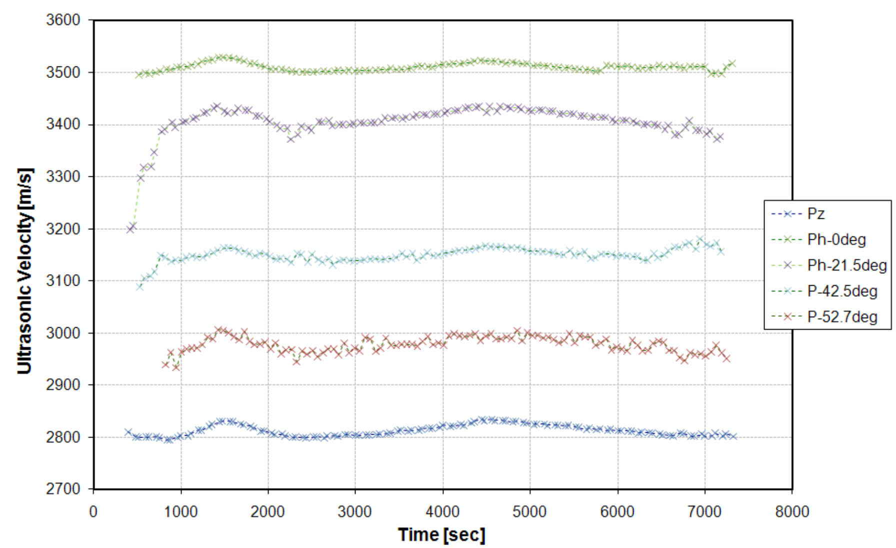


Bakelite triaxial experiment

- Hydrostatic cycling of cylindrical sample with bedding plane normal parallel to cylinder axis
- Measure five P-wave velocities
  - Vertical and horizontal
  - Three oblique directions

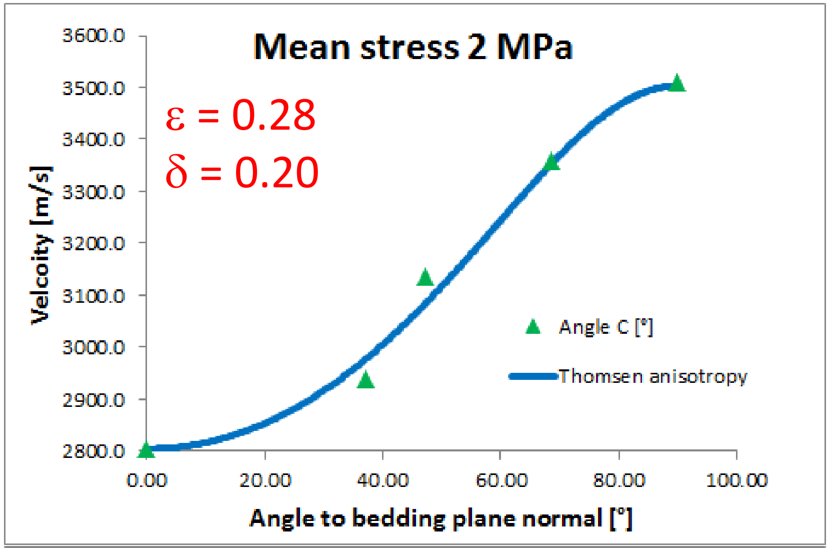
δ

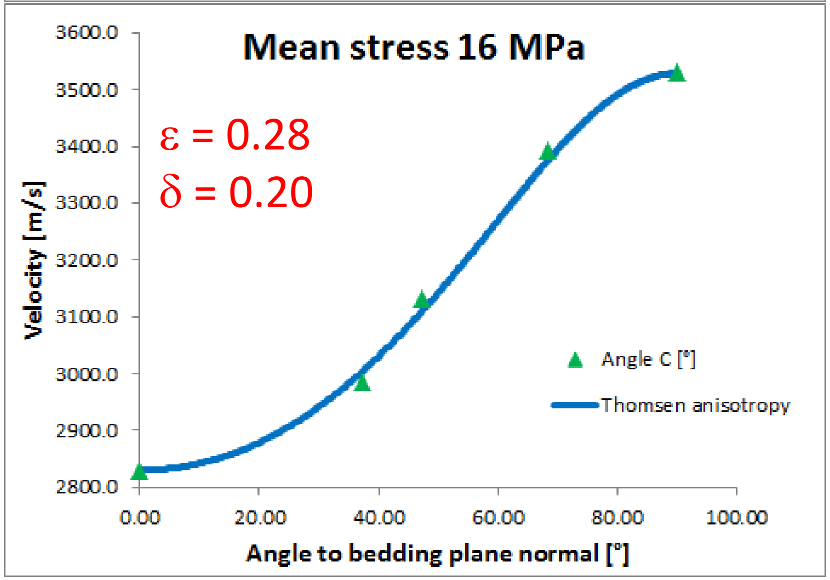




Bakelite triaxial experiment

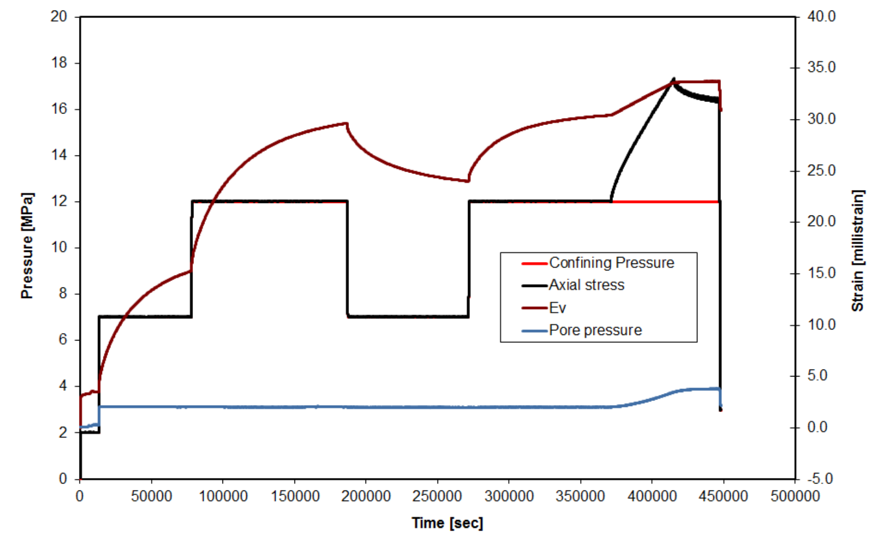
- Oblique velocities fits well with theoretical line for group velocities
- Lower δ in triaxial setup than measured at ambient conditions
- No change in ε nor δ when increasing hydrostatic pressure

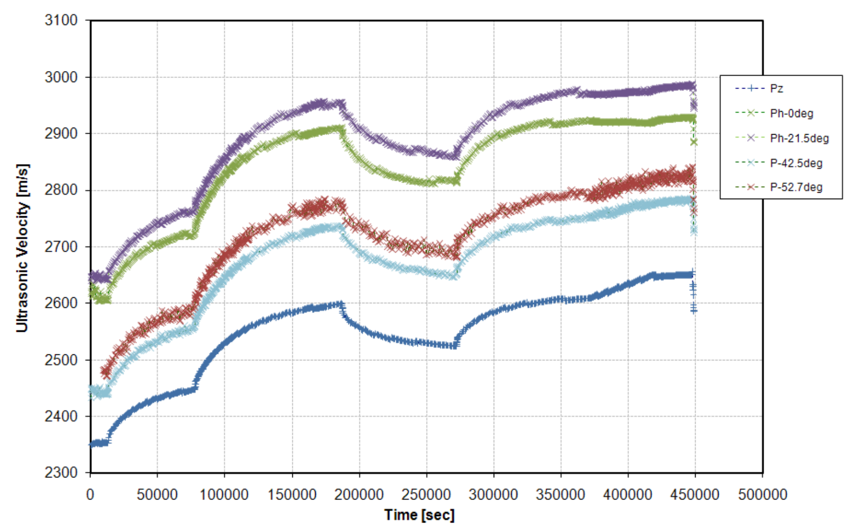




Pierre shale triaxial experiment

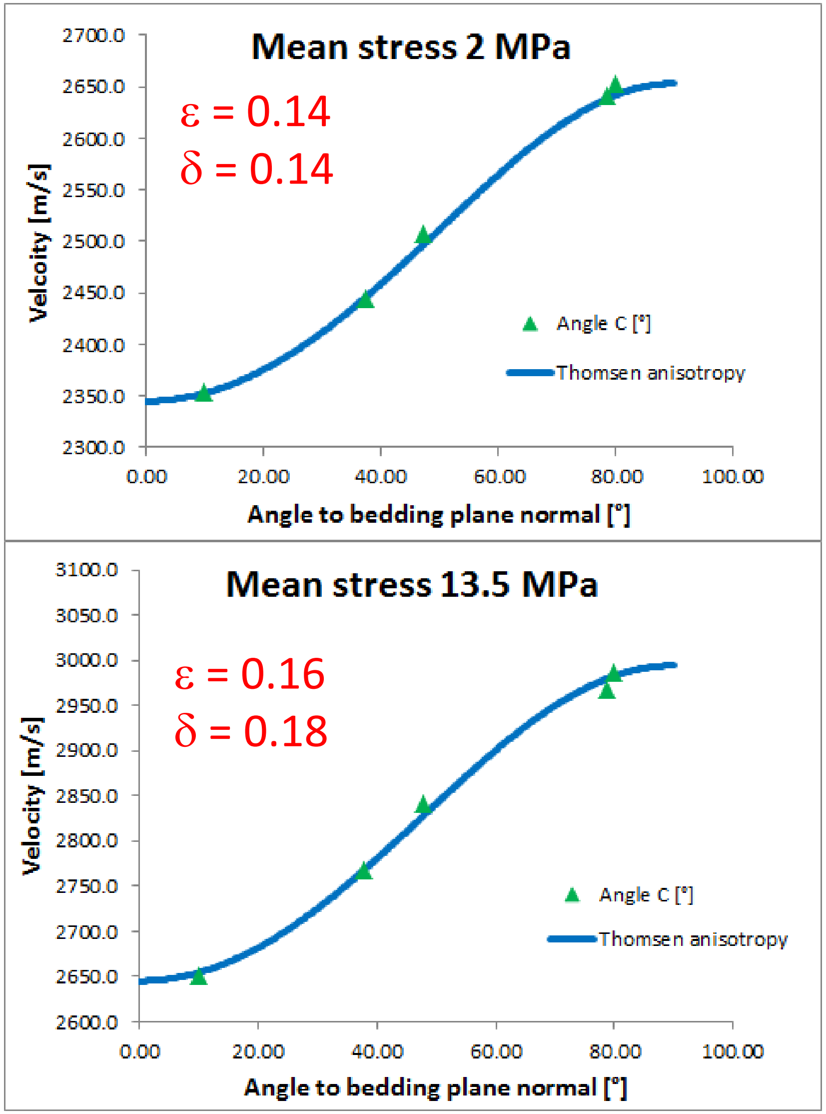
- Hydrostatic cycling of cylindrical sample
- Uniaxial undrained loading
- Measure five P-wave velocities
  - Vertical and horizontal
  - Three oblique directions





Pierre shale triaxial experiment

- Bedding plane normal was found to be slightly off cylinder axis (~10 degrees).
- Oblique velocities fits well with theoretical line for group velocities
- Higher δ in triaxial setup than measured at ambient conditions
- Increase in δ when increasing mean stress (small shear stress)



Summary

- An ultrasonic experimental setup has been developed which allows for measuring 4 oblique P-wave velocities in a triaxial setup
- FD simulations shows that these velocities corresponds to group velocities
- Triaxial experiments were performed to verify the setup
- Stress dependency of the Thomsen parameters ε and δ on Pierre shale.

Acknowledgements

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