Ultrasonic Imaging of Anisotropic Domains:
Fluid filled cracks and seismic anisotropy

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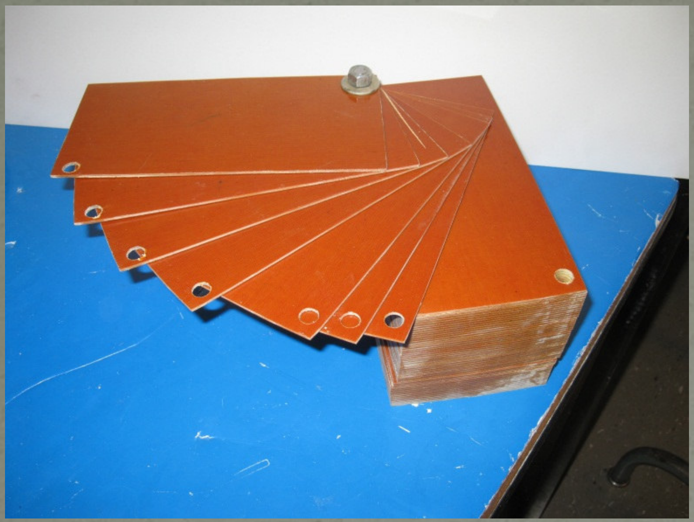
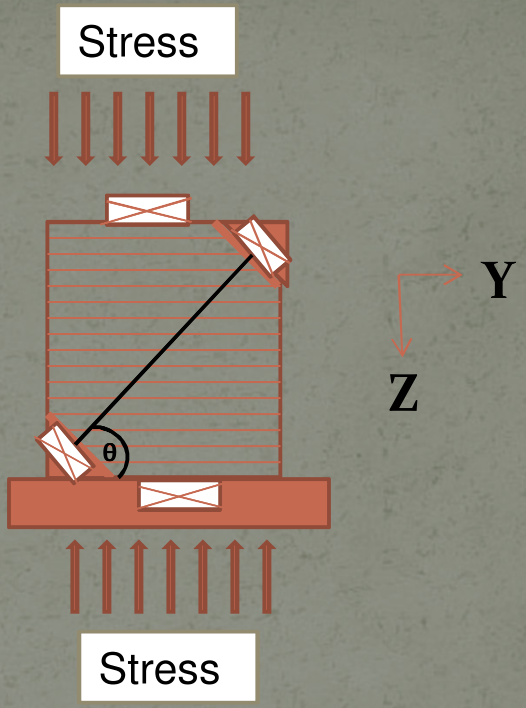
Outline

- Physical Modeling Examples
- Study Objectives
- Sample Description
- Experimental Methods
- Azimuthal P-Wave NMO results
- Travel time and Velocity results
- Stiffness coefficients and Anisotropic parameters
- Conclusion and Future work

Physical Modeling Examples: Uniaxial Stress VS Anisotropy





Uniaxial Stress and Ultrasonic Anisotropy in a Layered Orthorhombic Medium

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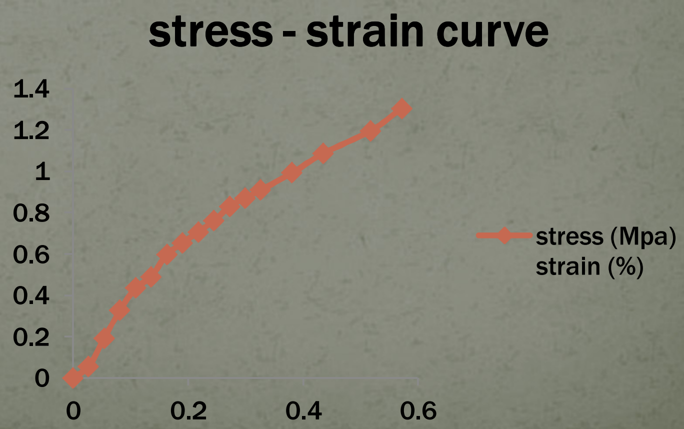
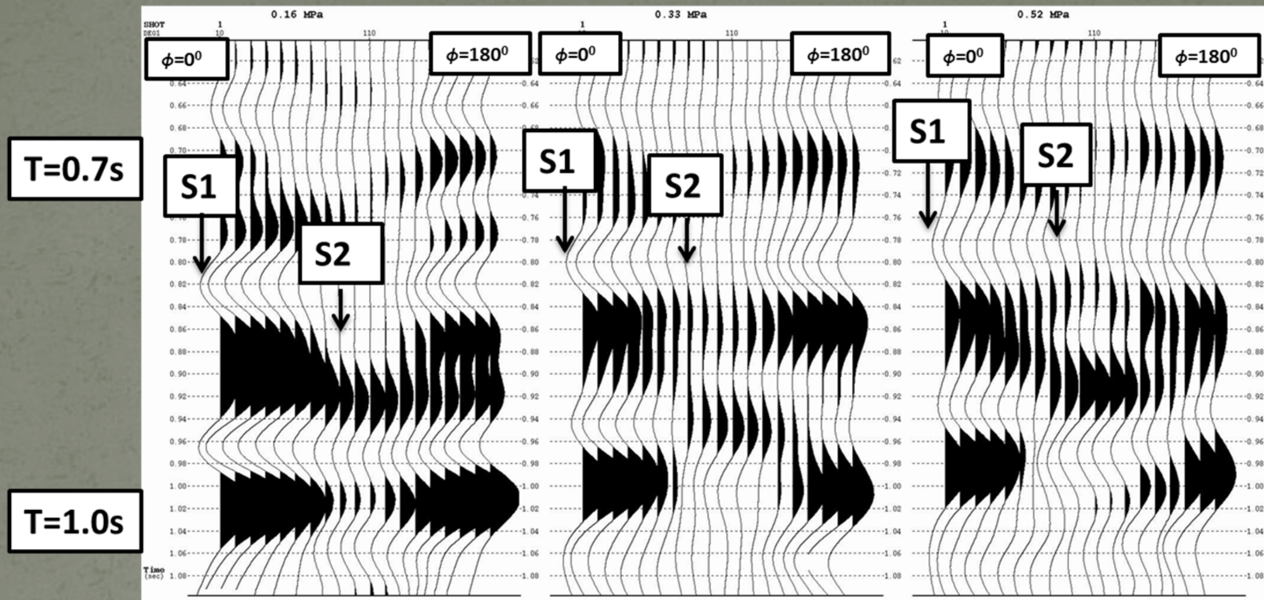
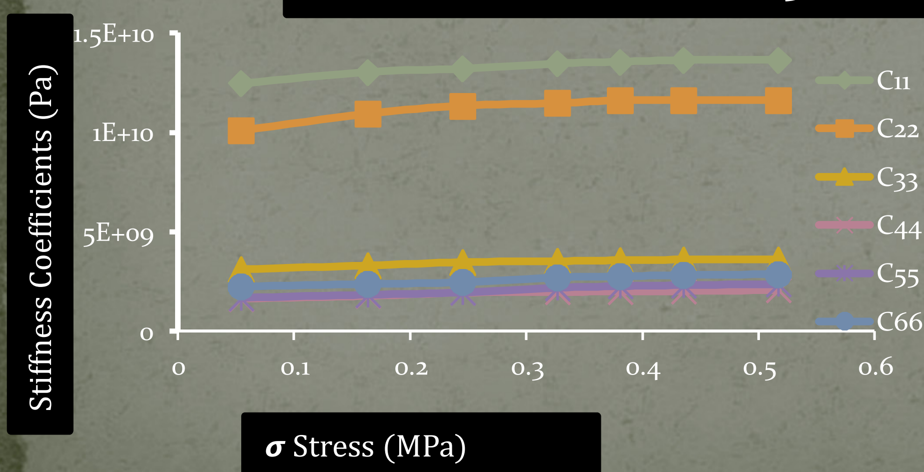
Nikolay Dyaur
Robert. R. Stewart

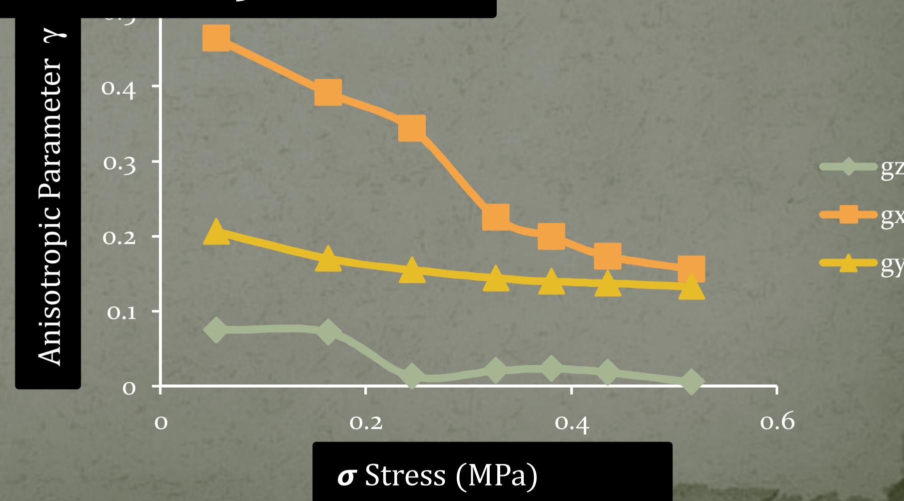


Physical Modeling Examples: Uniaxial Stress VS Anisotropy

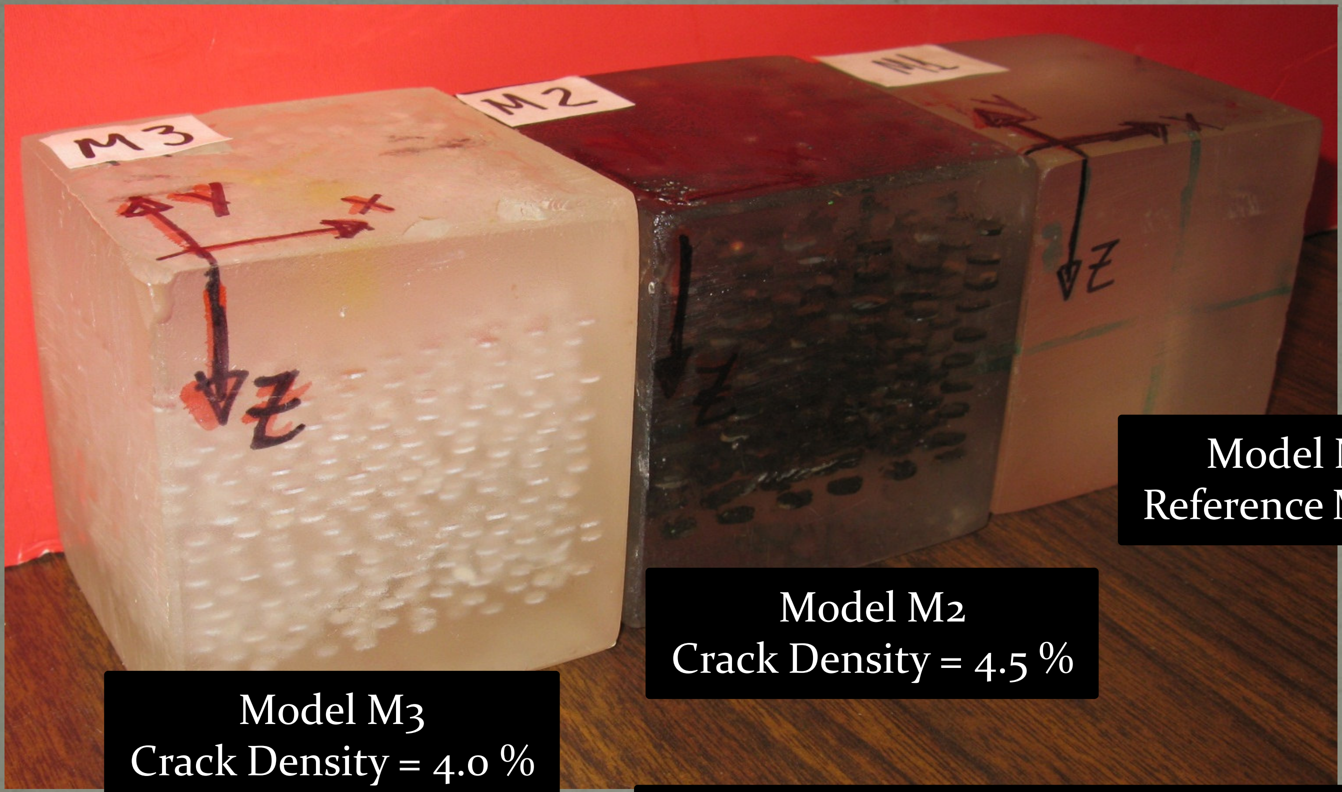


Shear wave seismogram in different stress regimes
a) 0.16MPa b) 0.36MPa c) 0.56MPa





Physical Modeling Examples: Source Frequency VS Anisotropy



Model M3
Crack Density = 4.0 %

Model M2
Crack Density = 4.5 %

Model M1
Reference Model

$$\varepsilon = \frac{N\pi r^2 h}{V}$$

Hudson, 1981

Effect of source frequency on seismic anisotropy

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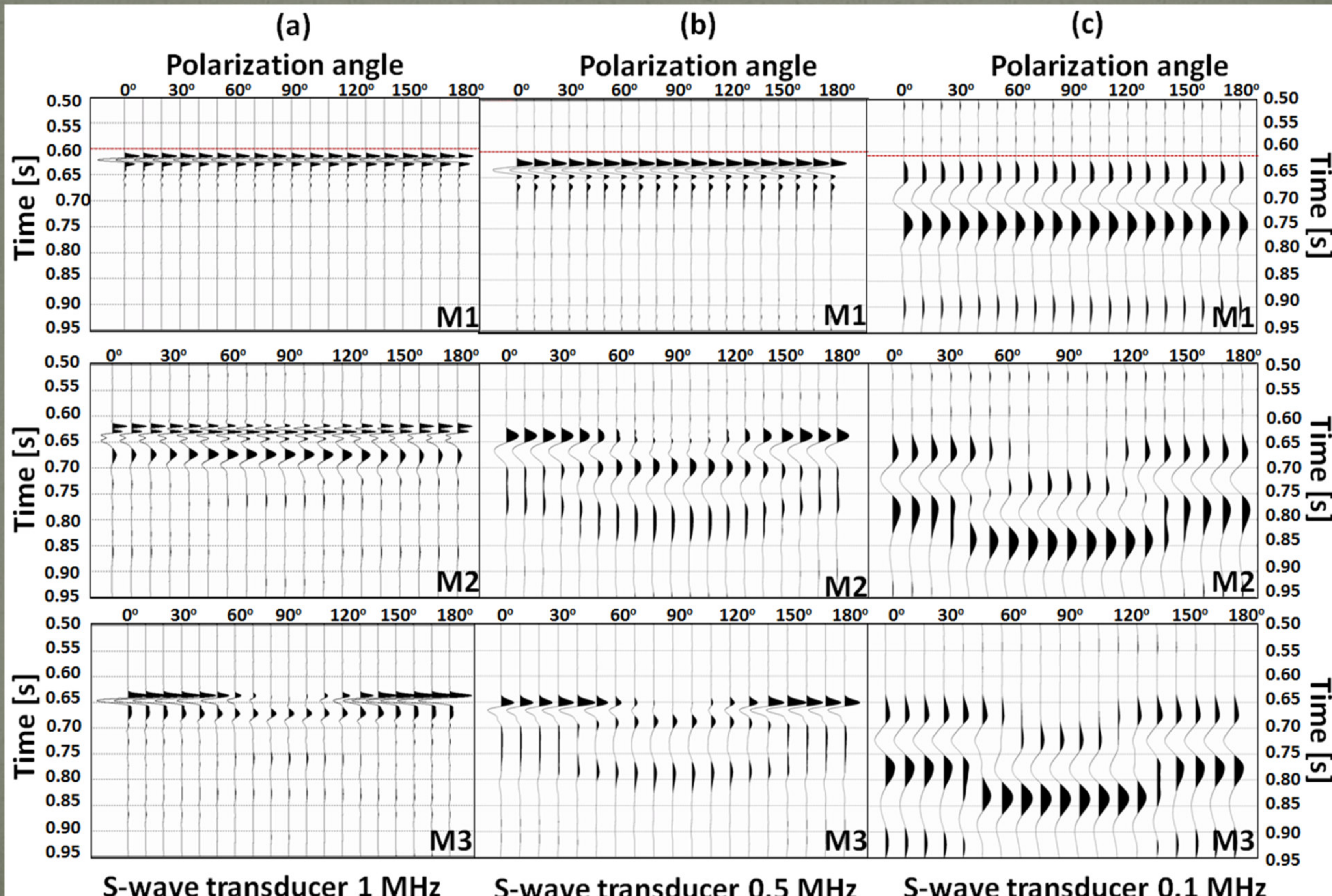
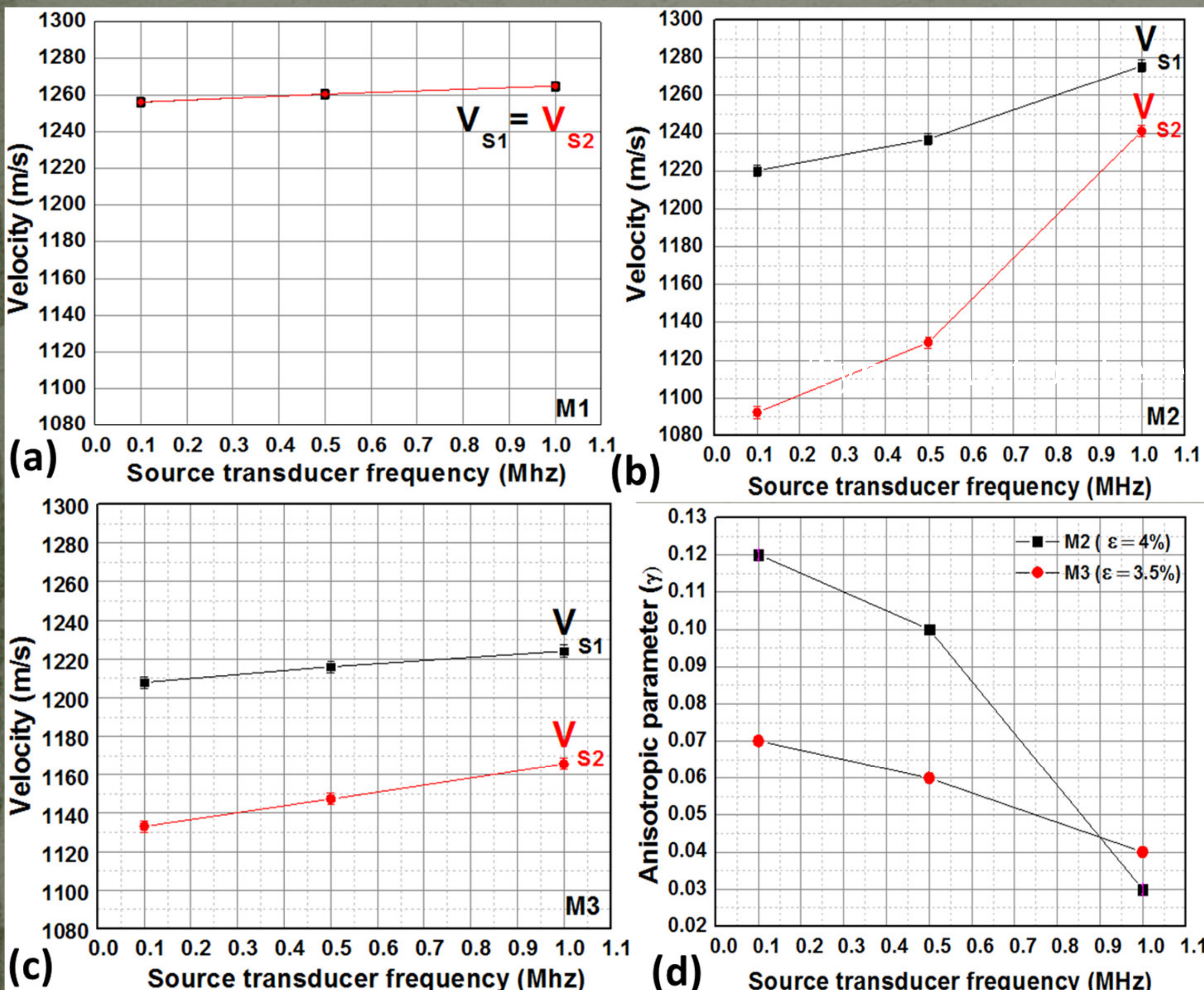
Physical Modeling Examples: Source Frequency VS Anisotropy



Physical Modeling Examples: Source Frequency VS Anisotropy



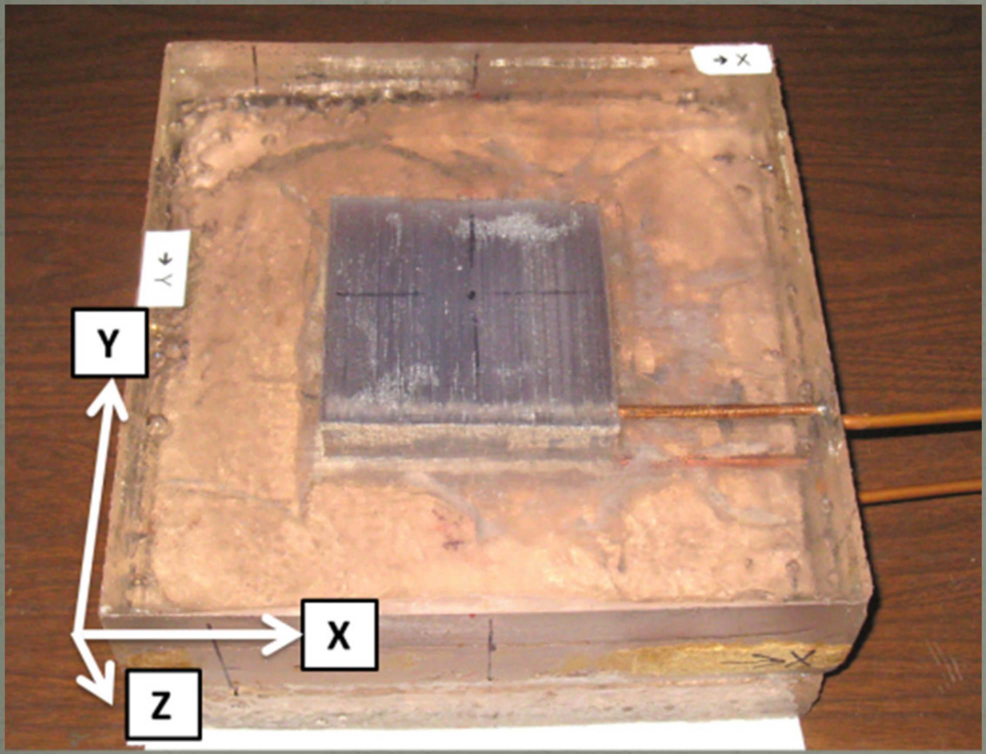
$$\Upsilon = \frac{1}{2}\left(\frac{V_{s1}^2}{V_{s2}^2} - 1\right)$$

Thomsen, 1986

Study Objectives

- To explore the effect of different fluids on seismic response and consequently anisotropy in an inherently anisotropic medium.
- To compare predictions of various theories of wave propagation in fractured media to lab measurements.

Sample Description



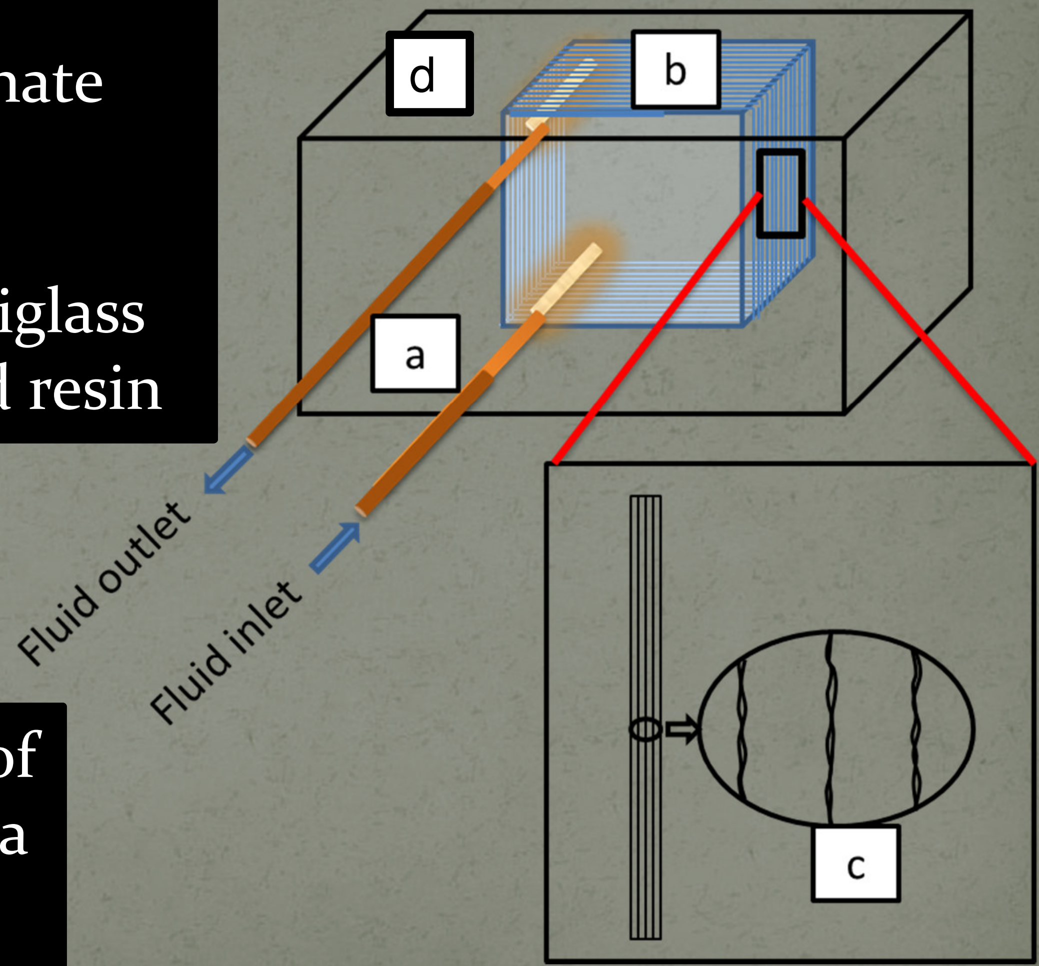
Constituent Materials:

- Resin
- Plexiglass (polycarbonate)
- Copper tubes

Model Dimensions = (296.9 X 296.7 X 131.6) mm

Sample Description – Schematic

(a) Copper tubes
(b) Plexiglass/polycarbonate stack
(c) Grooves or scratches between stacked plexiglass
(d) Isotropic background resin



Volume fraction/ratio of fractures plexiglass area to composite model =
0.12 : 0.88

Sample Description – Fractured area

- Fractured area is made up of 95 scratched plexiglass sheets each 1.1 mm to 1.3 mm thick
- Grooves or scratches on the sheets are 0.1 mm to 0.2 mm deep (on both sides)
- Fractures/scratches are randomly placed and run in all directions on the sheets
- Source-receiver transducers with dominant frequency 100kHz (dominant $\lambda \sim 30$ mm) was used in all experiments

Sample Description – Physical properties

Physical properties of Isotropic resin (background medium)

Vp = 2540m/s
Vs = 1250m/s
Density ρ = 1.22 g/cc
Vp/Vs = 2.032
Poisson's ratio $\sigma = 0.340$

$$\begin{pmatrix} \lambda+2\mu & \lambda & \lambda & 0 & 0 & 0 \\ \lambda & \lambda+2\mu & \lambda & 0 & 0 & 0 \\ \lambda & \lambda & \lambda+2\mu & 0 & 0 & 0 \\ 0 & 0 & 0 & \mu & 0 & 0 \\ 0 & 0 & 0 & 0 & \mu & 0 \\ 0 & 0 & 0 & 0 & 0 & \mu \end{pmatrix} \quad \text{Isotropic resin} =$$

$$\begin{pmatrix} 7.79 \pm 0.05 & 4.04 \pm 0.1 & 4.04 \pm 0.1 & 0 & 0 & 0 \\ 4.04 \pm 0.1 & 7.79 \pm 0.05 & 4.04 \pm 0.1 & 0 & 0 & 0 \\ 4.04 \pm 0.1 & 4.04 \pm 0.1 & 7.79 \pm 0.05 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1.87 \pm 0.06 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1.87 \pm 0.06 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.87 \pm 0.06 \end{pmatrix} \text{GPa}$$

Sample Description – Physical properties

Physical properties of scratched or fractured plexiglass stacks(cracked medium)

Vp (matrix) = 2300m/s
Vs (matrix) = 1320m/s
Density (matrix) ρ = 1.188 g/cc
Vp/Vs (matrix)= 1.742
Poisson's ratio σ (matrix) = 0.254

$\varepsilon = 0.35$
$\Upsilon = 0.39$
$\delta = 0.007$
Porosity ϕ = 2.5 %

Estimated from travel time and anisotropic measurements (Thomsen, 1995)

Crack density ζ = 14 %
Crack aspect ratio a = 4.2%

$$\begin{pmatrix} C_{11} & C_{13} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{33} & (C_{33} - 2C_{44}) & 0 & 0 & 0 \\ C_{13} & (C_{33} - 2C_{44}) & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{55} \end{pmatrix} =$$

$$\begin{pmatrix} 5.01 \pm 0.1 & 1.56 \pm 0.31 & 1.56 \pm 0.31 & 0 & 0 & 0 \\ 1.56 \pm 0.31 & 1.73 \pm 0.05 & 1.25 \pm 0.1 & 0 & 0 & 0 \\ 1.56 \pm 0.31 & 1.25 \pm 0.1 & 1.73 \pm 0.05 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.24 \pm 0.02 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.09 \pm 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.09 \pm 0.01 \end{pmatrix} \text{GPa}$$

Sample Description – Physical properties

Physical properties of whole sample/model
(composite medium)

$\varepsilon = 0.22$
$\Upsilon = 0.21$
$\delta = 0.051$
Porosity $\phi = 2.5$ %

$$\begin{pmatrix} C_{11} & C_{13} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{33} & (C_{33} - 2\,C_{44}) & 0 & 0 & 0 \\ C_{13} & (C_{33} - 2\,C_{44}) & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{55} \end{pmatrix} =$$

$$\begin{pmatrix} 7.40 \pm 0.05 & 2.81 \pm 0.36 & 2.81 \pm 0.36 & 0 & 0 & 0 \\ 2.81 \pm 0.36 & 3.61 \pm 0.1 & 2.04 \pm 0.1 & 0 & 0 & 0 \\ 2.81 \pm 0.36 & 2.04 \pm 0.1 & 3.61 \pm 0.1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.79 \pm 0.03 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.49 \pm 0.01 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.49 \pm 0.01 \end{pmatrix} \text{GPa}$$

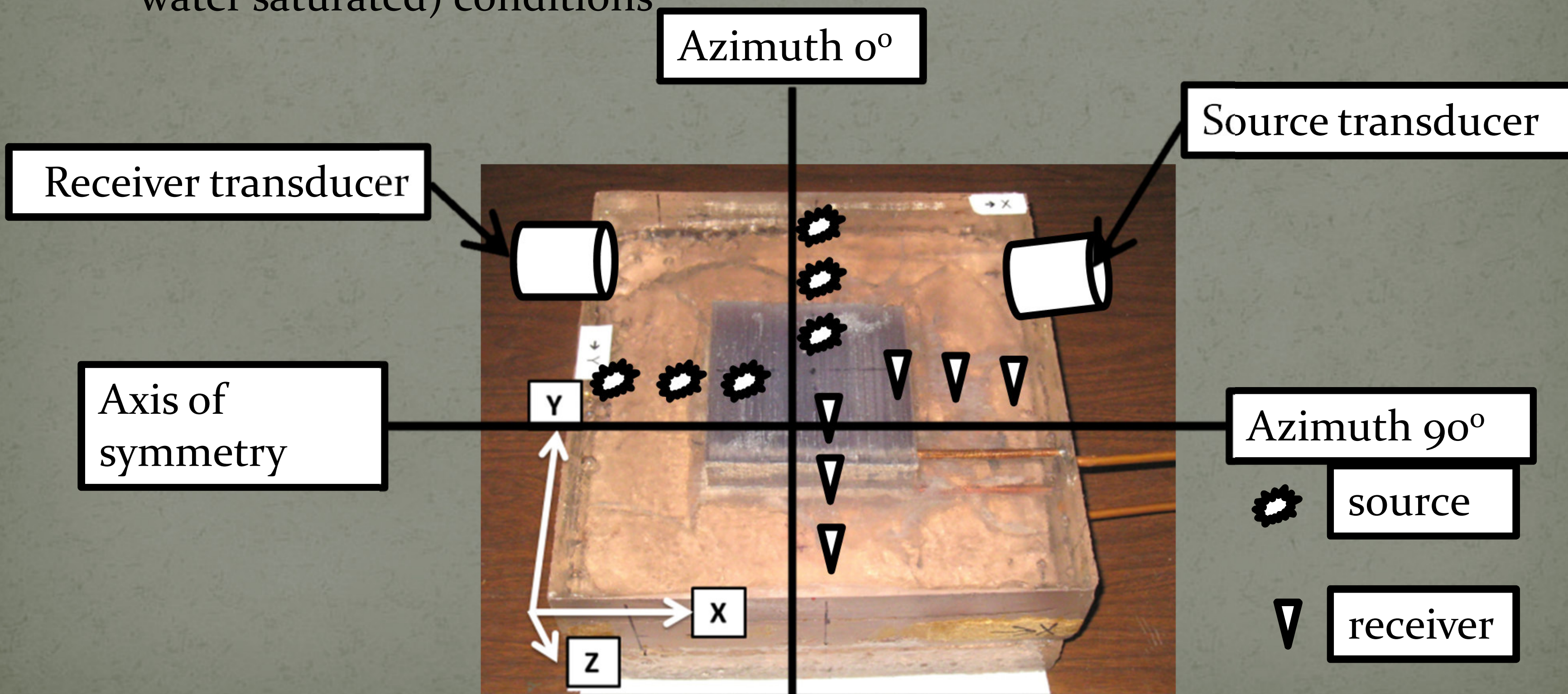
Sample Description - Summary

- ✓ Background resin medium was found to be isotropic and homogeneous.
- ✓ On close inspection, composite model was found to be slightly orthorhombic
  - ✓ $C11 \neq C22$ or $C33$
  - ✓ $C22 \approx C33$ (5% difference but were treated as equal in our analysis)
- ✓ Fractured plexiglass inclusion zone has HTI symmetry
- ✓ Based on model fabrication setup and inverted parameters (Thomsen, 1995), we consider our cracks to be somewhat penny-shaped with very low aspect ratio (4.2%)
- ✓ In all measurements, source wavelength (λ) was 15 to 20 times greater than fracture aperture (H) {$\lambda >> H$}

Experimental Methods

- Single source transmission measurements in all axes and directions at dry (Gas saturated), partially saturated (50% water saturation) and wet (100% water saturated) conditions

- Surface scaled CMP measurements at dry (Gas saturated) and wet (100% water saturated) conditions



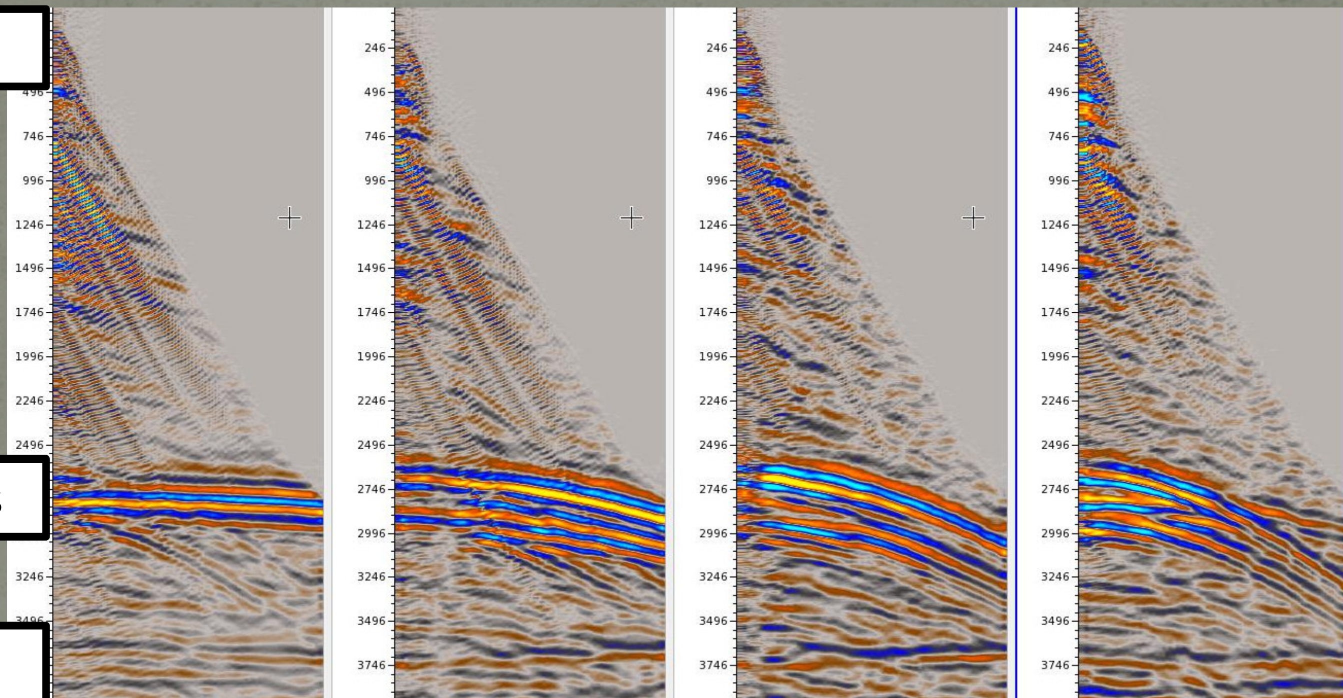
Azimuthal NMO analysis

Min offset = 400m, Max offset = 2200m, Offset interval = 30m

t=0s

t=2.5s

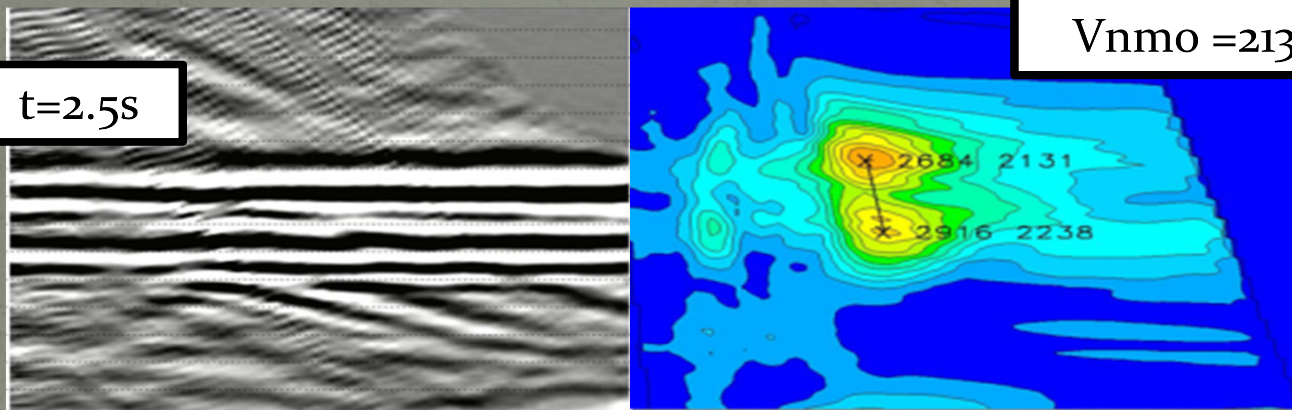
t=4s

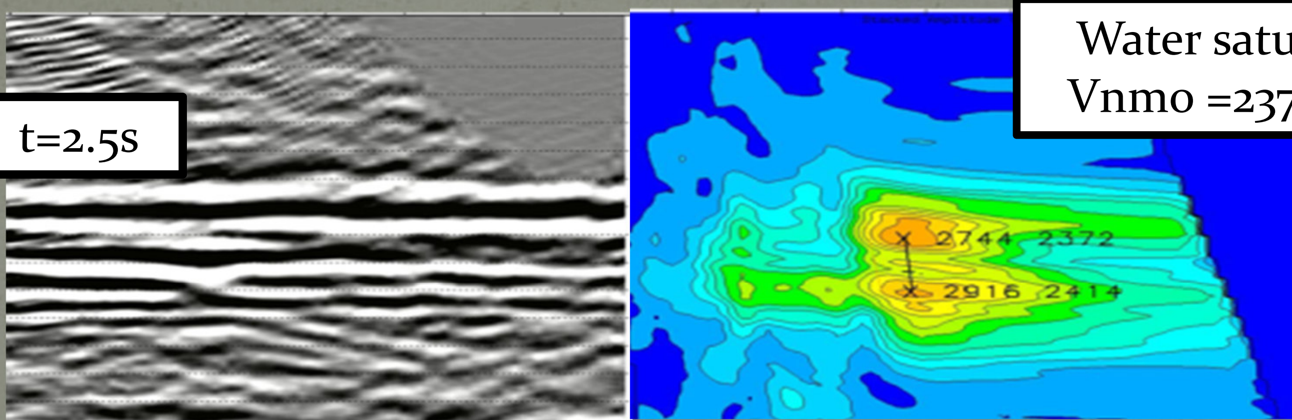


15° azimuth | 30° azimuth | 45° azimuth | 60° azimuth

All travel time and distance/offset measurements are scaled by a factor of 10,000

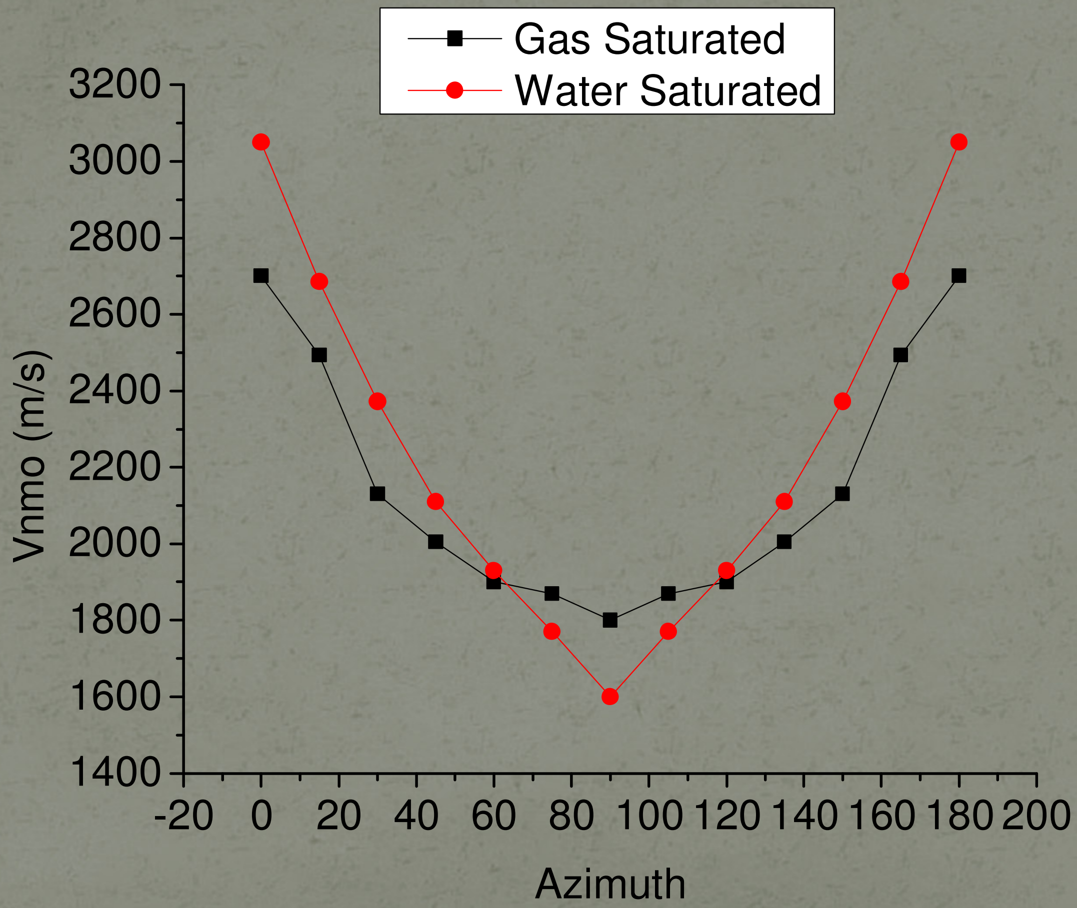
Azimuthal NMO analysis



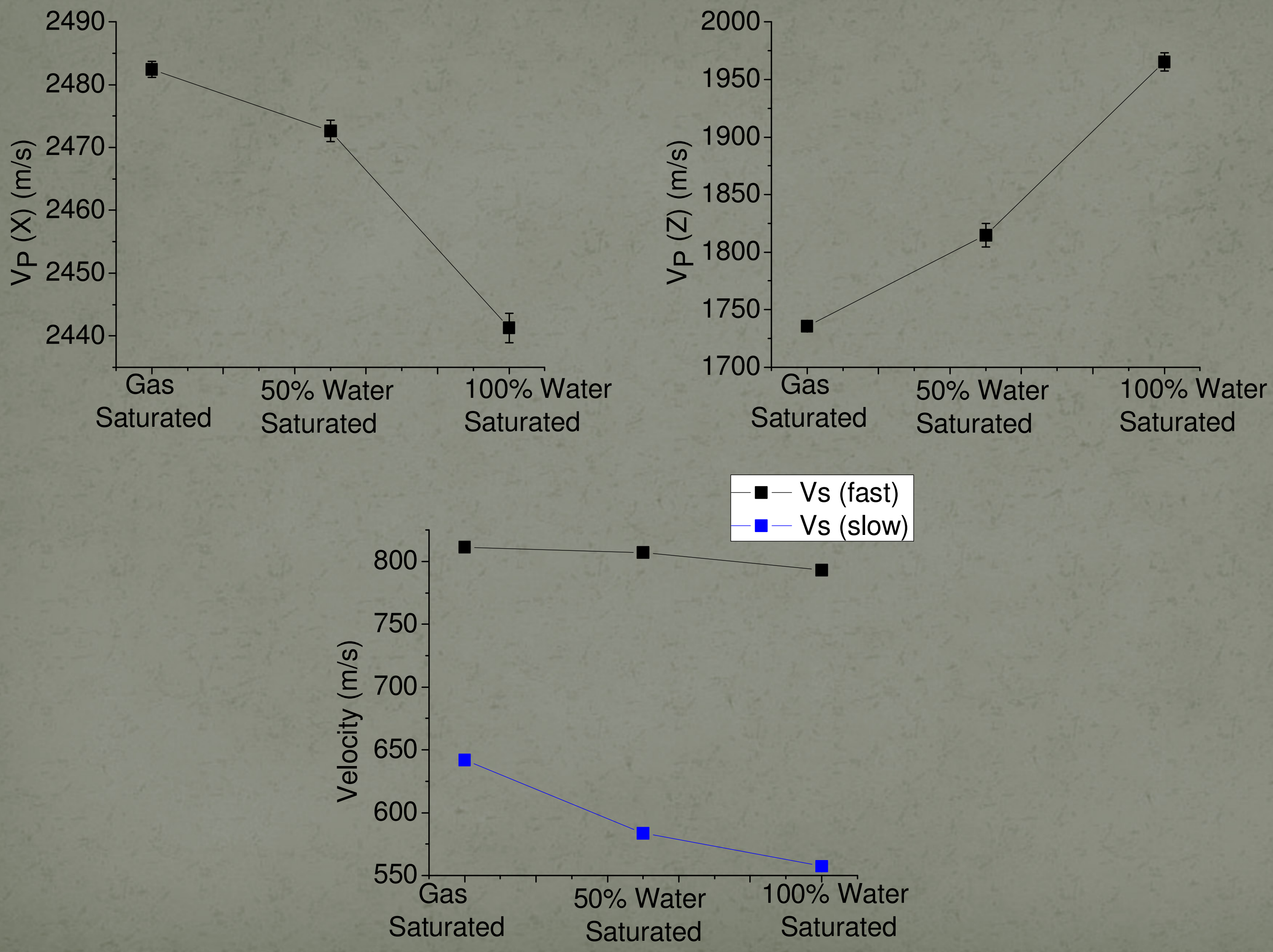


NMO corrected gather at 30° azimuth at gas and water saturated conditions

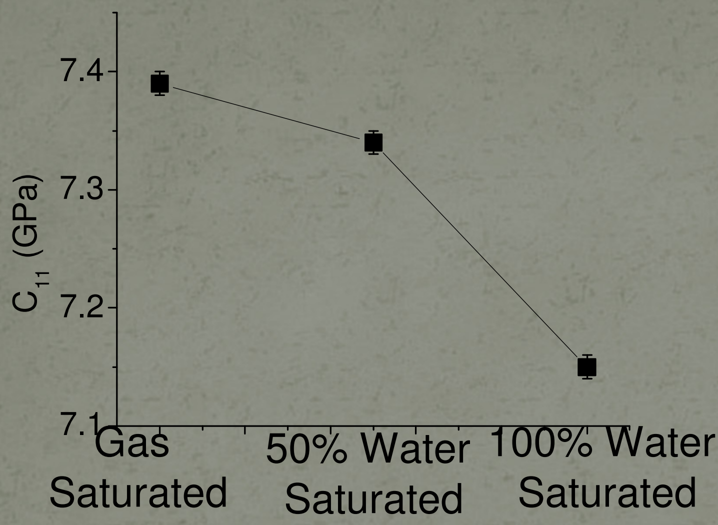
Azimuthal NMO analysis

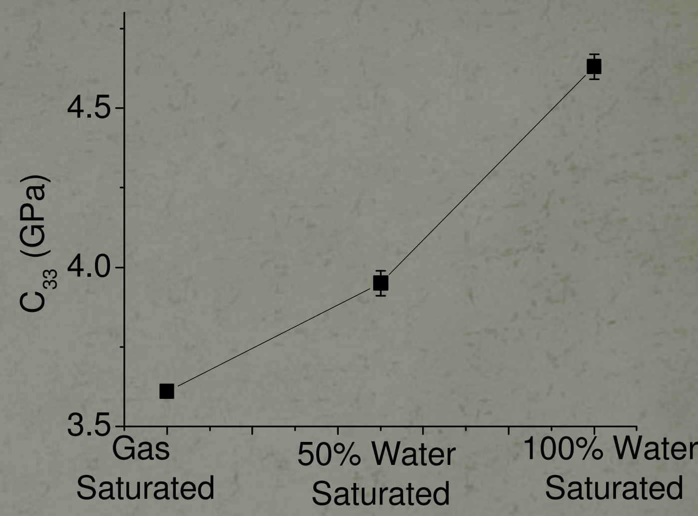


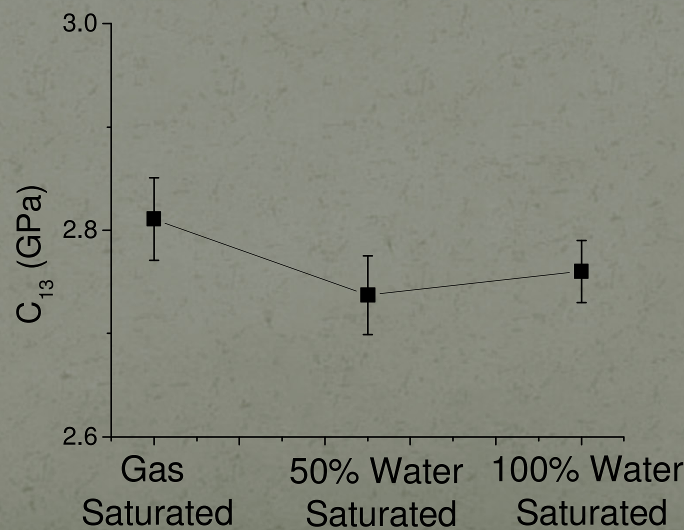
Phase velocities



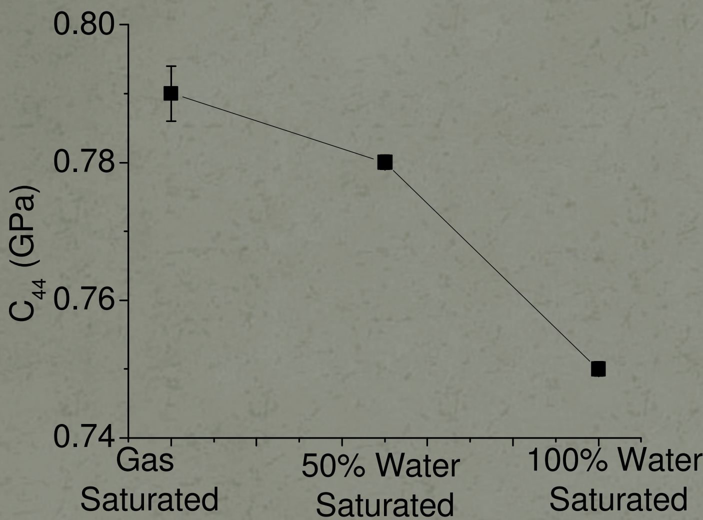
Stiffness coefficients

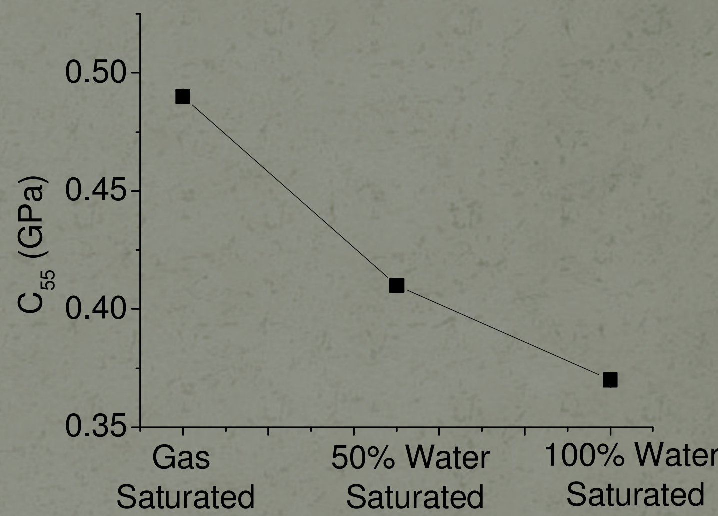






Stiffness coefficients





Stiffness coefficients

$$\begin{pmatrix} 7.40 & 2.81 & 2.81 & 0 & 0 & 0 \\ 2.81 & 3.61 & 2.04 & 0 & 0 & 0 \\ 2.81 & 2.04 & 3.61 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.79 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.49 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.49 \end{pmatrix} \text{GPa}$$

Gas Saturated

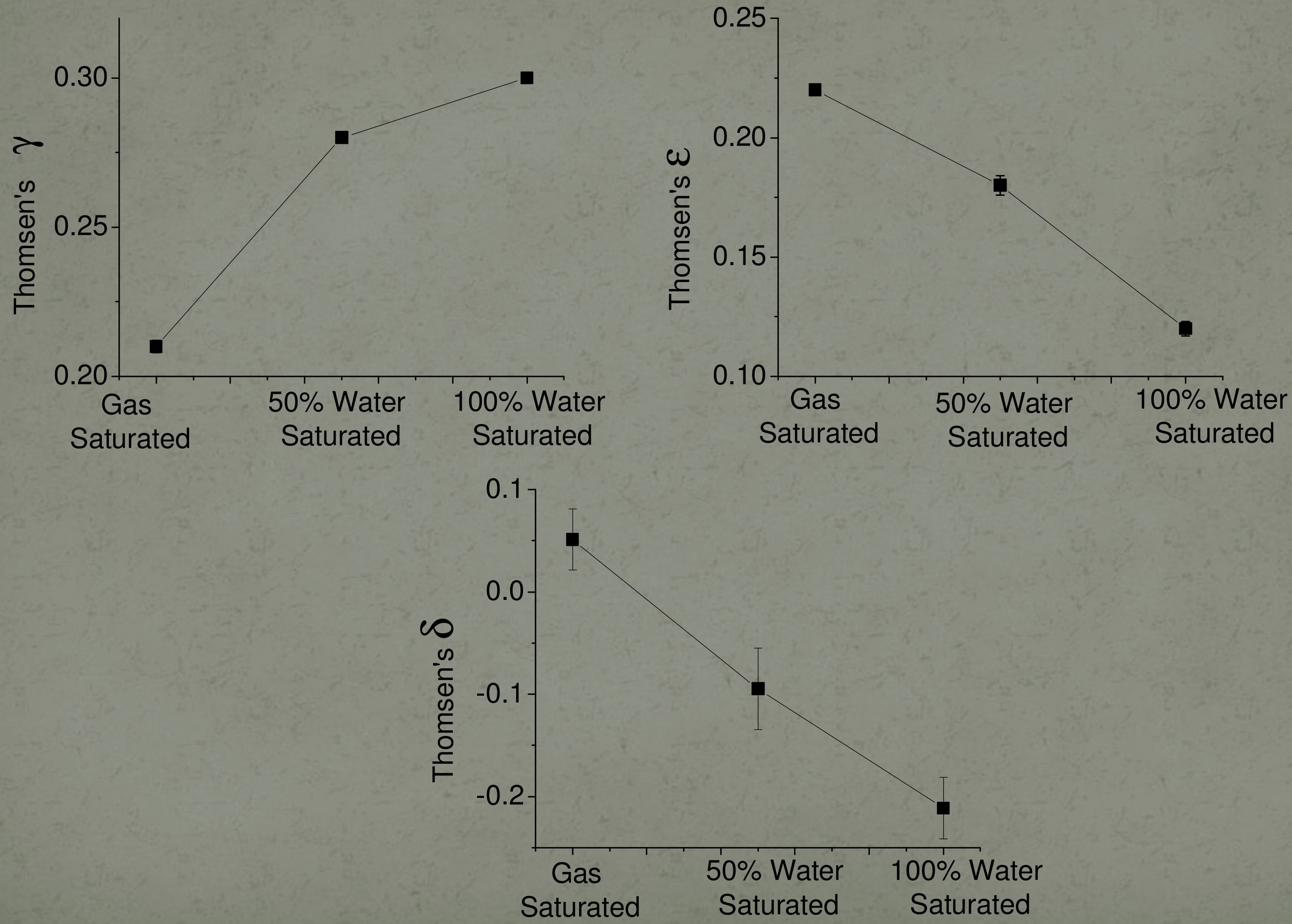
$$\begin{pmatrix} 7.15 & 2.76 & 2.76 & 0 & 0 & 0 \\ 2.76 & 4.63 & 3.89 & 0 & 0 & 0 \\ 2.76 & 3.89 & 4.63 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.75 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.37 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.37 \end{pmatrix} \text{GPa}$$

Water Saturated

$$\begin{pmatrix} -3.37 & -1.77 & -1.77 & 0 & 0 & 0 \\ -1.77 & +22 & +47.5 & 0 & 0 & 0 \\ -1.77 & +47.5 & +22 & 0 & 0 & 0 \\ 0 & 0 & 0 & -5.06 & 0 & 0 \\ 0 & 0 & 0 & 0 & -24.4 & 0 \\ 0 & 0 & 0 & 0 & 0 & -24.4 \end{pmatrix}$$

Percentage difference from gas to water saturated conditions

Anisotropic parameters



Conclusion/Future Work

- Experimental results show that shear wave splitting is affected by the nature of the saturating fluid.
- Results show a 45% decrease in ε and 30% increase in Υ as a function of water saturation.
- NMO velocities shows different trends with source-receiver azimuth as a function of water saturation.
- Stiffness coefficients C_{33} and C_{55} are most affected by change in the saturating fluid.

- Repeat experiment with a different saturating fluid (glycerin)
- Quantitative AVAZ analysis on CMP gathers
- Anisotropic reflectivity modeling from computed stiffness coefficients

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