Laboratory measured stress dependence in shales at seismic and ultrasonic frequencies

by

Dawid Szewczyk, Andreas Bauer, Rune M. Holt

ROSE meeting

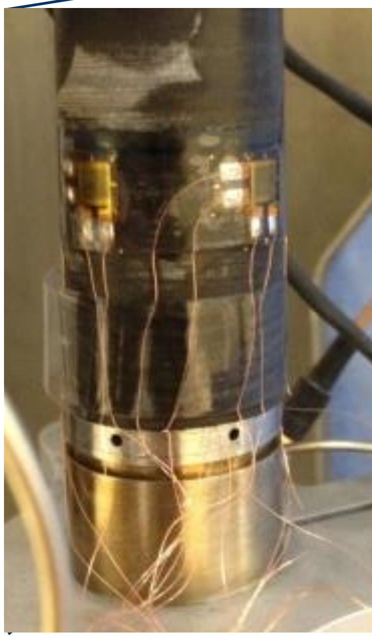
25th - 28th April 2016

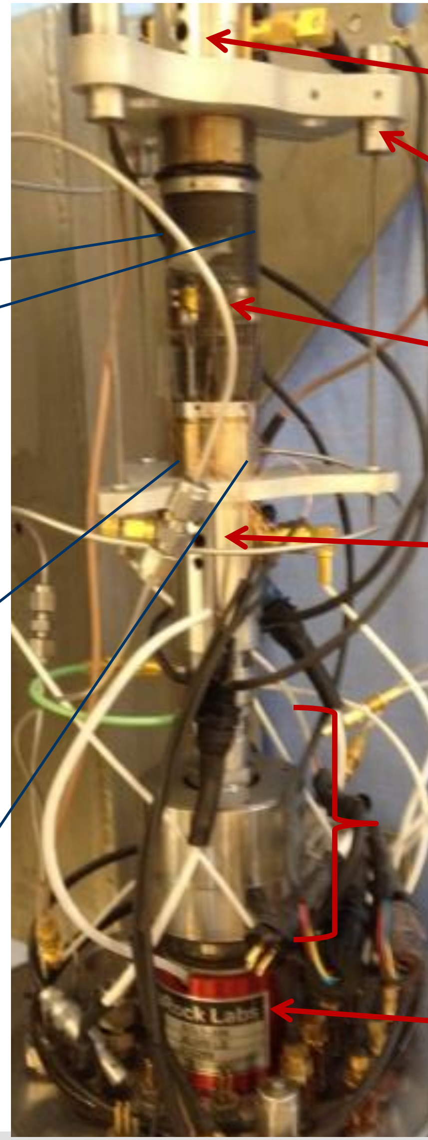
Trondheim, Norway

SINTEF

NTNU – Trondheim
Norwegian University of Science and Technology

Biaxial cell for seismic-dispersion measurements





Endcap with ultrasonic transducers (Vp, Vs) and pore-fluid line

LVDT

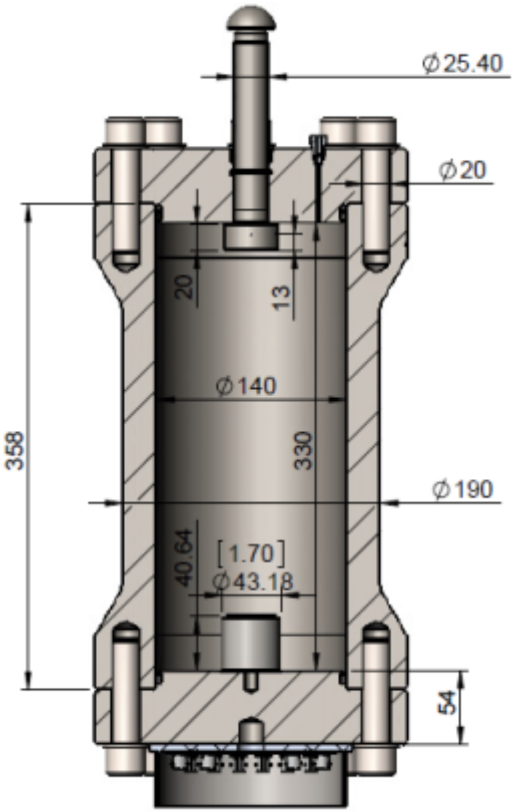
Rock sample (1" diameter) with 8 strain gages (4 axial, 4 radial) glued to it (rubber sleeve was removed)

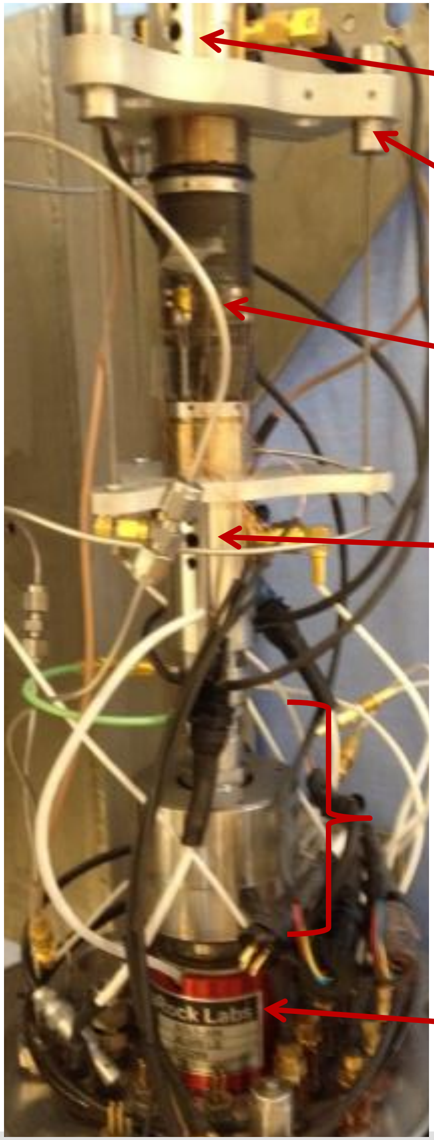
Endcap with ultrasonic transducers (Vp, Vs) and pore-fluid line

Low-frequency unit consisting of piezoelectric actuator and piezoelectric force sensor, $\varepsilon \sim 10^{-7} - 10^{-6}$

Internal load cell

Biaxial cell for seismic-dispersion measurements





Endcap with ultrasonic transducers (Vp, Vs) and pore-fluid line

LVDT

Rock sample (1" diameter) with 8 strain gages (4 axial, 4 radial) glued to it (rubber sleeve was removed)

Endcap with ultrasonic transducers (Vp, Vs) and pore-fluid line

Low-frequency unit consisting of piezoelectric actuator and piezoelectric force sensor, $\varepsilon \sim 10^{-7} - 10^{-6}$

Internal load cell

Stress dependence – Sample preparation

<u>Mancos shale:</u> outcrop, gas shale, preserved in oil, density ≈2.57 g/cm³, 1-11% porosity, 20-25% clay, 40-50% quartz, ≈1% -1,5% TOC, tested in as-received conditions

<u>Pierre shale:</u> outcrop material preserved in oil, density ≈2.40 g/cm³, 10-25% porosity, 40-80% clay, 5-25% quartz, saturation levels tuned

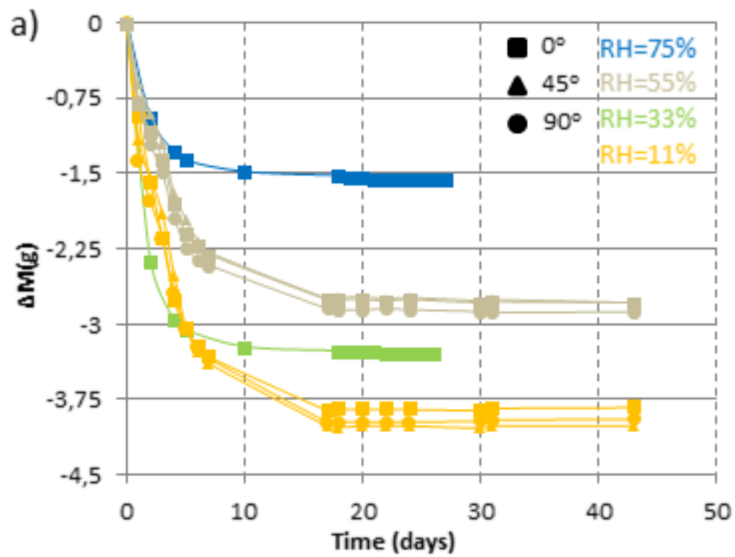
Expose samples to different relative humidity [RH]

11.3% [LiCl]

32.9% [MgCl]

54,7% [$Mg(NO_3)_2$]

75.4% [NaCl]



- **RH control → saturated solutions of different type of salts**
- **RH → saturated conversion: mineral density + XRD composition → ρ_T (0 porosity); $\rho_T + \rho_M$(measured) → ϕ; $\phi + V_S \rightarrow V_\phi$; $V_\phi + \Delta M \rightarrow S_W$**

SINTEF | NTNU – Trondheim Norwegian University of Science and Technology

Stress dependence – Data processing

Seismic frequencies → Rock engineering parameters (E, ν)
Ultrasonic frequencies → P- and S-wave velocities

Conversion

Isotropic materials:

$$E_{Isot} = \frac{\rho V_S^2 (3V_P^2 - 4V_S^2)}{V_P^2 - V_S^2} \qquad \nu_{Isot} = \frac{V_P^2 - 2V_S^2}{2(C_{V_P^2} - V_S^2)}$$

TI medium:

$$E_{V-Anisot} = C_{33} - \frac{C_{13}^2}{(C_{11} - C_{66})} \qquad \nu_{VH-Anisot} = \frac{C_{13}}{2(C_{11} - C_{66})}$$

$$C_{33} = \varrho V_{PV}^2, \quad C_{44} = \varrho V_{SV}^2, \quad C_{11} = \varrho V_{PH}^2, \quad C_{66} = \varrho V_{SH}^2$$

$$C_{13} = \frac{\sqrt{\left(2\rho V_{qP}{}^2 - \rho V_{PH}{}^2 sin^2\theta - \rho V_{PV}{}^2 cos^2\theta - \rho V_{SV}{}^2\right)^2 - \left((\rho V_{PH}{}^2 - \rho V_{SH}{}^2) sin^2\theta - (\rho V_{PV}{}^2 - \rho V_{SV}{}^2) cos^2\theta\right)^2}}{2 sin\theta cos\theta} - \rho V_{SV}{}^2$$


0°


45°


90°

Stress dependence – Data processing

# of sample	Shale	Orientation with respect to bedding	Saturant	RH theoretical (RH measured in the day of experiment)	Saturation	Change of volume during stabilization (%)
S 01, 02, 03	Mancos "B"	0º, 45º, 90º	As received	- (~86%)	~ 0.71	0
S 04, 05, 06	Pierre	0º, 45º, 90º	LiCl	11.3% (18.9%)	~ 0.12	~ -3 ÷ -4
S 07	Pierre	0º	$MgCl_2$	32.9% (33.9%)	~ 0.27	-3,10
S 08, 09, 10	Pierre	0º, 45º, 90º	$Mg(NO_3)_2$	54.4% (55.1%)	~ 0.50	~ -2,5 ÷ -3,2
S 11	Pierre	0º	NaCl	75.4% (76%)	~ 0.72	-3,16

Vertical properties + Thomsen parameters → Elastic coefficients (C_{ij})

$$C_{11} = \frac{E_V(\nu_{VH}-1)}{(\nu_{VH}+1)(2\nu_{VH}-1)} - \frac{2E_V(\nu_{VH}-1)(2\nu_{VH}^2-\nu_{VH}+1)}{(\nu_{VH}+1)^2(2\nu_{VH}-1)^2}\varepsilon + \frac{4\nu_{VH}^2E_V}{(\nu_{VH}+1)^2(2\nu_{VH}-1)}\gamma + \frac{2\nu_{VH}^2E_V(\nu_{VH}-1)}{(\nu_{VH}+1)^2(2\nu_{VH}-1)^2}$$

$$C_{33} = \frac{E_V(\nu_{VH}-1)}{(\nu_{VH}+1)(2\nu_{VH}-1)} - \frac{8\nu_{VH}^2E_V(\nu_{VH}-1)}{(\nu_{VH}+1)^2(2\nu_{VH}-1)^2}\varepsilon + \frac{4\nu_{VH}^2E_V}{(\nu_{VH}+1)^2(2\nu_{VH}-1)}\gamma + \frac{2\nu_{VH}^2E_V(\nu_{VH}-1)}{(\nu_{VH}+1)^2(2\nu_{VH}-1)^2}\delta$$

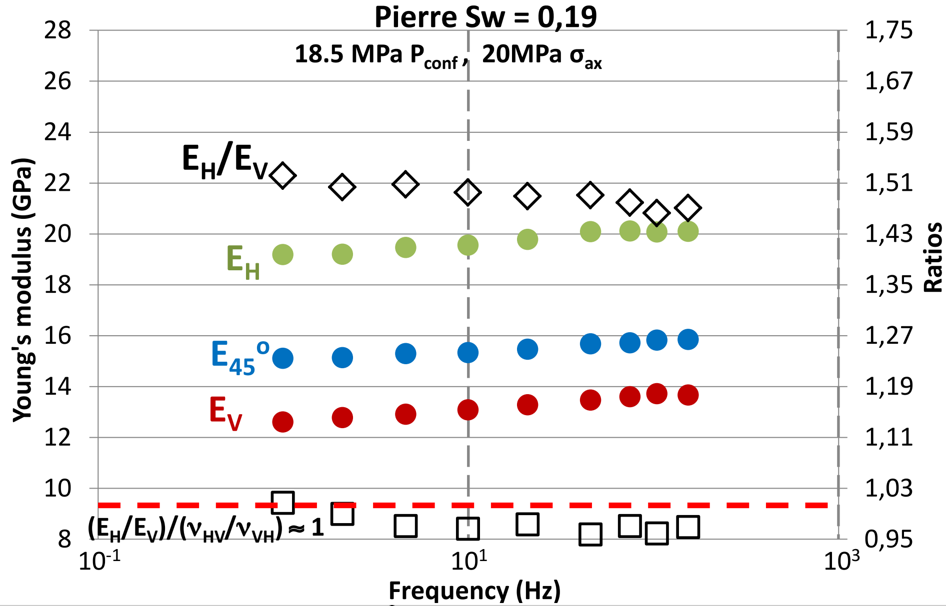
$$C_{44} = \frac{E_V}{2(\nu_{VH}+1)} + \frac{2\nu_{VH}E_V(\nu_{VH}-1)}{(\nu_{VH}+1)^2(1-2\nu_{VH})}\varepsilon + \frac{\nu_{VH}E_V}{(\nu_{VH}+1)^2}\gamma - \frac{(\nu_{VH}-1)(2\nu_{VH}+1)E_V}{2(\nu_{VH}+1)^2(1-2\nu_{VH})}\delta$$

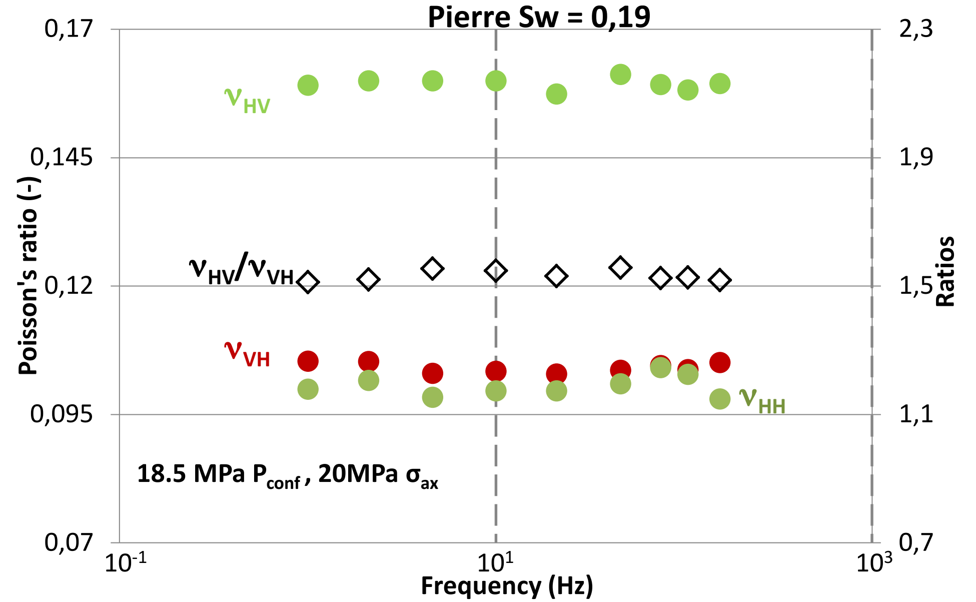
$$C_{66} = \frac{E_V}{2(\nu_{VH}+1)} + \frac{2\nu_{VH}E_V(\nu_{VH}-1)}{(\nu_{VH}+1)^2(1-2\nu_{VH})}\varepsilon + \frac{E_V(2\nu_{VH}+1)}{(\nu_{VH}+1)^2}\gamma - \frac{(\nu_{VH}-1)(2\nu_{VH}+1)E_V}{2(\nu_{VH}+1)^2(1-2\nu_{VH})}\delta$$

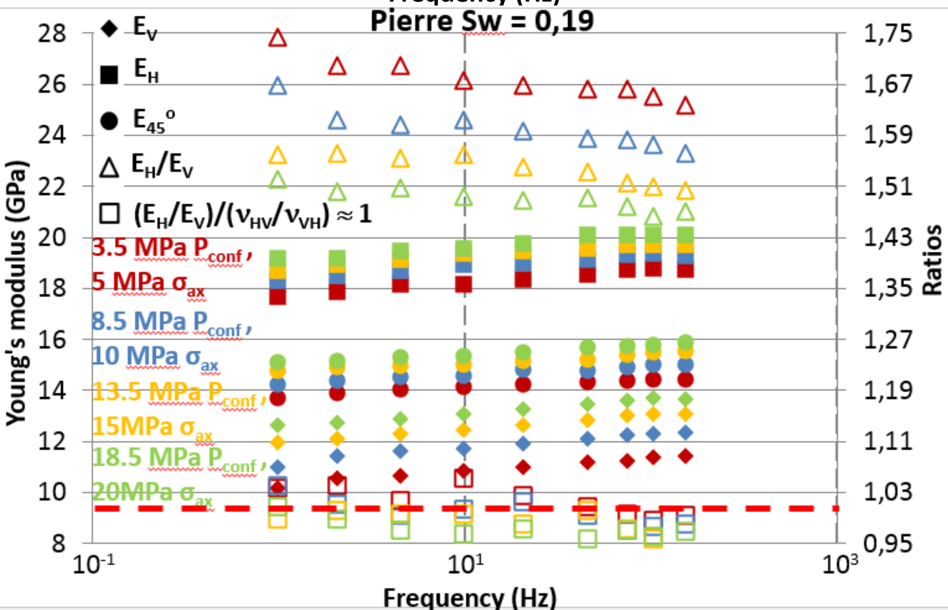
$$C_{13} = \frac{-E_V\nu_{VH}}{(\nu_{VH}+1)(2\nu_{VH}-1)} - \frac{4\nu_{VH}E_V(\nu_{VH}-1)}{(\nu_{VH}+1)^2(2\nu_{VH}-1)^2}\varepsilon + \frac{2\nu_{VH}E_V}{(2\nu_{VH}-1)(\nu_{VH}+1)^2}\gamma + \frac{\nu_{VH}E_V(\nu_{VH}-1)}{(\nu_{VH}+1)^2(2\nu_{VH}-1)^2}\delta$$

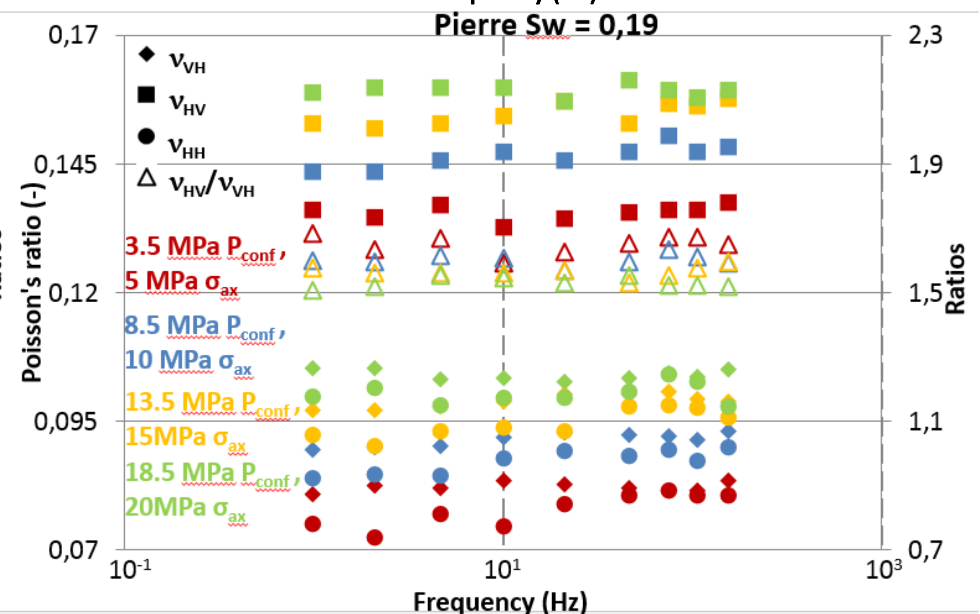
Stress dependence – Quality check

- TI symmetry requires: $\dfrac{\nu_{HV}}{E_H} = \dfrac{\nu_{VH}}{E_V}$

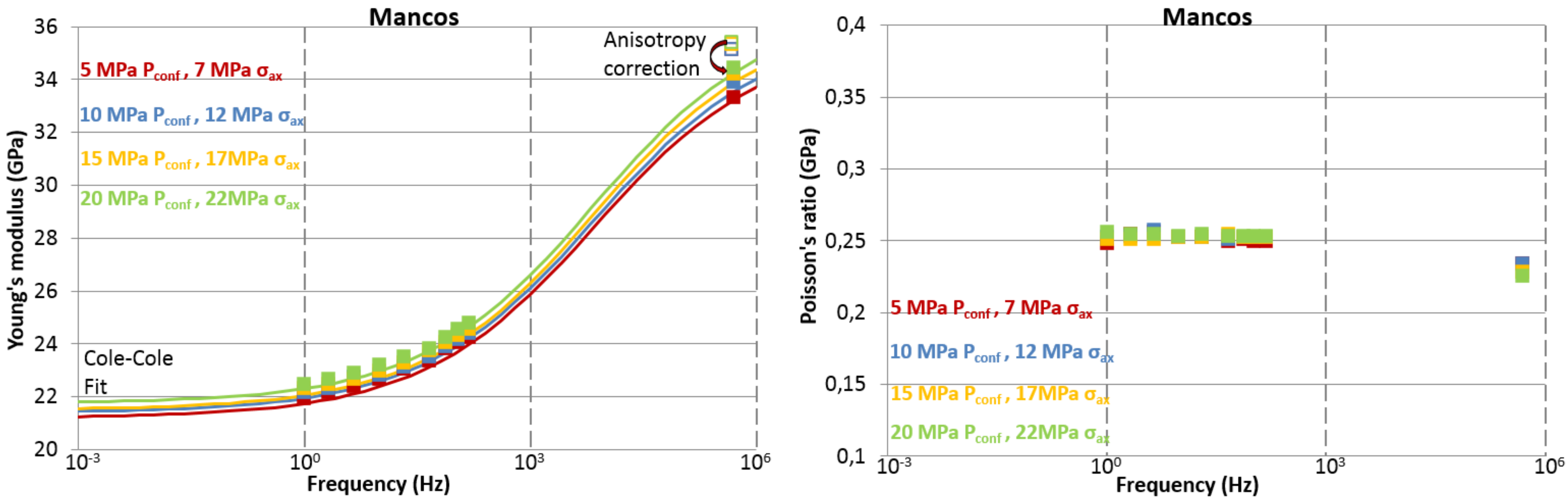






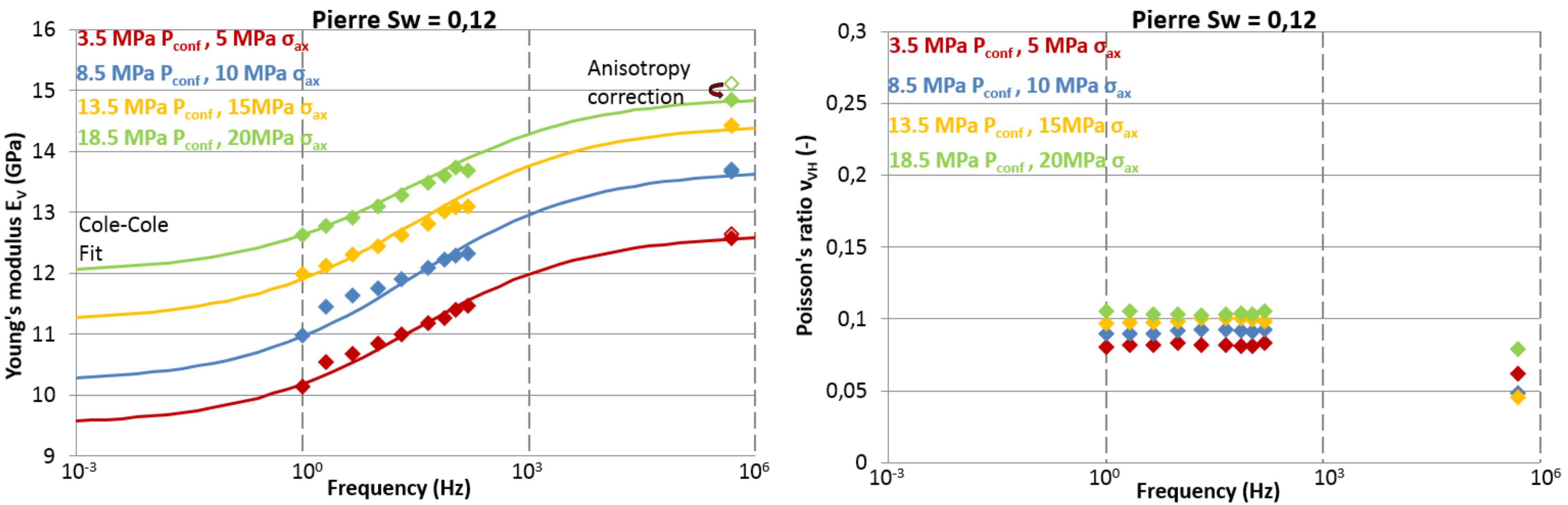


Stress dependence – E_V - Mancos shale



- **Dispersion → ~ 50% in E_V (~ 10% at seismic frequencies)**
- **Stress sensitivity ~ 0.15%/MPa**
- **Absolute E_V changes similar at seismic and ultrasonic frequencies (relative changes are higher at seismic frequencies due to dispersion)**
- **Poisson's ratio non-dispersive at seismic frequencies and rather stress independent**

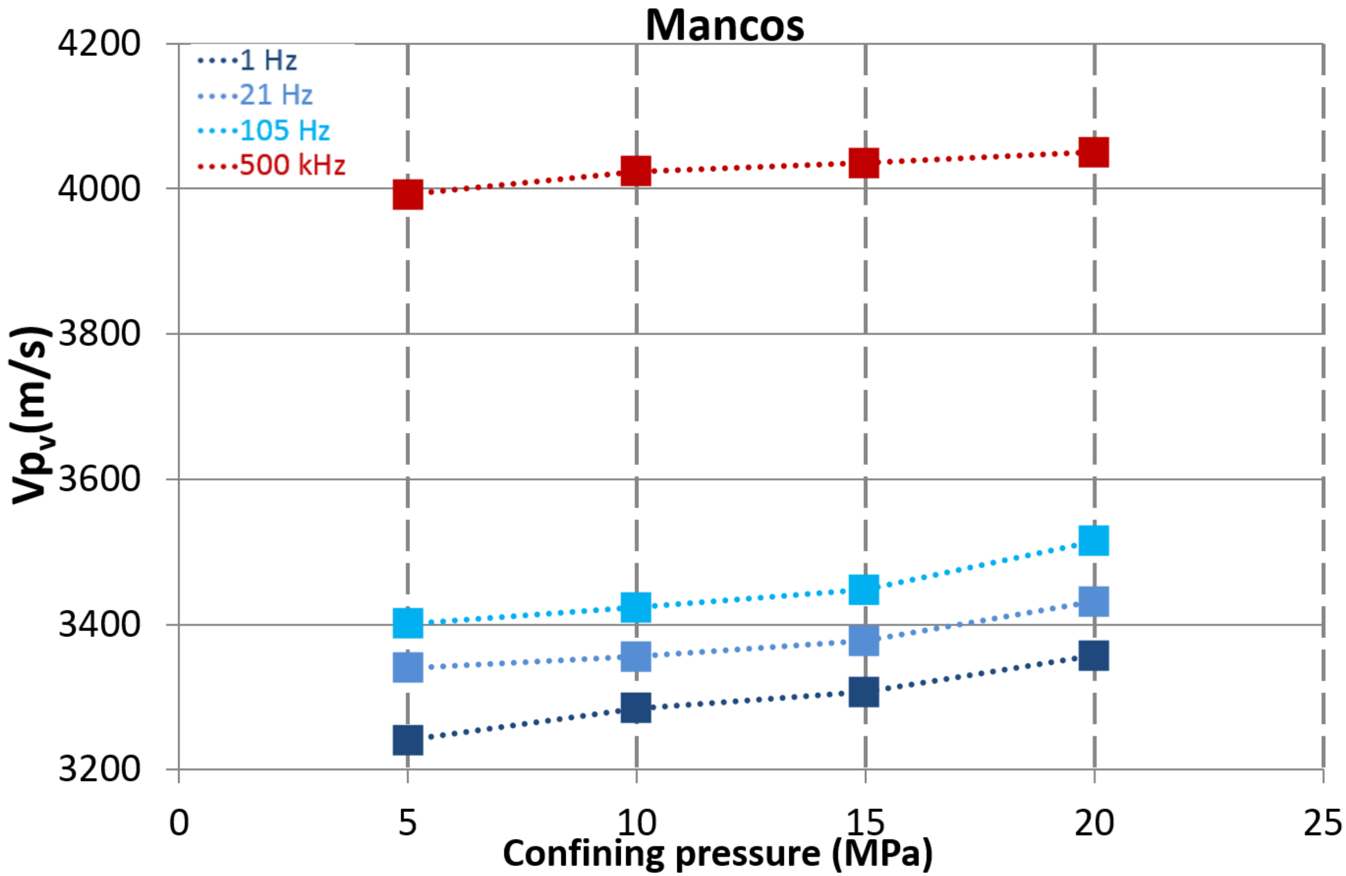
Stress dependence – E_V - Pierre shale



- Dispersion → ~ 24% in E_V at low stresses and ~ 17% at high stresses (increases with increasing S_W)
- Stress sensitivity ~ 1.6%/MPa and decreases with increasing saturation (0.7%/MPa for S_W=0.72)
- Absolute E_V changes similar at seismic and ultrasonic frequencies (relative changes are smaller at ultrasonic frequencies due to dispersion)
- Poisson's ratio → non-dispersive at seismic frequencies (from S_W=0.5 some dispersion may be observed), clear stress dependency

Stress dependence – V_{PV}-Mancos shale

Frequency (Hz)	Stress sensitivity (m/s/MPa)
1	7.45
21	7.38
105	7.29
500 k	3.7



- Stress sensitivity → clear difference between seismic and ultrasonic frequencies (~ twofold higher at seismic regime)
- Dispersion → ~ 23% in V_{PV} between 1 Hz and 500 kHz
- Dispersion decreases with increasing stress

Stress dependence – V_{PV}- Pierre shale

$S_W=0.12$

Frequency (Hz)	Stress sensitivity (m/s/MPa)
1	18.37
500 k	14.30

$S_W=0.27$

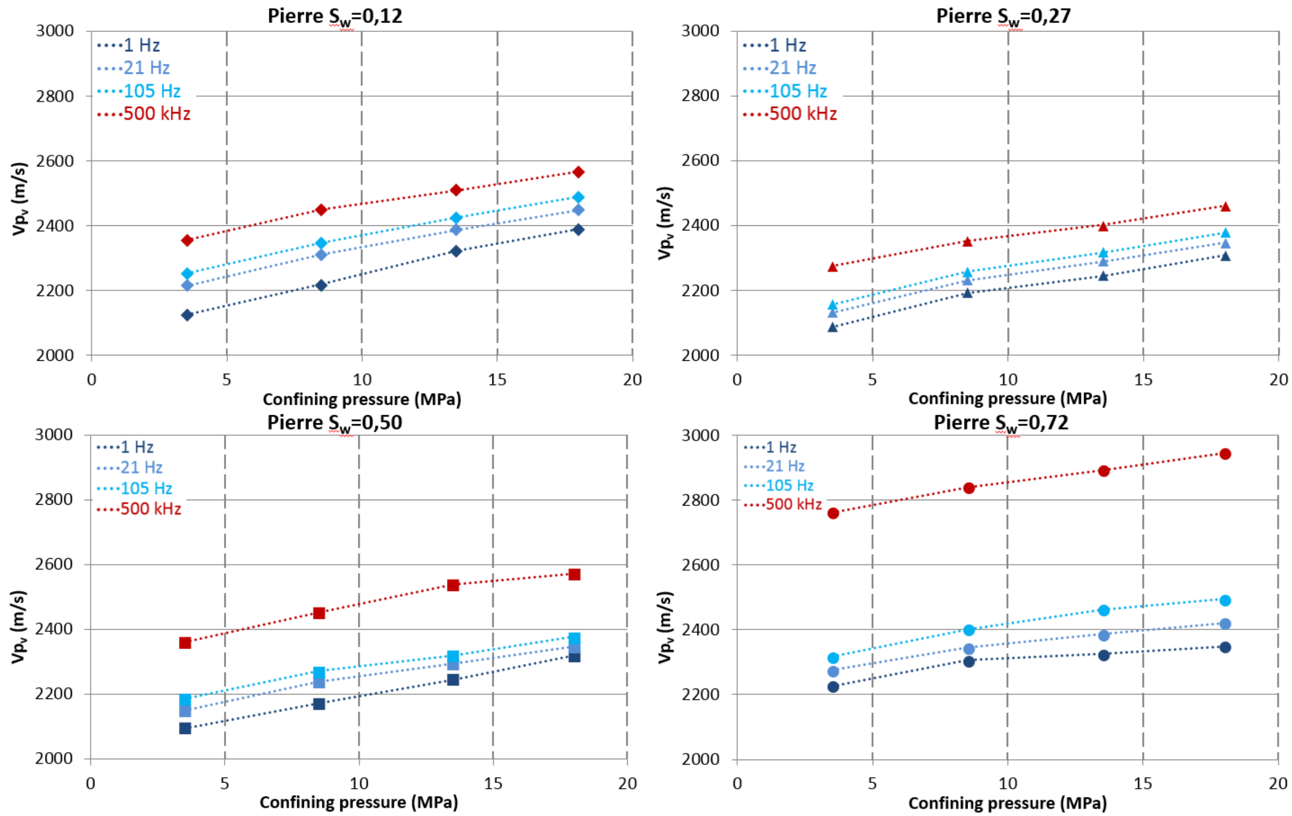
Frequency (Hz)	Stress sensitivity (m/s/MPa)
1	14.76
500 k	12.60

$S_W=0.50$

Frequency (Hz)	Stress sensitivity (m/s/MPa)
1	15.28
500 k	14.95

$S_W=0.72$

Frequency (Hz)	Stress sensitivity (m/s/MPa)
1	7.95
500 k	12.48



- Stress sensitivity → different for seismic and ultrasonic and saturation dependent
- Dispersion → ~ 10% in V_{PV} between 1 Hz and 500 kHz (S_W=0.12) and saturation dependent
- Dispersion decreases with increasing stress (beside S_W=0.72)
- Effects of saturation increase → stress sensitivity decreases, dispersion increases

Summary

- Absolute E_V changes as a response to hydrostatic loading are similar at seismic and ultrasonic frequencies for both shale types however due to dispersion stress sensitivity is frequency dependent.
- Increase in water saturation level causes increase in E_V dispersion and softening of the shale at seismic frequencies (data not shown in presentation, more in Andreas Bauer talk).
- Stress sensitivity of V_{PV} is frequency dependent (up to twofold decrease from seismic to ultrasonic frequencies) and decreases with the increase of saturation.
- Increase in applied stress decreases dispersion of V_{PV} .
- Increase in water content increases dispersion of V_{PV} .

Acknowledgements

The authors would like to acknowledge support from:

- The BIGCCS program at NTNU and SINTEF.
- The Research Council of Norway.
- The KPN-project "Shale Rock Physics: Improved seismic monitoring for increased recovery" at SINTEF Petroleum Research.