Acoustic Velocities of Shales: Stress and Frequency Dependence

Andreas Bauer, Dawid Szewczyk, Rune M. Holt

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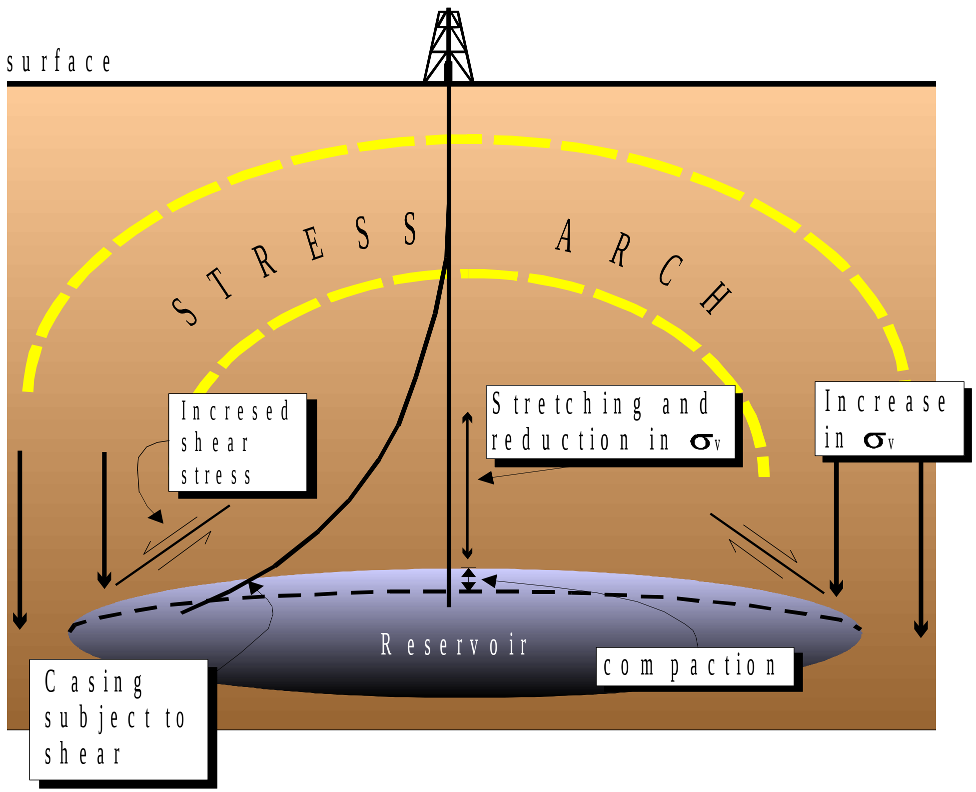
Stress dependence of seismic velocities

- Depletion / Inflation of reservoir reults in stress changes in and around the reservoir, resulting in seismic-velocity and impedance changes.



- Homogeneous, isotropic space ⇒ $\Delta\bar{\sigma} = 0$ outside the reservoir
- Material contrast ⇒ ; $\Delta\bar{\sigma} \neq 0; \Delta p_f \neq 0$

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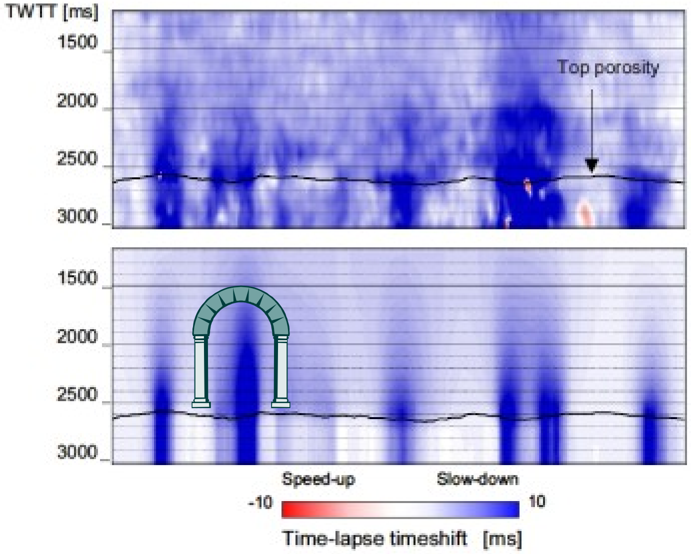
Stress dependence of seismic velocities

- Timelapse seismic data can be inverted for stress and strain changes in the subsurface (→ caprock integrity) and reservoir compaction (→ detection of undepleted pockets), provided that accurate goemechanical and rock physics models are available.

  - Geomechanical model: links pore-pressure changes to stress and strain changes. Critical input parameters: geometry of lithologies and rock stiffnesses
  - Rock physics model: links stress and strain changes to seismic velocity changes (rocks are non-linear elastic media!).

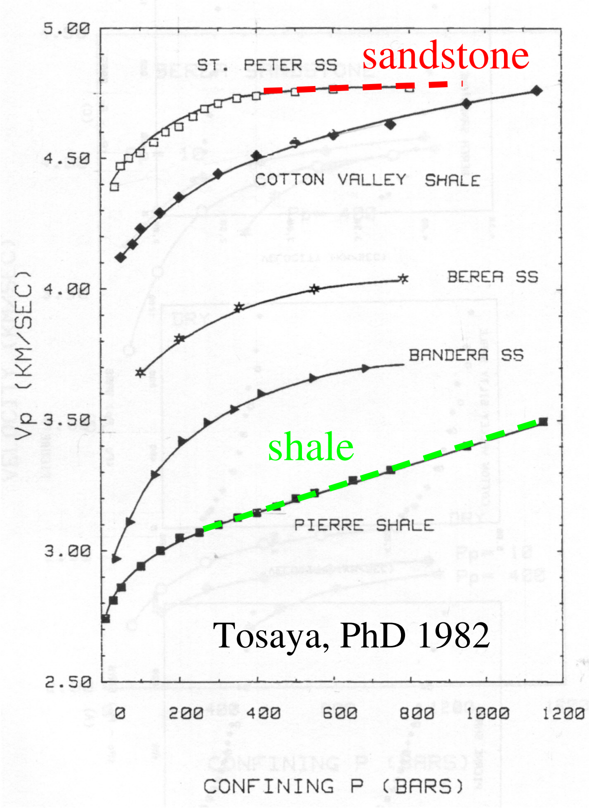


Hatchell & Bourne, 2005

Stress dependence of seismic velocities

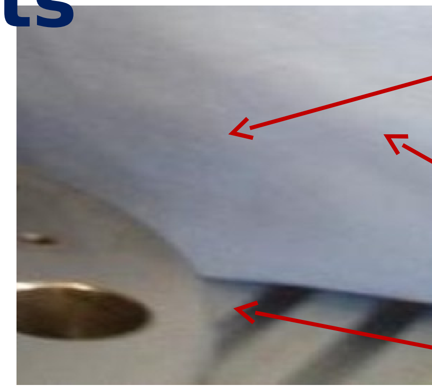
Issues:

- ❑ How to obtain rock stiffnesses?
  - ➢ Reservoir rocks: Core material might be available
  - ➢ Overburden rocks (often shale): **stiffnesses obtained from seismic or sonic data using correlations. How good are those correlations?**
- ❑ How to obtain the stress and stress-path dependence of seismic velocities
  - ➢ Rock physics models often based on laboratory measurements at ultrasonic frequencies; dispersion effects are usually ignored
  - ➢ Recent tests with different types of shales show large seismic dispersion **Better understanding of dispersion effects needed**



New compaction cell for seismic-dispersion measurements

- Compaction tests
- Control of confining stress, axial stress, and pore pressure
- Ultrasonic velocities, v_P, v_S
- Dynamic stiffness (Young's modulus, Poissons's ratio) at seismic frequencies (1 – 155 Hz)



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

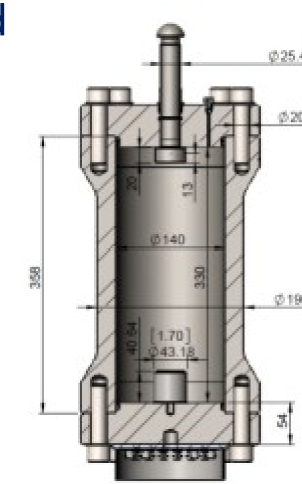
LVDT

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

Internal load cell



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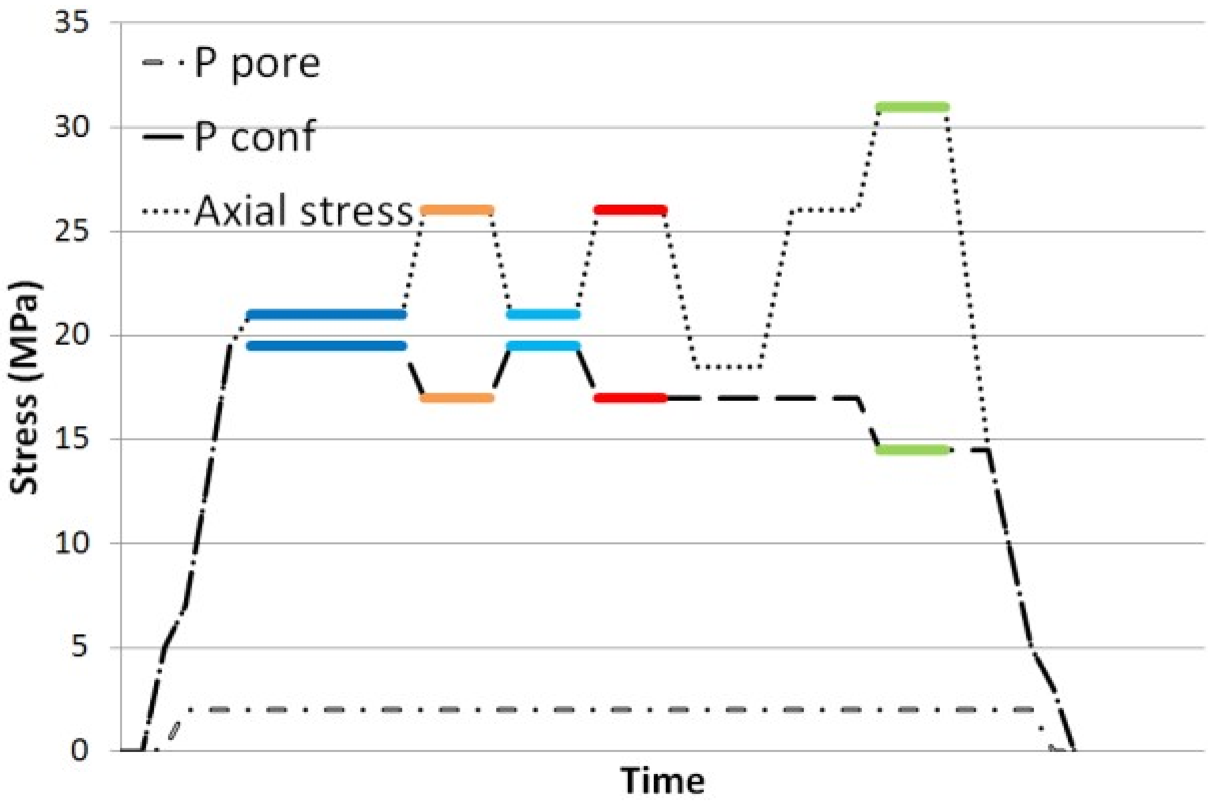
Pierre shale: Stress dependence of velocities

Stress path: Constant mean stress loading / unloading + triaxial unloading/loading



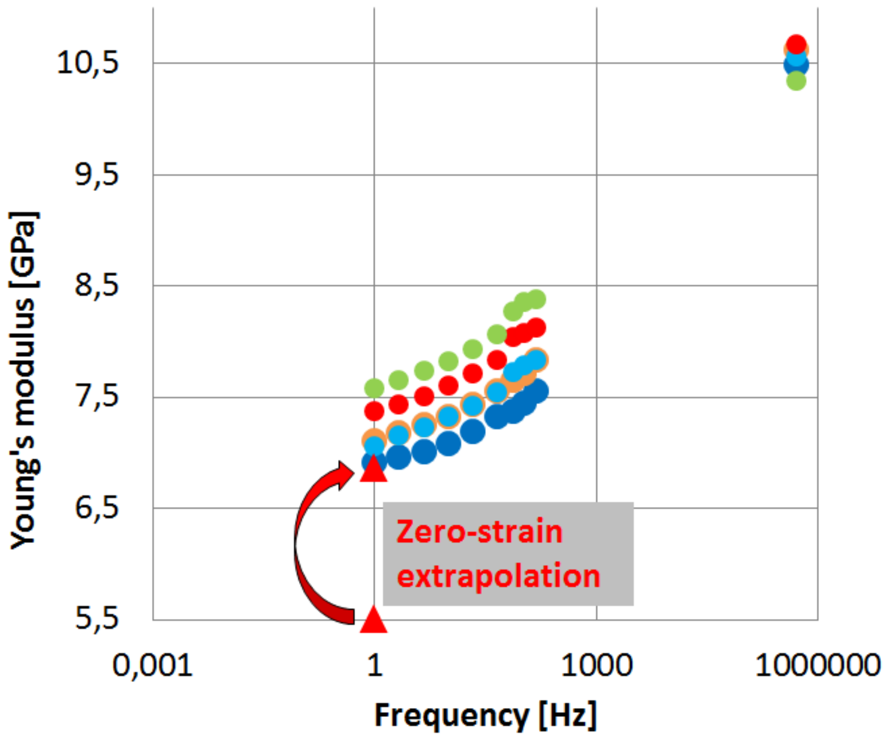
Pore fluid: brine (3.5% NaCl)

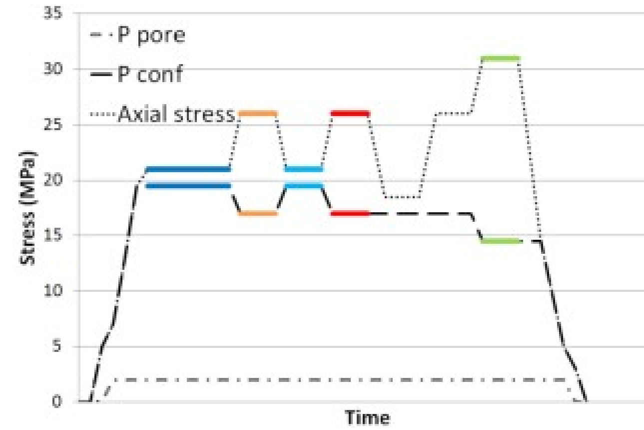
Use metal mesh for side drainage

Change in deviatoric stress at constant mean stress corresponds to the stress path in the overburden and sideburden of a depleting / inflating reservoir for a homogeneous subsurface

Pierre shale: Stress dependence of velocities

Preliminary results





- Zero-strain static Young's modulus consistent with low-frequency measurements
- Seismic Young's modulus increases with increasing deviatoric stress
- Stress effects not fully reversible (due to plastic deformation, or experimental artefact?)
- Stress sensitivity is different for seismic and ultrasonic frequencies, and even changes sign at high deviatoric stress

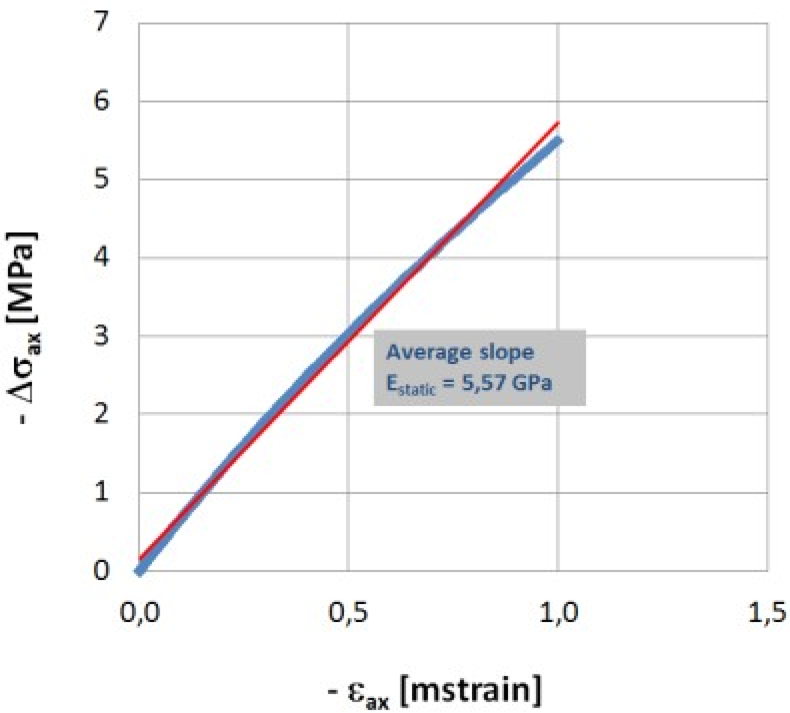
Zero-strain limit of static Young's modulus

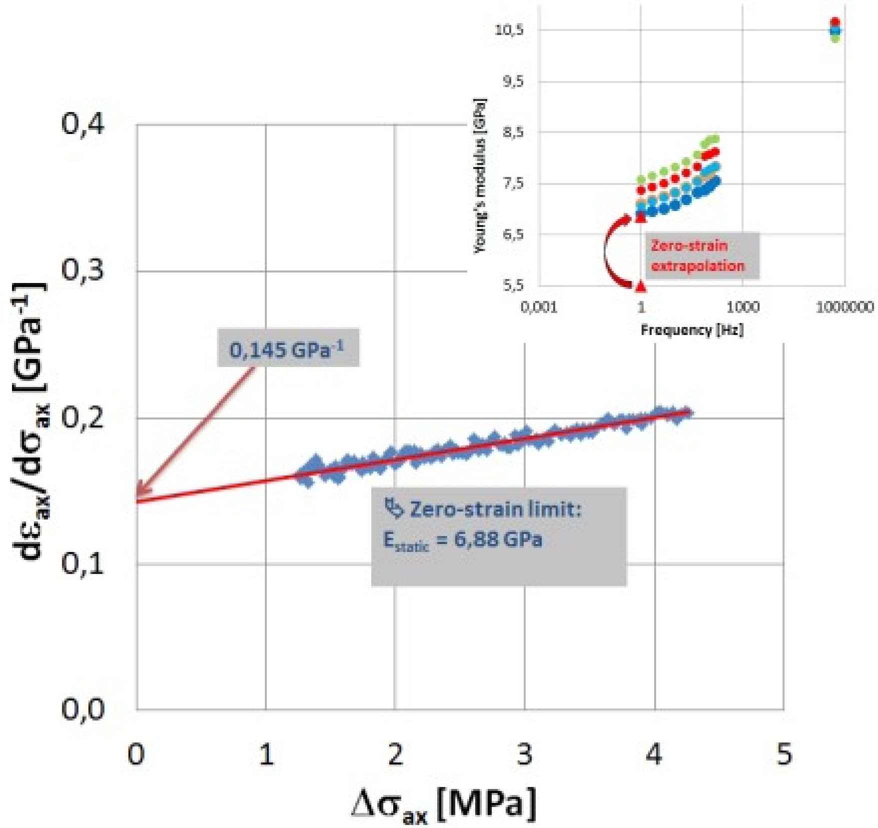
tic Young's modulus has elastic and non-elastic component

ring triaxial unloading, the non-elastic component vanishes in the limit of zero st

umption (proven for sandstones)*: **$d\varepsilon_{ax}/d\sigma_{ax}$ increases linearly with $\Delta\sigma_{ax}$**

* Fjær, Stroisz, Holt, ARMA 12-537 (2012)





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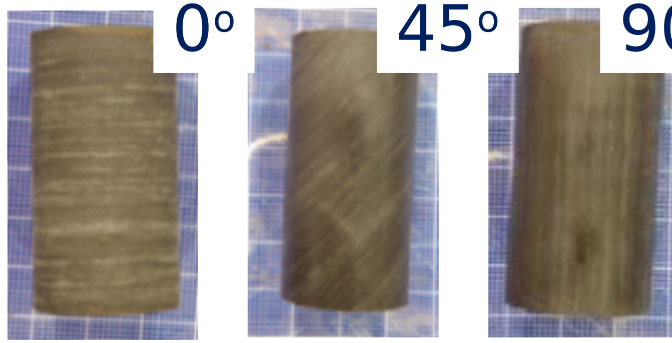
Mancos shale: Stress dependence of velocities

- Three sample orientations (allowing for the determination of all 5 independent stiffness-matrix components: C_{11}, C_{33}, C_{44}, C_{66}, C_{13})

$$\vec{C} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix}$$

with $C_{66} = \frac{1}{2}(C_{11} - C_{12})$



Samples were tested as received; no pore-pressure control (saturation state corresponds to a rel. humidity of ≈ 86%)

$C_{33} = \rho V_{PV}^2$; $C_{11} = \rho V_{PH}^2$; $C_{44} = \rho V_{SV}^2$; $C_{66} = \rho V_{SH}^2$

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

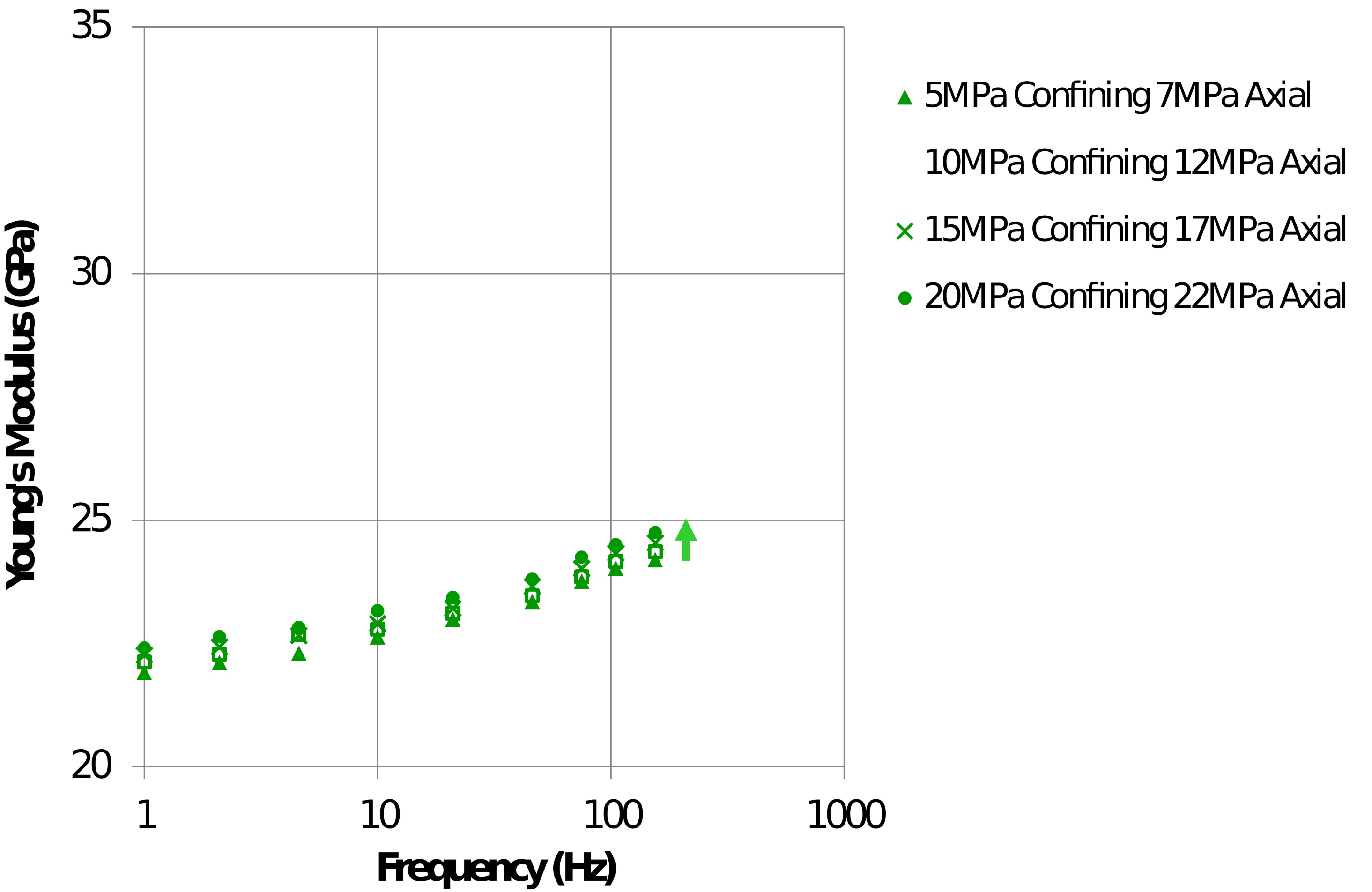
- Stress states:

1. P_{conf} = 5 Mpa, σ_{ax} = 7 MPa
2. P_{conf} = 10 Mpa, σ_{ax} = 12 MPa
3. P_{conf} = 15 Mpa, σ_{ax} = 17 MPa
4. P_{conf} = 20 Mpa, σ_{ax} = 22 MPa

Comment: A constant deviatoric stress of 2 MPa was applied in axial direction in order to improve the signal quality of the low-frequency data; the impact of this deviatoric stress on the rock stiffness was ignored in the anisotropy analysis, which is justified since the angular dependence of the velocities is much larger than the stress effect.

Mancos shale: Stress dependence of velocities

ults of low-frequency measurements



Mancos shale: Stress dependence of velocities

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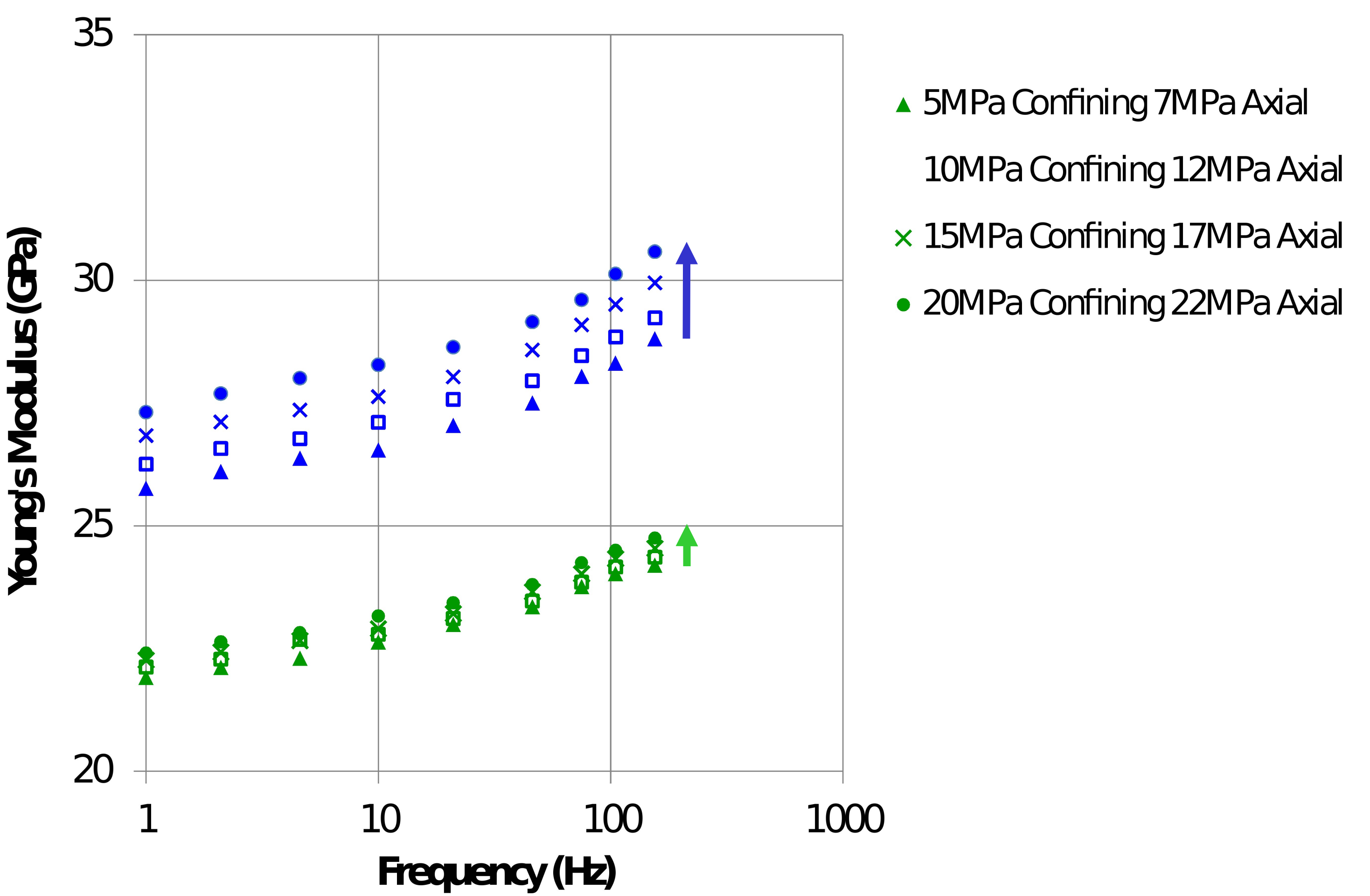
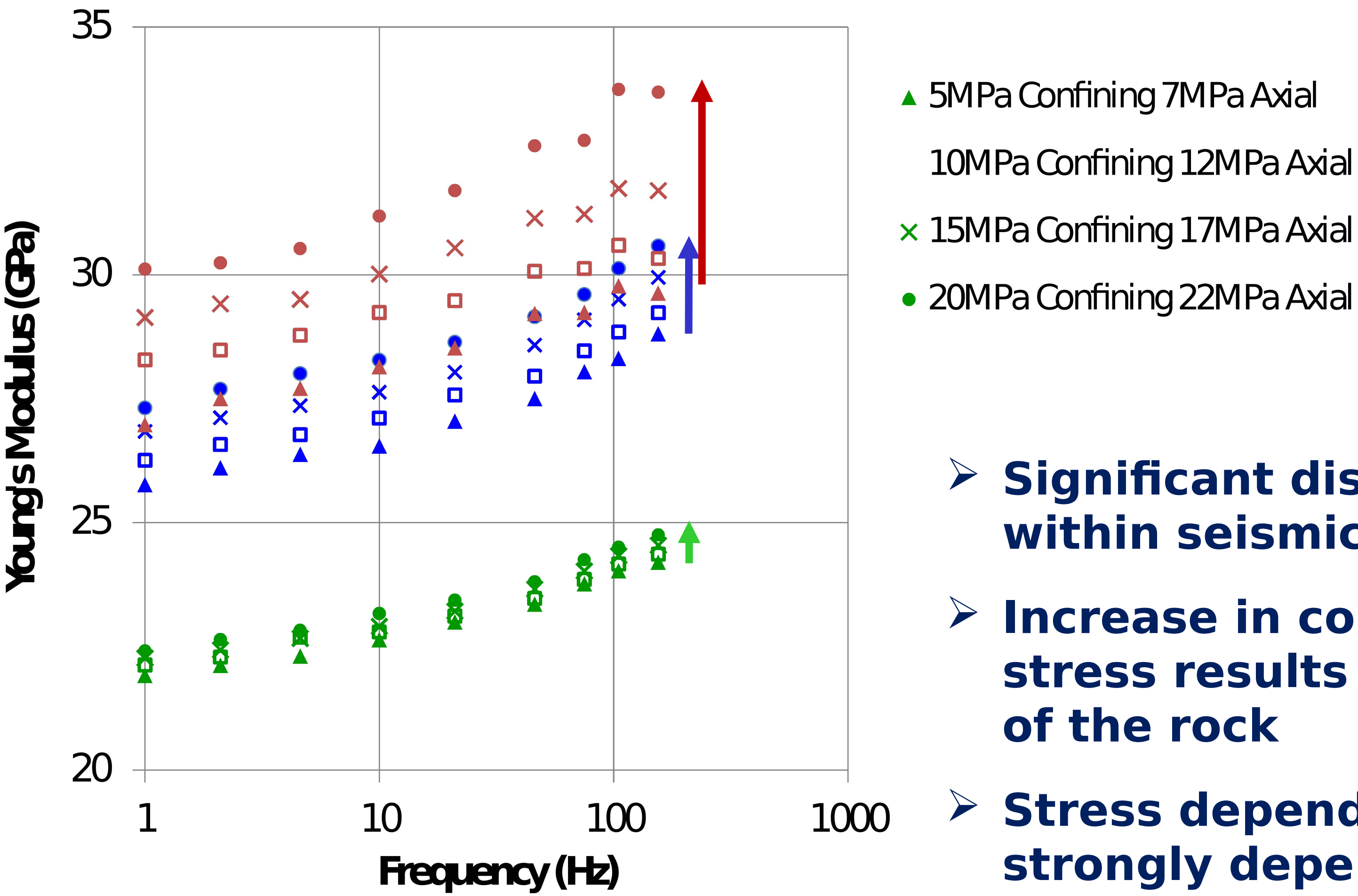
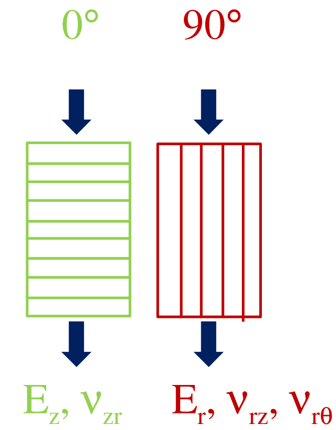


Mancos shale: Stress dependence of velocities

s of low-frequency measurements – Youngs-modulus

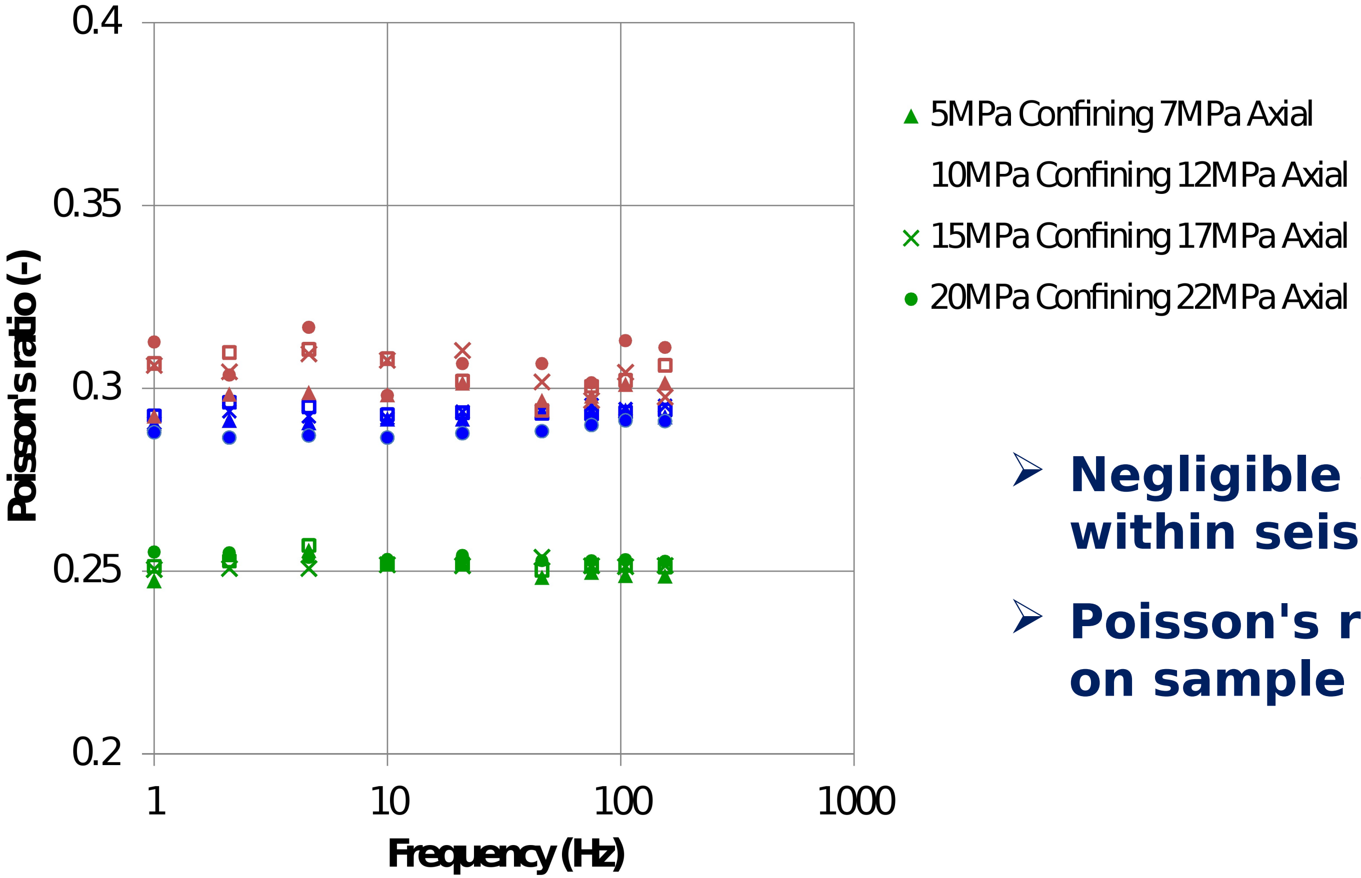


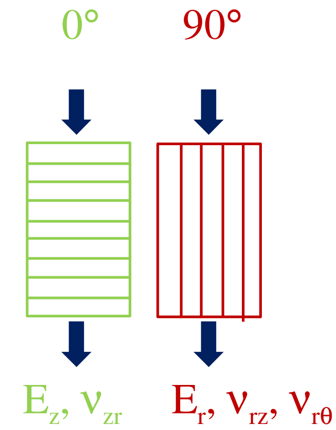


- **Significant dispersion within seismic band**
- **Increase in confining stress results in stiffening of the rock**
- **Stress dependence strongly depends on sample orientation**

Mancos shale: Stress dependence of velocities

of low-frequency measurements – Poisson's ratio (average)

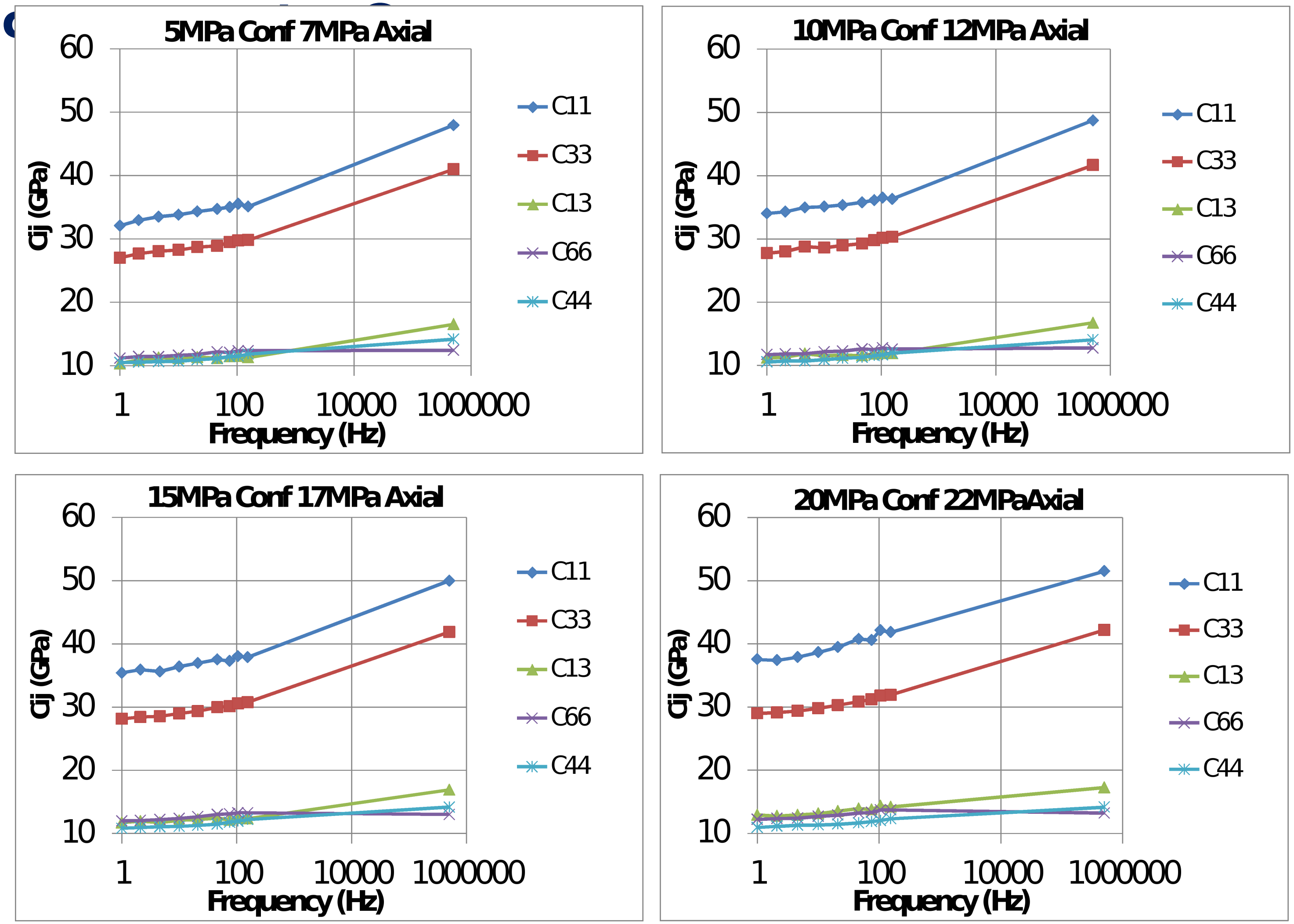




- **Negligible dispersion within seismic band**
- **Poisson's ratio depends on sample orientation**

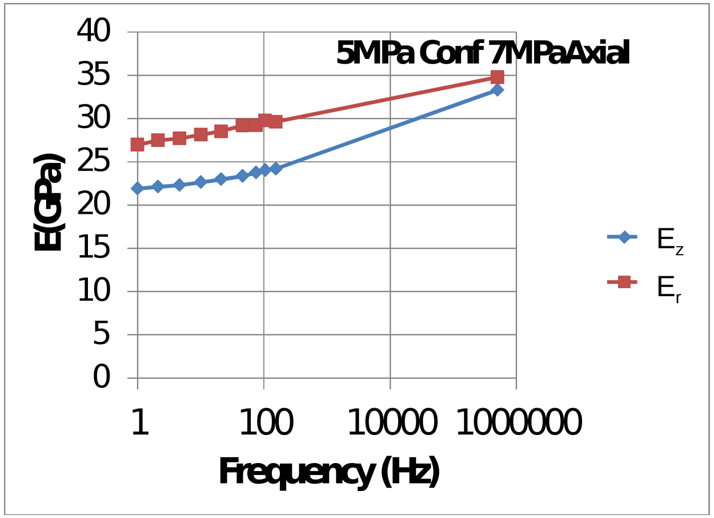
Mancos shale: Stress dependence of velocities

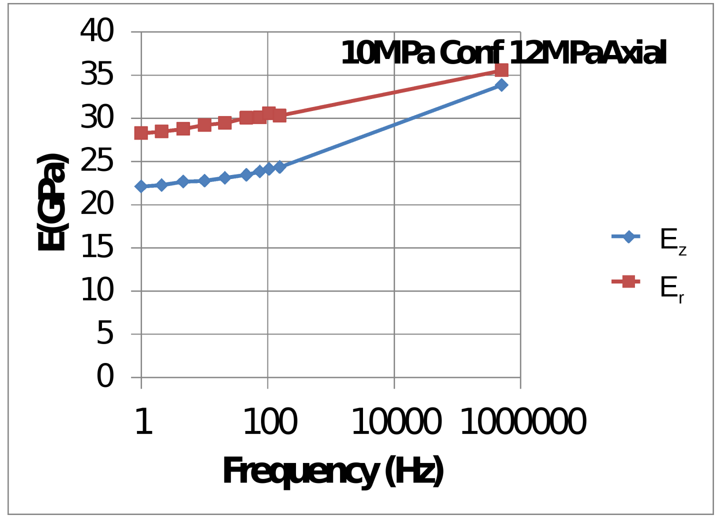
Results of combined low-frequency and ultrasonic measurements – Dispersion Stiffness matrix c

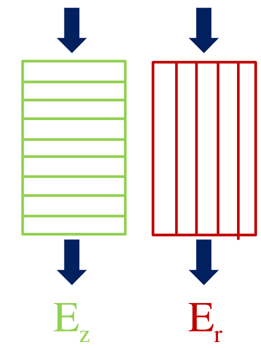


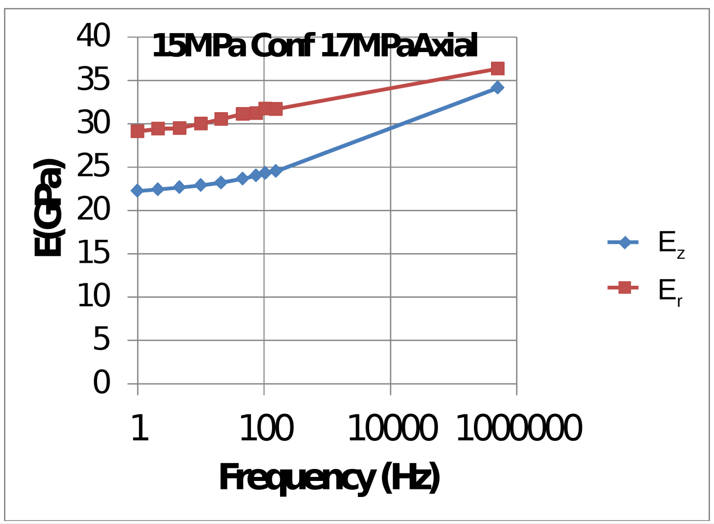
Mancos shale: Stress dependence of velocities

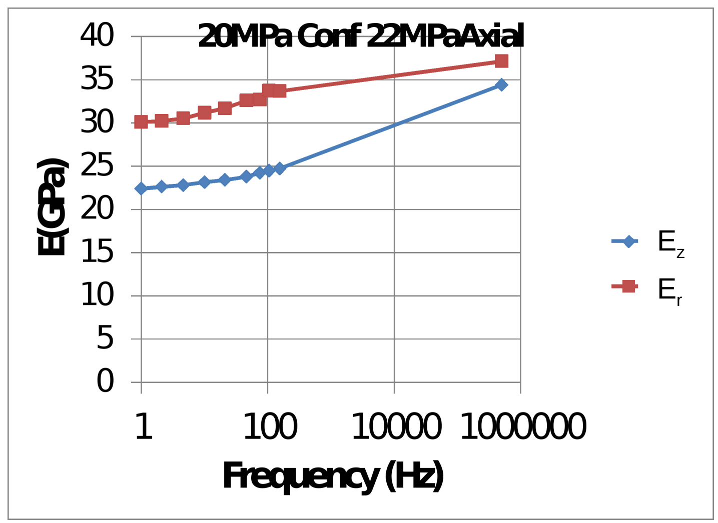
Results of combined low-frequency and ultrasonic measurements – Young's moduli, E_z, E_r







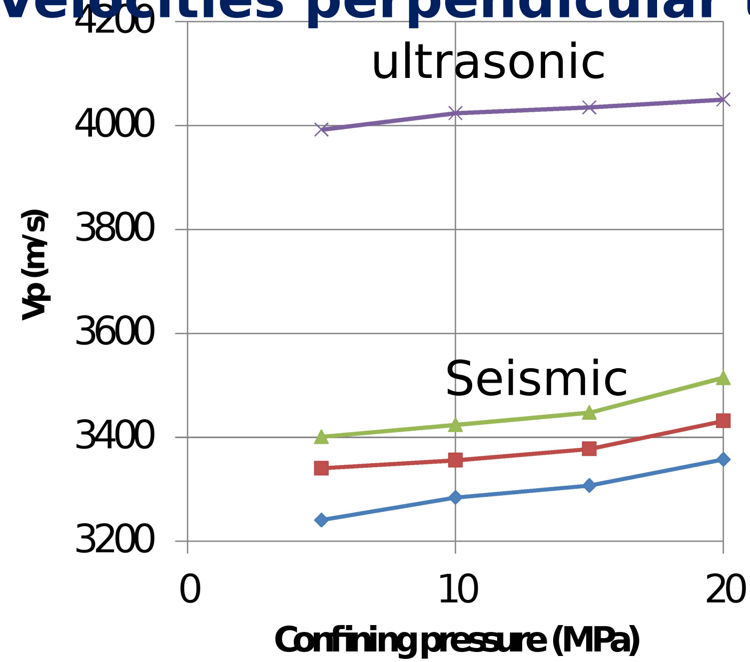


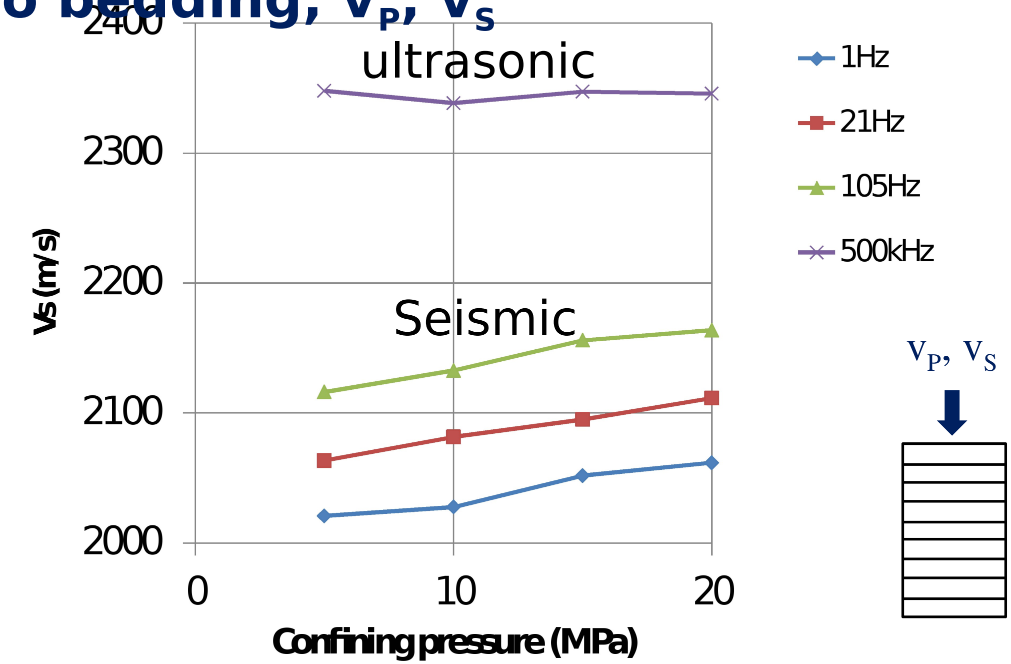


Significantly larger difference in E_z and E_r at seismic frequencies

Mancos shale: Stress dependence of velocities

Results of combined low-frequency and ultrasonic measurements – Velocities perpendicular to bedding, v_P, v_S





- **Larger stress dependence of v_P and v_S at seismic frequencies**
- **v_S at ultrasonic frequencies exhibits neglible change with stress, while v_S at seismic frequencies increases gradually with stress**
- **Preliminary results only! Anisotropy data needs to be checked for consitency**

Summary

- Shales, both fully saturated (Pierre) and partially saturated (Mancos), exhibit significant seismic dispersion
- Dispersion mechanism in shales not yet understood
- Seismic dispersion in shales is strongly affected by stress
- Stress dependence of v_P and v_S is not the same at seismic and ultrasonic frequencies ⇒ Rock physics models based on ultrasonic data may not apply
- Shale anisotropy has to be taken into account
- More experimental studies and improved rock-physics models needed