Elastic dispersion derived from a combination of static and dynamic measurements

Erling Fjær[1,2]

Anna M. Stroisz[2]

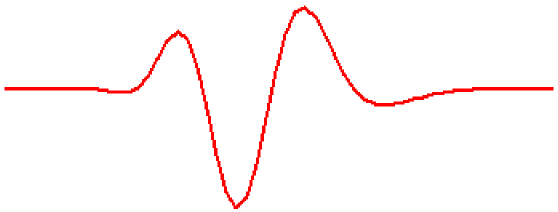
Rune M. Holt[2,1]

[1]SINTEF Petroleum Research

[2]Norwegian University of Science and Technology

Long term challenge:

- measuring acoustic velocities
  at seismic frequencies
  in the laboratory



Wavelength >> sample size
⇒ no travelling wave

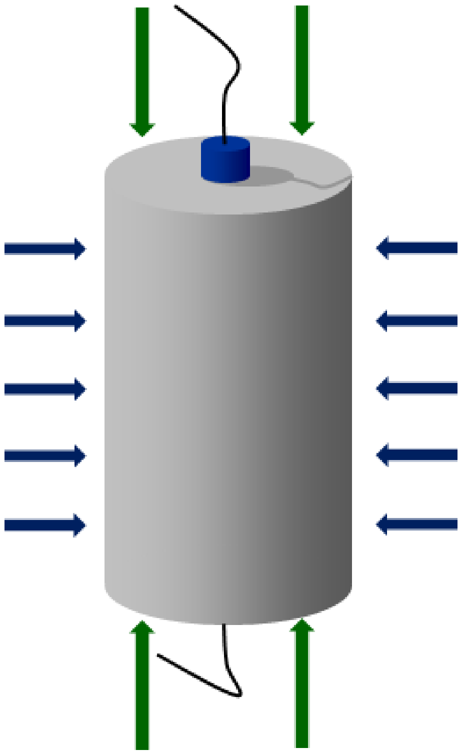
Extremely small deformations ($\varepsilon \sim 10^{-7}$)
⇒ resolution is a problem

Stress path vs wave mode
⇒ anisotropy can be a problem

We claim that:

- velocity dispersion between ultrasonic and seismic frequencies can be estimated from a standard rock mechanical test set-up with acoustic velocity measurements

Laboratory tests:



Standard triaxial set-up + acoustics

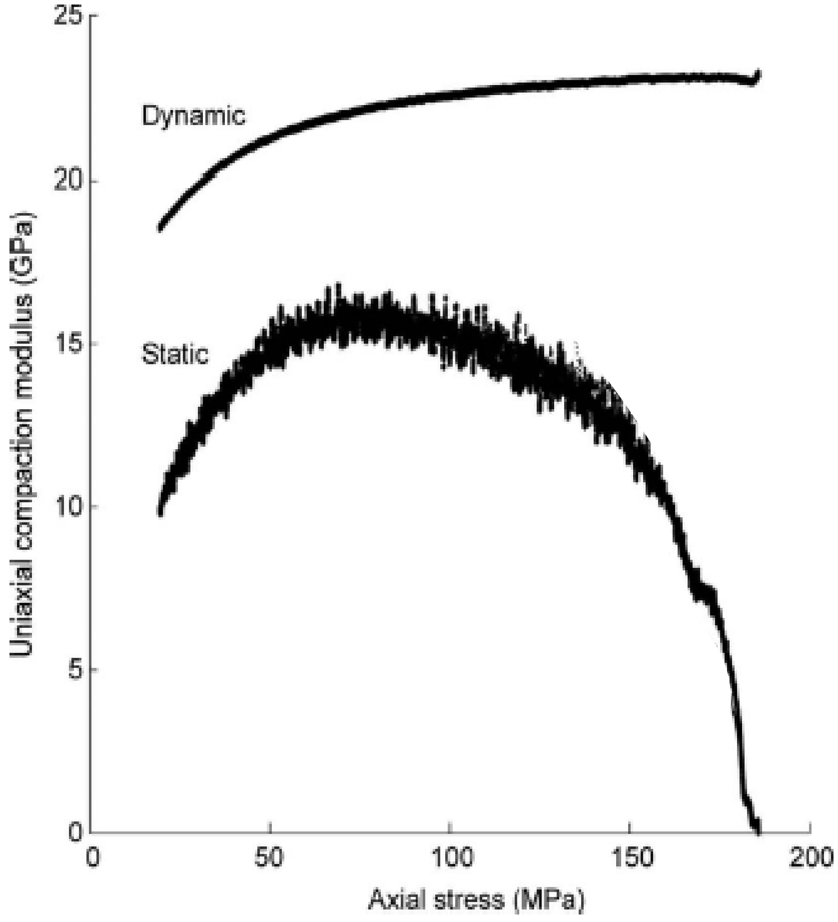
Measurements:

- Stress
- Strain
- Acoustic wave velocities

Enables simultaneous measurements of
- static moduli (slope of stress-strain curve)
- dynamic moduli (density x velocity^2)

Static and dynamic moduli of soft rocks are different.

The difference changes along the stress path.



Potential causes for the difference between static and dynamic moduli:

- Strain rate
- Rock volume involved
- Drainage conditons
- Anisotropy
- Non-elastic processes

Measures to isolate strain rate effects

1. Homogeneous rock

No wavelength effect

Same rock involed for both static and dynamic measurements

Potential causes for the difference between static and dynamic moduli:

- Strain rate
- ~~Rock volume~~ involved
- Drainage conditons
- Anisotropy
- Non-elastic processes

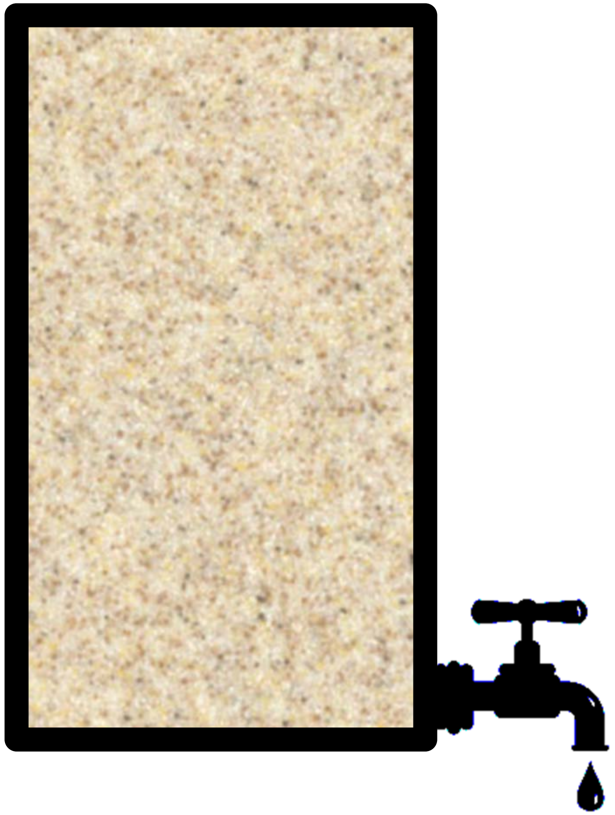
Measures to isolate strain rate effects

2. Consistent drainage conditions

Static moduli: usually drained

Dynamic moduli: undrained

$\Rightarrow$ dry, partially saturated, or undrained



Potential causes for the difference between static and dynamic moduli:

- Strain rate
- ~~Rock volume~~ involved
- ~~Drainage~~ conditons
- Anisotropy
- Non-elastic processes

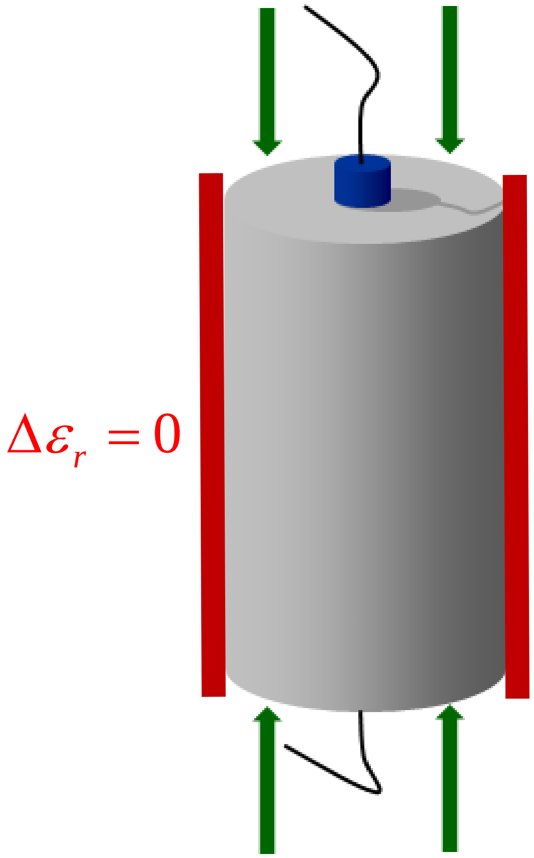
Measures to isolate strain rate effects

3. Stress path: K_0

Static modulus = slope of stress-strain curve: $$H = \frac{\Delta \sigma_z}{\Delta \varepsilon_z}$$

Dynamic modulus given by axial P-wave velocity: $$H_e = \rho V_P^2$$

$\Rightarrow$ Same modulus, static and dynamic



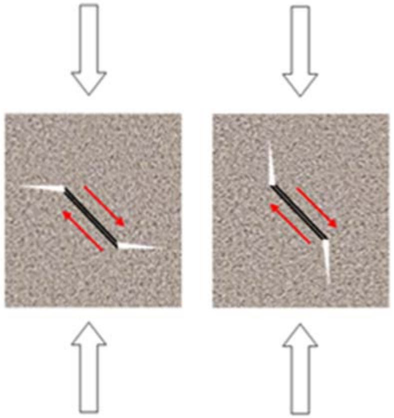
Potential causes for the difference between static and dynamic moduli:

- Strain rate
- ~~Rock volume~~ involved
- ~~Drainage~~ conditons
- ~~Anisotropy~~
- Non-elastic processes

Non-elastic processes causing differences between static and dynamic moduli in dry rocks:

Crushing of asperities at grain contacts or crack faces

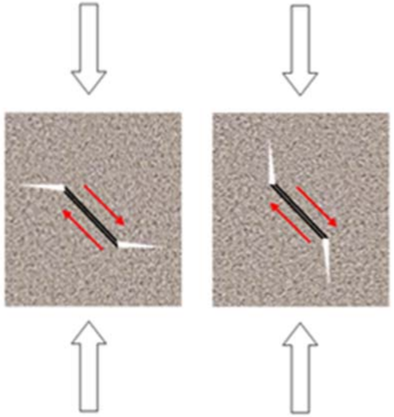
Occurs only during loading



Friction controlled shear sliding of closed cracks (accompanied by opening or closing of "wing cracks")

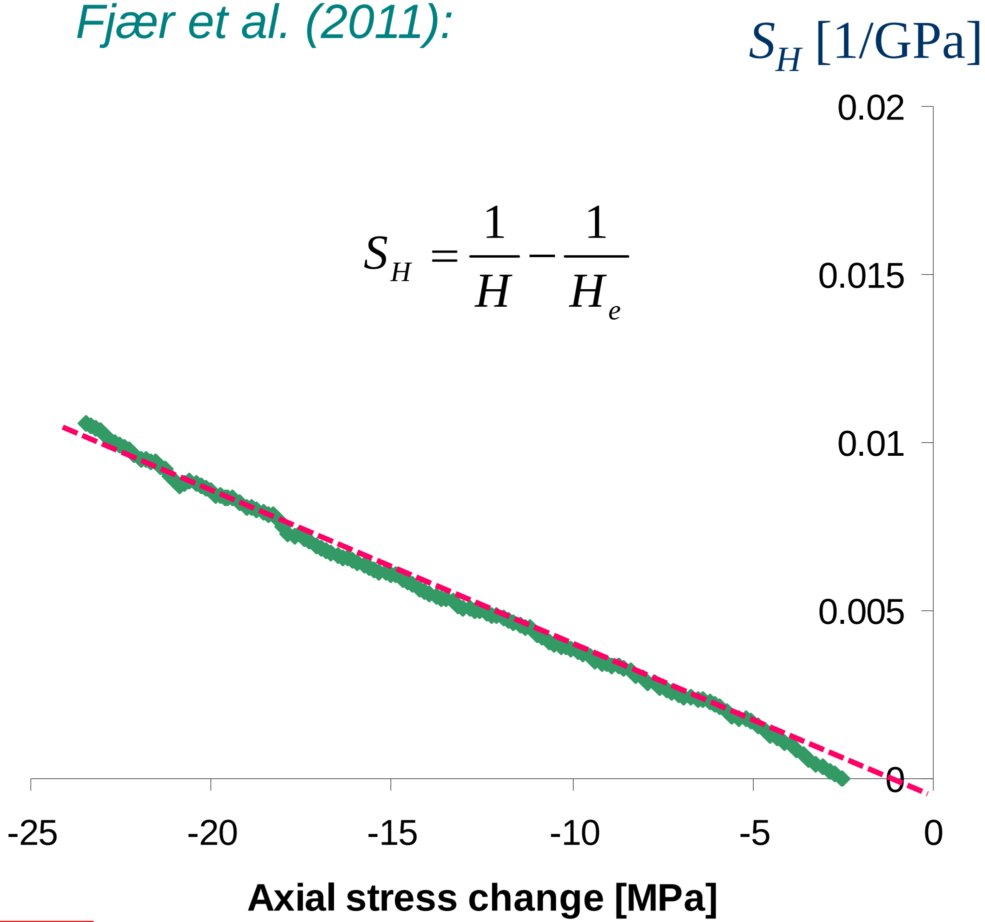
Occurs both during loading and unloading

Unloading:



Non-elastic processes

Fjær et al. (2011):



Observation:

Non-elastic compliance $S_H = \frac{1}{H} - \frac{1}{H_e}$

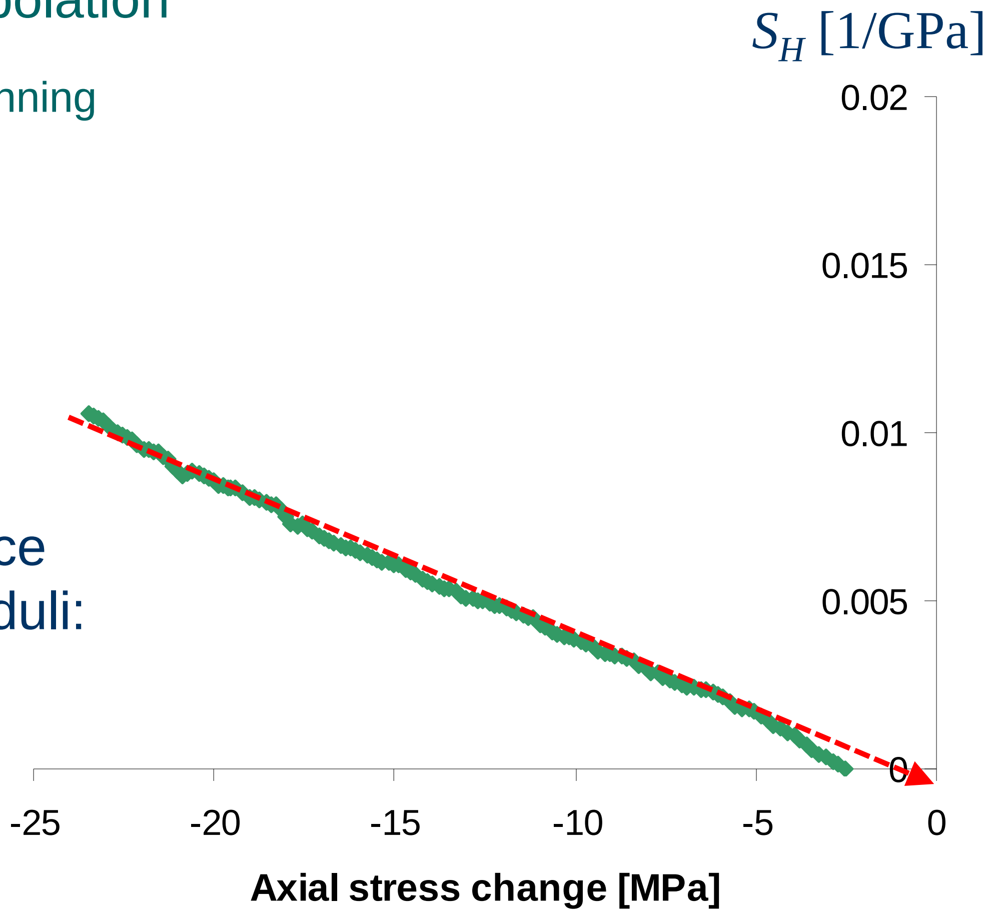
increases linearly with decreasing stress

Measures to isolate strain rate effects

4. Unloading & backwards extrapolation

Linear extrapolation towards the beginning
of the unloading path eliminates
non-elastic contributions

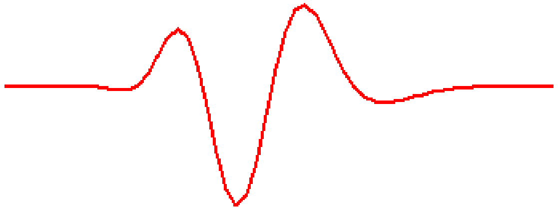
$\rightarrow H^{tp}$



Potential causes for the difference between static and dynamic moduli:

- Strain rate
- ~~Rock volume involved~~
- ~~Drainage conditons~~
- ~~Anisotropy~~
- ~~Non-elastic processes~~

Strain rate



Average strain rate for
dynamic measurements:

$$\langle \dot{\varepsilon} \rangle = 4 f \Delta\varepsilon$$

$\Delta\varepsilon \sim 10^{-7}$ = strain amplitude

$f = 5 \cdot 10^{5}\ \mathrm{Hz}$ = frequency

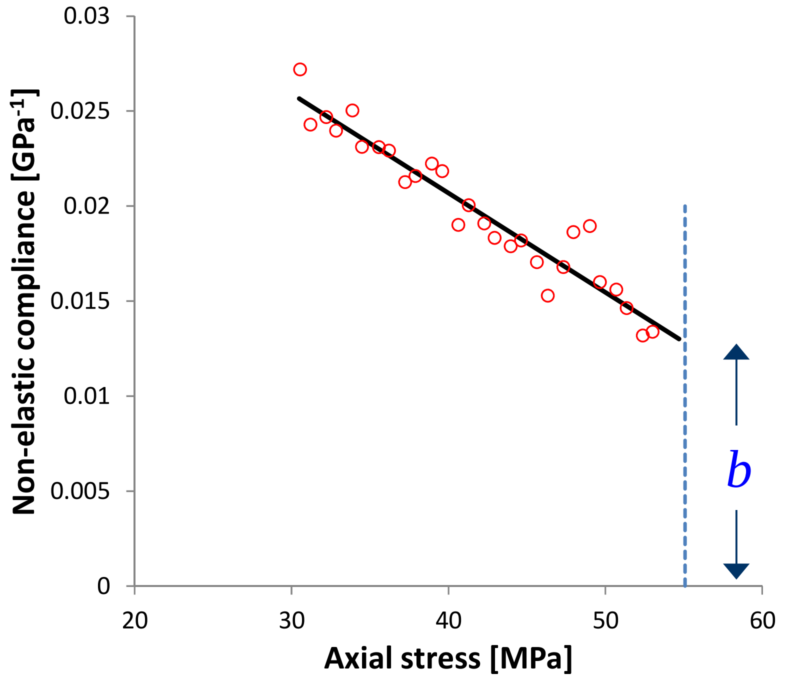
$$\Rightarrow \langle \dot{\varepsilon} \rangle \approx 10^{-1}\ \mathrm{s}^{-1}$$

Mancos shale

Partly saturated,
with 13% illite/smectite,
5% kaolinite, etc.

– probably significant dispersion

$$V_{\mathrm{P,Low}} = \frac{V_{\mathrm{P,High}}}{\sqrt{1 + b\rho V_{\mathrm{P,High}}^2}}$$



Main sources of uncertainty:

ΔC_{33} (static stiffness)
– related to stress and strain measurements

$\Delta V_{P,High}$ (ultrasonic velocity)
– related to ~~calibration~~ and traveltime measurements

Δb (linear trendline parameter)
– related to fluctuations in the non-elastic compliance

$\Delta \rho$ (density)
– related to weight and volume measurements

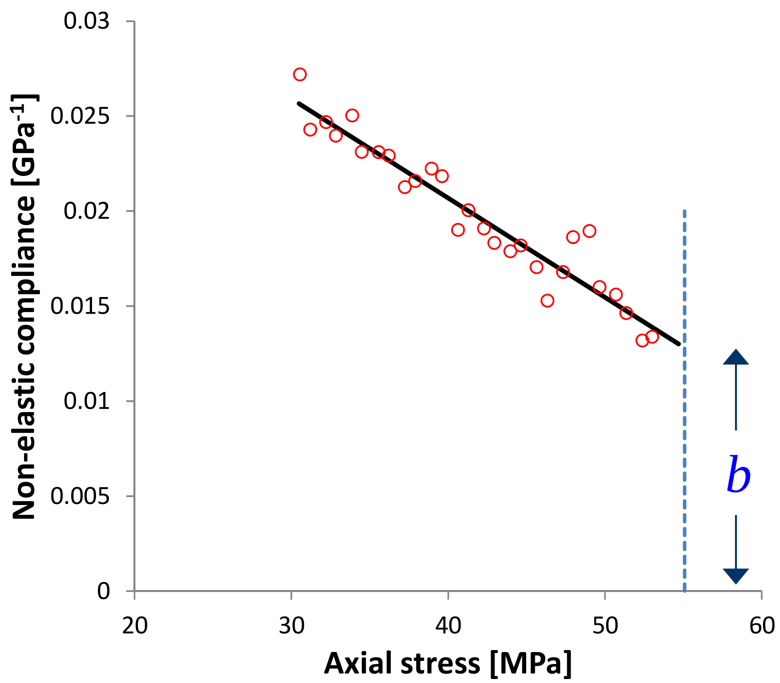
Comparing
repeated measurements

Mancos shale

Partly saturated,
with 13% illite/smectite,
5% kaolinite, etc.

– probably significant dispersion

$$V_{\mathrm{P,Low}} = \frac{V_{\mathrm{P,High}}}{\sqrt{1 + b\rho V_{\mathrm{P,High}}^2}}$$



σ_z MPa	σ_r MPa	b 10^{-4} GPa^{-1}	$V_{\mathrm{P,High}}$ m/s	$V_{\mathrm{P,High}} - V_{\mathrm{P,Low}}$ m/s
55	18	129 ± 12	4 163 ± 42 (± 8)	846 ± 148 (± 114)

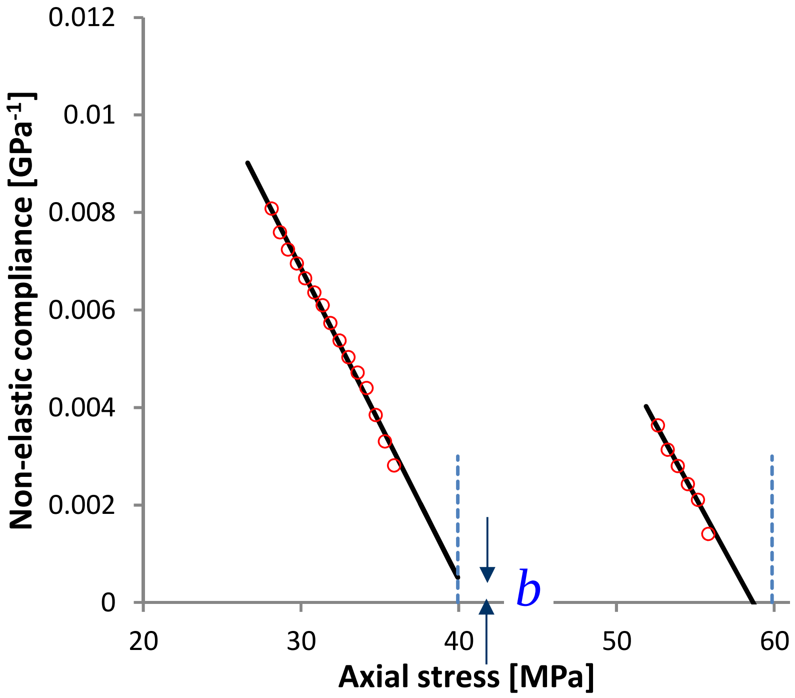
Significant dispersion, far beyond the resolution limit for the method

Castlegate sandstone

Dry, clay free

– presumably no significant dispersion

$$V_{\mathrm{P,Low}} = \frac{V_{\mathrm{P,High}}}{\sqrt{1 + b\rho V_{\mathrm{P,High}}^2}}$$



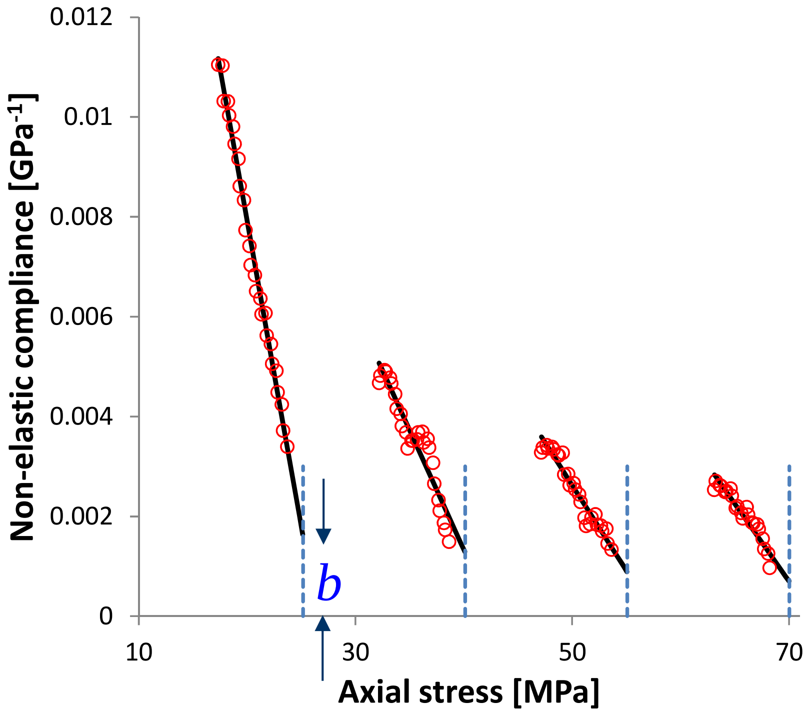
No measurable dispersion

Berea sandstone

Dry, 8% clay

– possibly some dispersion

$$V_{\mathrm{P,Low}} = \frac{V_{\mathrm{P,High}}}{\sqrt{1 + b\rho V_{\mathrm{P,High}}^2}}$$

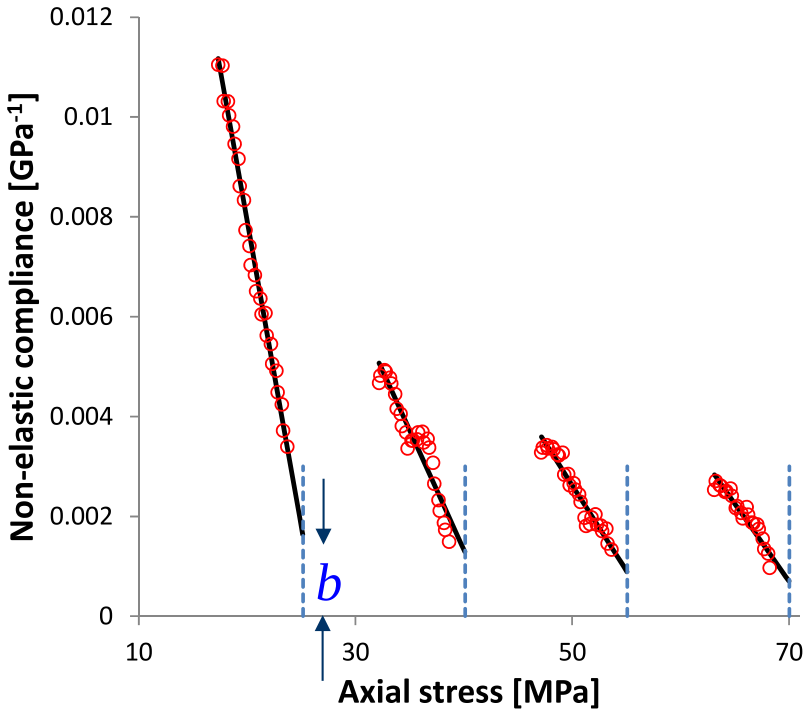


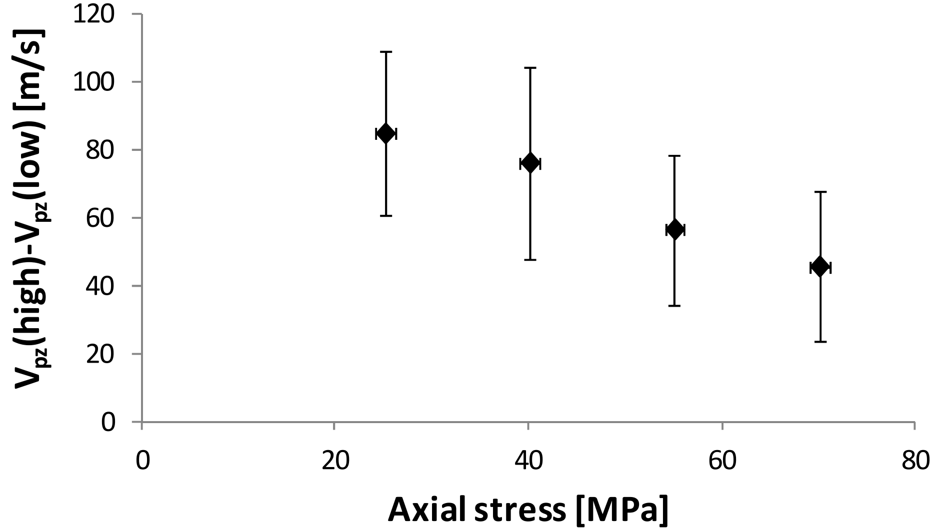
Berea sandstone

Dry, 8% clay

– possibly some dispersion

$$V_{P,Low} = \frac{V_{P,High}}{\sqrt{1 + b\rho V_{P,High}^2}}$$





Significant, measurable dispersion, decreasing with increasing stress

Conclusions:

- We argue that velocity dispersion between ultrasonic and seismic frequencies can be estimated from a standard rock mechanical test with acoustic velocity measurements.

- The demand for accuracy is not extreme. Standard, good quality measurements is sufficient.

- Application of this method on two sandstone and one shale sample indicates that dispersion increases with clay content and decreases with stress. Intrinsic dispersion associated with clay, and patchy saturation, are potential causes.

Acknowledgements

The first author wishes to thank Petrobras (CENPES) and PUC-Rio for all support, including funding, during a sabbatical year in Rio de Janeiro when this study was accomplished.

The experimental data presented here originates from Strategic Institute Programs funded by the Norwegian Research Council (Geomechanical Data) and by SINTEF (Gas Shales for Exploration and Exploitation).