ROSE Meeting 23-24 April 2012

Static and dynamic moduli, dispersion and brittleness of shales and shale wannabes

Rune M Holt, NTNU & SINTEF

With contributions from Andreas Bauer, Erling Fjær, Olav-Magnar Nes & Jørn F Stenebråten; SINTEF

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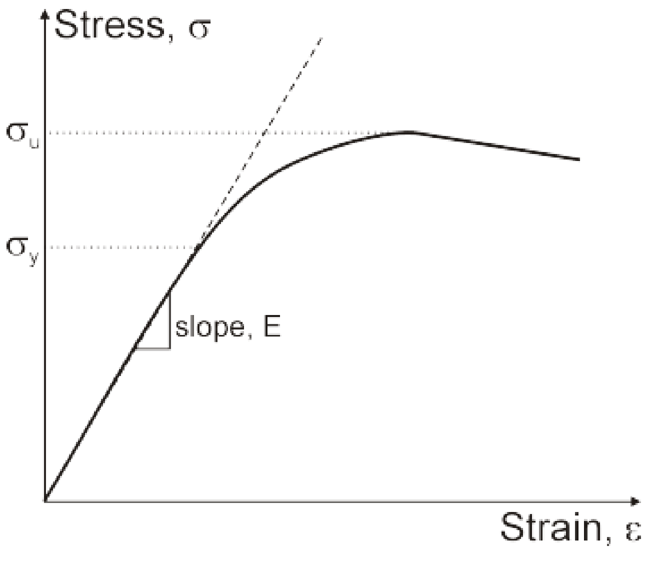
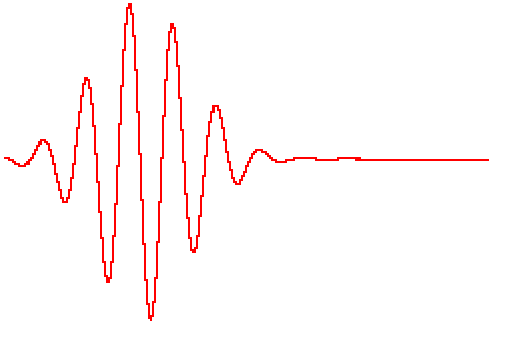
Static & Dynamic Moduli

- (Quasi-) Static modulus given by the slope of a stress-strain curve



- Dynamic modulus = ρv^2 given by the bulk density ρ and the wave speed v



For uniaxial strain, the static modulus $H=d\sigma_z/d\varepsilon_z$ should be equal to ρv_P^2

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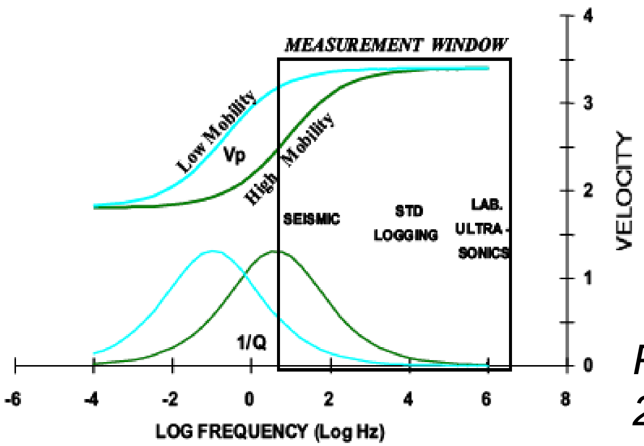
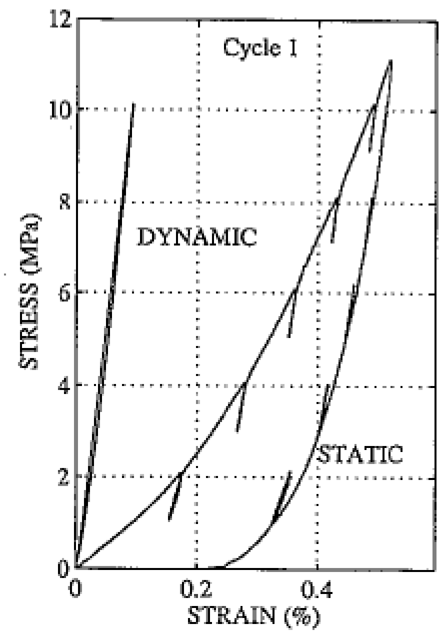
Static & Dynamic Moduli

- Sources of discrepancy:
  - Different strain amplitudes: Nonlinear effects & Plasticity
  - Different frequencies: Dispersion



From M. Batzle et al., 2005

Plona & Cook, 1995: Castlegate sandstone (dry)



Static & Dynamic Moduli: Motivation

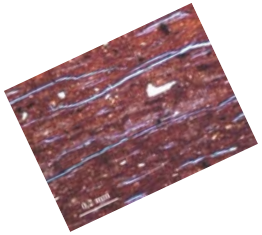
Static mechanical behaviour of shales needed for

- Borehole stability assessment (strength, plasticity)
- Overburden characterization (Cap rock seal; Leakage / fault reactivation / fracturing associated with depletion / injection)
- (Gas) Shale reservoir stimulation: Where to fracture ("Fracability" - Brittleness / Fracture toughness); Where do fractures go?

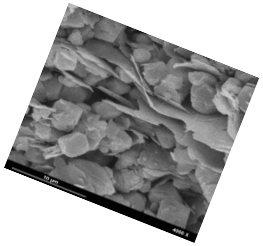
Can static properties be estimated from seismic / log measurements?

Shale

- Multiple uses of shale ⇔ Multiple definitions!
  - Geologically:
    - ✓ A fine-grained sedimentary rock formed by compaction of silt and clay minerals, exhibiting fissility & lamination
  - Rock mechanically:
    - ✓ Clay minerals should constitute a load-bearing framework

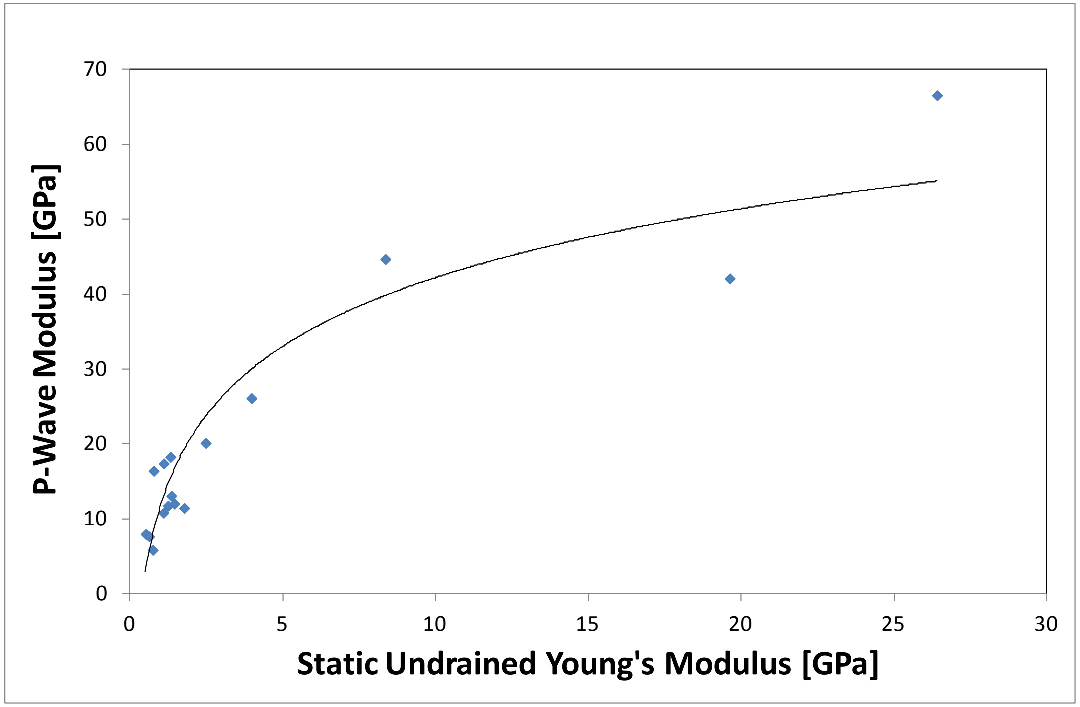


  - Gas shales:
    - ✓ Low permeability (source) rock; preferrably black…
- In practice: User-defined definition, but the user should explain which definition is used…
- Here:
  - Overburden shales from Borehole stability JIPs in the 90'ies
  - Pierre Shale (20 – 25% porosity, 40-60% clay)
  - Mancos Shale (6-8 % porosity, 20-25 % clay)



Correlation between Static & Dynamic Moduli

- Using a random selection of old CU 3axial tests with overburden Northe Sea shales (+ Pierre & Mancos)
- Notice: Usually only P-wave velocity was measured



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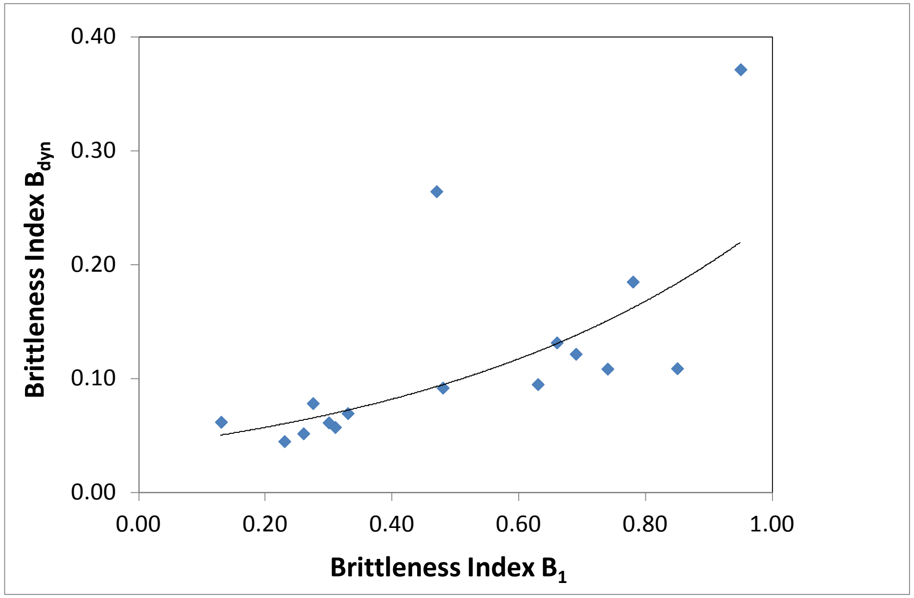
Brittleness from dynamic modulus?



$$B_1 = \frac{\varepsilon_{el}}{\varepsilon_{tot}}$$

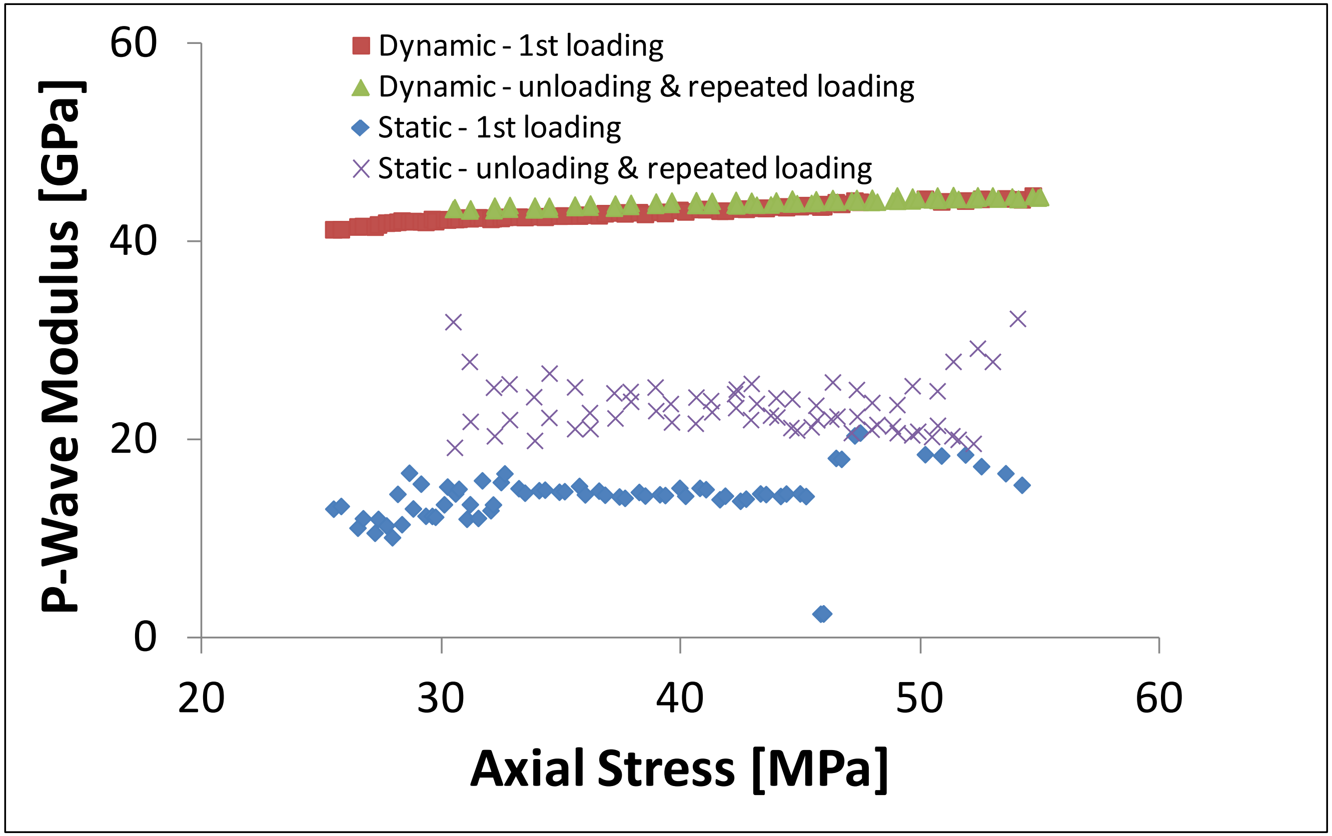
B_1 is taken from the shape of the static stress-strain curves

- ”Brittleness” is a key in describing the ability of shale to fracture

- There are 20+ definitions of ”brittleness” in the literature…

- If based on ”lack of plasticity” (B_1), the static – dynamic correlation enables a dynamic brittleness index B_{dyn} to be estimated only from the P-wave modulus

Direct comparison
Static *vs*. Dynamic Moduli



Uniaxial strain test with Mancos Shale:

Static drained uniaxial compaction modulus: 15 – 20 GPa (20-25 GPa during unloading)

Ultrasonic P-Wave modulus:
>40 GPa

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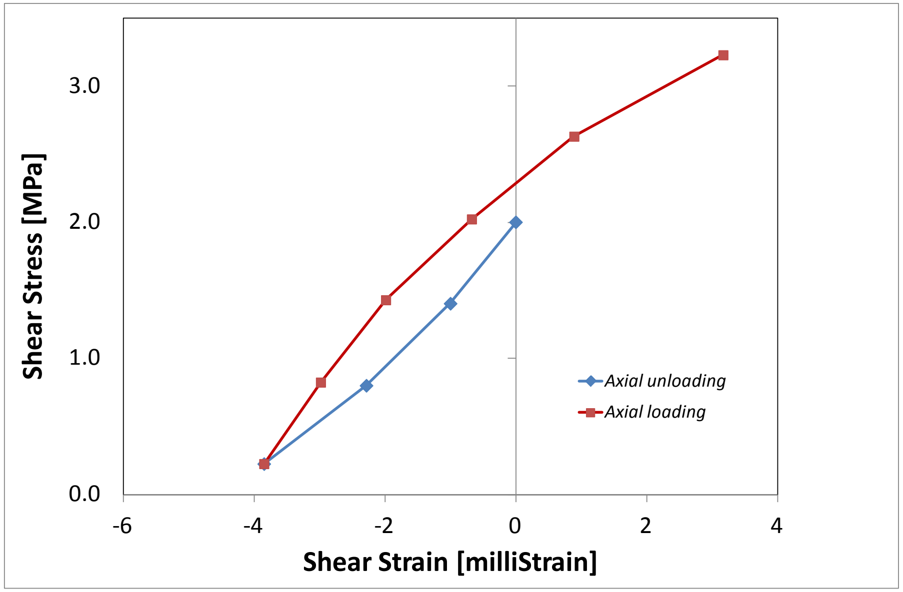
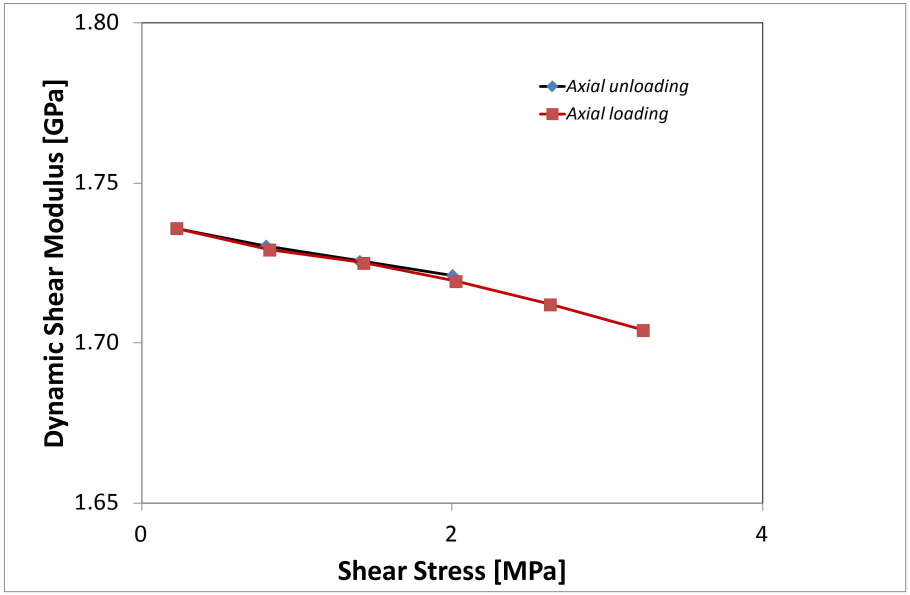
Direct comparison
Static *vs*. Dynamic Moduli





Undrained Constant Mean Stress test with Pierre Shale:

Static Shear Modulus $G_{fr,stat}$ ~ 0.4 GPa
Dynamic Shear Modulus $G_{fr,dyn}$~ 1.7 – 1.8 GPa (v_S ~ 860 m/s)

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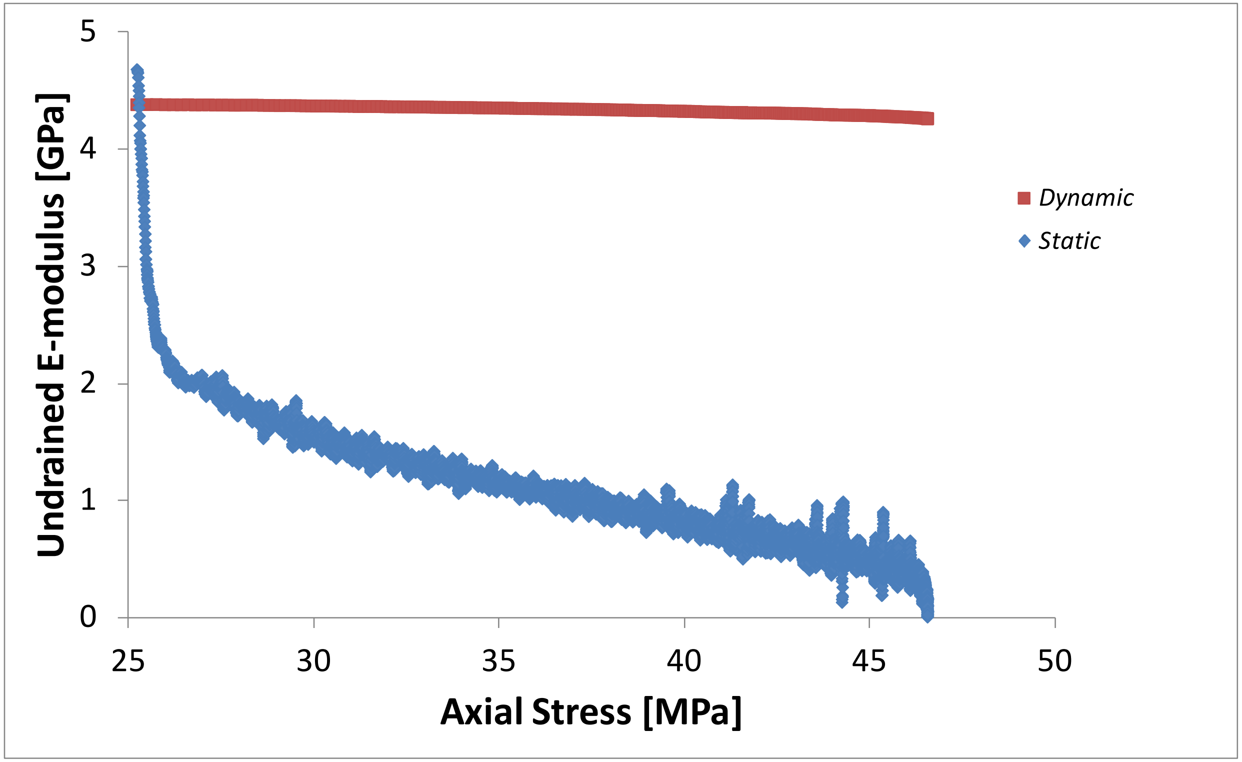
Direct comparison Static *vs*. Dynamic Moduli



Undrained 3axial test with Pierre Shale

Dynamic modulus estimated from axial P- & S-wave velocities (neglecting anisotropy)

Undrained static modulus decays towards failure

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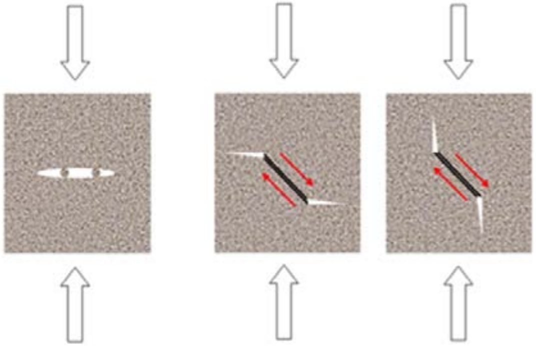
Static & Dynamic Moduli

If we wish to apply this in the field, a fundamental understanding of the static – dynamic discrepancy is required.



Strain amplitude effects (dominant in soft sandstones):

- Grain contact plastification
- Sliding cracks

Possible dispersion mechanisms in shale:

- Patchy saturation due to heterogeneity or partial saturation
- Intrinsic attenuation caused by bound water associated with clay minerals
- NOT squirt or Biot flow in the traditional sense…

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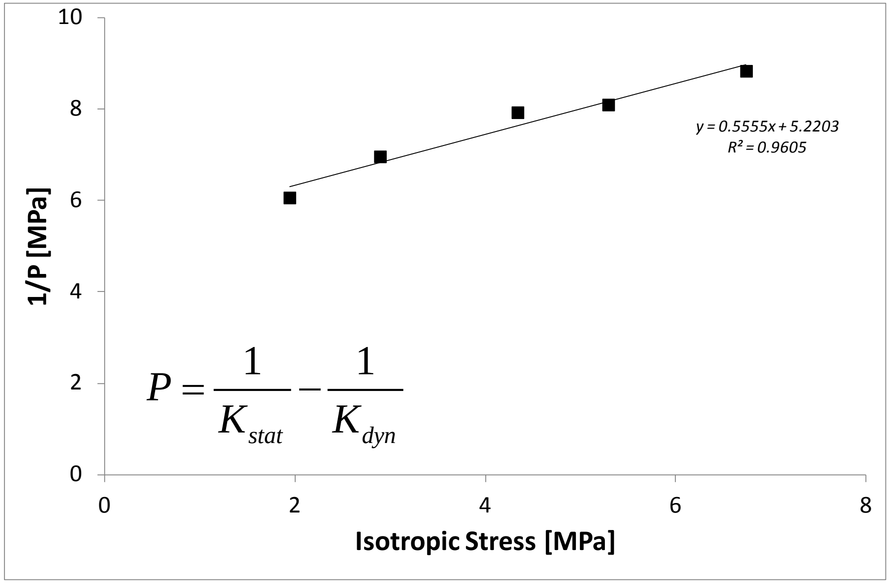
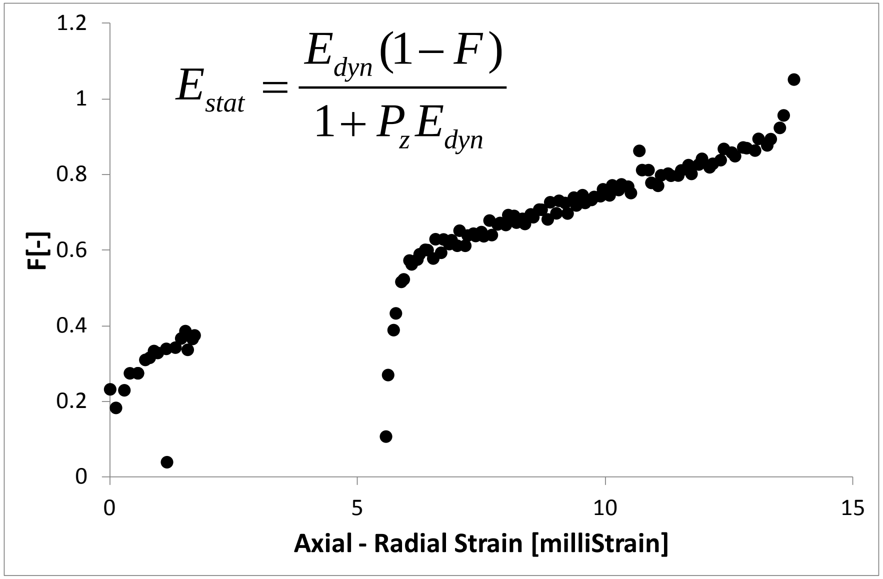
Strain amplitude effects in shale

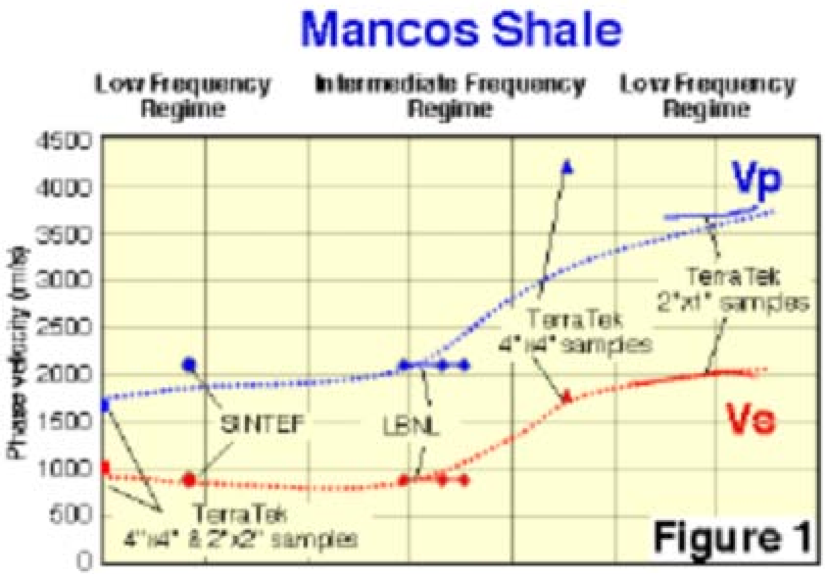




From a triaxial test, the dependence of P and F *("Petroleum Related Rock Mechanics" by Fjær et al., 2008)* on stress and strain as observed in Mancos Shale is resemblant to that seen in soft sandstones =>

Strain amplitude correction for shale may be performed in a similar way

Dispersion in shale



From Suarez-Rivera et al., 2001

Mancos Shale was found to exhibit strong P-wave dispersion (close to 40 %) by Suarez-Rivera *et al*. (2001)

Sarker & Batzle (2010) observed no dispersion in Mancos saturated with decane.

Several other shale measurements indicate various degrees of dispersion (Duranti *et al*., 2005; Hofmann, 2005).

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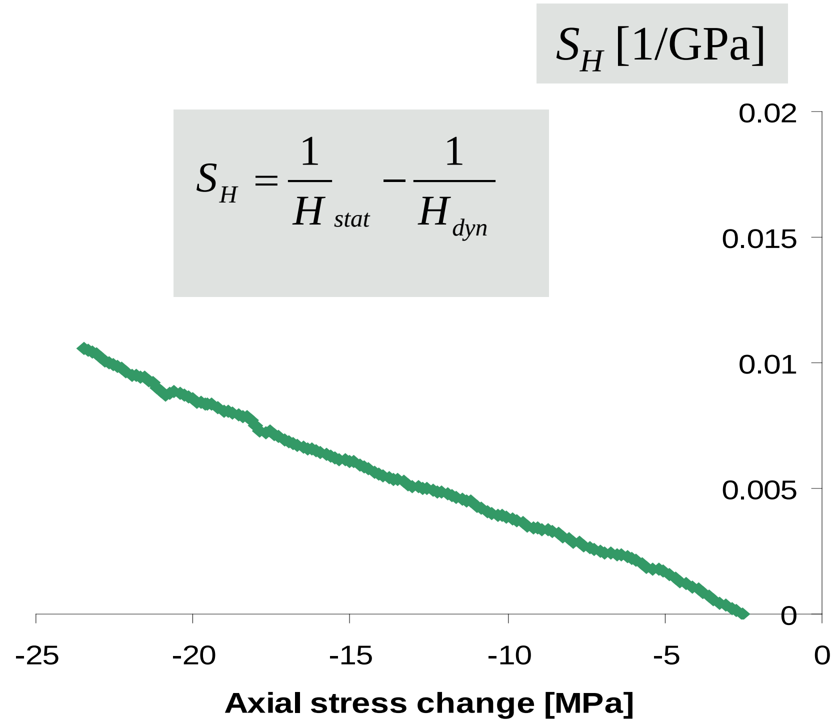
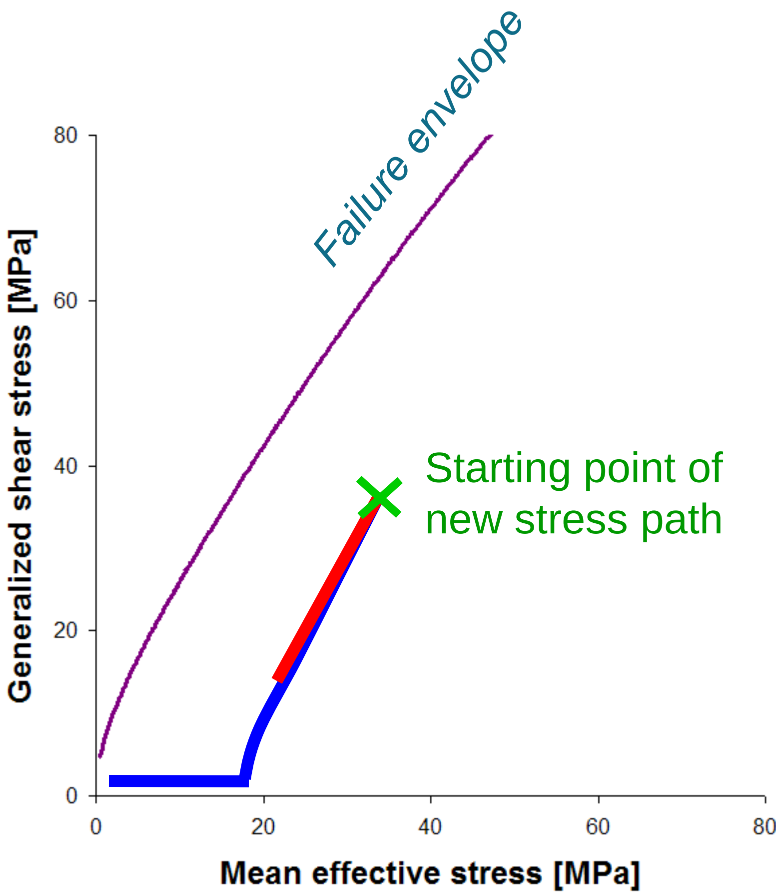
Dispersion from static tests





At the start of the unloading stress path:

- No compaction, so no grain contact plastification
- No internal surface sliding before static friction is overcome

=> Extrapolation of the difference between static and dynamic compliances to the turning point of the stress path provides an estimate of the elastic modulus at a frequency given by the strain rate

Fjær et al., ARMA (2011; 2012):

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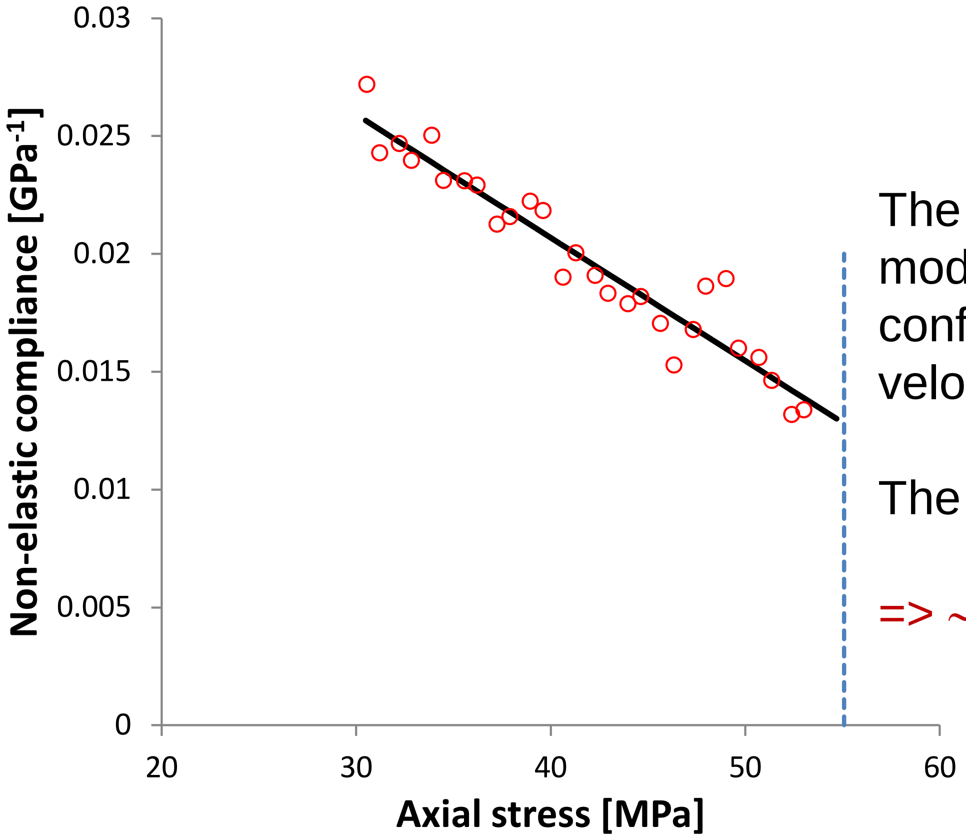
Mancos shale (outcrop), 8% porosity, 24% clay, not fully water saturated

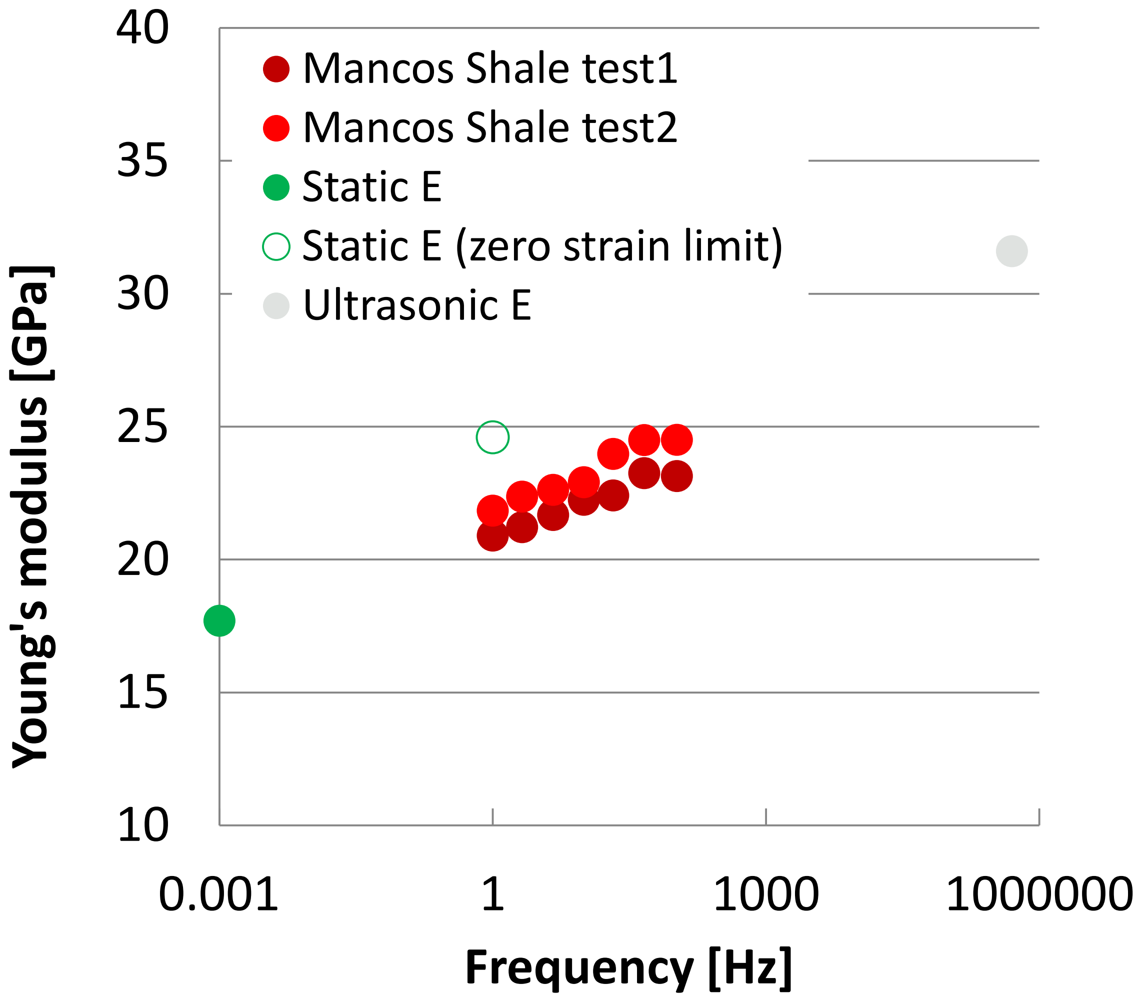


The extrapolated elastic uniaxial compaction modulus estimated at 55 MPa axial (& 18 MPa confining) stress corresponds to a P-wave velocity of ~ 3315 m/s at 1 Hz frequency.

The ultrasonic v_P is ~ 4165 m/s at 500 kHz

=> ~ 25 % velocity dispersion

Dispersion from dynamic tests



Measured at ambient conditions in SINTEF's Low Frequency Quasi-Static set-up

Strain amplitude ~ 10^{-6}

Confirms dispersion in Mancos shale

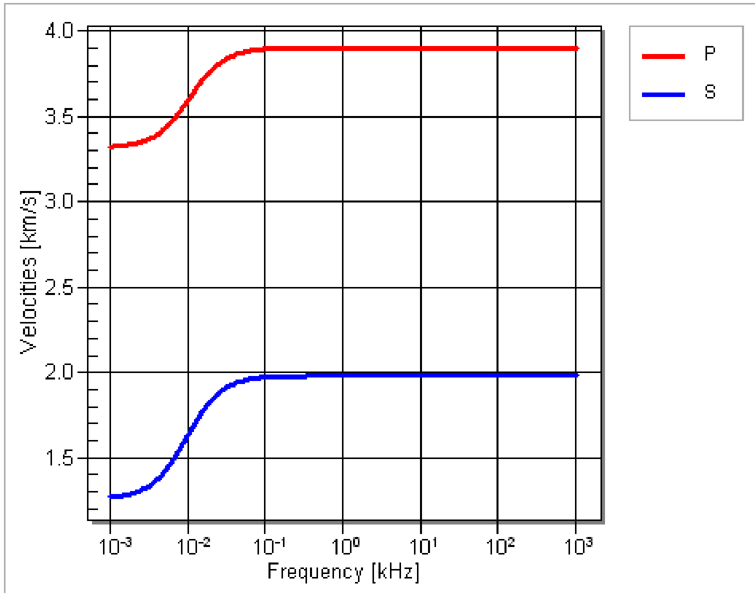
Dispersion mechanisms in shale

Intrinsic dispersion due to bound water?

Modelled by introducing bound water in a rock physics model for clay & shale (Holt & Fjær, 2003)

Complex shear stiffness of bound water controls dispersion; viscosity controls the transition frequency (here: 10^8 Pa·s)

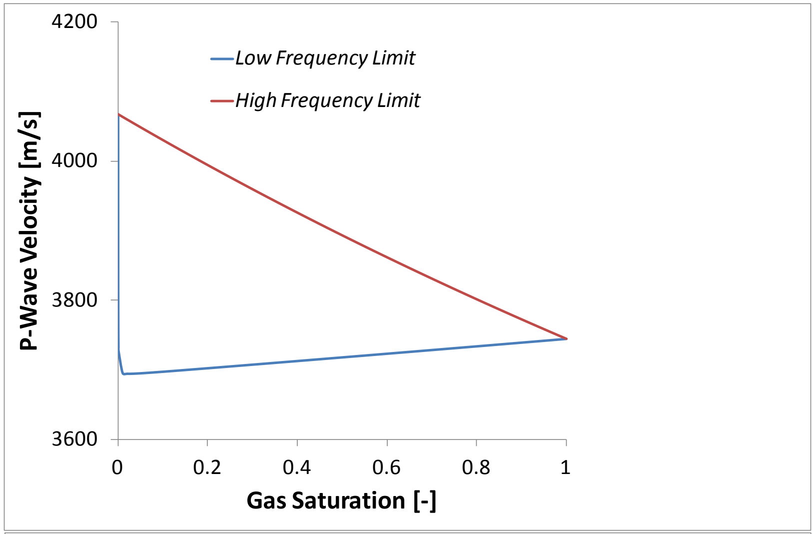
This dispersion mechanism should be most prominent in high clay content & smectite rich shales

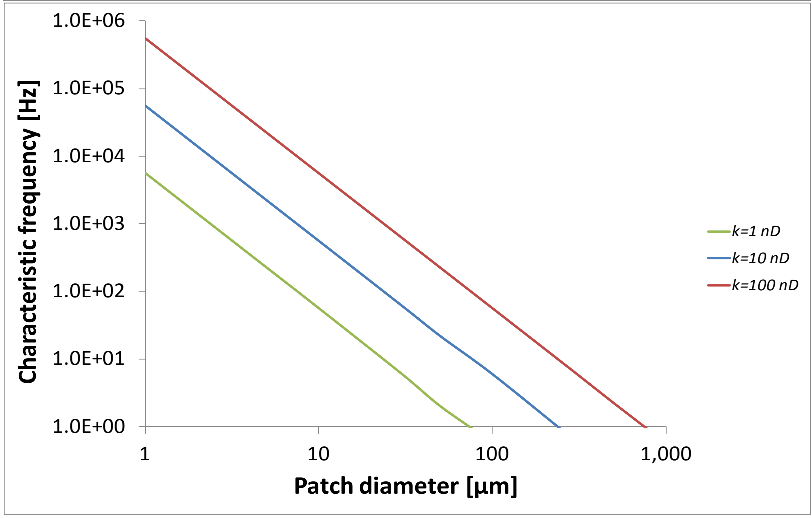


Dispersion mechanisms in shale

Patchy saturation in not fully saturated shales

- Model of White / Dutta-Ode (from Mavko *et al.*)
  - Gas bubbles surrounded by water shell – ”Patch size here refers to water domain
- ”Fitted” to Mancos kind of shale
- Transistion frequency between seismic and ultrasonic for patch size < 100 µm at 10 nD permeability
- May explain variability in lab data reflecting unknown saturation
- Largest dispersion near full saturation





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Concluding remarks

- Dynamic moduli by far exceed static moduli in shales
- Strain amplitudes and Frequency dispersion may be equally important sources of the difference
- Apparent correlation may be improved by dedicated calibration study
- Challenges:
  - Quantification of saturation and saturation distribution
  - Time-consuming tests (in fully saturated shales) & sample quality

Acknowledgement

- Most of this work has been performed as part of the Gas Shale Strategic Program at SINTEF Petroleum Research
- Mutual inspiration with the ROSE program at NTNU

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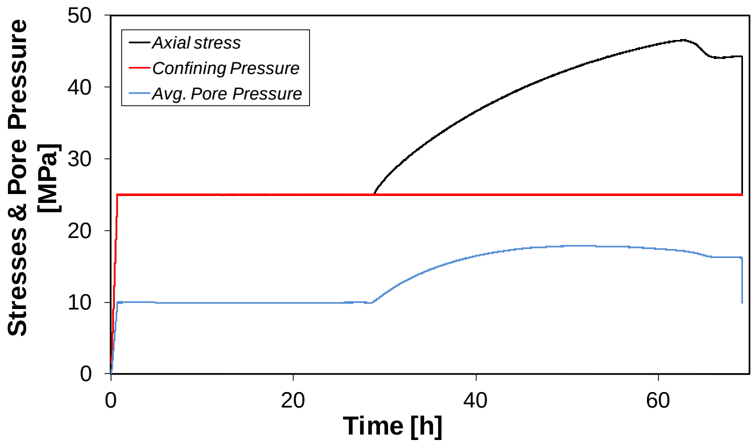
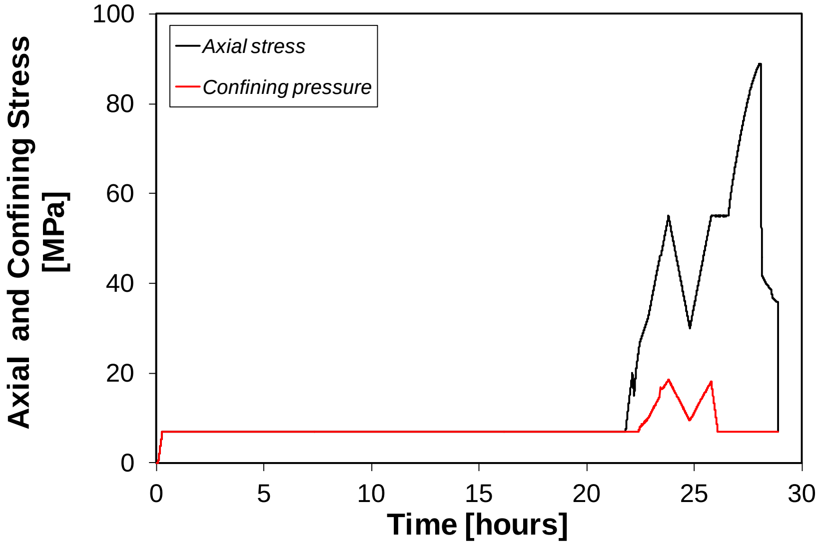
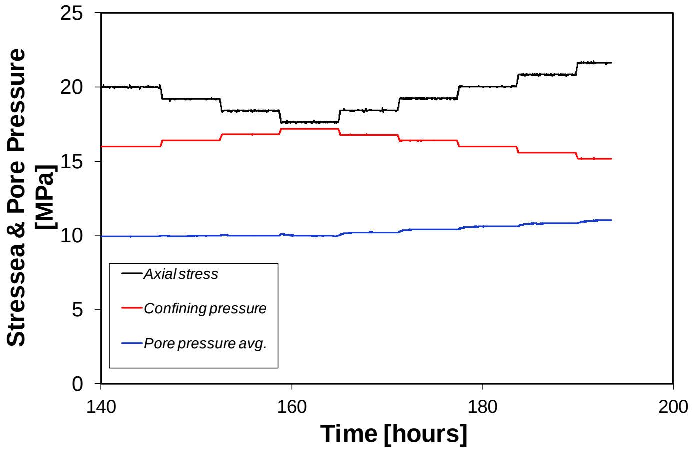
Laboratory procedures



CU 3ax with Pierre Shale
(+ overburden shales)



Drained 3ax + K_0 test with Mancos Shale
(NOT fully water-saturated)



Undrained Constant mean Stress
(”ISSP”) with Pierre Shale

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