ROSE meeting
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Relating static and dynamic stiffness of shales: effects of frequency and stress

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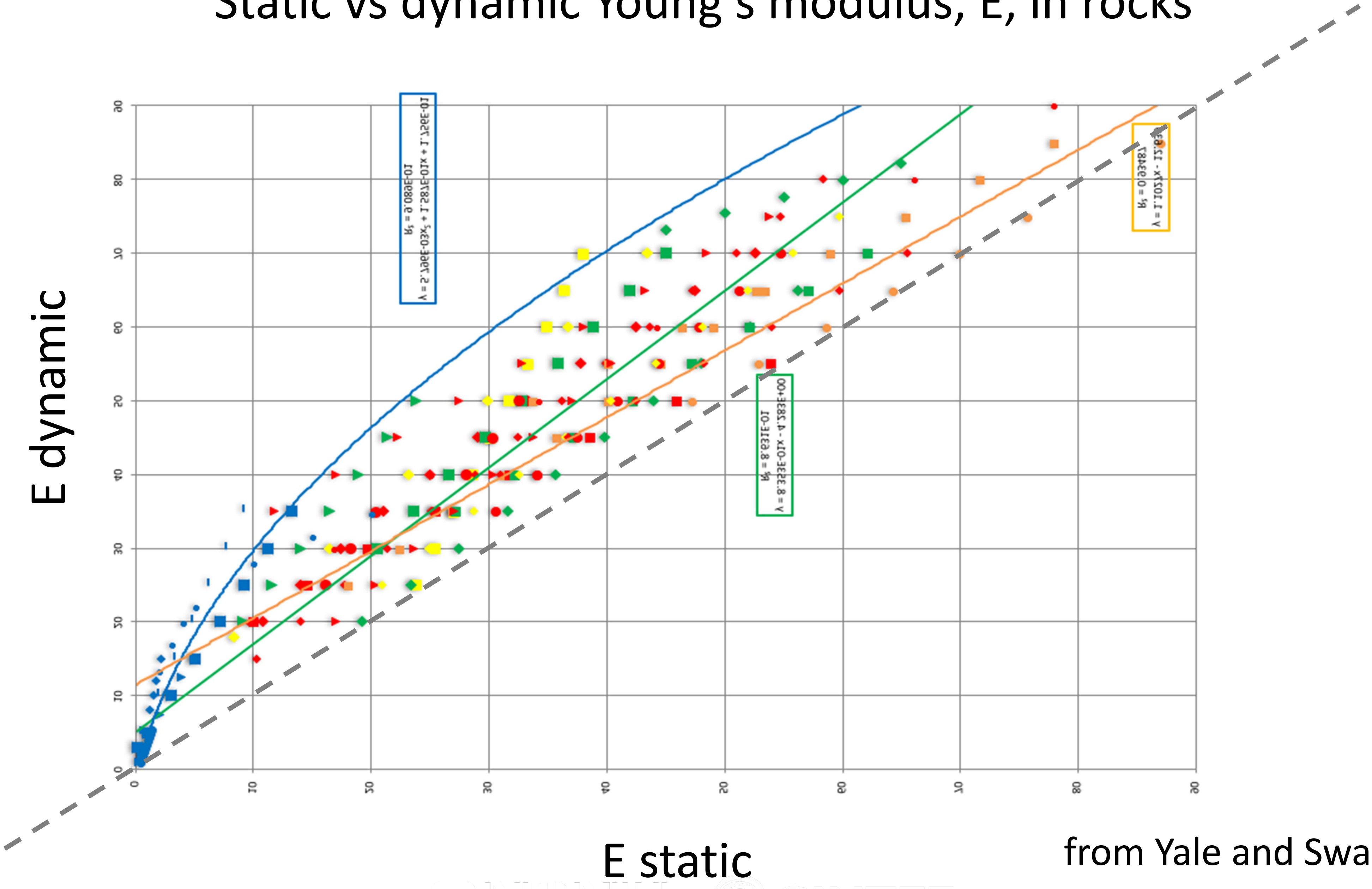
Motivation

Static vs dynamic Young's modulus, E, in rocks



from Yale and Swami (2017)
ARMA 17-0644

Elastic media:

- Stiffness <u>does not</u> depend on frequency or stress amplitude
- Static stiffness = dynamic stiffness

Rocks are not elastic media

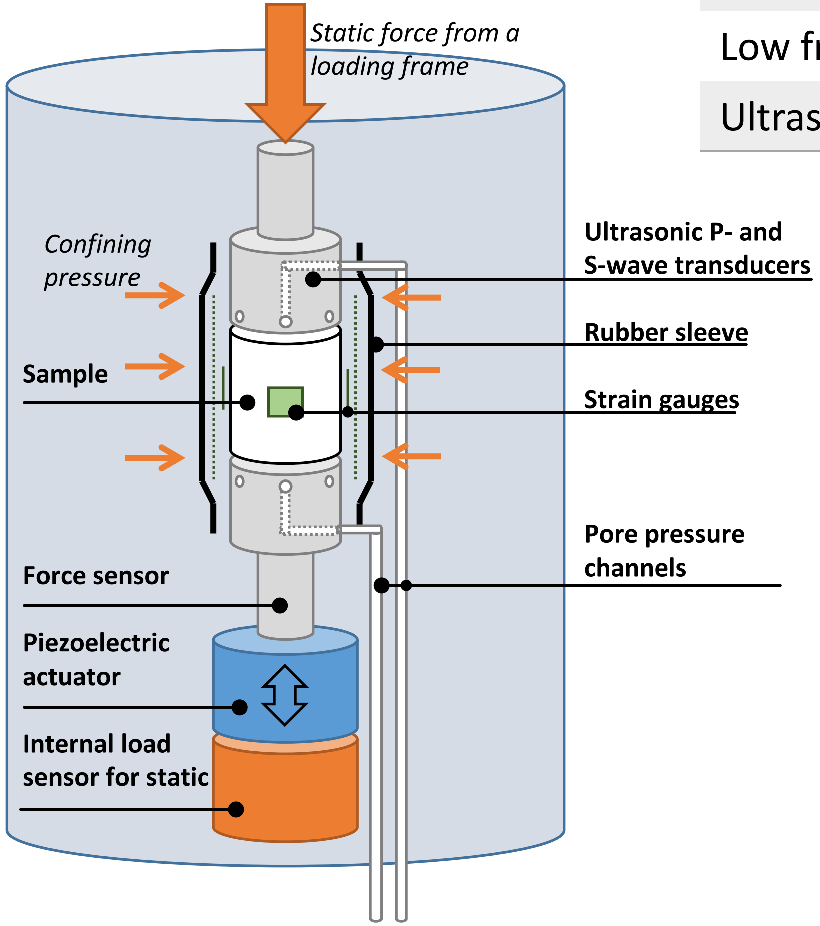
- Static stiffness $\neq$ dynamic stiffness

Main reasons:

- Static stiffness is often drained, but dynamic is undrained
- Static stiffness depends on stress amplitude (order of MPa), while dynamic is in elastic regime
- Stiffness is dependent on stress rate (frequency dispersion)

Research methodology

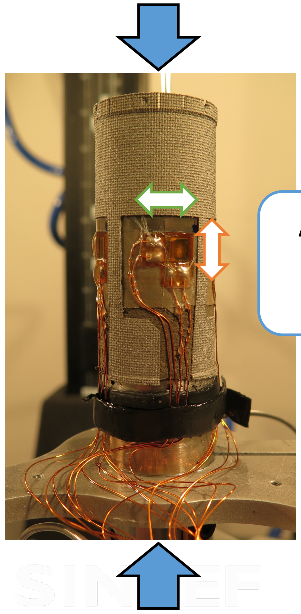
Low frequency apparatus



Measurement	Measured parameters	Frequency	Strain amplitude
Static (undrained)	Young's modulus, E Poisson's ratio, ν	Corresponds to ~0.5 Hz	Up to order of 10^{-3} m/m
Low frequency	E, ν	0.5-150 Hz	$\leq 10^{-6}$ m/m
Ultrasonic	P- and S-wave velocities	500 kHz	~10^{-10} m/m

Low frequency measurement technique

Axial stress (σ_{ax}) modulations are applied



Axial (ε_{ax}) and radial (ε_{rad}) strains are recorded

$$E_{dyn} = \frac{\sigma_{ax}}{\varepsilon_{ax}};$$

$$\nu_{dyn} = \frac{\varepsilon_{rad}}{\varepsilon_{ax}}$$

Linking velocities to engineering parameters

Stiffness matrix for TI medium (e.g. shales)

$$\begin{pmatrix} C_{11} & C_{11}-2C_{66} & C_{13} & 0 & 0 & 0 \\ C_{11}-2C_{66} & C_{11} & C_{13} & 0 & 0 & 0 \\ C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{pmatrix}$$

5 independent constants

$$C_{33} = E_V(1-\nu_{HH}^2)\Lambda$$

$$C_{44} = \left(\frac{4}{E_{45}} - \frac{1}{E_V} - \frac{1}{E_H} + \frac{C_{13}}{(C_{11}-C_{66})C_{33}-C_{13}^2}\right)^{-1}$$

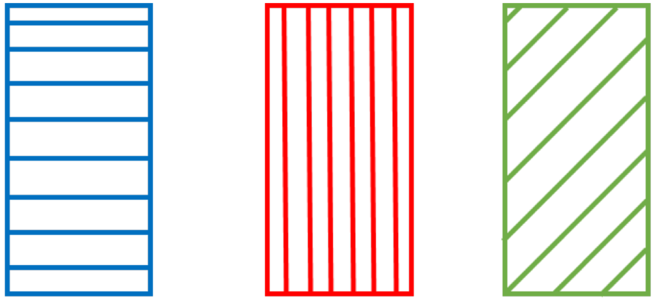
$$C_{11} = E_H(1-\nu_{HV}\nu_{VH})\Lambda$$

$$C_{66} = E_H / 2(1+\nu_{HH})$$

$$C_{13} = E_H\nu_{VH}(1+\nu_{HH})\Lambda$$

$$\Lambda = \left(1-\nu_{HH}^2 - 2\nu_{HV}\nu_{VH} - 2\nu_{HV}\nu_{VH}\nu_{HH}\right)^{-1}$$

Ultrasonic measurement: V_{P0}, V_{S0} V_{P90}, V_{S90} V_{P45}



Low frequency measurement: E_V, ν_{VH} E_H, ν_{HV}, ν_{HH} E_{45}

$$\rho v_{PV}^2 = C_{33}$$

$$\rho v_{PH}^2 = C_{11}$$

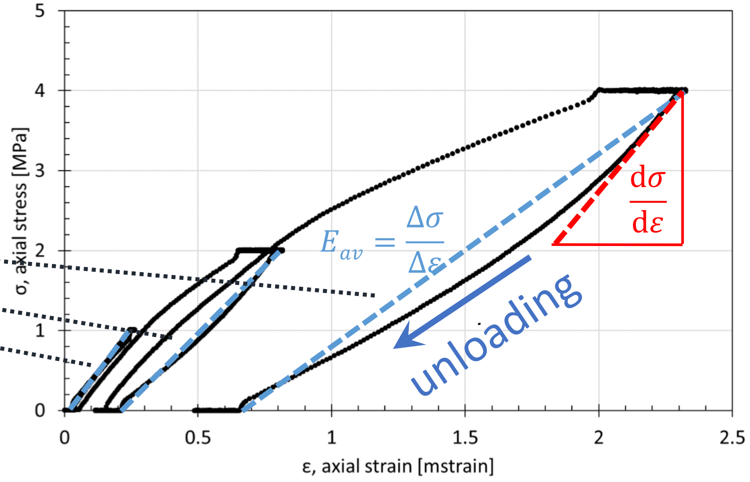
$$\rho v_{SV}^2 = C_{44}$$

$$\rho v_{SH}^2 = C_{66}$$

Results

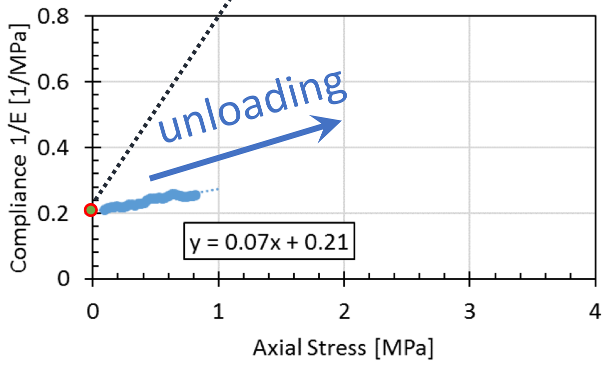
Stress amplitude effect on stiffness
Opalinus Clay is highly non-elastic

	E [GPa]		
	(1MPa)	(2MPa)	(4MPa)
Average Stress-strain slope	4.3	3.3	2.3
Zero-strain extrapolation	4.8	5.0	4.8

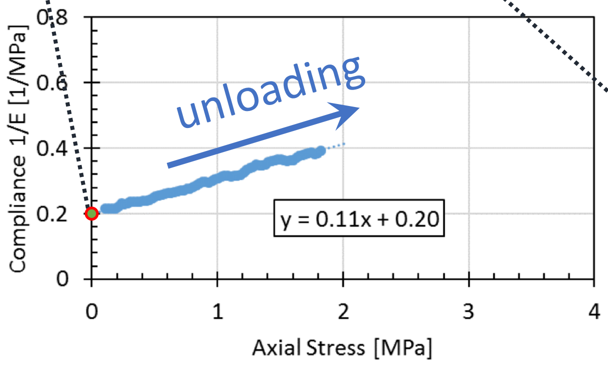


Stress amplitude:

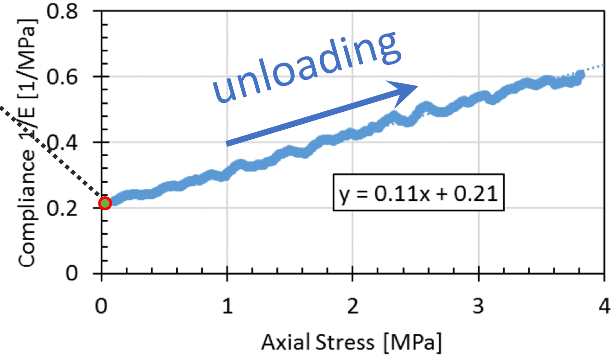
$\Delta\sigma_{ax}$: 1 MPa



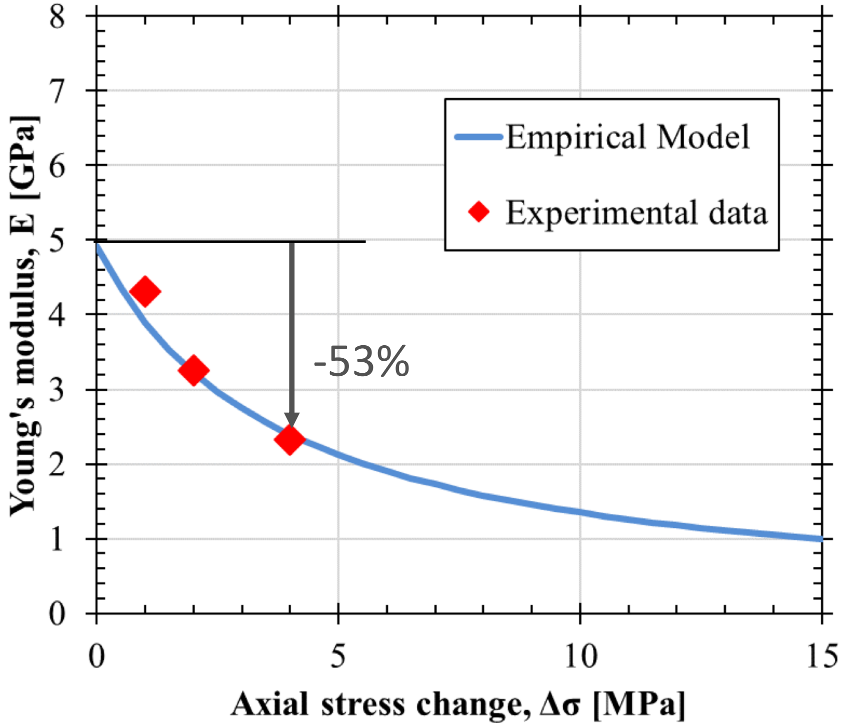
$\Delta\sigma_{ax}$: 2 MPa



$\Delta\sigma_{ax}$: 4 MPa

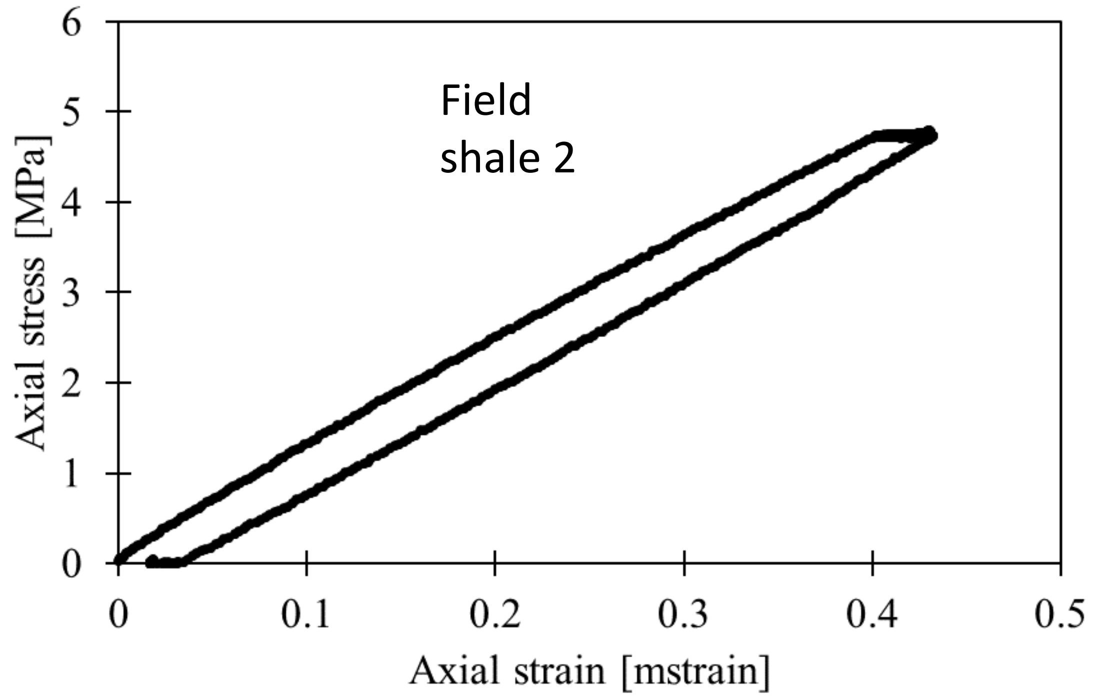


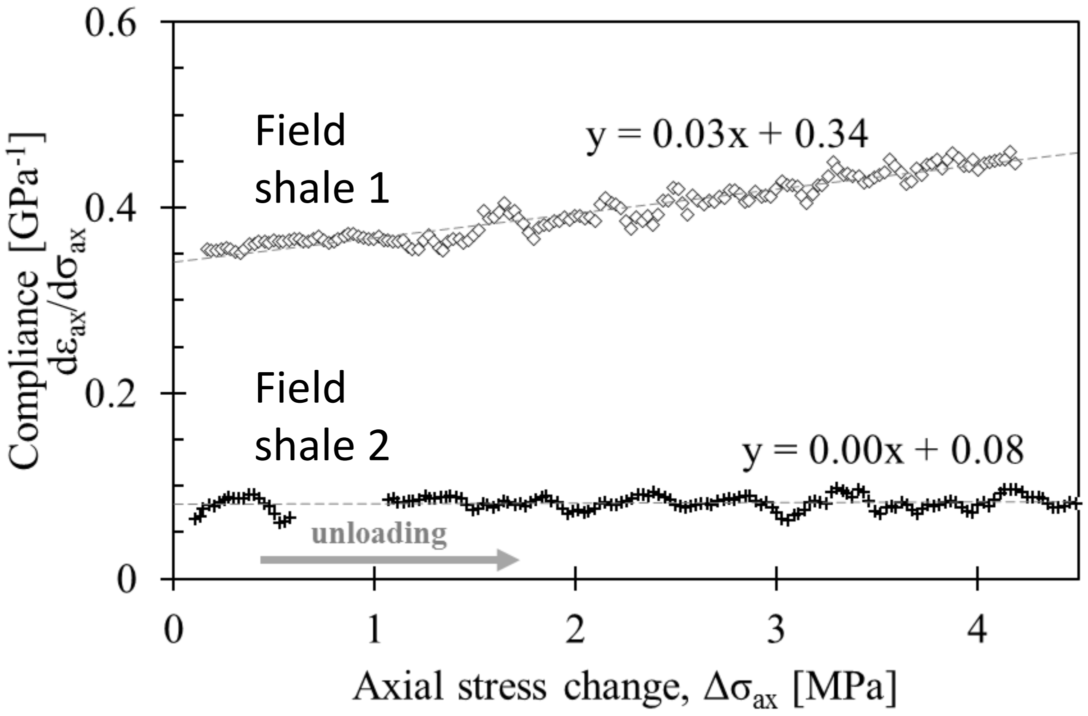
Young's modulus dependance on frequency and stress amplitude



Opalinus Clay

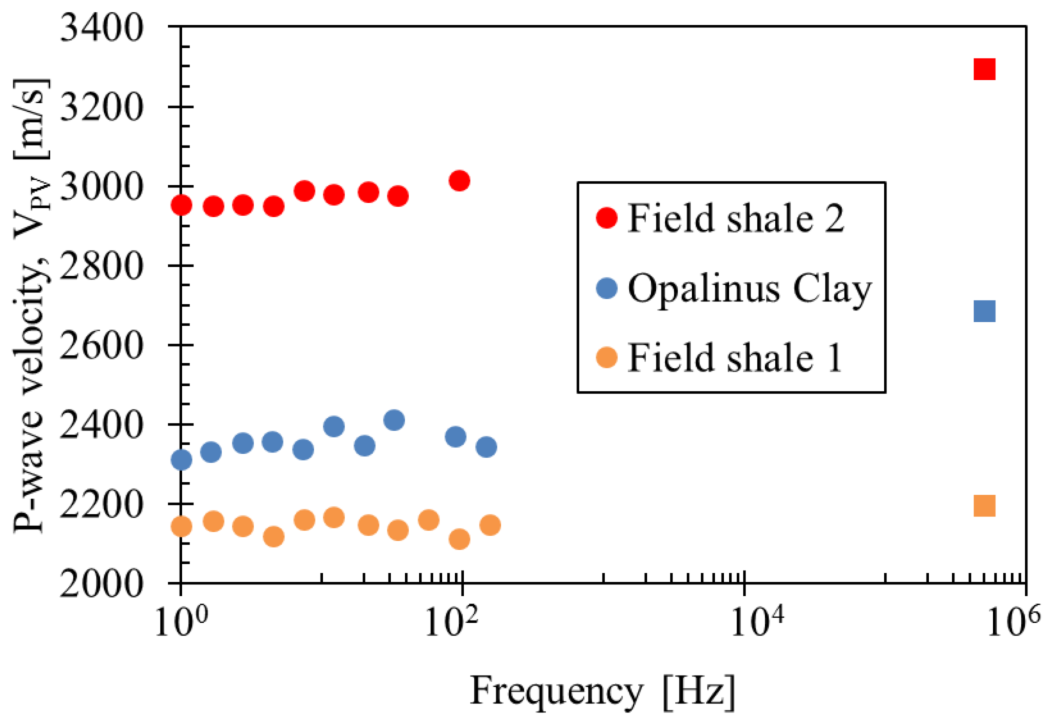
Other shales





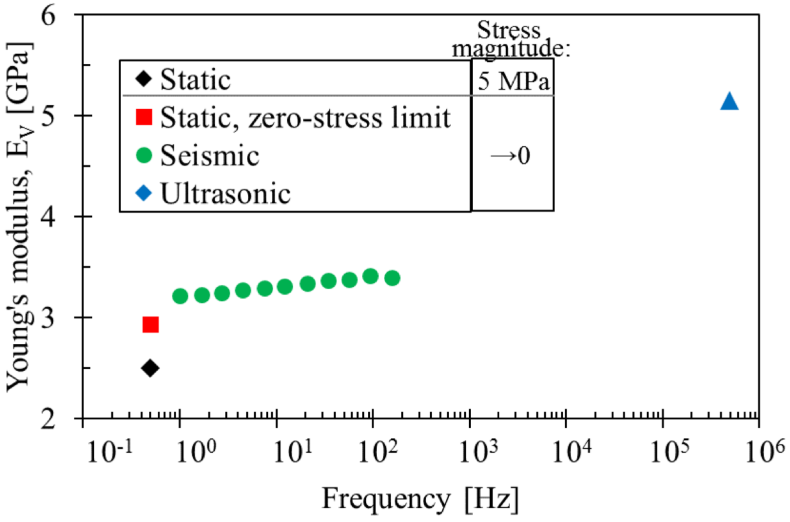
Field shale 2 demonstrates nearly perfect elastic response

Velocity dispersion

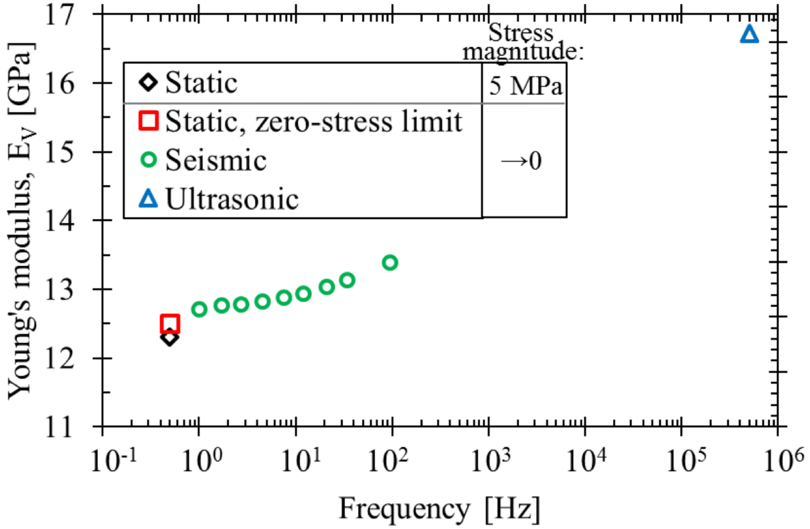


Young's modulus dispersion

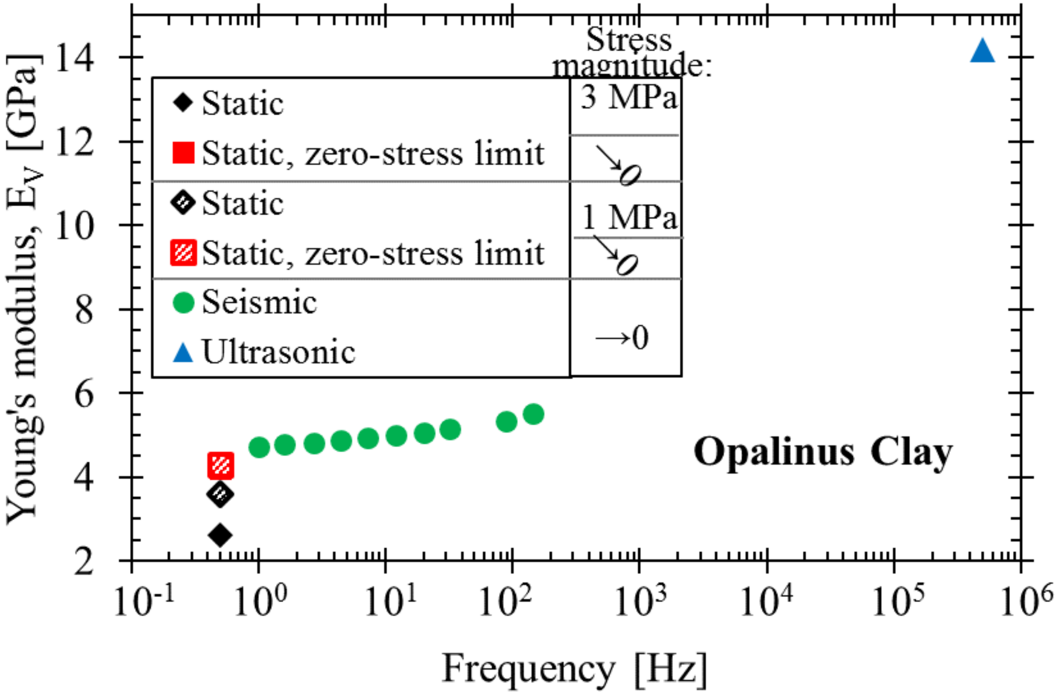
Field shale 1



Field shale 2



Opalinus Clay



Conclusions

- ❑Static and dynamic stiffness are linked by both stress amplitude (non-elasticity) and stress rate (dispersion) effects
- ❑Rocks are non-elastic for strains > 1 μstrain, both during loading <u>and</u> unloading
- ❑With decreasing stress/strain amplitude, the static undrained stiffness approaches the dynamic stiffness of low frequency
- ❑In saturated shales, frequency dispersion may strongly affect stiffness
- ❑Different mechanisms are responsible for non-elastic effects and dispersion

Thank you

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- BP