Controls on the Geomechanical Properties of Unconventional Resource Formations*

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Abstract

Historic interest in the geomechanical properties of shales arose from understanding frac barriers and borehole stability. Little effort was focused on understanding the controls on the geomechanical properties of shales. Now that shales represent a plentiful source of liquid and gas hydrocarbons requiring stimulation, i.e. hydraulic fracturing, there is a renewed interest. Shales are differentiated from mudstones by their fissility which imparts an intrinsic mechanical anisotropy. The degree of anisotropy is strong and often attributed to the clay and organic content; however, the anisotropy is typically ignored, and shales are treated as isotropic elastic materials where required characteristic geomechanical properties are reduced to two elastic moduli, typically Young's modulus and Poisson's ratio and failure strength (UCS). Shales present formidable sampling challenges and are often not measured in their preserved state. Moduli measurements can be static or dynamic; logs produce dynamic measurements averaged over the wavelength of the logging tool. The smoothing masks the importance of highly laminated shale interfaces. The static measurements place stricter sample requirements in requiring length/diameter ratios greater than two. To overcome some of these restrictions, researchers have turned to new technologies like nanoindentation and atomic force microscopy to extract geomechanical properties from friable and limited sample quantities, including cuttings. However, these technologies are limited to measurements at ambient conditions and at modest temperatures. The problem with geomechanical properties is their intrinsic dependence on many independent variables such as saturation, mineralogy, organics, pore pressure, stress levels, etc. and in the case of shale, orientation. The wealth of data reported to date - some 260 measurements of Young's modulus and Poisson's ratios and some 417 measures of failure strength—are devoid of the required conditional information to allow trends and systematics to be developed. The collective data sets lack sample orientations, mineralogies and specified testing stress

conditions. A very small subset possesses enough details to begin to analyze cause and effect, but the numbers are too small to be statistically significant. However, for failure strengths reported as a function of confining pressure, there is a clear increase in strength with applied stress, roughly 2 MPa for each MPa increase in confining pressure. The geomechanical properties of shale are strongly influenced by age; the younger shales and those rich in smectite, tend to be more ductile and cause borehole problems and are more resistant to fracture stimulation. Many of the unconventional shale resource plays are naturally fractured, and these fractures are commonly mineralized. The mineralized fractures are inherently weaker than the host shale and represent the weakest interfaces during stimulation. To understand the geomechanical properties of shales, we need to understand the elasticity of the matrix, the role of anisotropy and natural fractures both filled and open. What is clearly needed going forward is a better and more comprehensive and consistent reporting of sample and test conditions.

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Henao, T., C. H. Sondergeld and C. S. Rai, 2017, Intact and shear reactivation strength of Eagle Ford and Woodford shales from multistage triaxial testing, URTeC:2670543

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Xia, Z., C. H. Sondergeld, C. S. Rai and D. Zhang, 2019, Static and dynamic mechanical properties and anisotropy of Barnett Shale, (submitted)

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Geomechanical Properties

These include:

Elastic moduli (E, ν, K, G)

Uniaxial compressive strength (UCS)

Failure strength (triaxial)

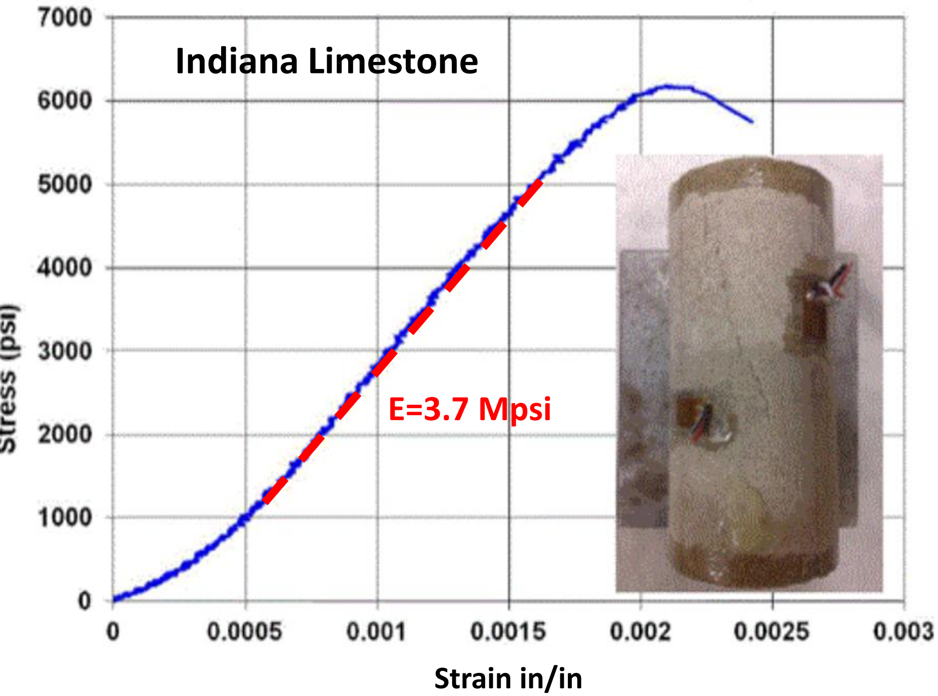
Brittleness

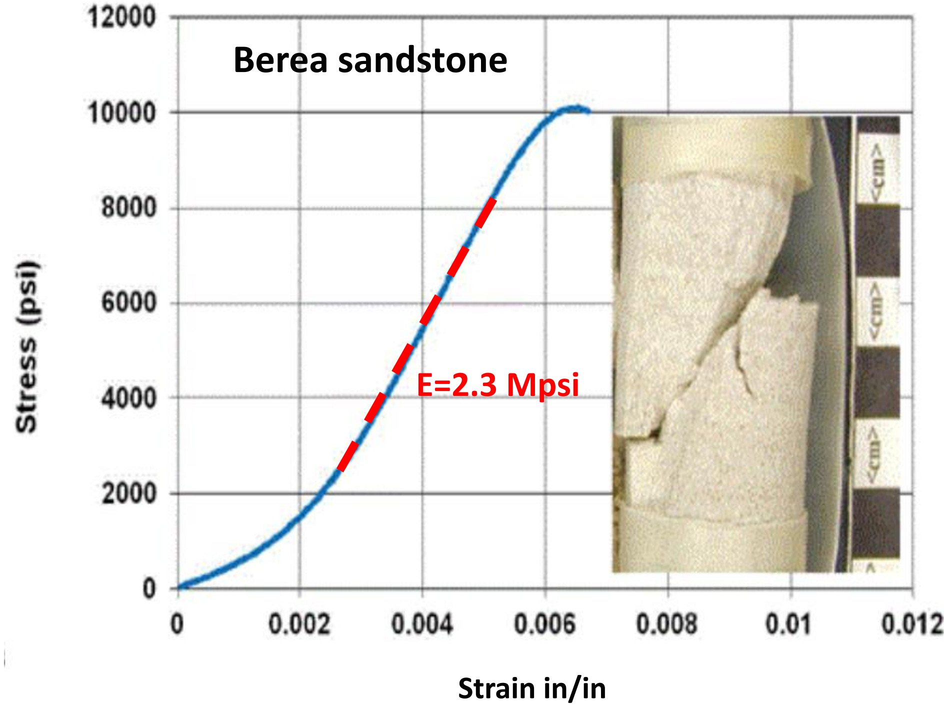
Anisotropy (ε, δ, γ, C_{ij})

Creep

Fluid effects

Typical stress-strain behavior of rock: Uniaxial tests





Brittleness:

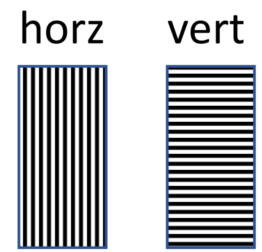
$$B_1 = \frac{\varepsilon_{elas}}{\varepsilon_{tot}}$$

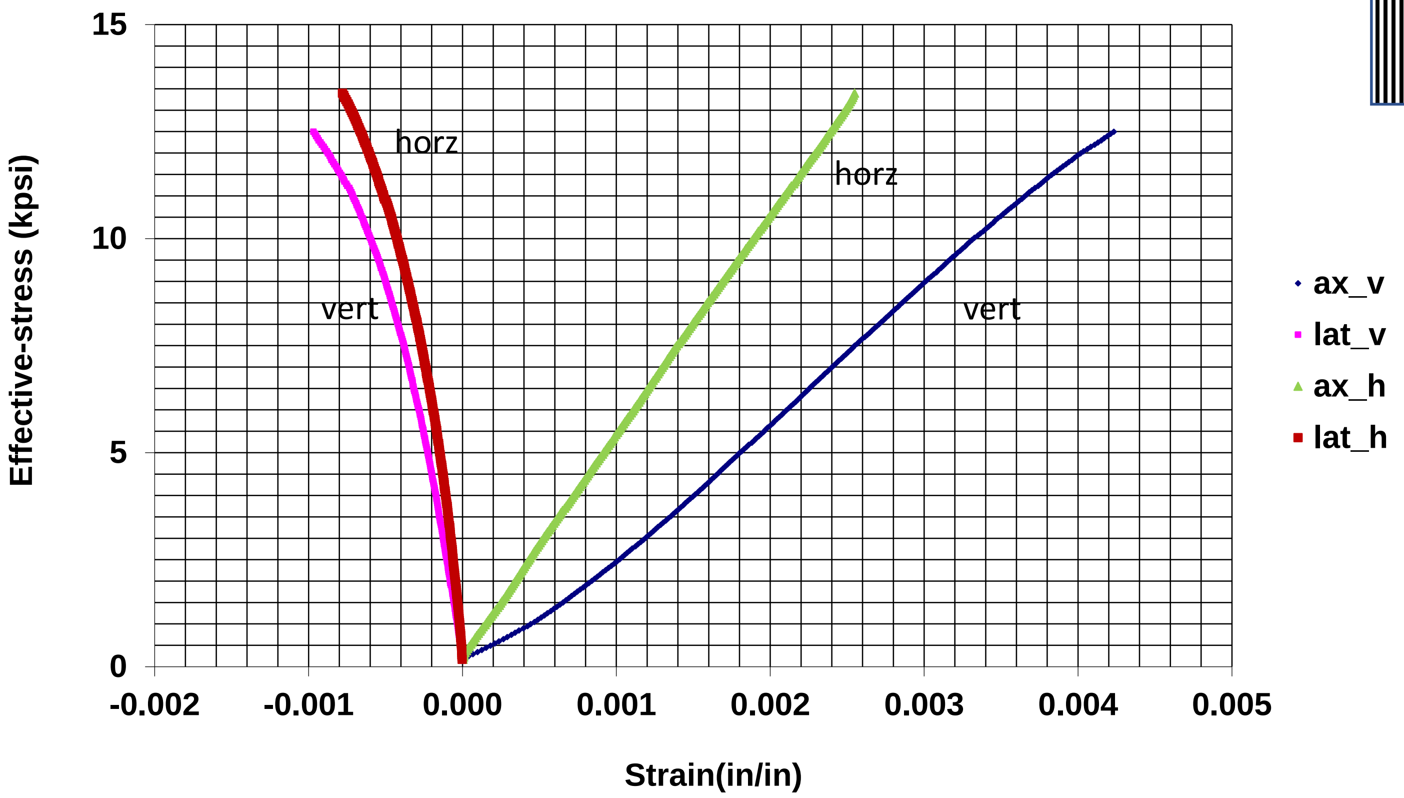
B_1 =0.72

B_1 =0.75

OU-IC³

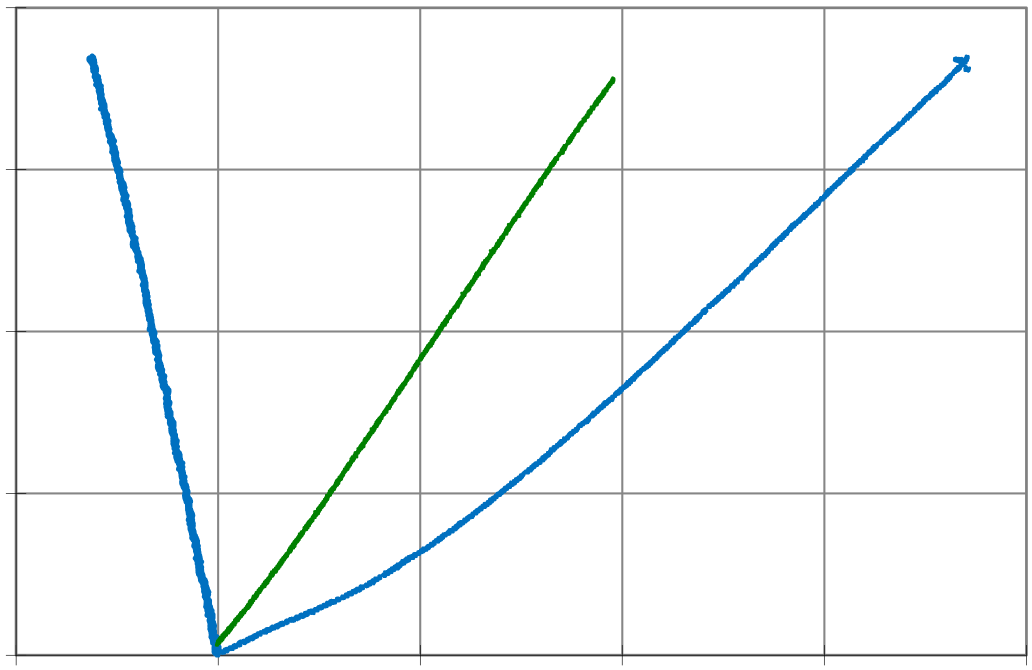
Lyons sandstone: Uniaxial compression



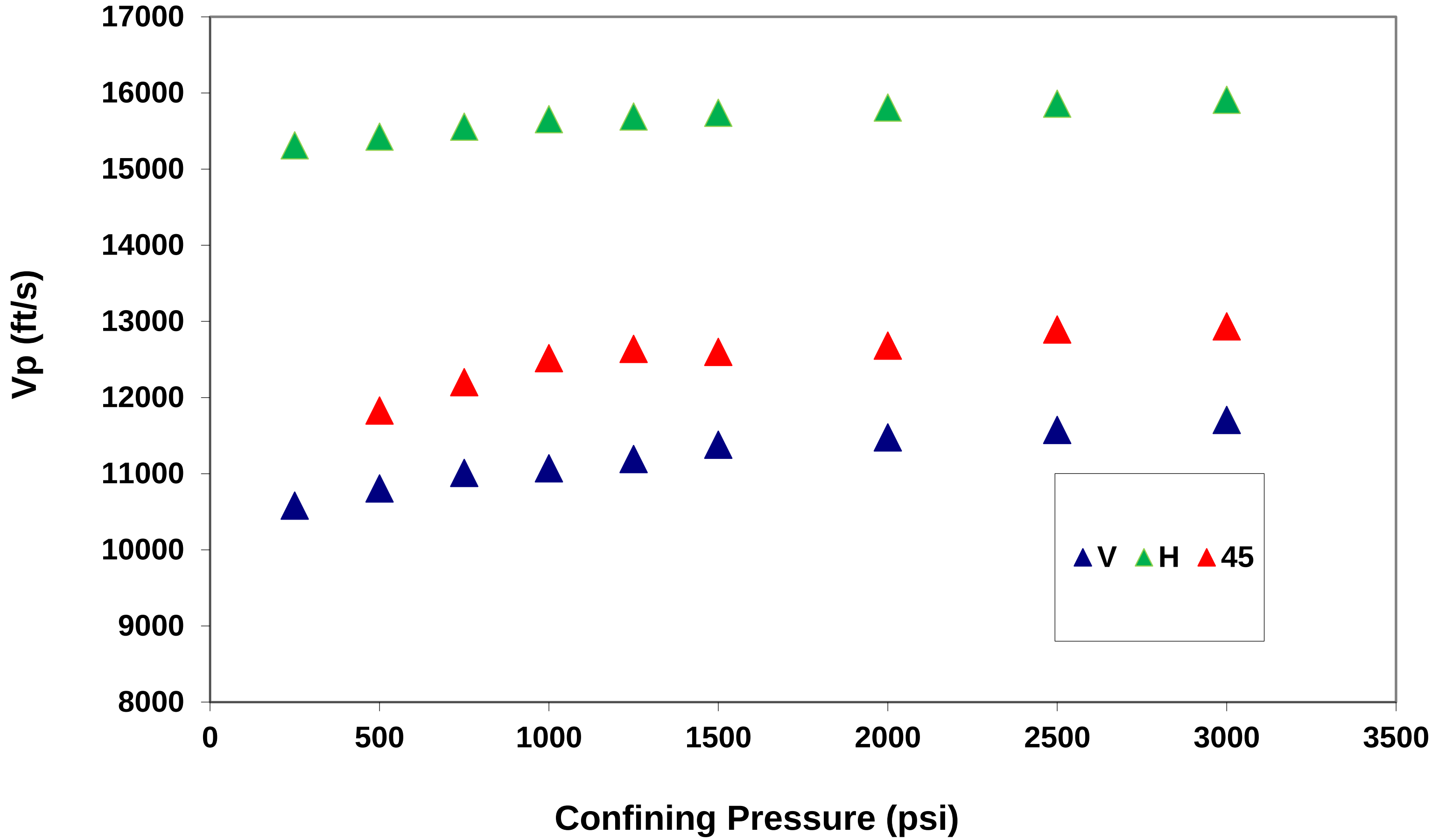


Eh= 5.3 Mpsi, ν=0.16
Ev= 3.3 Mpsi, ν=0.13
Eh/Ev=1.6

Shale: Uniaxial Test-Anisotropy



Velocity anisotropy : Floyd Shale



Why is anisotropy important?

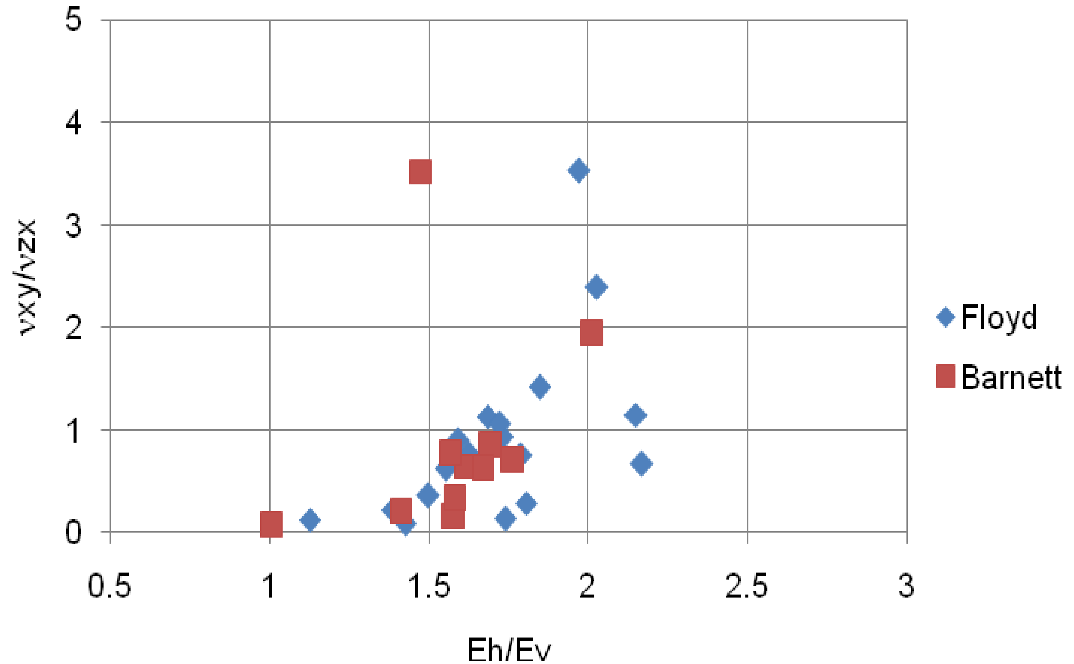
Uniaxial strain: calculation of horizontal stress. These contain fracture propagation.

Isotropic formation

$$\sigma_h = \left(\frac{\nu}{1-\nu}\right)\sigma_v$$

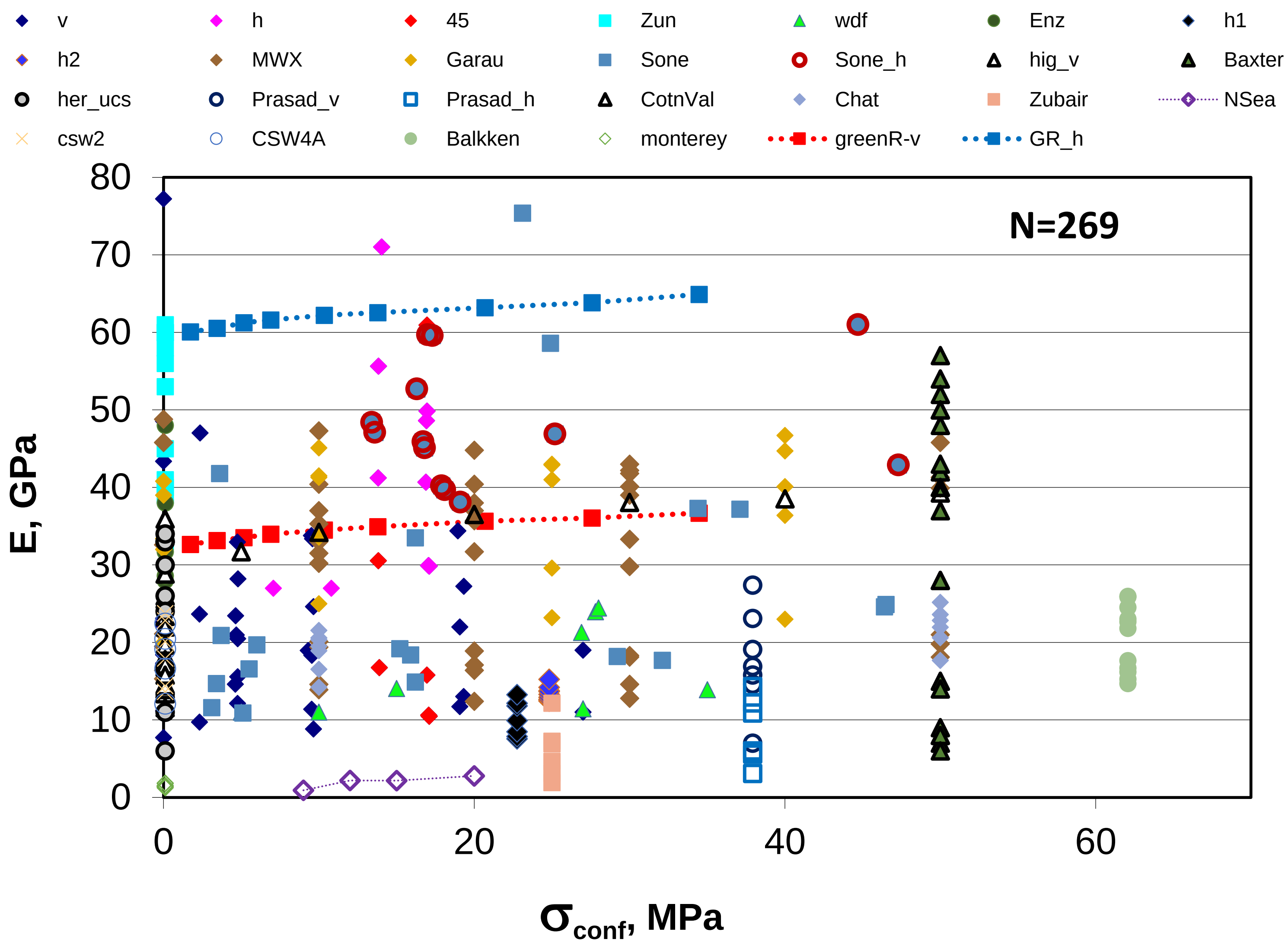
Anisotropic formation

$$\sigma_h = \frac{E_h}{E_v}\left(\frac{\nu_v}{1-\nu_h}\right)\sigma_v$$

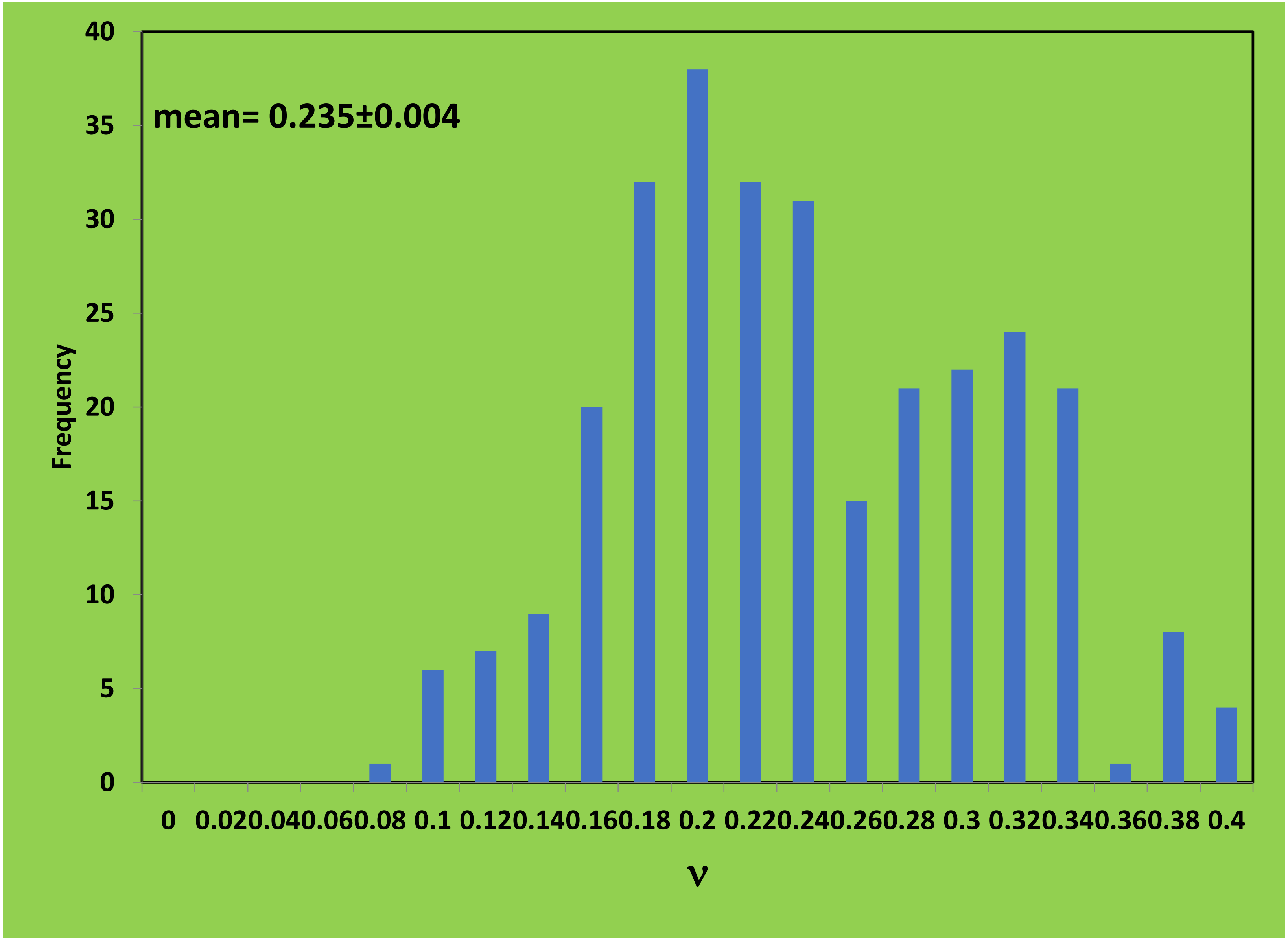


Sondergeld et al., 2010

Young's modulus, E : shales



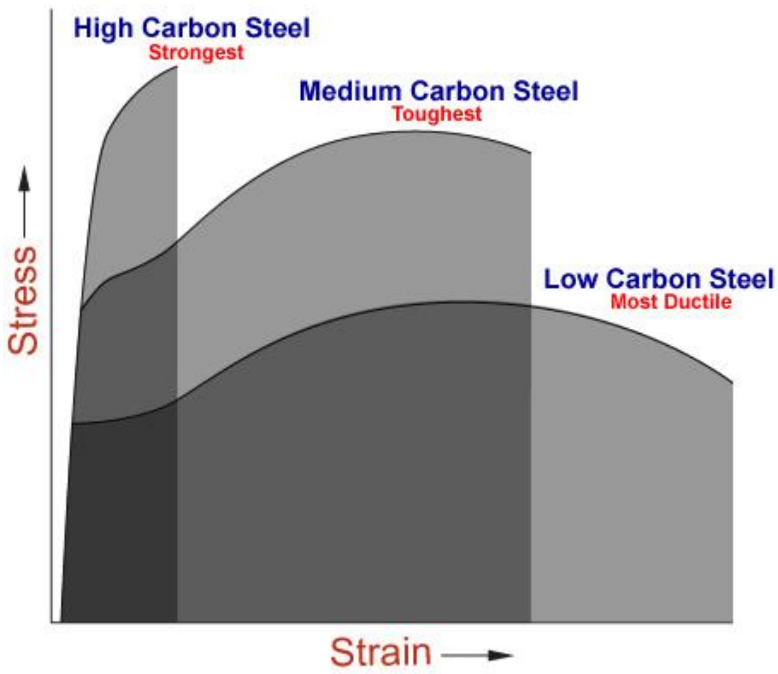
Poisson's Ratio, ν : shales



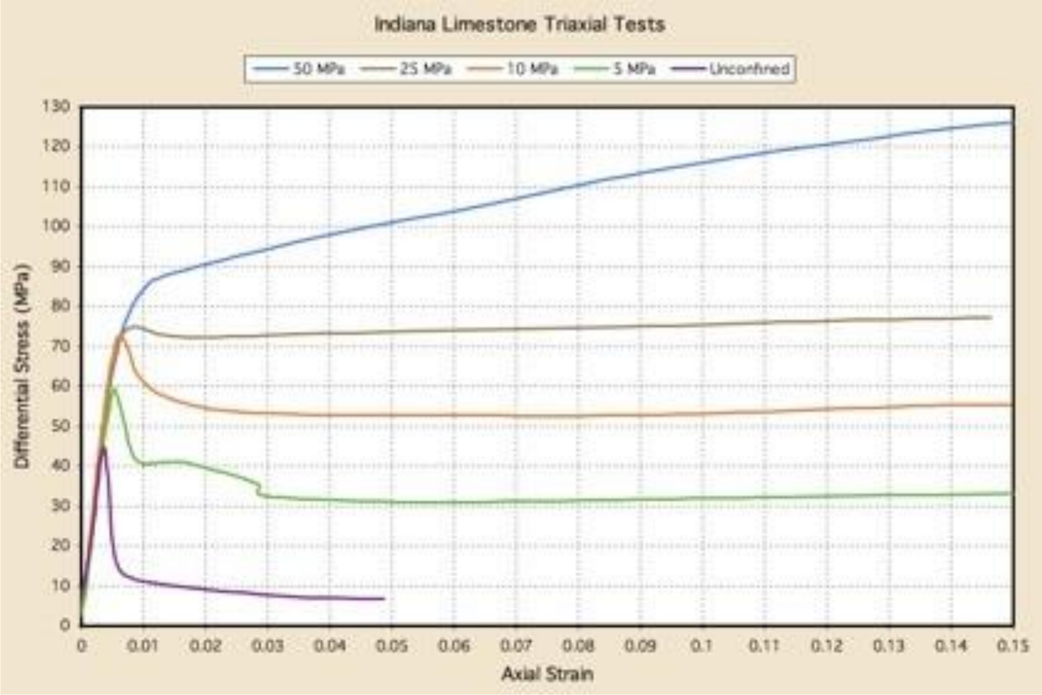
Brittleness and Moduli????

$$Brittleness = 100\left\{\left[\left(\frac{E-1}{8-1}\right)+\left(\frac{\nu-.4}{.15-.4}\right)\right]/2\right\}$$

Rickman et al., 2008



https://practicalmaintenance.net/?p=968



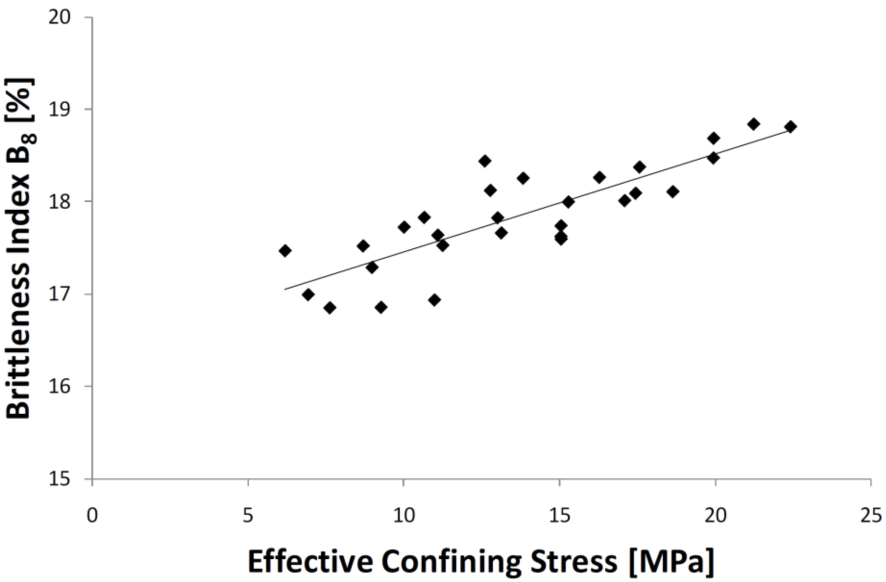
http://www.higgs-palmer.com/HIGGS-PALMER/Rock_Testing.html

Which moduli are used in the equation for brittleness?

Brittleness: Moduli has wrong pressure dependence

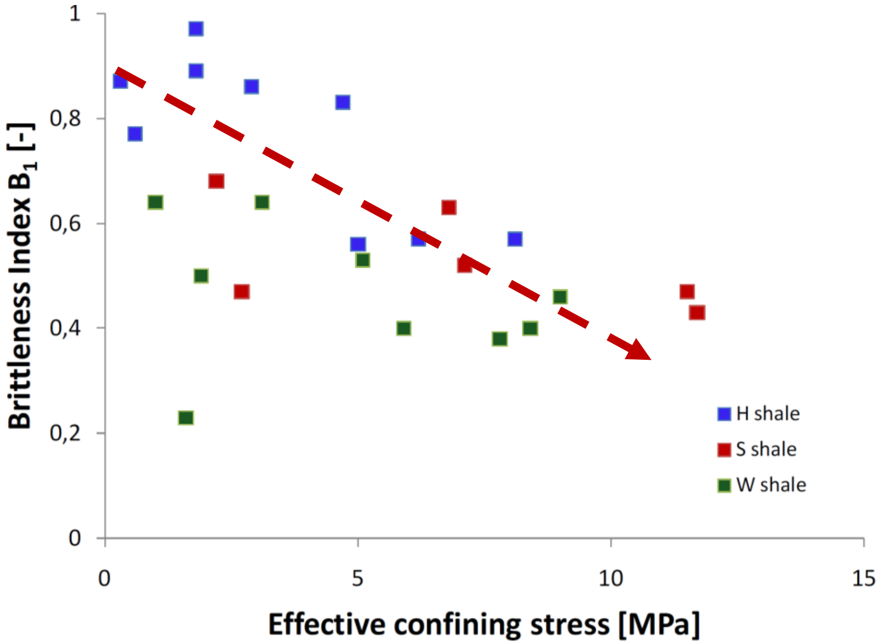
dynamic

$$B_8 = 100\left\{\left[\left(\frac{E-1}{8-1}\right)+\left(\frac{\nu-.4}{.15-.4}\right)\right]/2\right\}$$



static

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

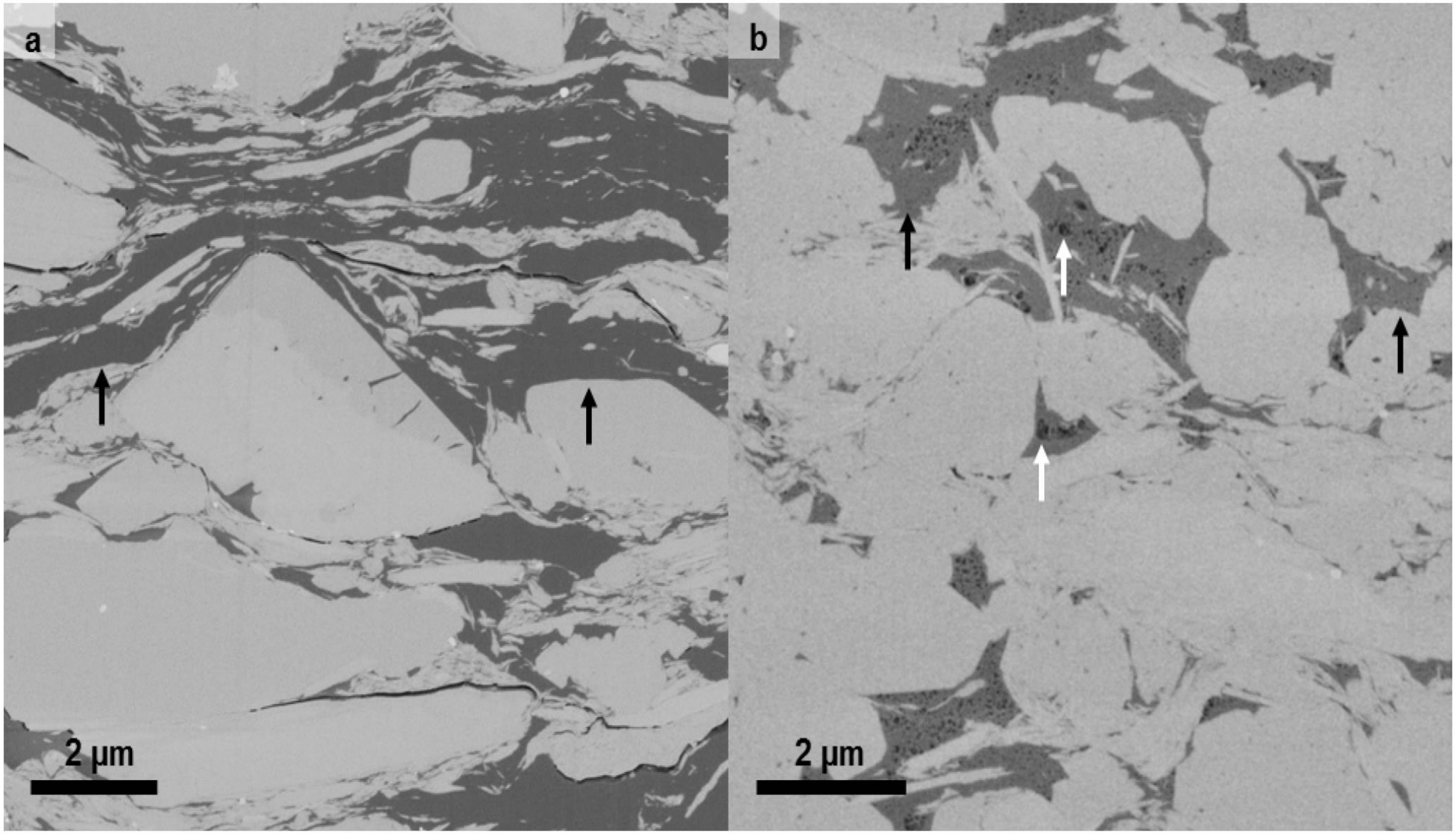


shale	Age	Porosity,%	Clay, %
H	Tertiary	28-46	30-85
S	Cretaceous	21	47
W	Tertiary	28	44

Holt et al., 2011

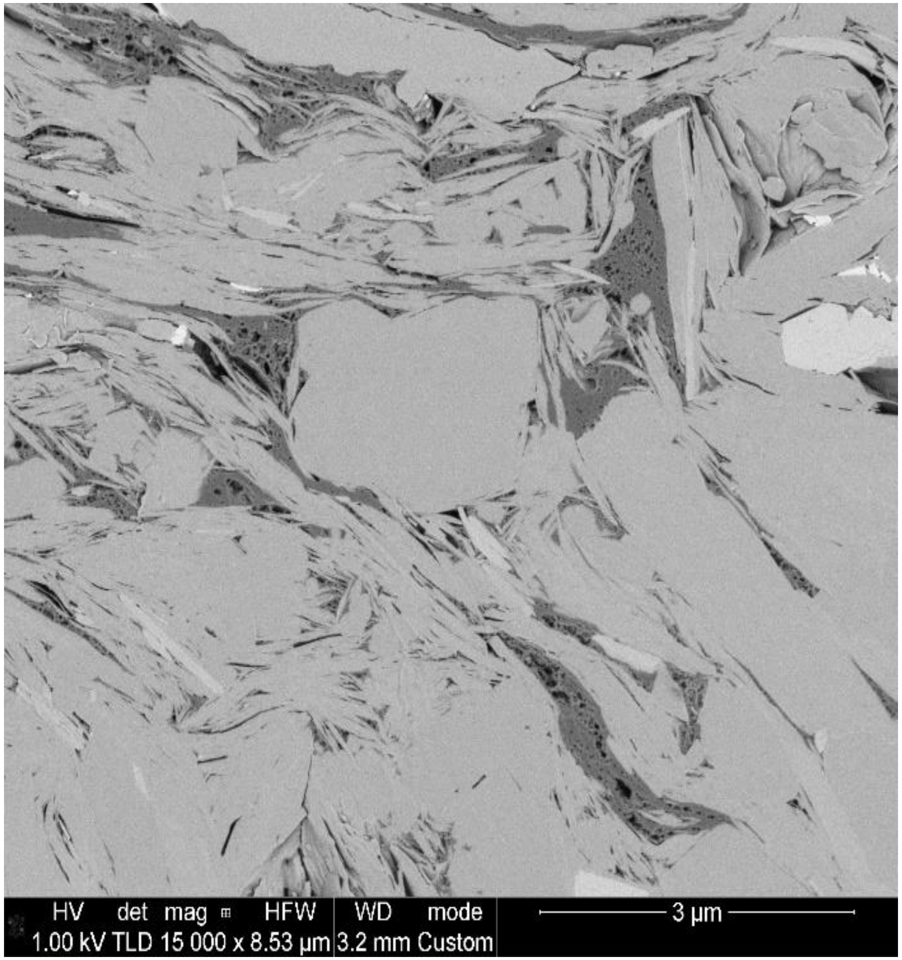
What do shales look like?

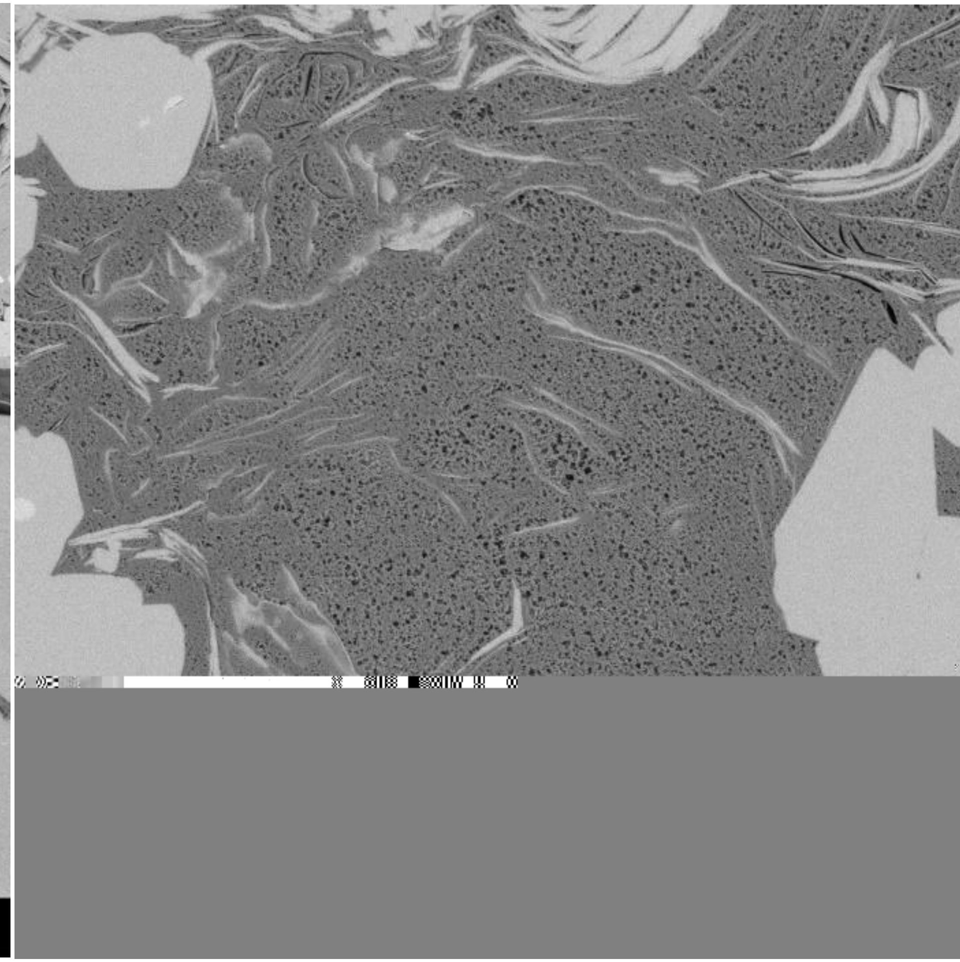
Organics grain supporting? **Organics grain shielded?**



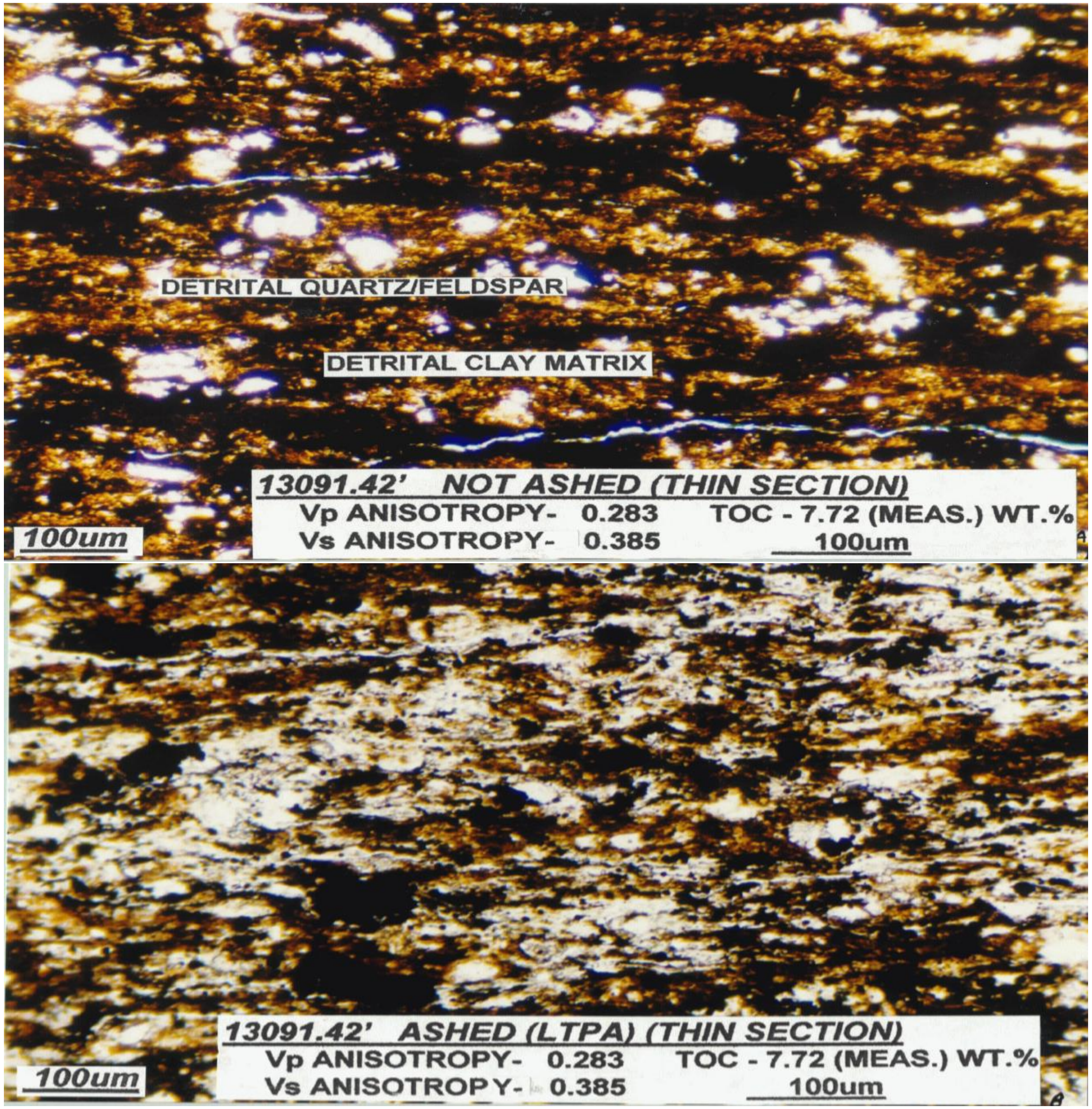
Inorganics: quartz, clays, carbonate
Organics: maturity
Pores (organic and inorganic)

SEM images of Marcellus Shale





Kimmeridge: Ashing of organics

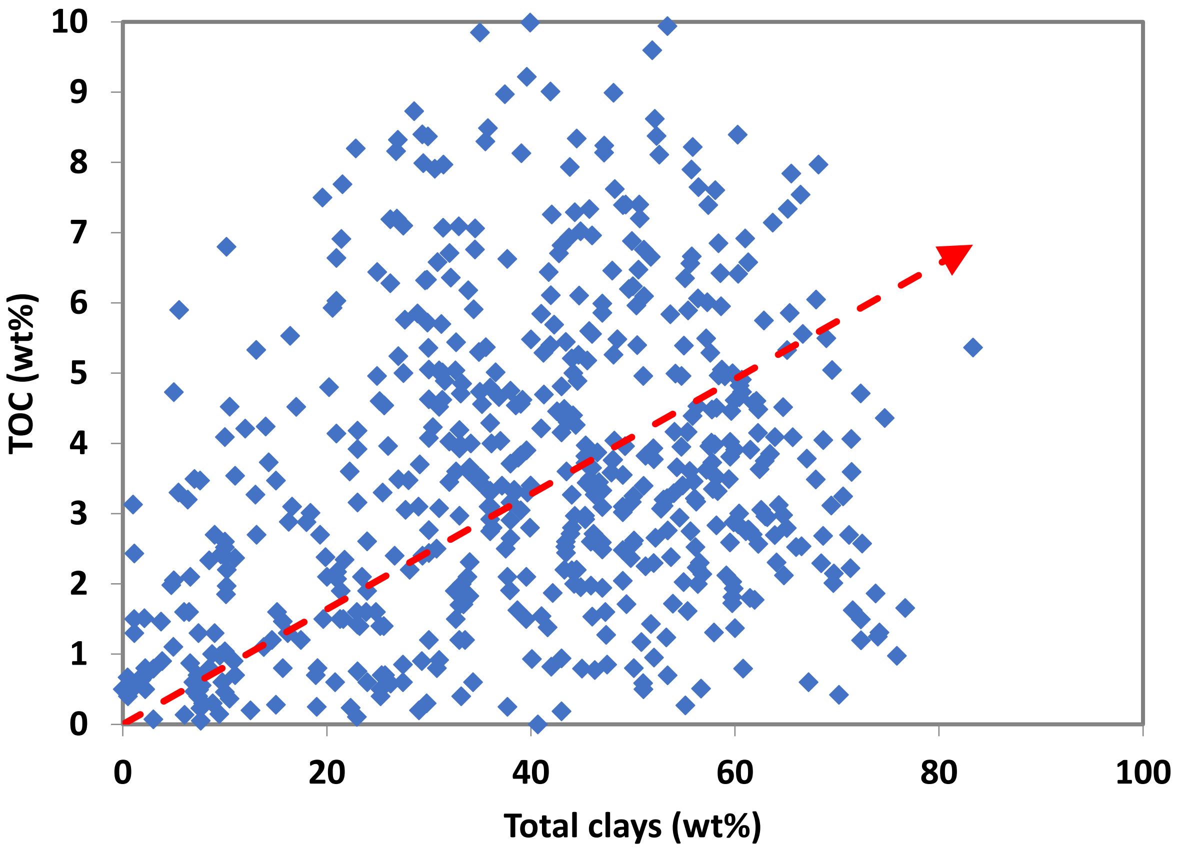


Note the preferred alignment of organics!

Sondergeld and Rai, 2011

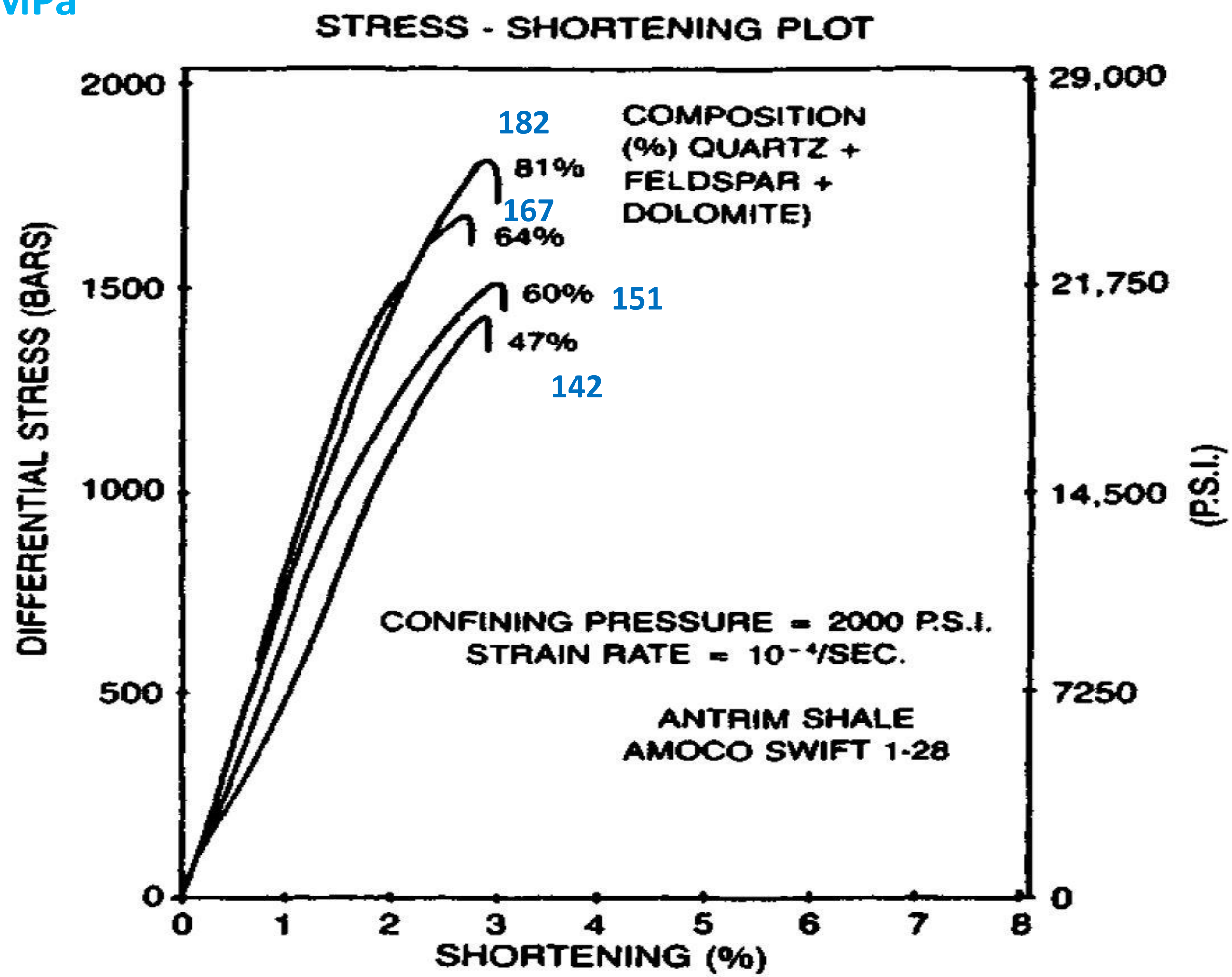
TOC vs Clay for 586 shales

No universal trend. There exists a weak correlation.



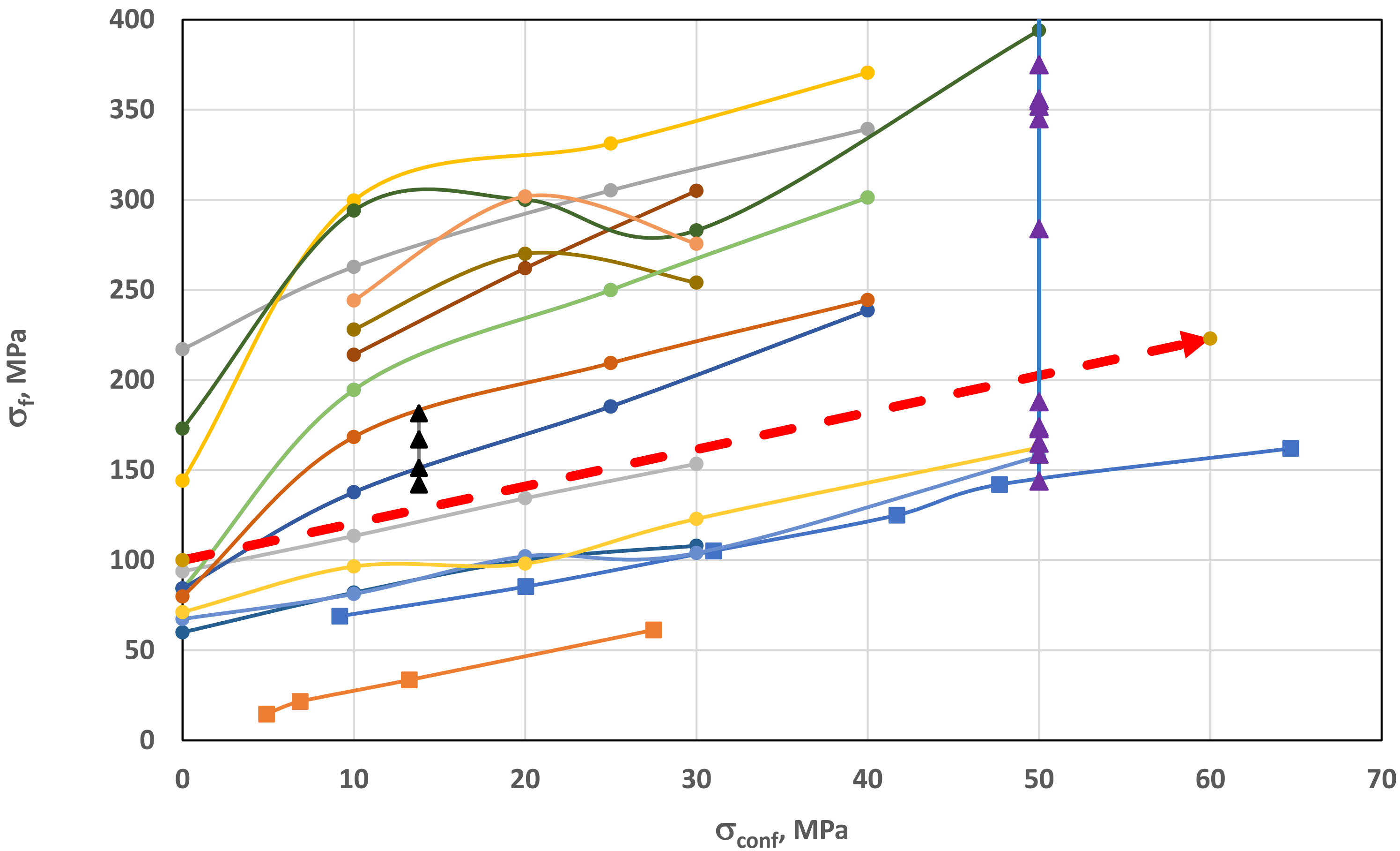
Antrim shale failure strength dependence on mineralogy

Blue= σ_f, MPa

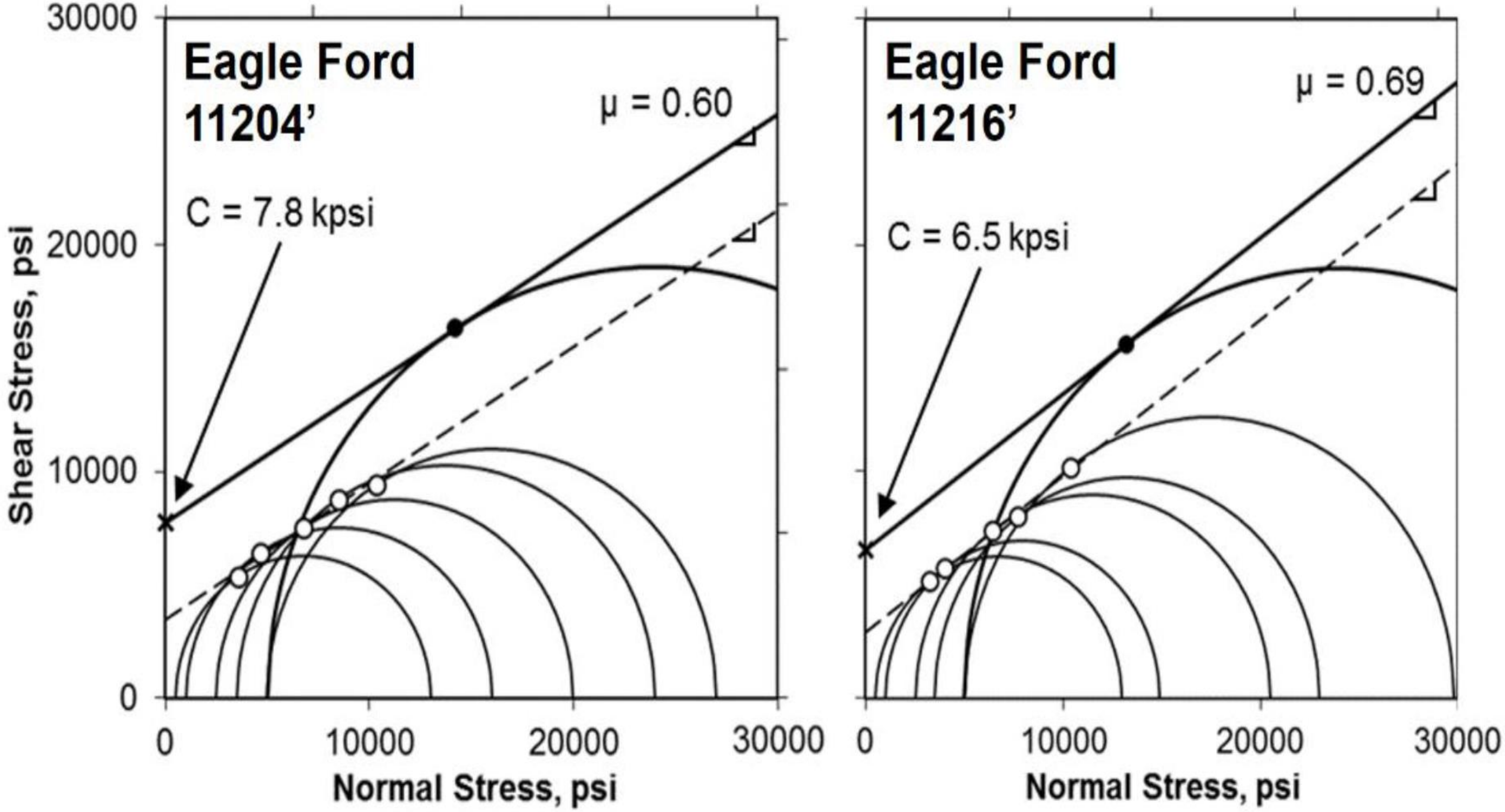


Nelson, 2001

Shale failure strength vs confining pressure

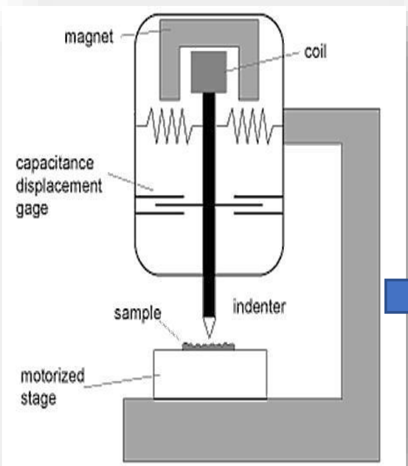


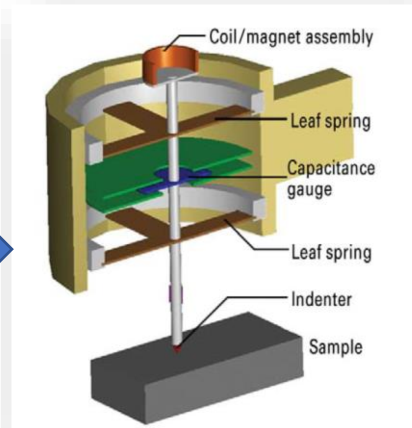
Multistage testing: Eagle Ford Shale



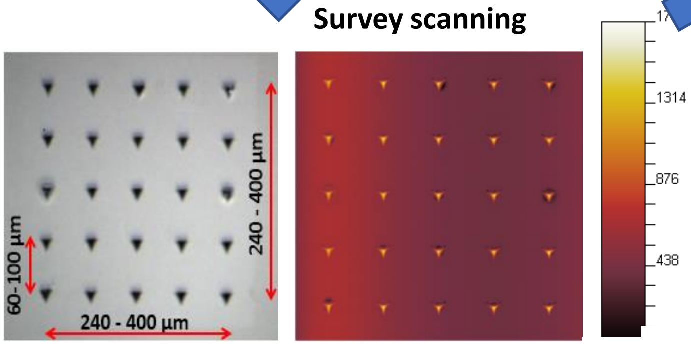
Henao et al., 2017

Overview of Nanoindentation



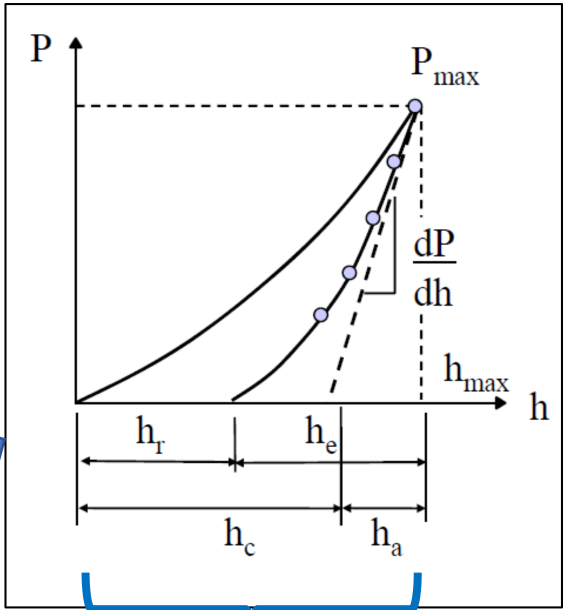


Survey scanning



nm

An array of 5x5 indentations on fused silica seen under microscope

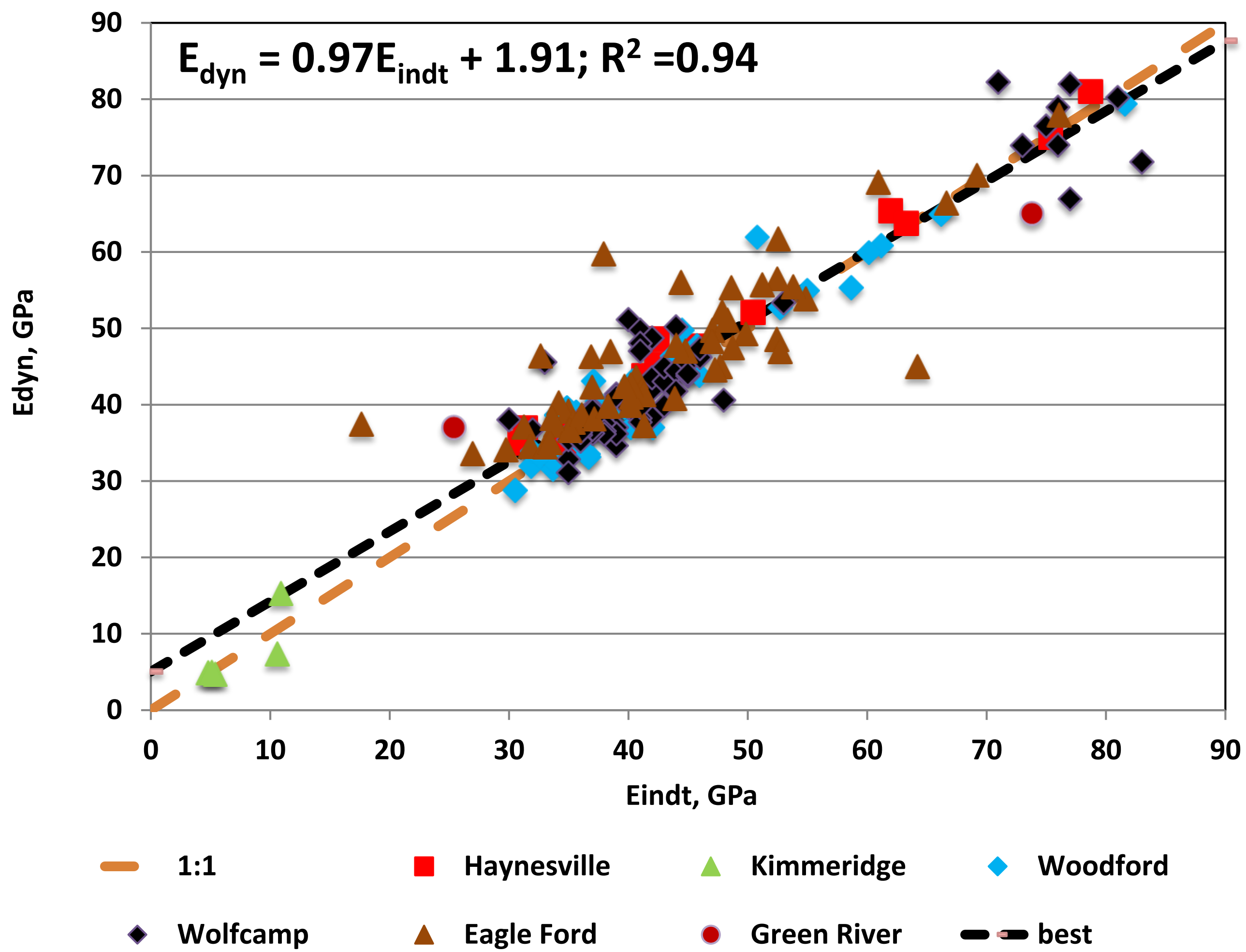


$$E^* = \frac{dP}{dh}\frac{1}{2h_p}\frac{1}{\beta}\sqrt{\frac{\pi}{24.5}}$$

$$\frac{1}{E^*} = \frac{1-\upsilon^2}{E} + \frac{1-\upsilon'^2}{E'}$$

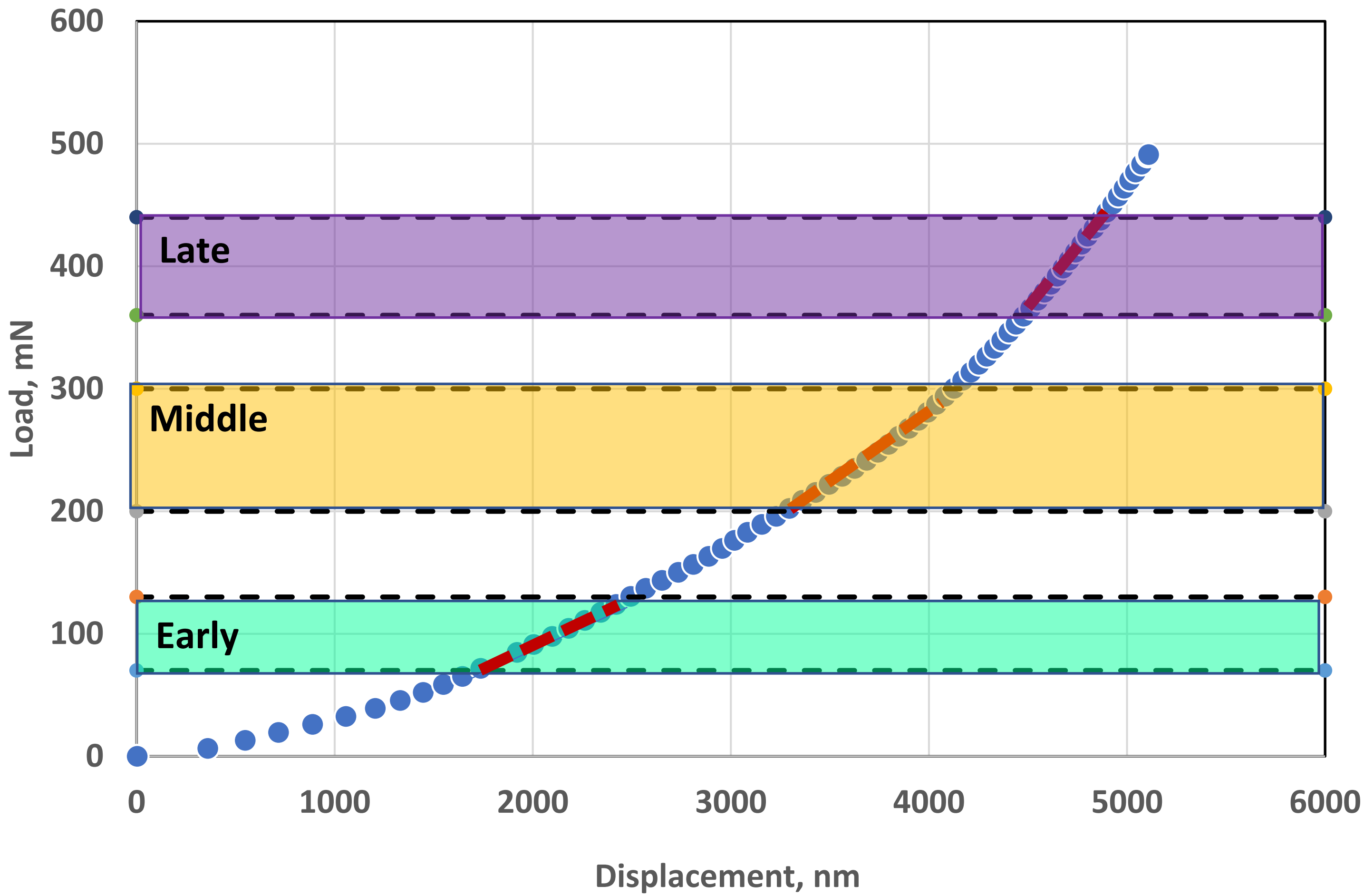
sample diamond

Comparison : E_{indt} and E_{dyn}



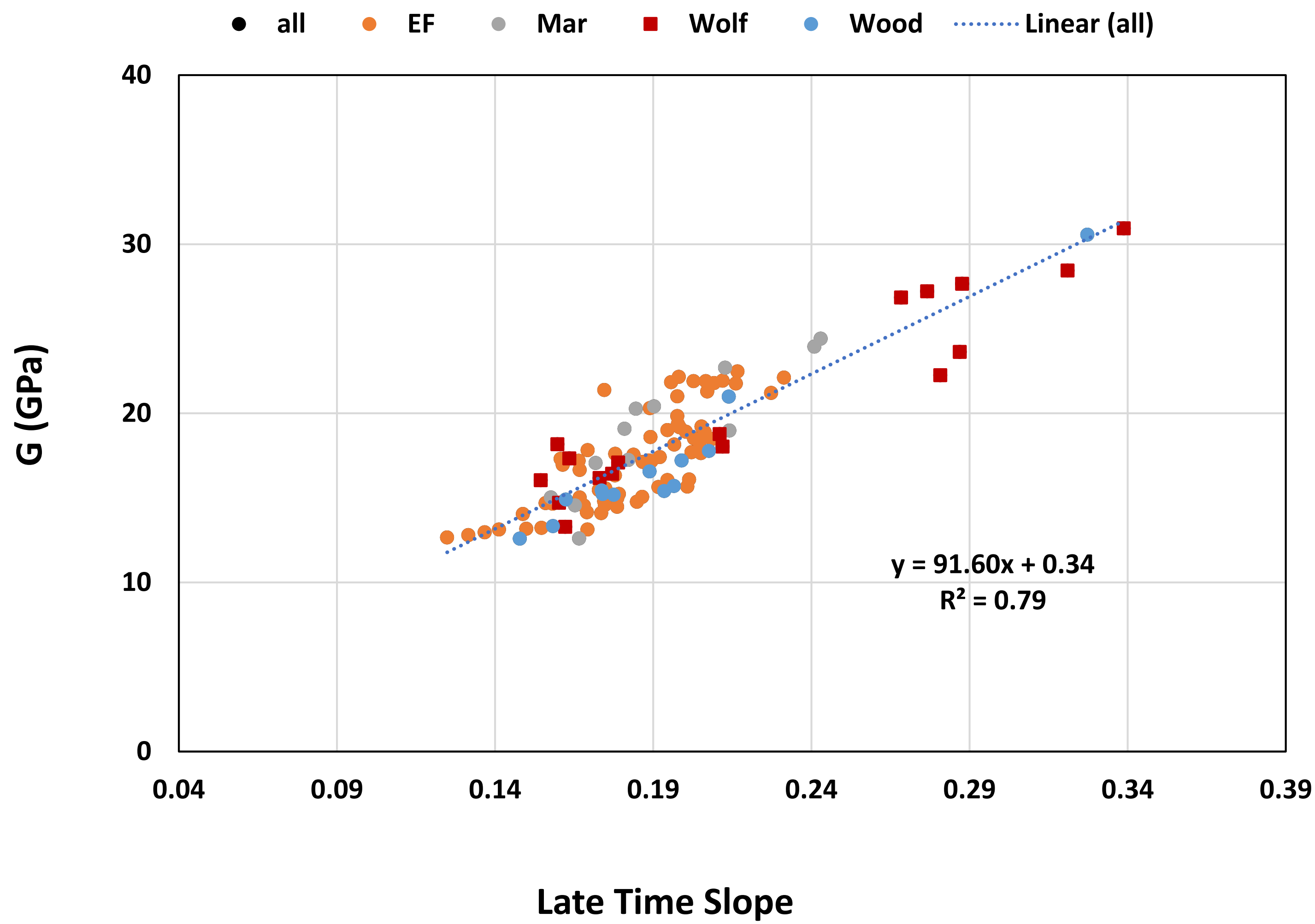
Kumar et al., 2012; Shukla et al., 2013

Fitting slopes for estimating shear modulus



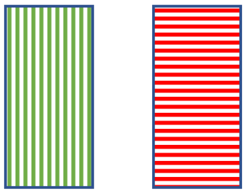
Gupta et al. 2018

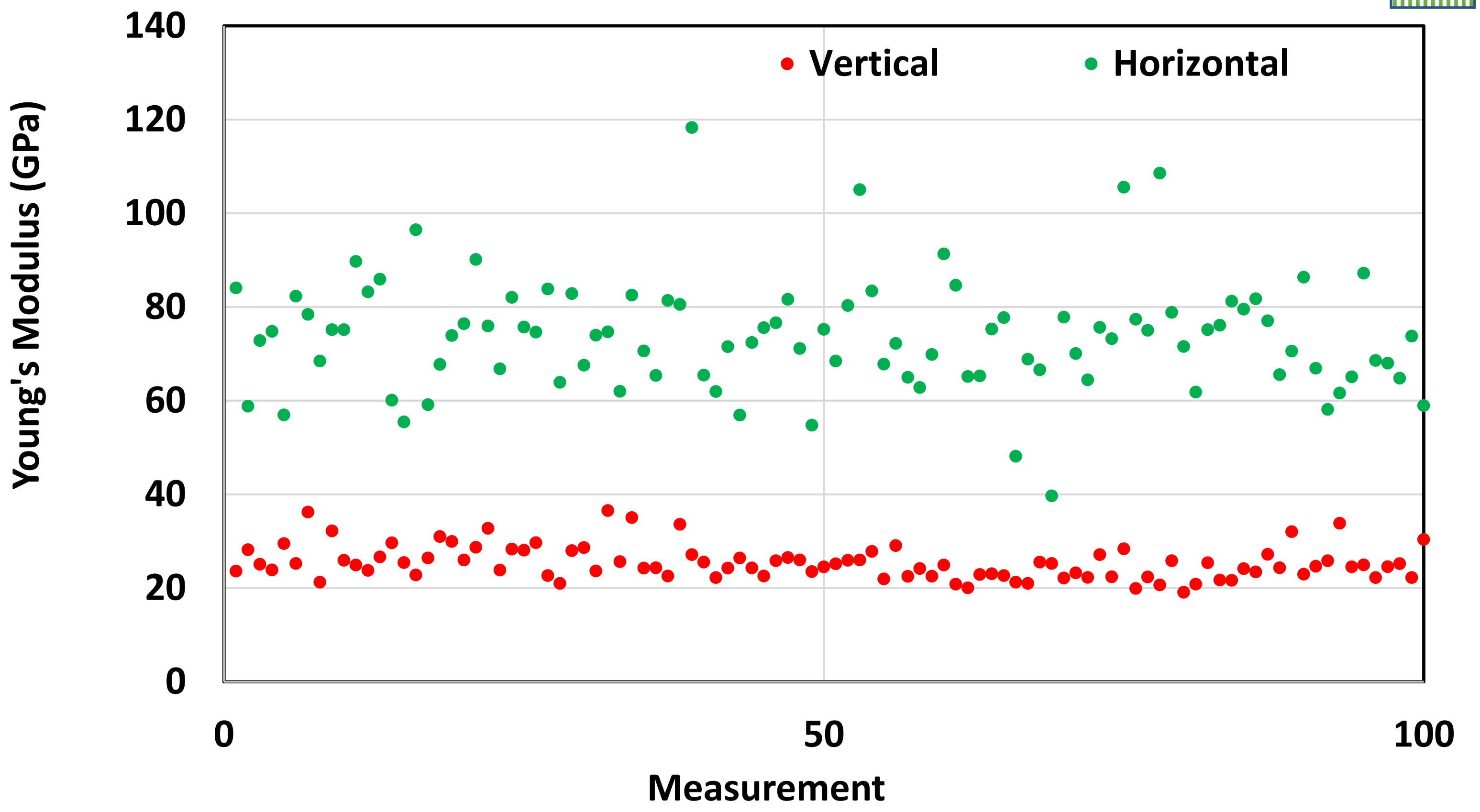
Shear modulus, G, from nanoindentation



Gupta et al., 2018

Individual nanoindentation moduli dependence on orientation





Gupta et al., 2018

Cumulative MICP injection curve

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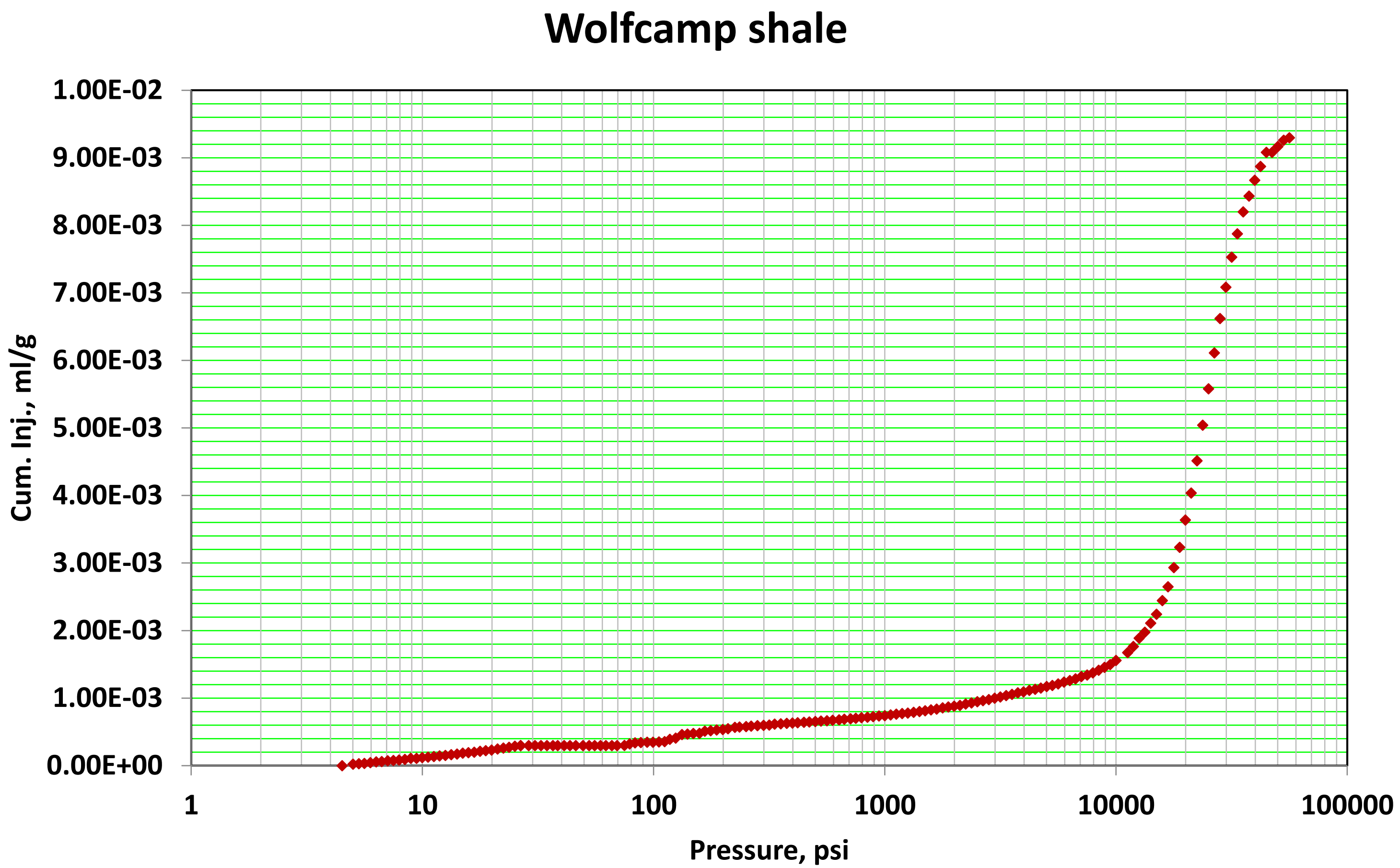
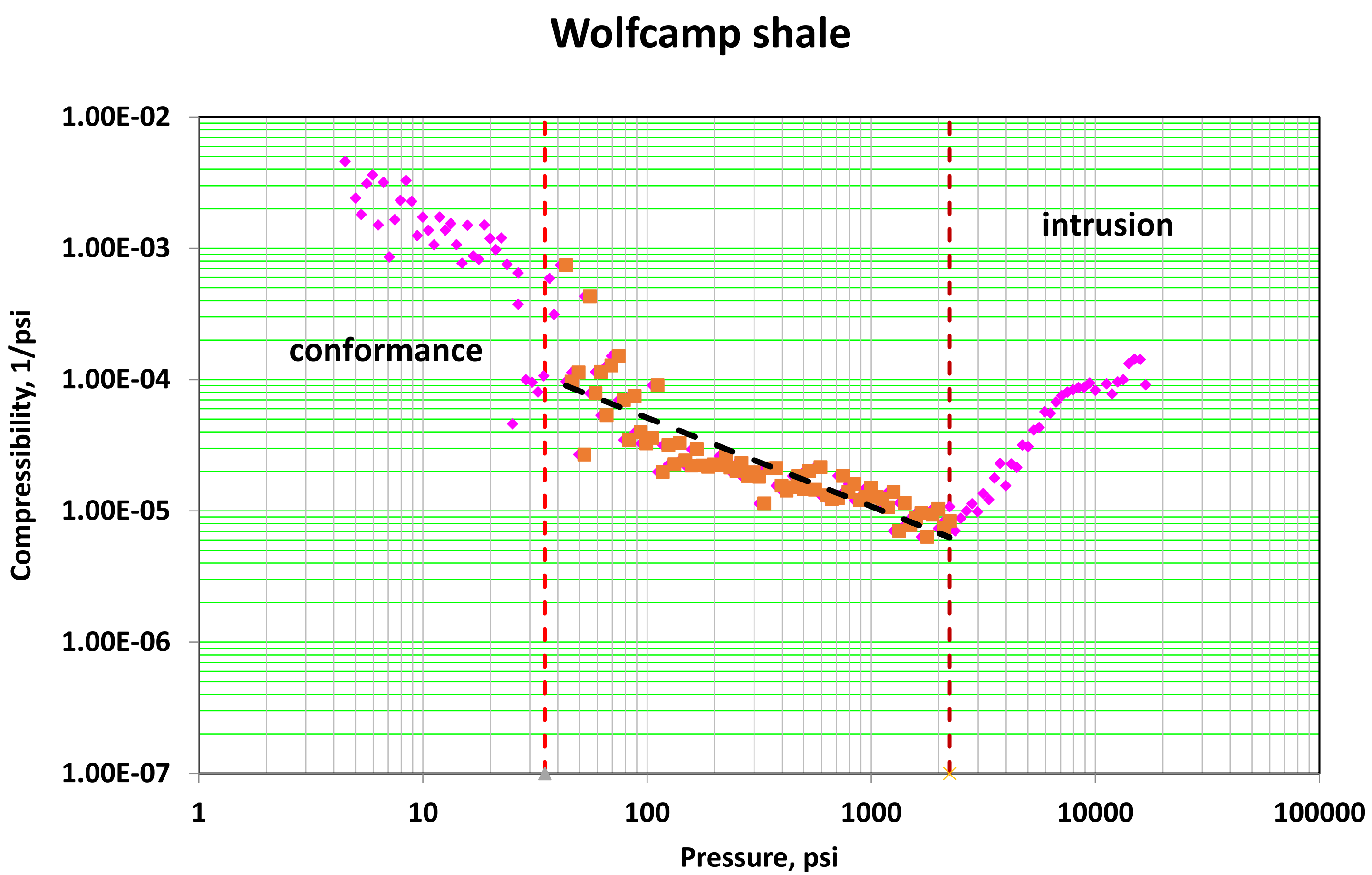
$$\beta_b = \frac{1}{V_b P}\frac{dV_b}{D(lnP)}; K = \frac{1}{\beta}$$



Note the gradual slope to the baseline!

OU-IC[3]

Computed compressibilities from MICP

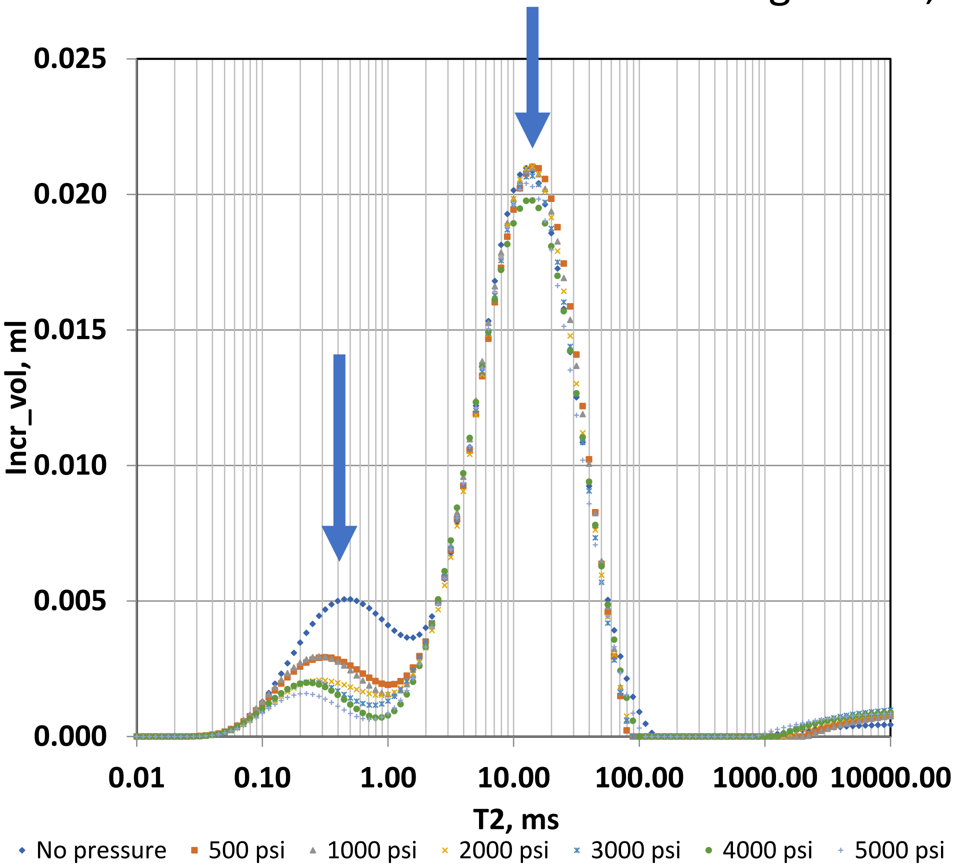


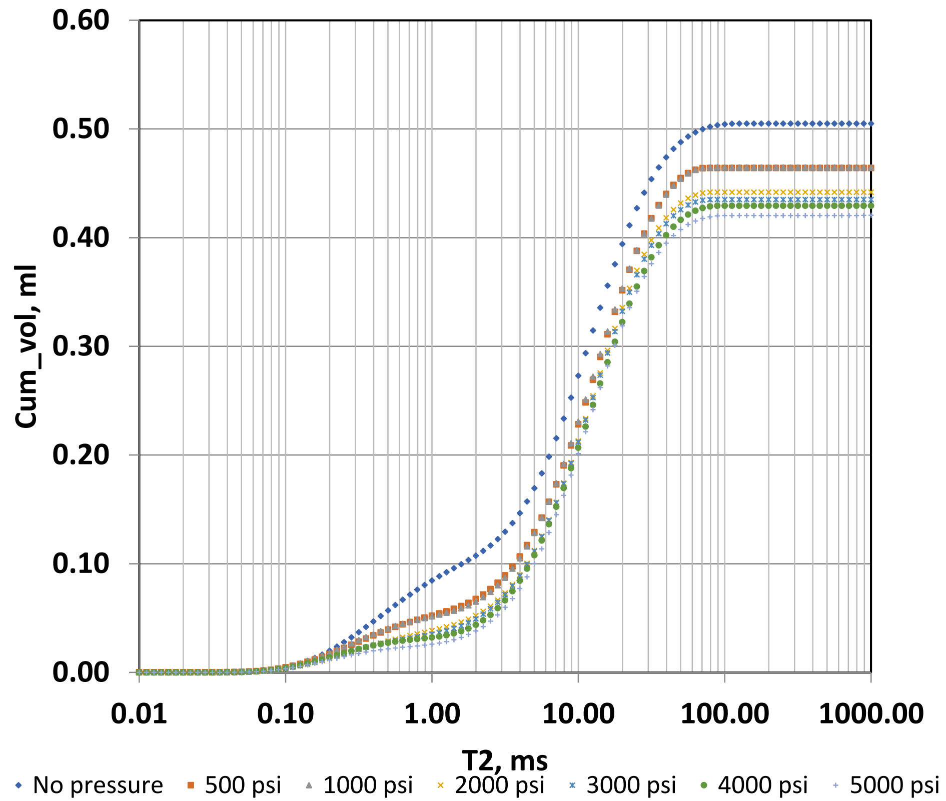
Bailey, 2009

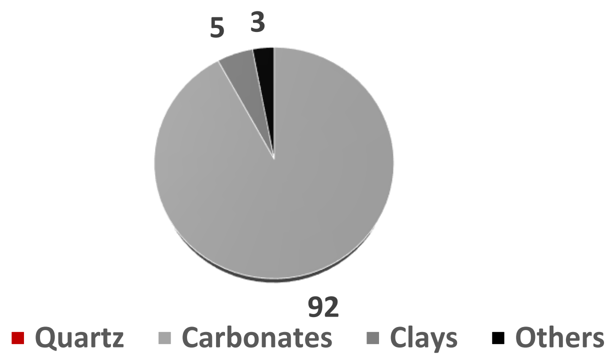
Pore compressibility measurement using NMR

Dodecane saturated sample

Eagle Ford, x596.6







Porosity, %	TOC, %
1.95	0.9

Mahomad and Tinni, 2013

Comparison: MICP and NMR pore compressibility

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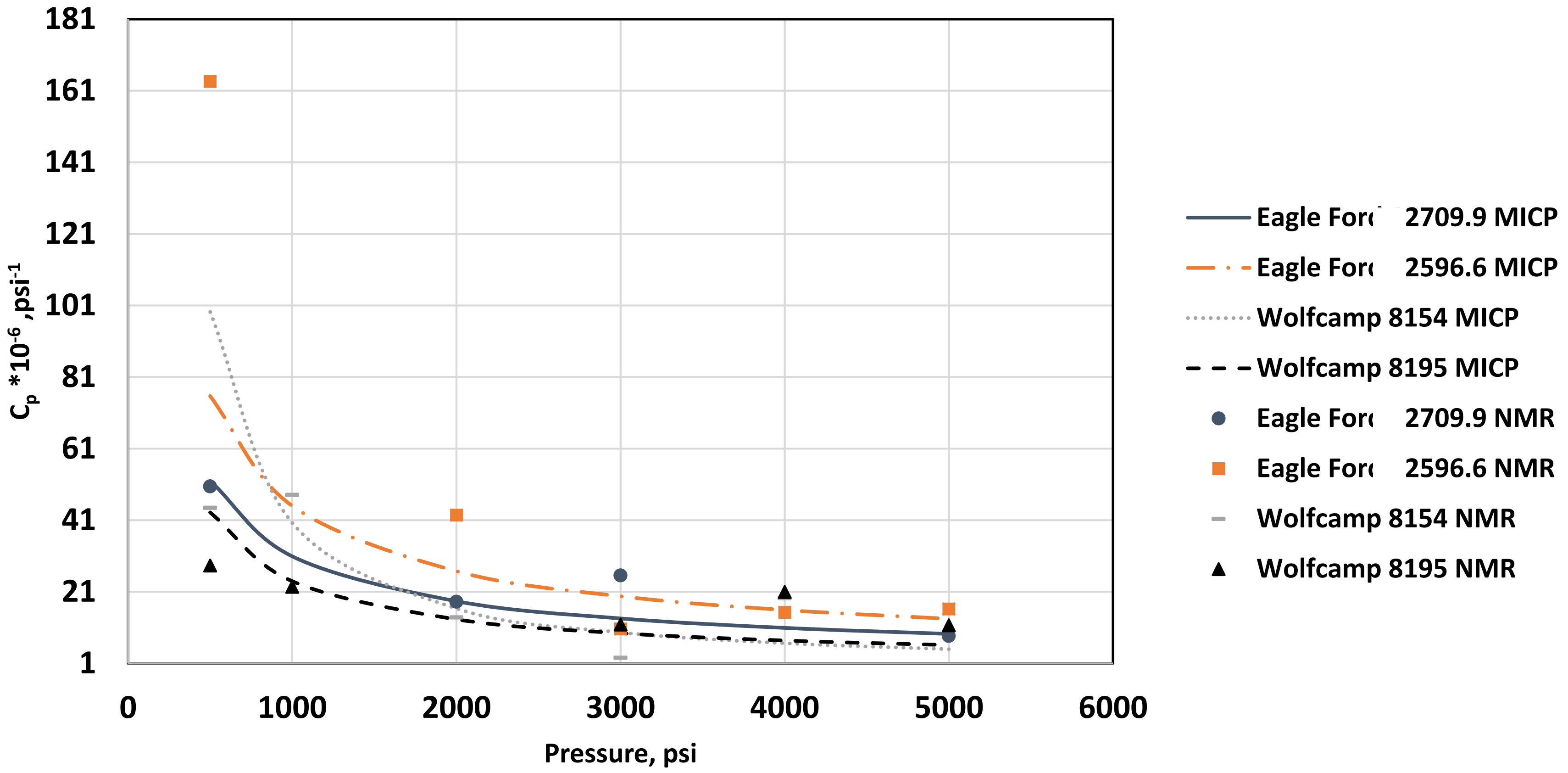
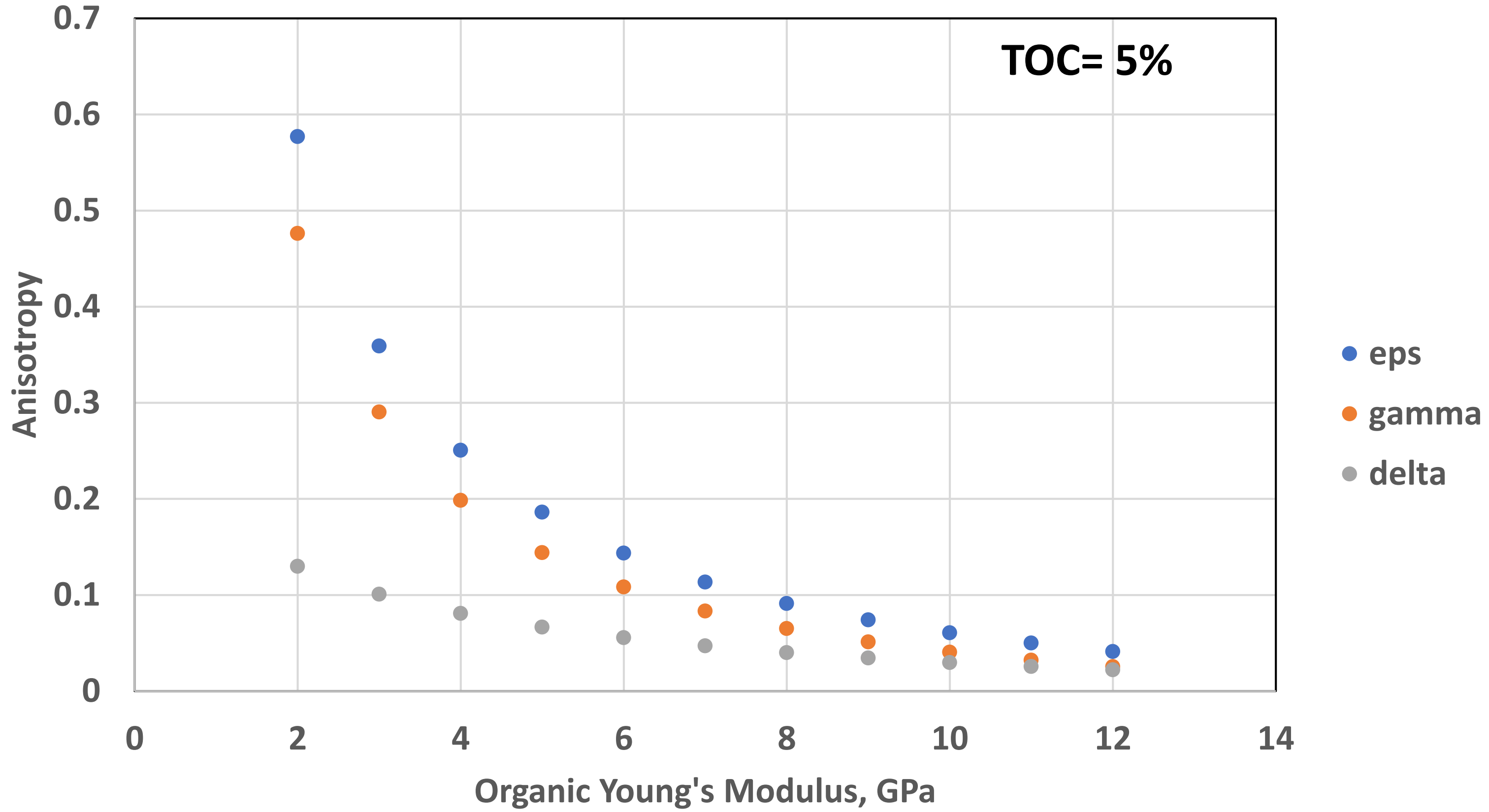


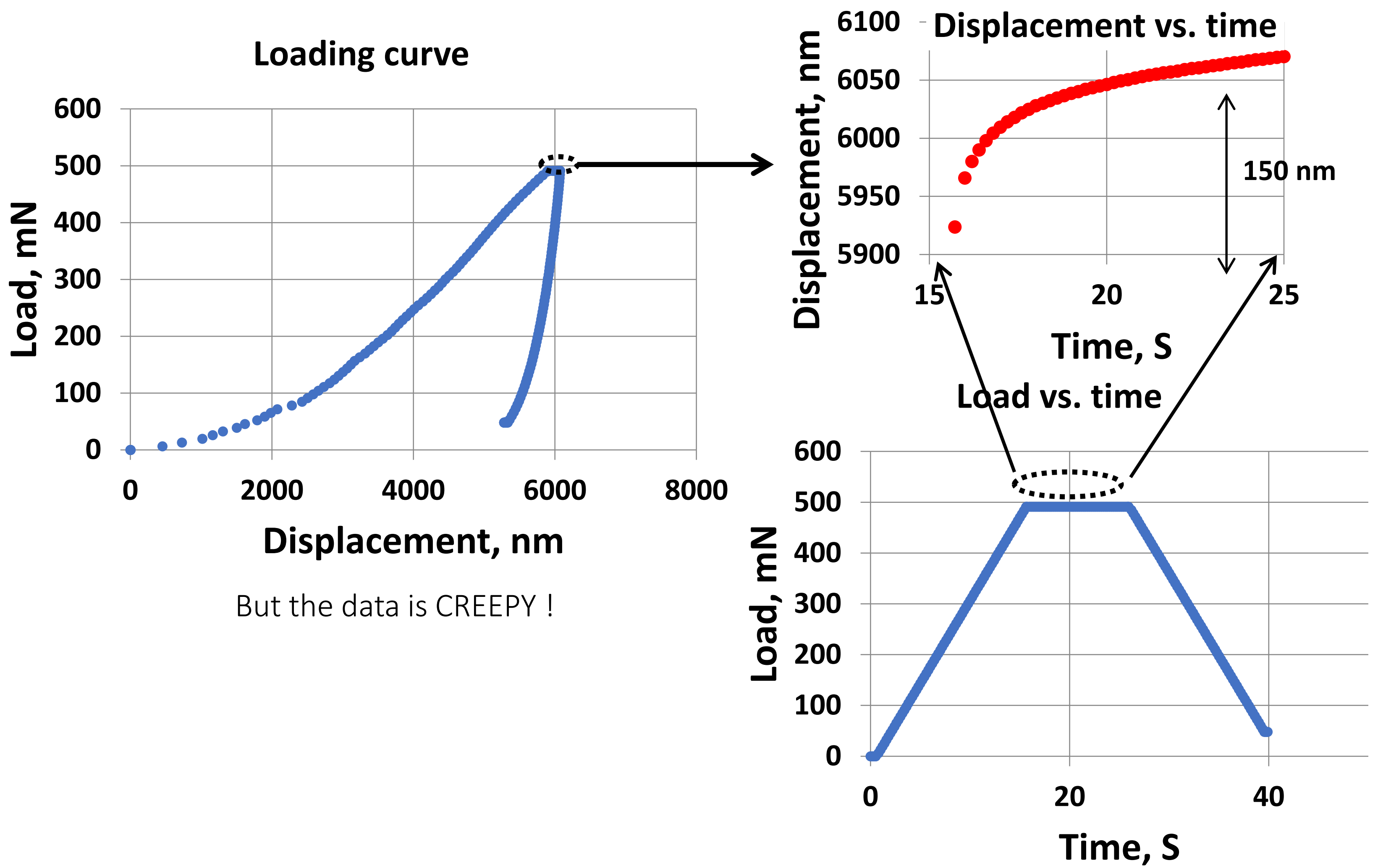
Agreement is better at high pressure

Anisotropy vs organic maturity



Expectation is that anisotropy would decrease with maturity

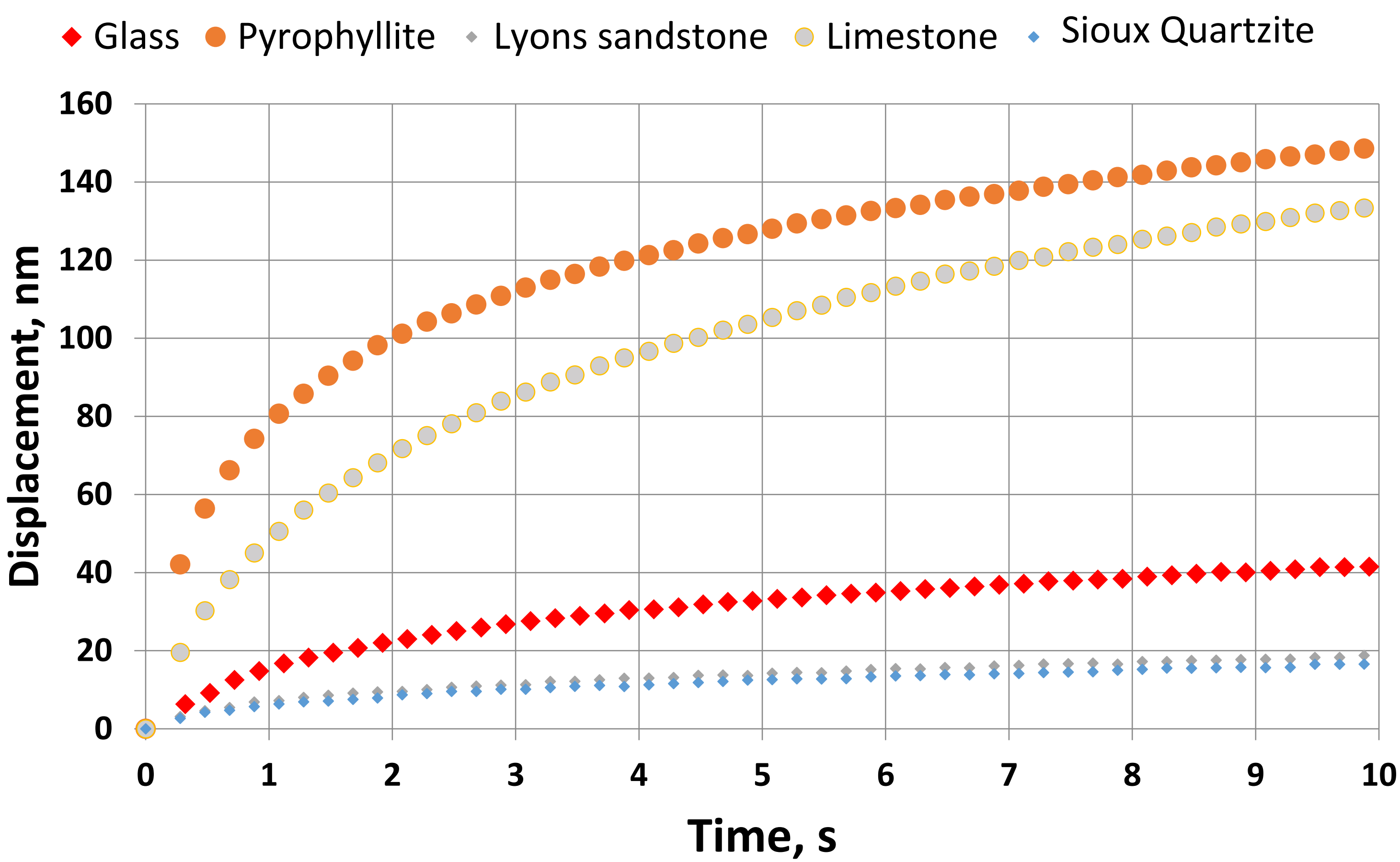
Nanoindentation measurement of creep behavior



But the data is CREEPY !

Wick, 2015; Mighani et al., 2015

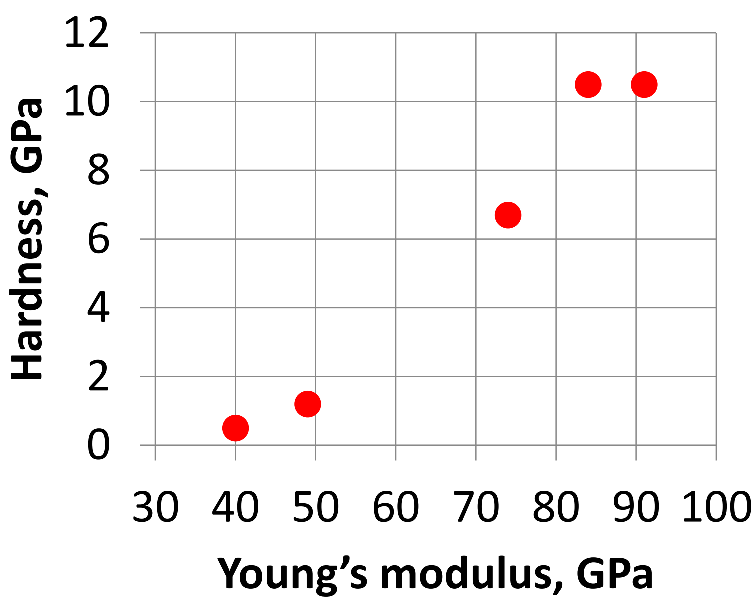
Creep for different materials

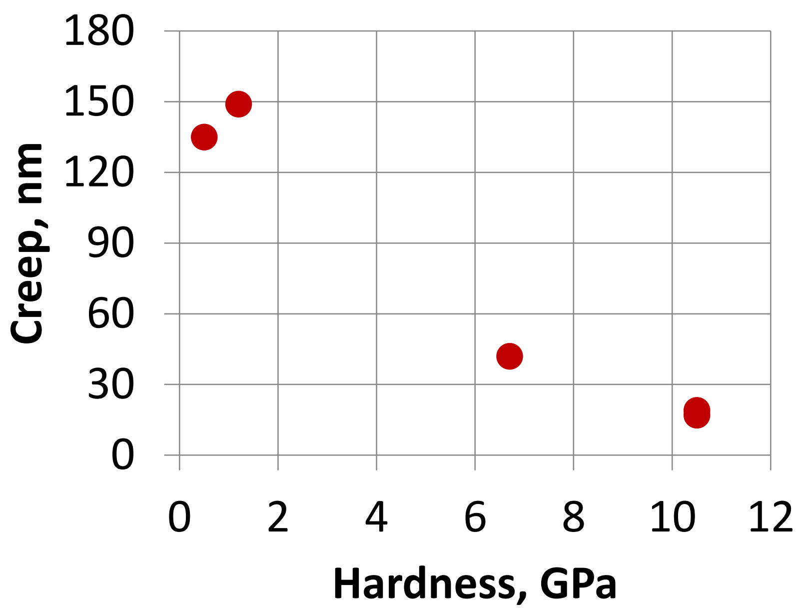


Mighani et al. 2015

Creep comparison for different materials

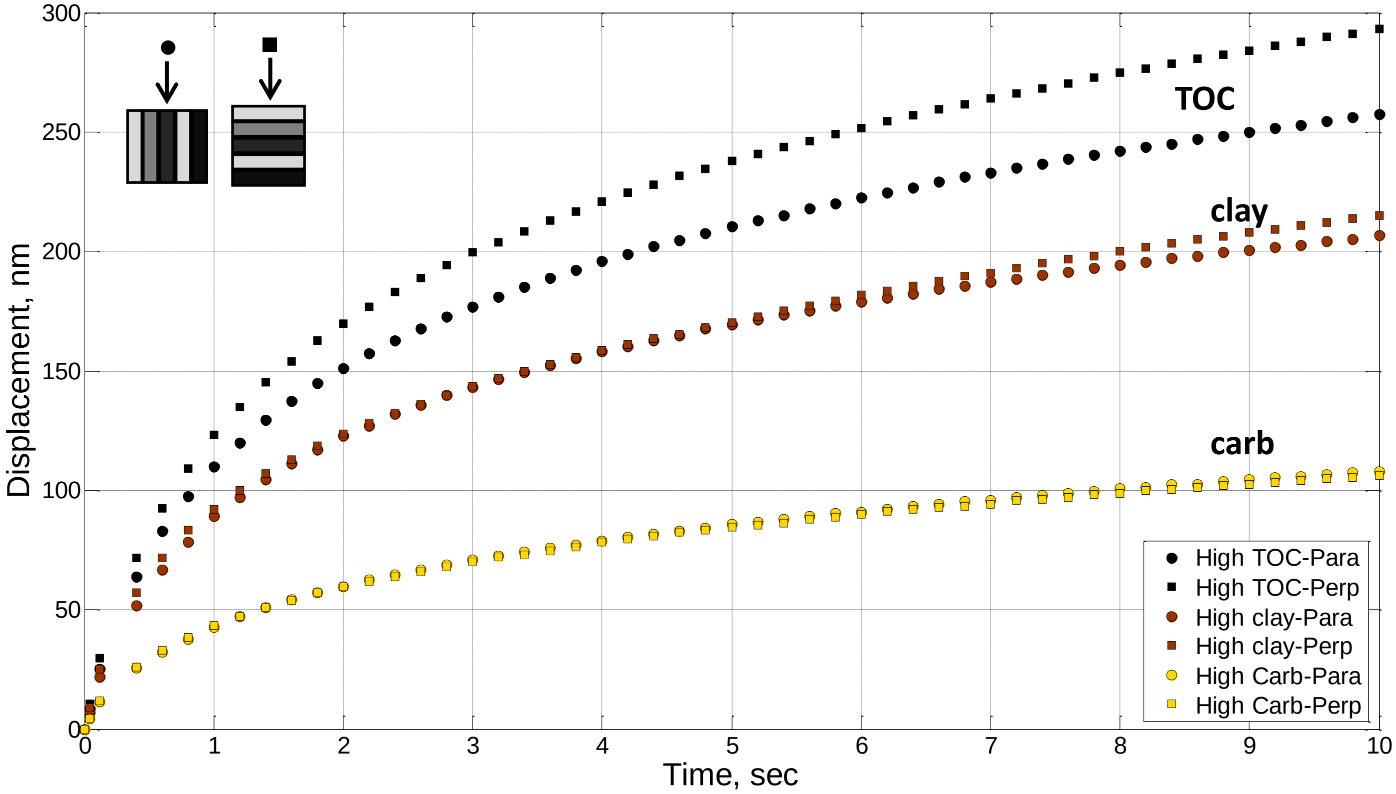
	Young's modulus (GPa)	Hardness (GPa)	Initial depth before creep (nm)	Creep (nm)
Glass	74	6.7	2170	42
pyrophyllite	49	1.2	5924	149
Sioux Quartzite	91	10.5	2013	19
Limestone	40	0.5	3200	135
Lyons sandstone	84	10.5	1836	17





Mighani et al., 2015

Creep in shales - Wolfcamp



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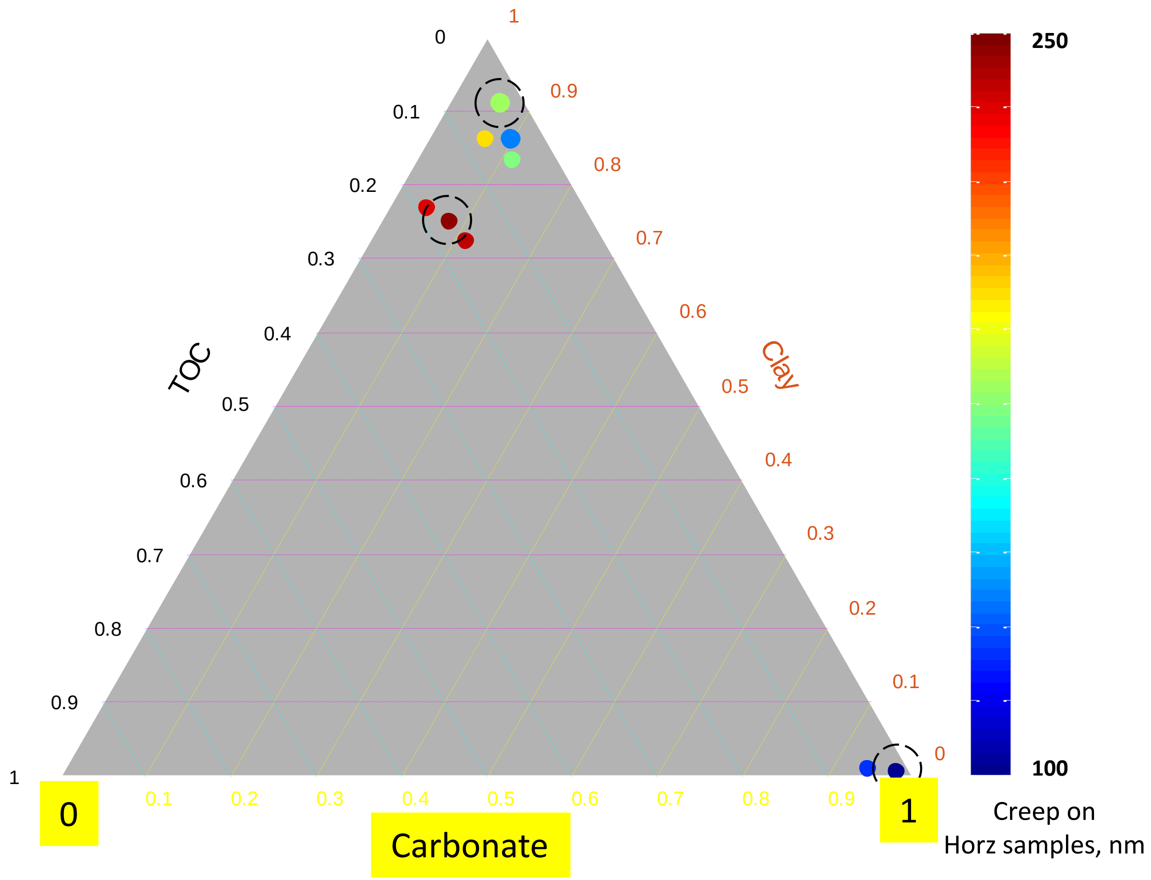
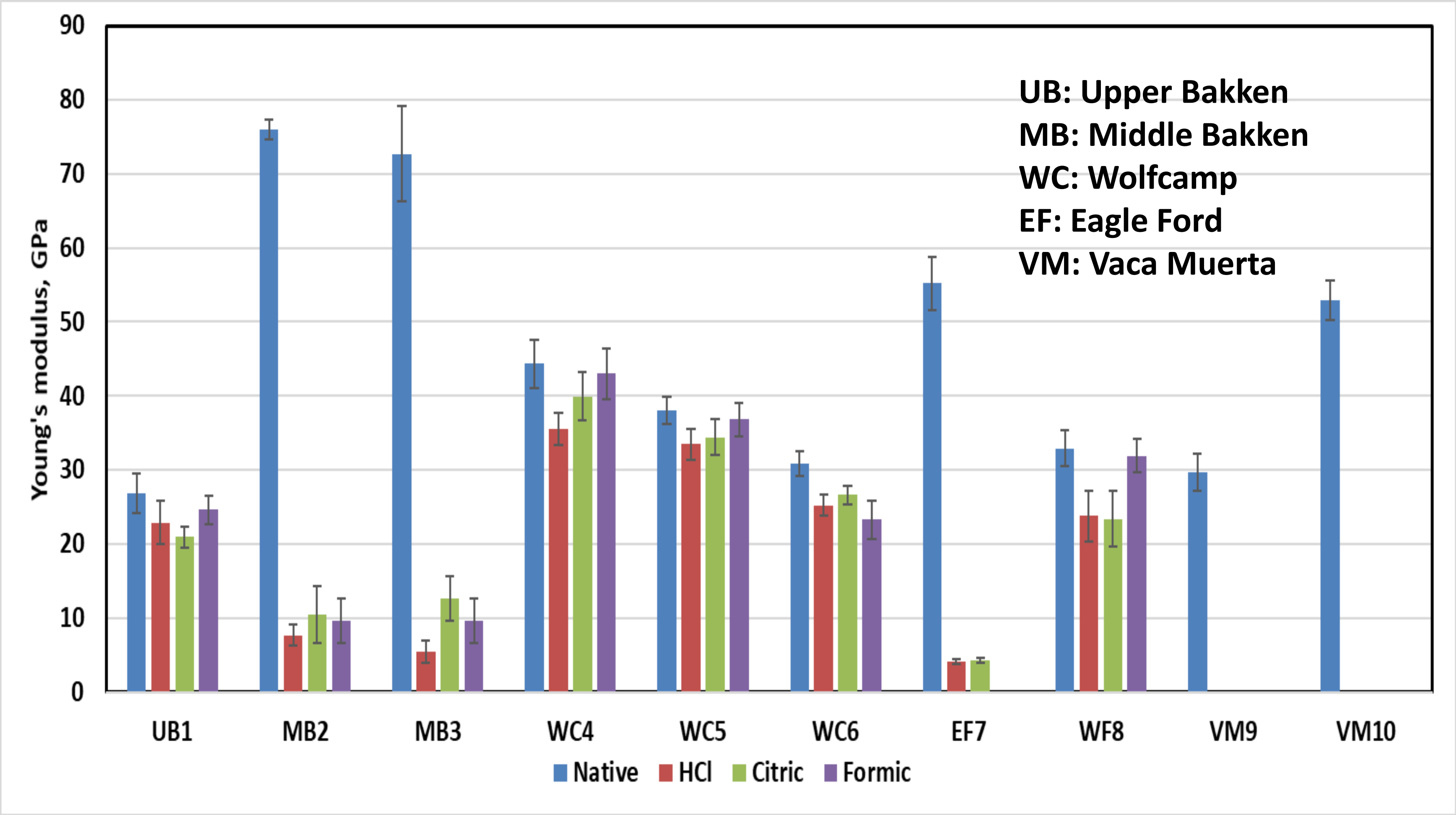


Mighani et al., 2015

Shale: Young's modulus sensitivity to acids



Wick, 2015

Summary

Shales present formidable problems in recovering samples suitable for geomechanical testing.

Multistage testing can produce failure envelopes from a single sample.

New technologies such as nanoindentation can recover elastic moduli, creep parameters, fluid sensitivity and an indication of anisotropy.

MICP can recover compressibility.

Why do we treat shale as geomechanically isotropic?

There are 8 different measures of brittleness and the one we use has a pressure dependence which is counter intuitive! moduli ≠ brittleness

Summary

We need better testing documentation:

Composition,
Porosity,
TOC,
Age,
Orientation,
Static/dynamic,
Static (strain rate),
Test pressure/temperature,
Saturation (fluid, dry?),
Drained/undrained
Preserved?

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