Viscoplastic Deformation of Shale Gas Reservoir Rocks and its Relation to the In-Situ Stress Variations Observed in a Well from Barnett Shale*

Hiroki Sone[1] and Mark Zoback[2]

Search and Discovery Article #41181 (2013)**
Posted August 19, 2013

*Adapted from oral presentation given at AAPG Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19-22, 2013

[1]GeoForschungZentrum, Potsdam (sone@gfz-potsdam.de)
[2]Department of Geophysics, Stanford University, Stanford, CA

Abstract

We have studied the viscoelastic/viscoplastic properties of various shale gas reservoir rocks through laboratory triaxial creep experiments under confining pressures representative of in situ conditions. We find that the viscoelastic stress relaxation behavior of these rocks vary considerably and is generally larger for rocks with more clay and organic content. The strain response of the rock is adequately described by a power-law function of time, and its magnitude is approximately linear against the magnitude of the applied differential pressure but insensitive to the confining pressure. Motivated by these observations, we described the rheology of the shales in the framework of linear viscoelasticity in order to calculate the differential stress accumulation/relaxation that would occur in these reservoirs over geological time scales. Variation in viscoelastic properties within the Barnett Shale can create differential stress variations on the order of one to tens of MPa, consistent with fluctuations in stress difference inferred from observations of wellbore failures. Although time-dependent deformational behaviors of intact reservoir rocks are not studied routinely in the lab, we suggest that it can have a significant impact in determining the current in-situ state of stress when reservoir deformation takes place over geological time scales.

Reference Cited

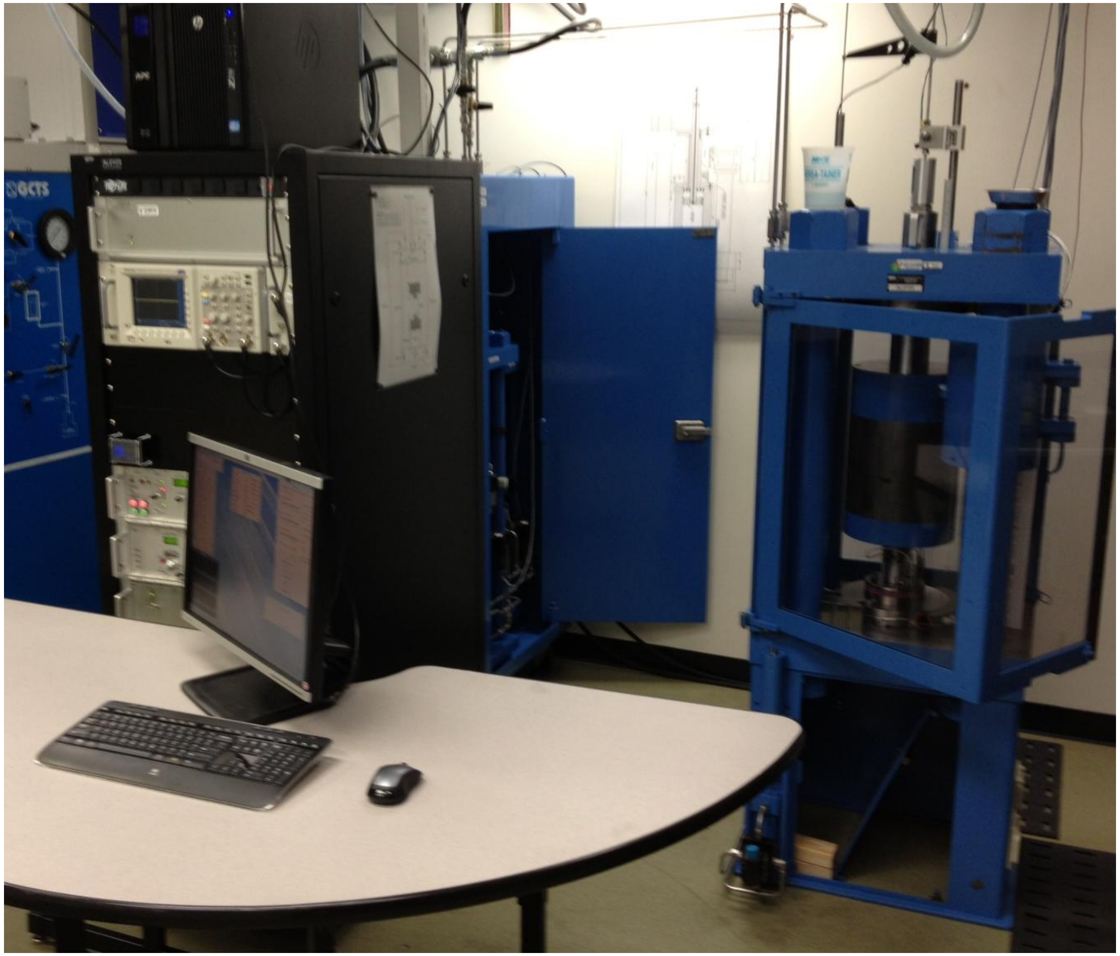
Hagin, P.N., and M.D. Zoback, 2004, viscous deformation of unconsolidated reservoir sands (Part II): Linear Viscoelastic models: Geophysics, v. 69/3, p. 742-751.

Viscoplastic Deformation of Shale Gas Reservoir Rocks and its Long-Term Effect on the In-Situ State of Stress

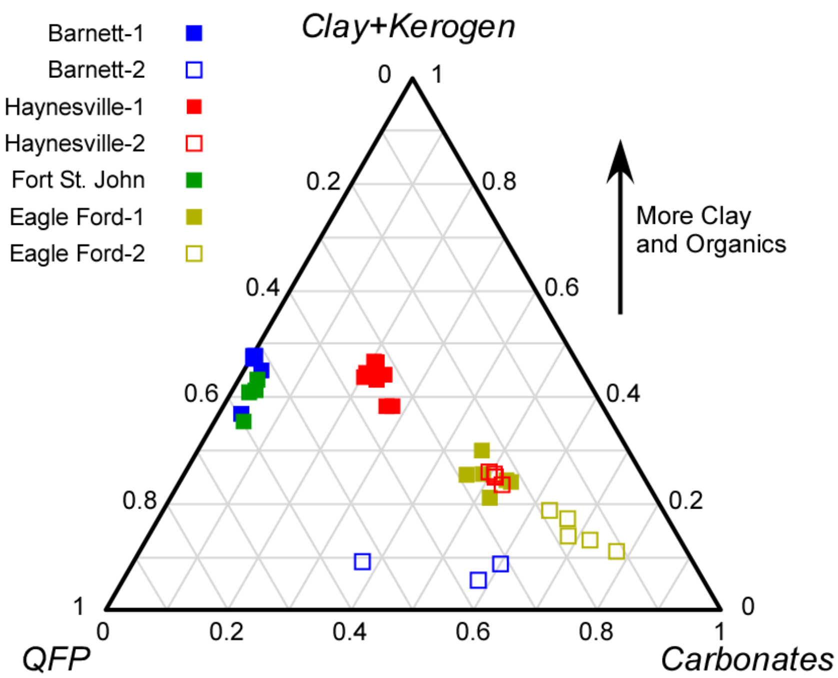
Hiroki Sone* and Mark D. Zoback
Department of Geophysics
Stanford University
* Now at GeoForschungZentrum, Potsdam

STANFORD UNIVERSITY

Creep Studies of Shale



Gas Shale Samples



Barnett-1

Barnett-2

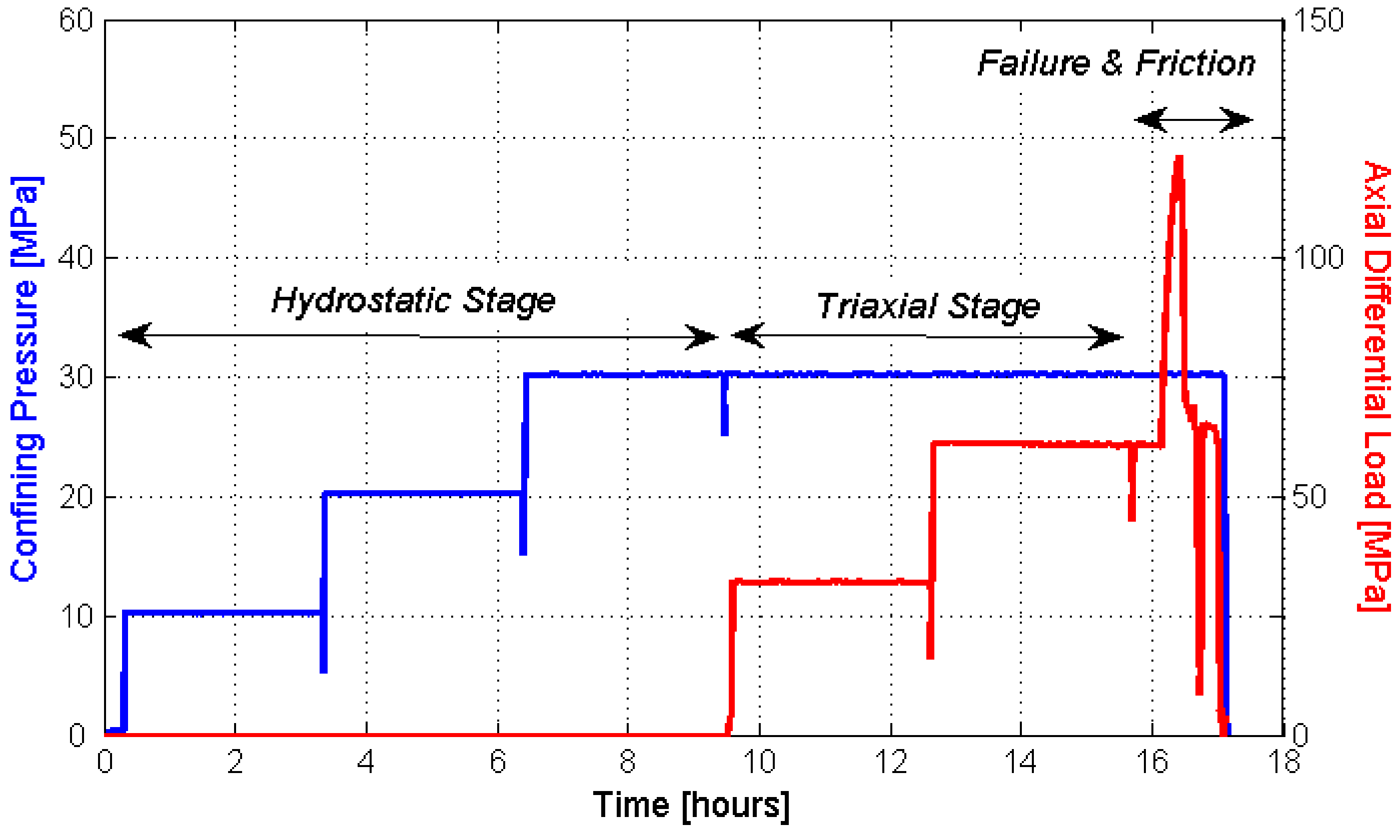
- 4 different shale gas reservoirs
- Barnett, Haynesville, Eagle Ford divided into subgroups
  subgroup-1 more clay-rich and organic-rich than subgroup-2
- 1” diameter cylindrical samples
- Cylinder axis vertical and horizontal to bedding plane

Organic Rich Shales

Sample group	Clay	Carbonate	QFP	TOC (wt%)
Barnett-dark	29-43	0-6	48-59	4.1-5.8
Barnett-light	2-7	37-81	16-53	0.4-1.3
Haynesville-dark	36-39	20-23	31-35	3.7-4.1
Haynesville-light	20-22	49-53	23-24	1.7-1.8
Fort St. John	32-39	3-5	54-60	1.6-2.2
Eagle Ford-dark	12-21	46-54	22-29	4.4-5.7
Eagle Ford-light	6-14	63-78	11-18	1.9-2.5

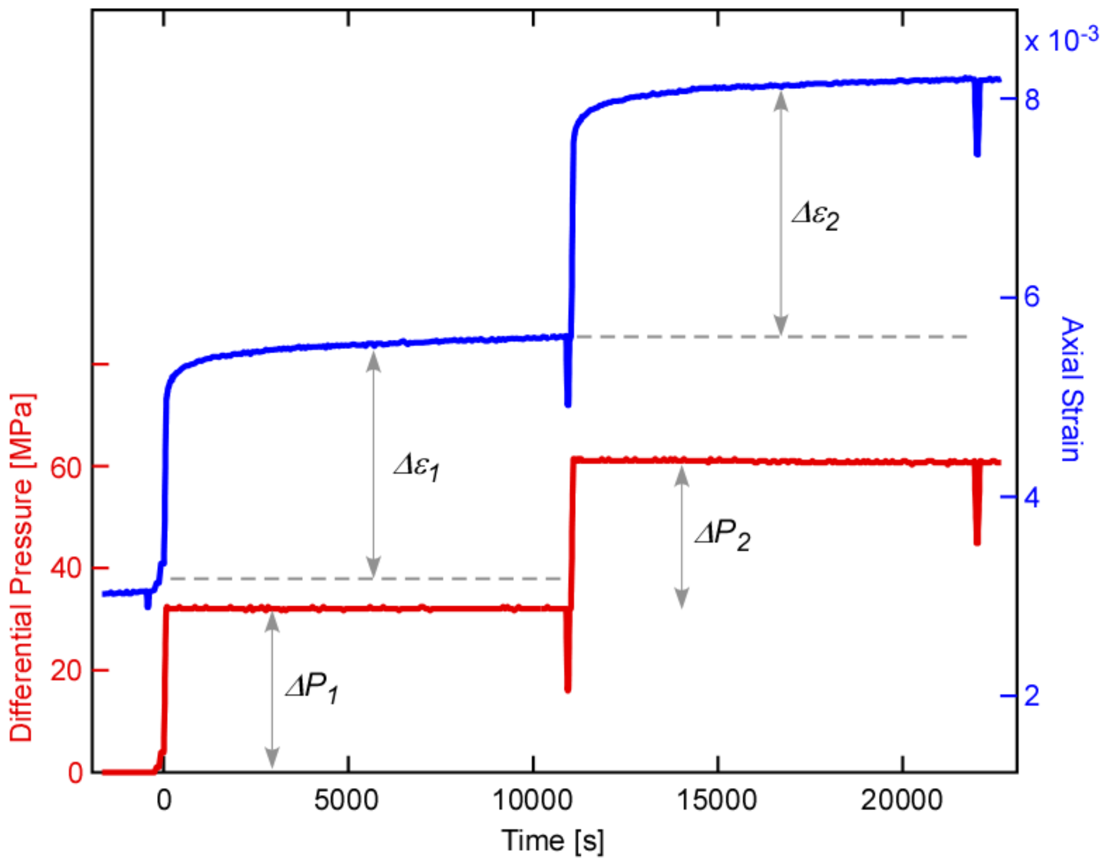
- 3-10 % porosity
- All room dry, room temperature experiments
- In-situ (and lab) effective stress between 15-30 MPa

Typical Experimental Procedure



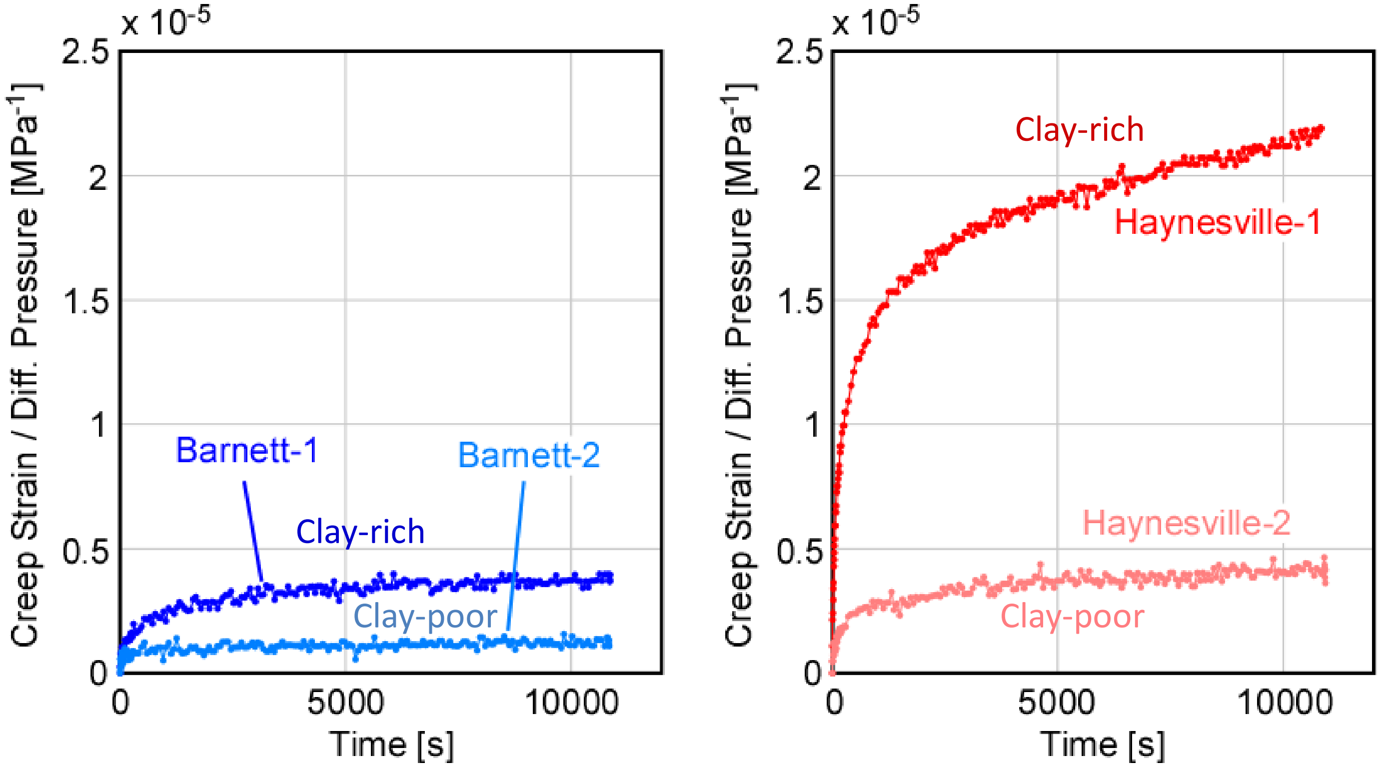
- Hydrostatic Stage: Bulk modulus, hydrostatic creep
- Triaxial State: Young's modulus, Poisson ration, triaxial creep
- Failure&Friction: Onset of dilatancy, intact/frictional strength

Experimental Procedure



- Confining pressure 10-60 MPa
- Differential pressure applied in several steps
- Held differential pressure constant for 3 hrs ~ 2 weeks
- Observed creep behavior to constrain J(t)

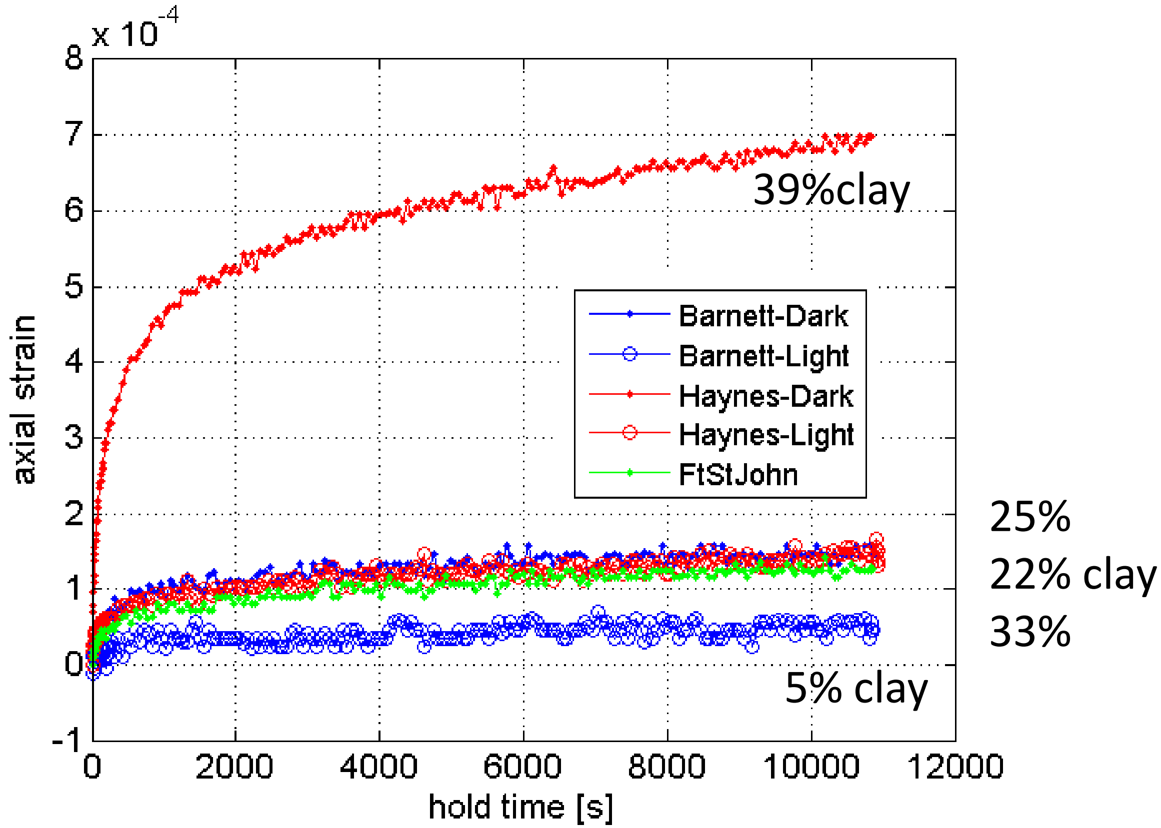
Clay/Organic Content Promotes Ductility

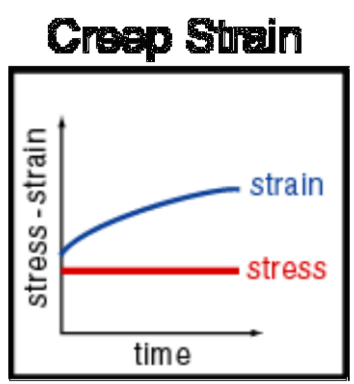


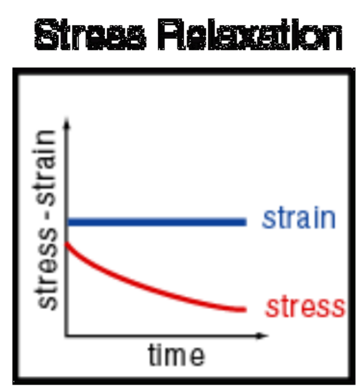
- Creep (ductility) is more pronounced in clay-rich, organic-rich rocks in all reservoirs

- Volume reduction and velocity increase during creep suggests creep is accommodated by compaction in clays and organics

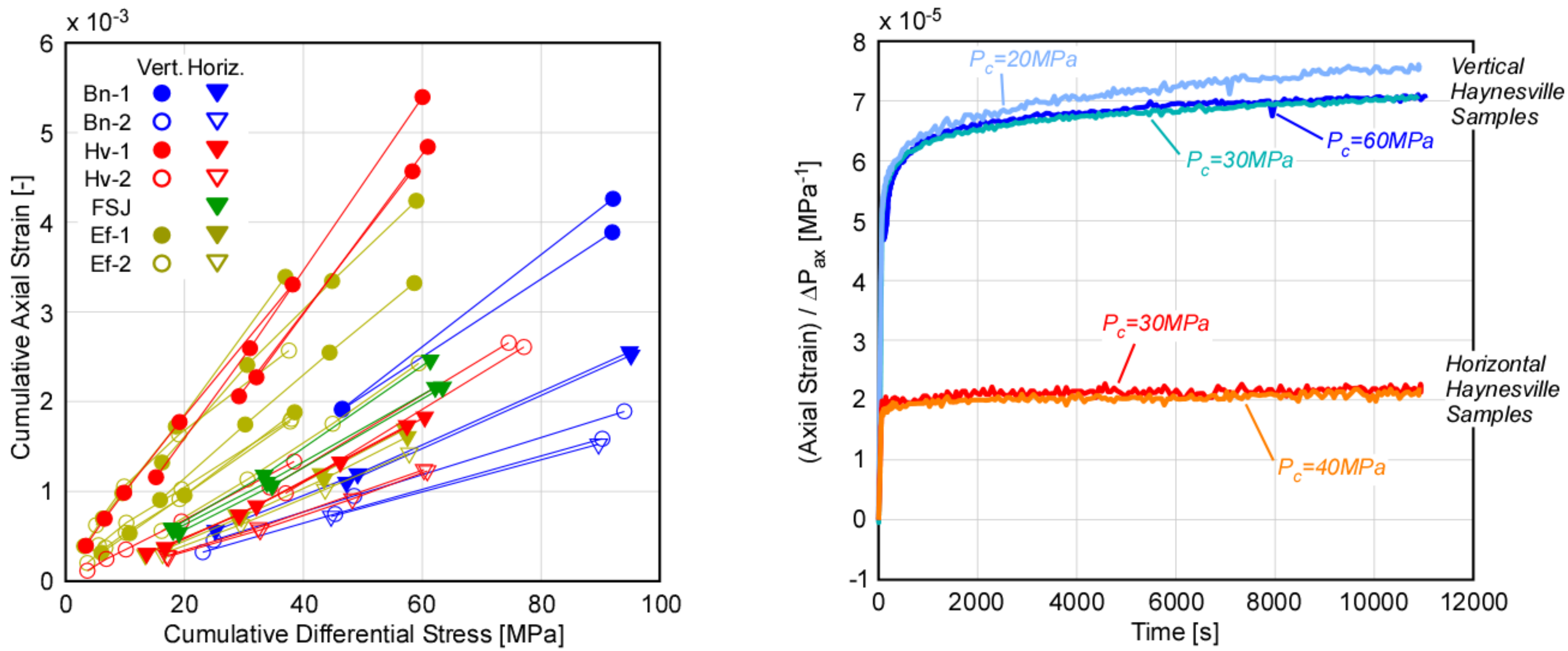
Clay/Organic Content Promotes Ductility







Pressure Dependence



- Relation between cumulative strain and axial pressure is roughly proportional
- The amount of deformation is not dependent on the confining pressure (isotropic stress)

  → *Strain is linear against differential pressure*

  → *Justifies the use of linear viscoelasticity*

Quantitative Analysis via Linear Viscoelasticity

- **Addition of time parameter to linear elasticity**
  modulus C → E(t),
  compliance S → J(t)

  E(t): Relaxation Modulus
  J(t): Creep Compliance

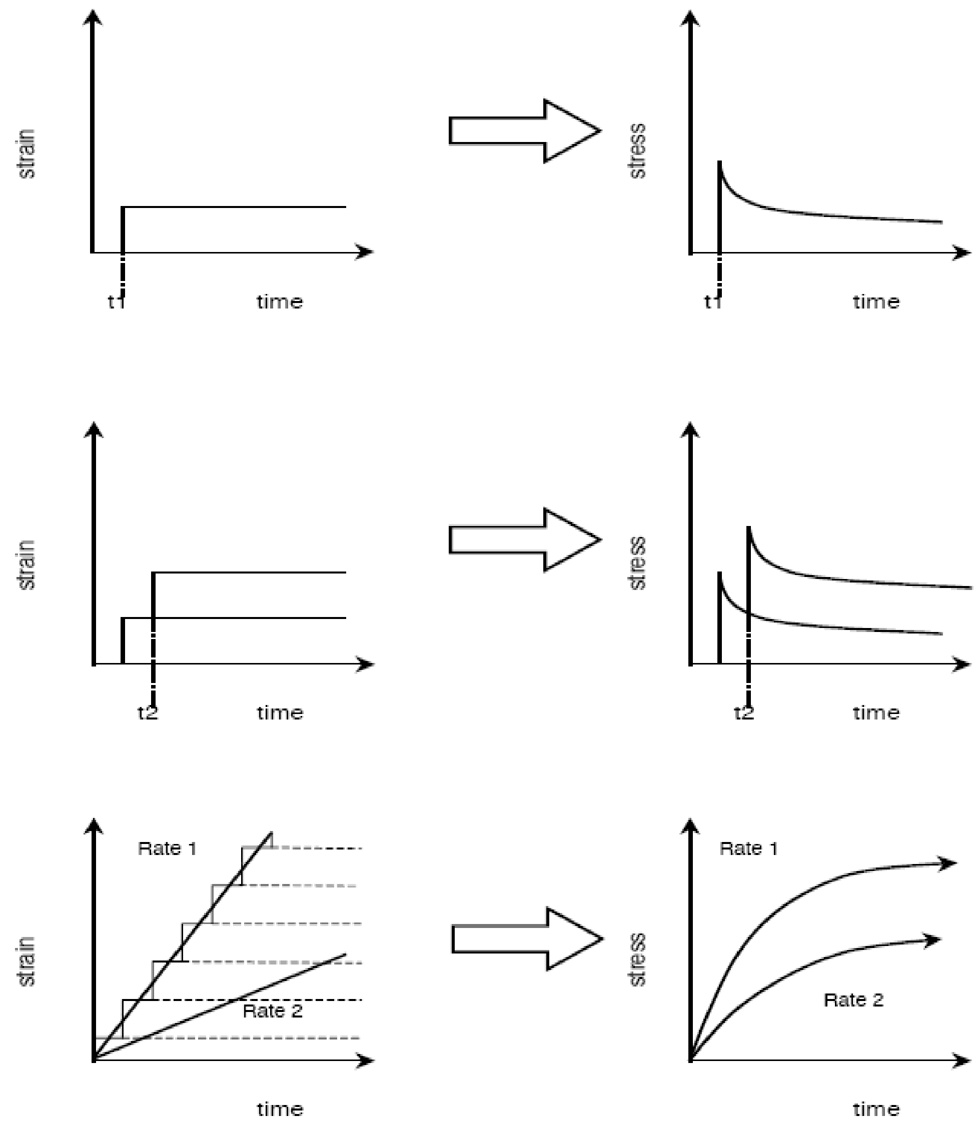
- **Linear superposition**

$$\sigma(t) = \int_0^t E(t-\tau)\frac{d\varepsilon}{d\tau}d\tau$$

$$\varepsilon(t) = \int_0^t J(t-\tau)\frac{d\sigma}{d\tau}d\tau$$

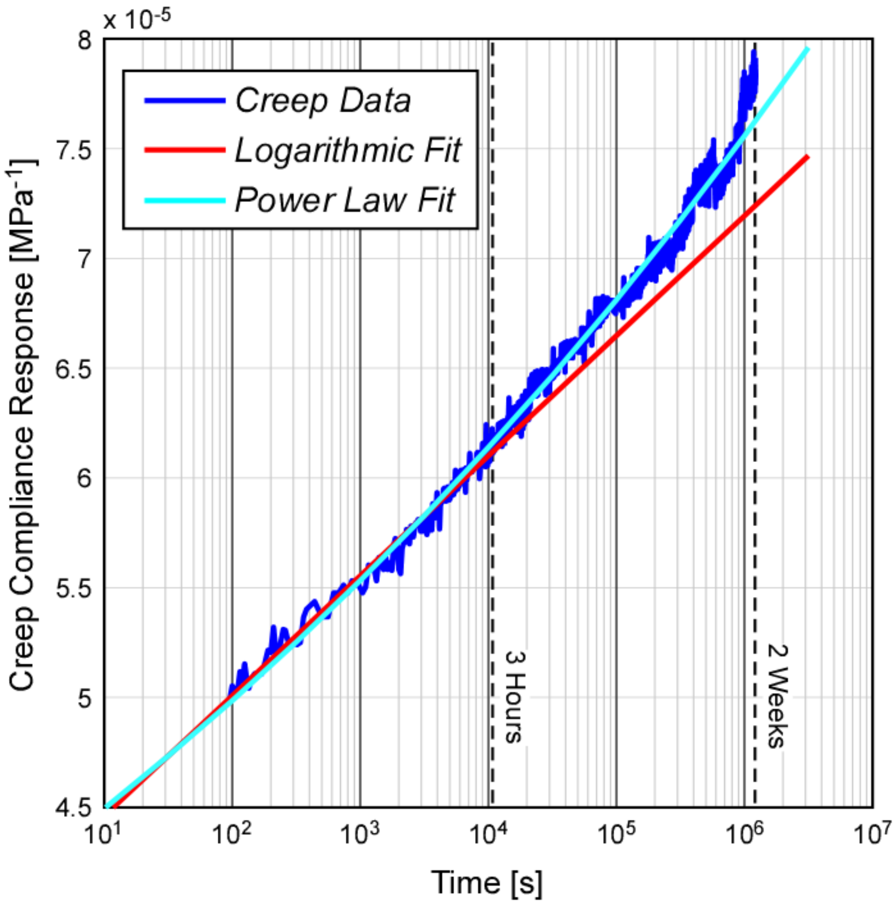
In the Laplace domain,

$$E(s)J(s) = \frac{1}{s^2}$$



Hagin and Zoback (2004)

Power-law Creep Compliance, J(t)=Bt^n



- Characteristics of creep
  1. Creep does not reach asymptote
  2. Creep rate continues to decrease
- Power-law expression has better long-term predictability of creep behavior
- Power-law expression also known to be useful for concrete, asphalt

Convenience of the Power-law

- Relaxation Modulus, E(t), is easily obtained

$$J(t) = Bt^n$$

$$J(s) = \frac{B\Gamma(n+1)}{s^{1+n}}$$

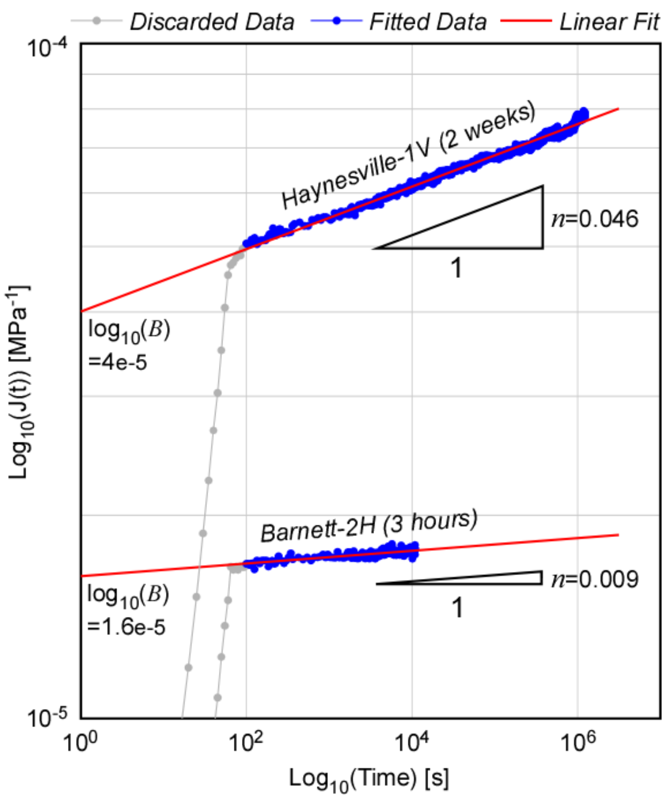
$$E(s) = \frac{1}{s^2 J(s)} = \frac{1}{B\Gamma(n+1)} \frac{1}{s^{1-n}}$$

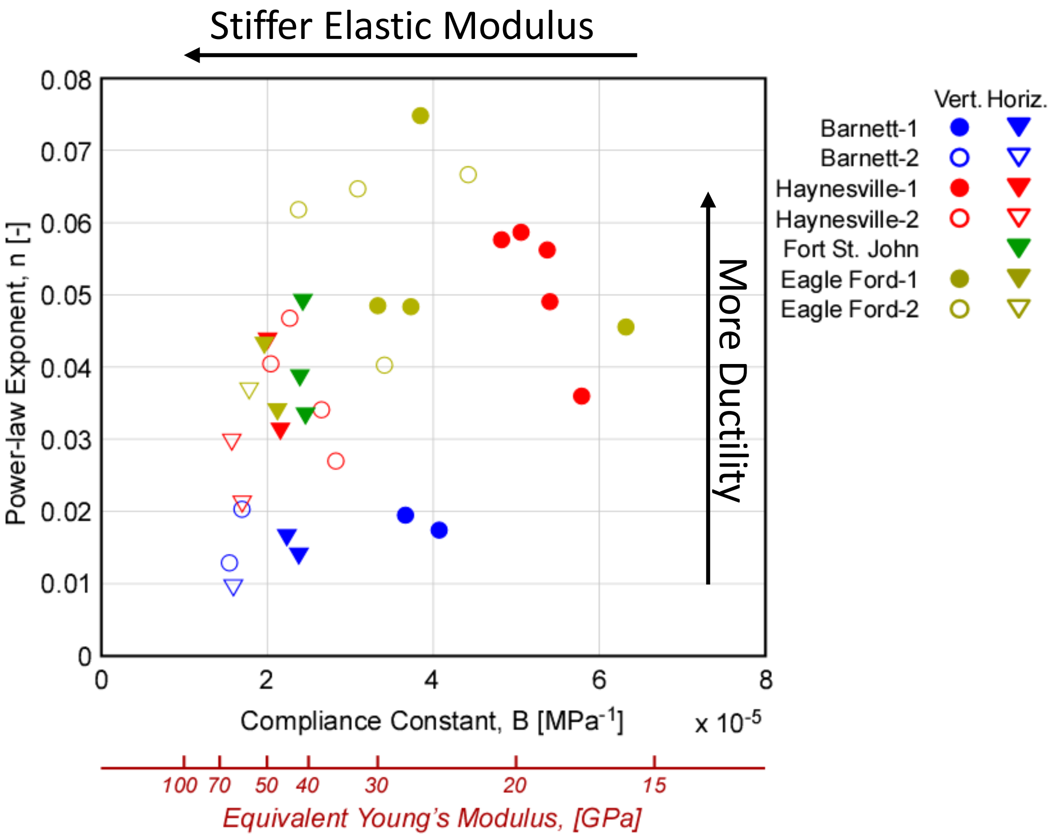
$$E(t) = \frac{1}{B\Gamma(1+n)\Gamma(1-n)} t^{-n} \approx \frac{1}{B} t^{-n} \quad (n << 1)$$

$$\sigma(t) = \dot{\varepsilon} \frac{1}{B(1-n)} t^{1-n}$$

- 1/*B* is roughly equal to the elastic Young's modulus
- *n* is the power-law exponent, the degree of ductility, or how much time-dependent deformation you get

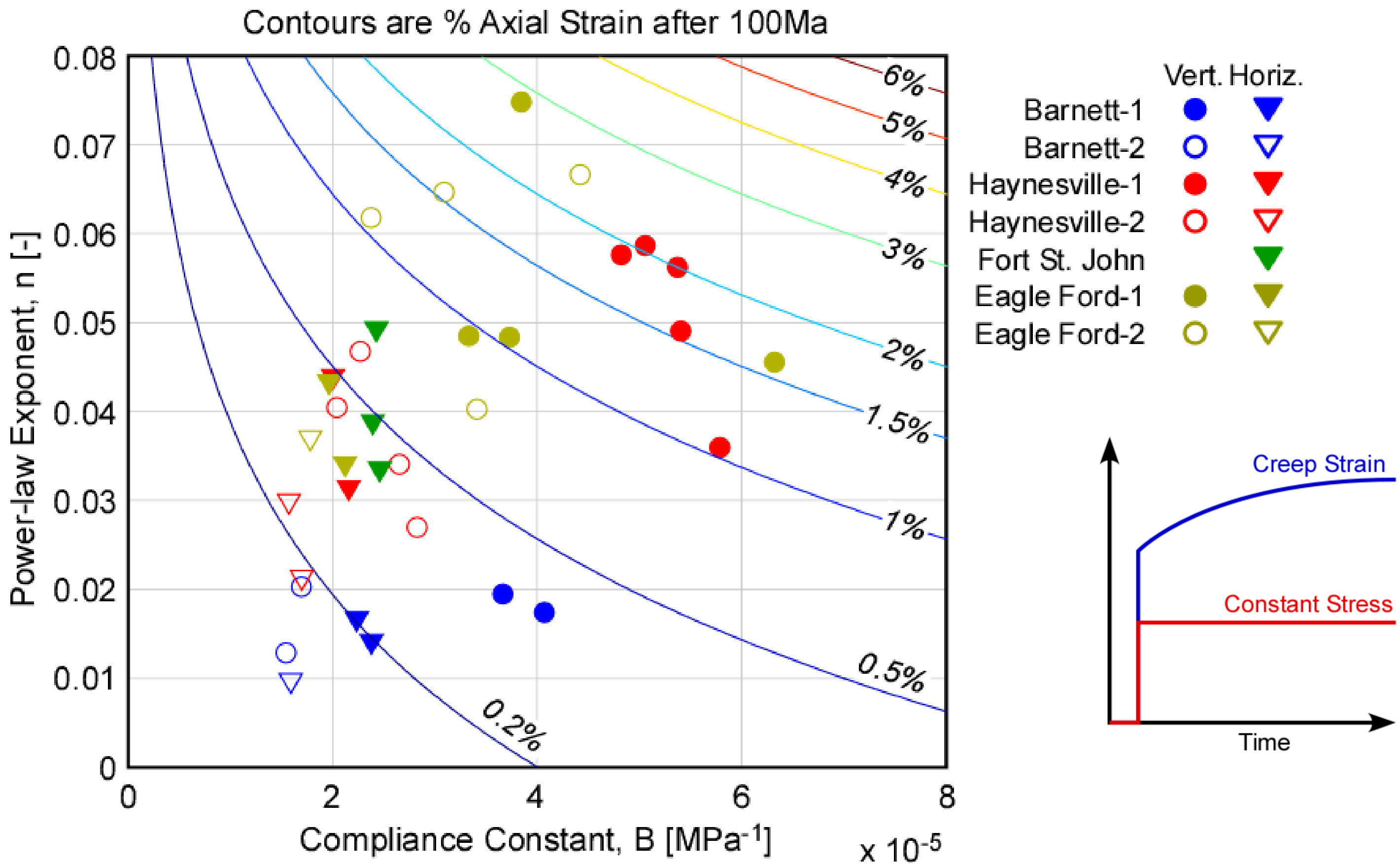
Constitutive Parameters in $J(t)=Bt^n$





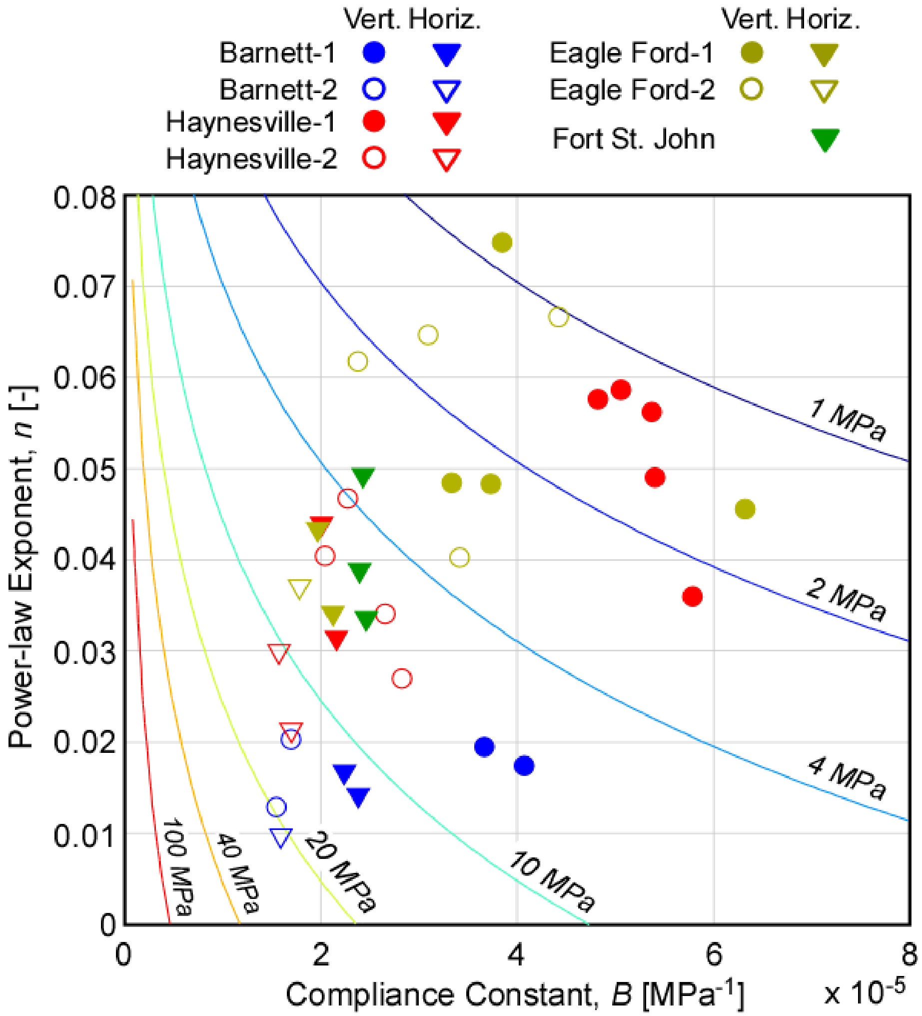
- Creep data fit by a line in log-log space
  - → ***B*** and ***n*** are obtained for each sample
- Samples exhibit wide variety of behavior

Creep Strain over Geological Time



- Contours are % strain under 50 MPa differential load
- Reasonable axial strain magnitudes of 0.1~3%

Predicting Stress Anisotropy over Geological Time

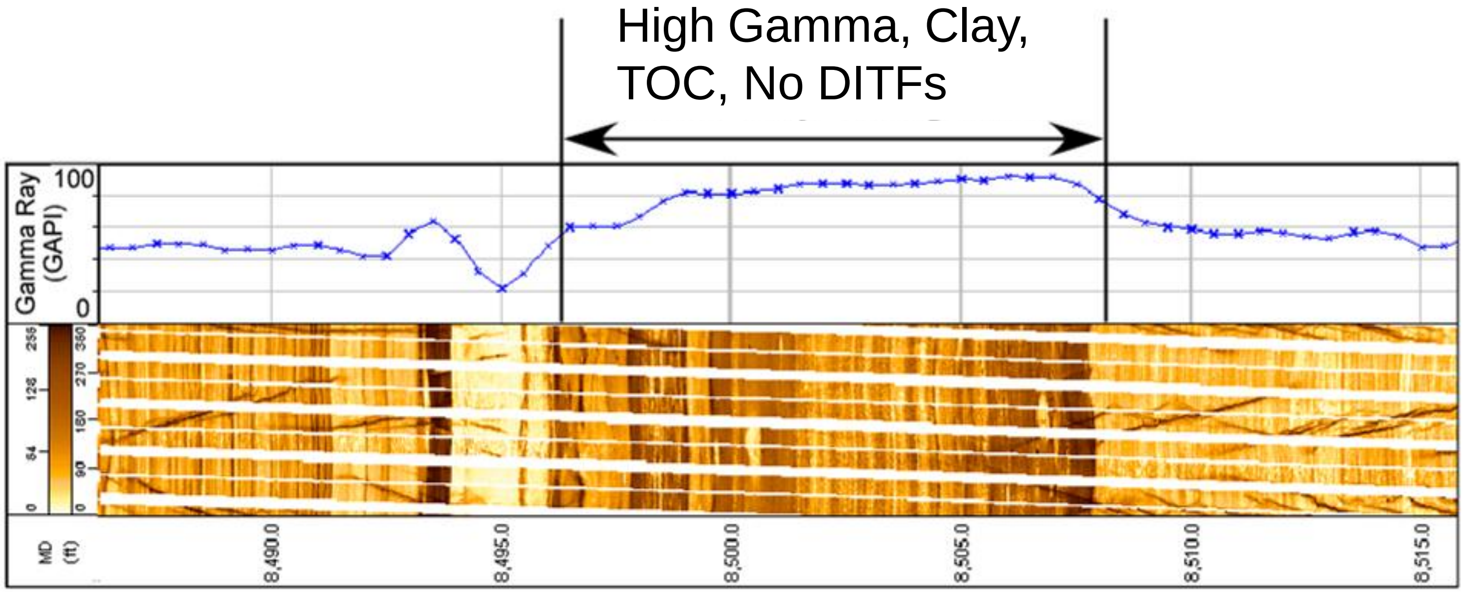


- Stress Accumulation under constant strain rate
  - 150 Ma - Half of age of Barnett shale
  - 10^{-19} s^{-1} - Stable intraplate

$$\sigma(t) = \dot{\varepsilon} \frac{1}{B(1-n)} t^{1-n}$$

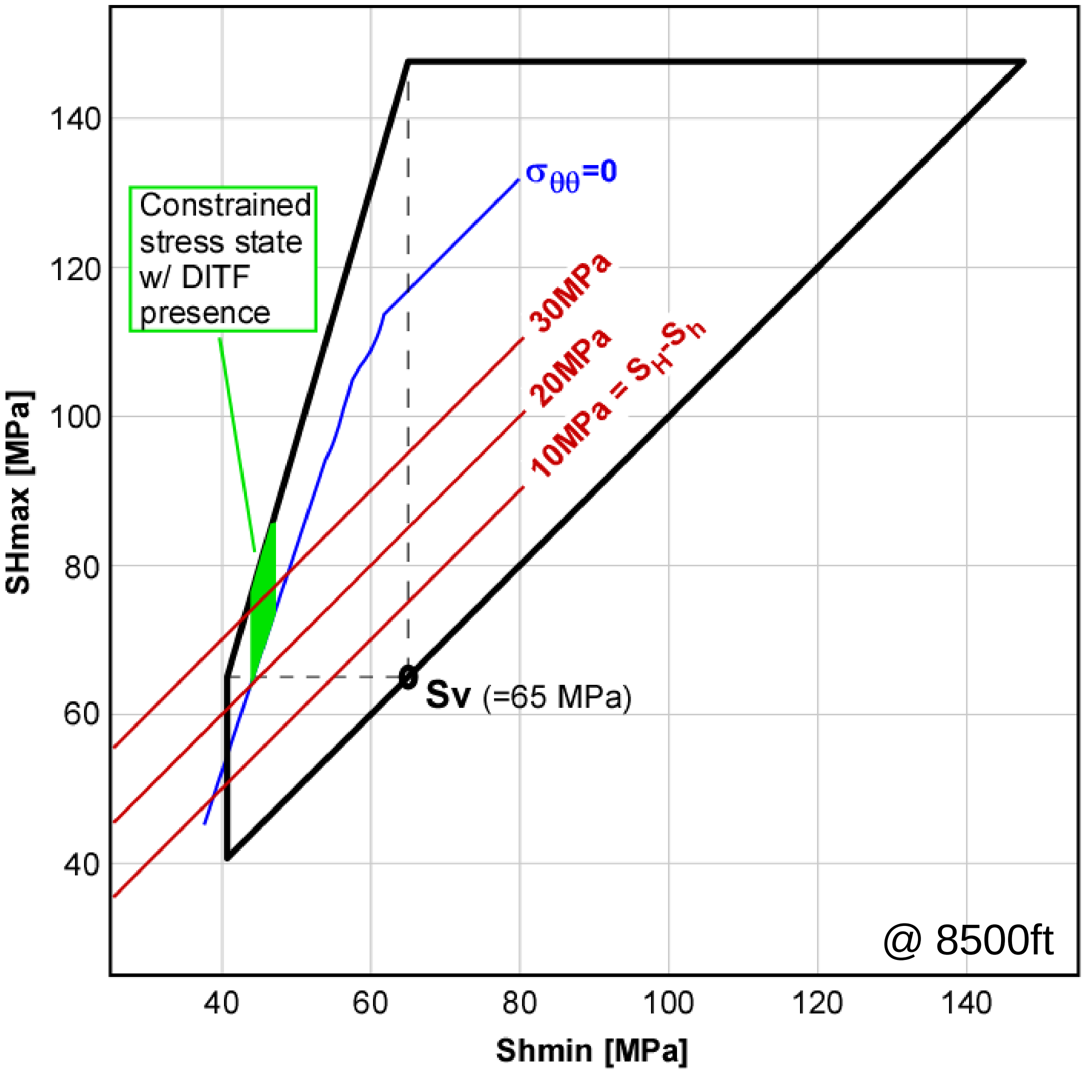
- Significant stress relaxation observed for high *n*

Stress Variation in the Barnett Shale



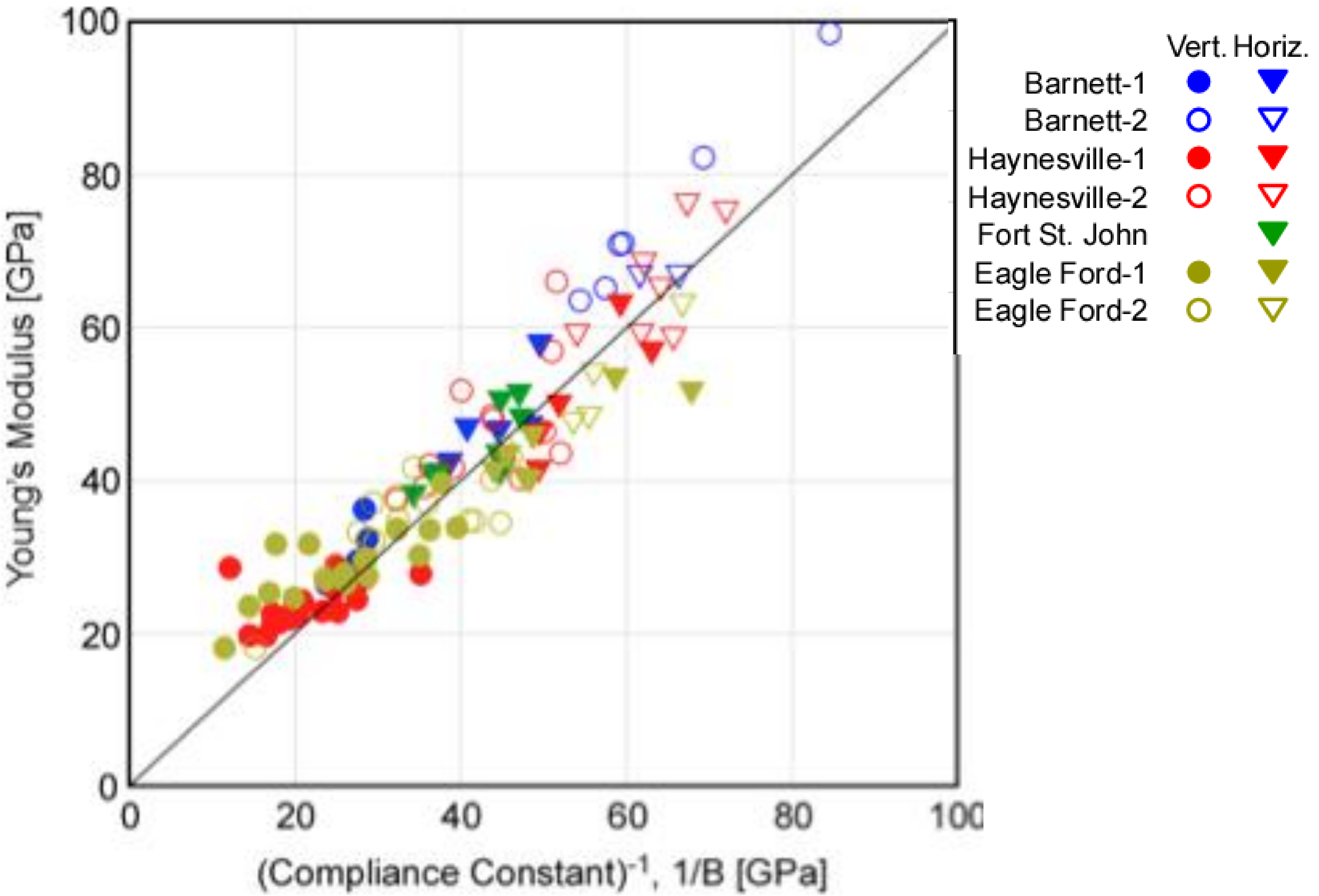
- DITF's disappears frequently in clay-/organic-rich layers
- Horizontal Stress Differences (S_{Hmax}-S_{hmin}) is relatively small in these clay-/organic-rich layers

Independent Estimate of Stress Magnitude

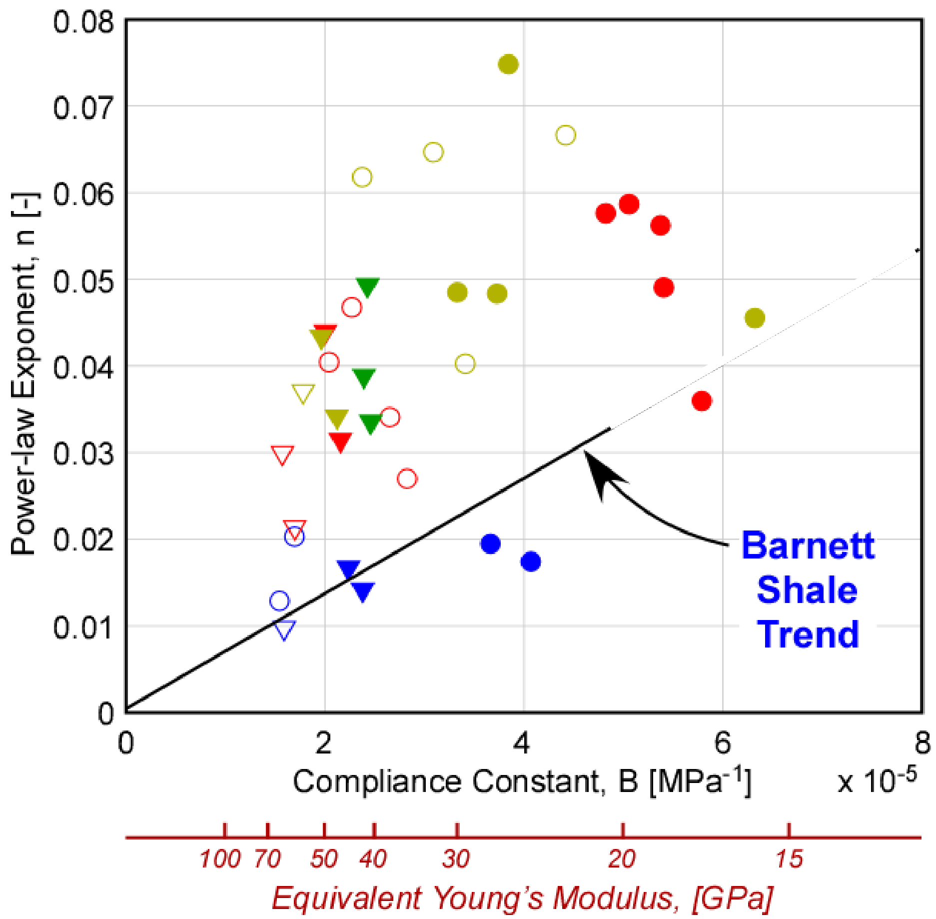


- Green region: stress state constrained from DITF presence
- Red lines: contours of constant horizontal stress difference
- DITF occurrence changes at around 20-25 MPa horizontal stress difference (S_{Hmax}-S_{hmin})

A Useful Correlation

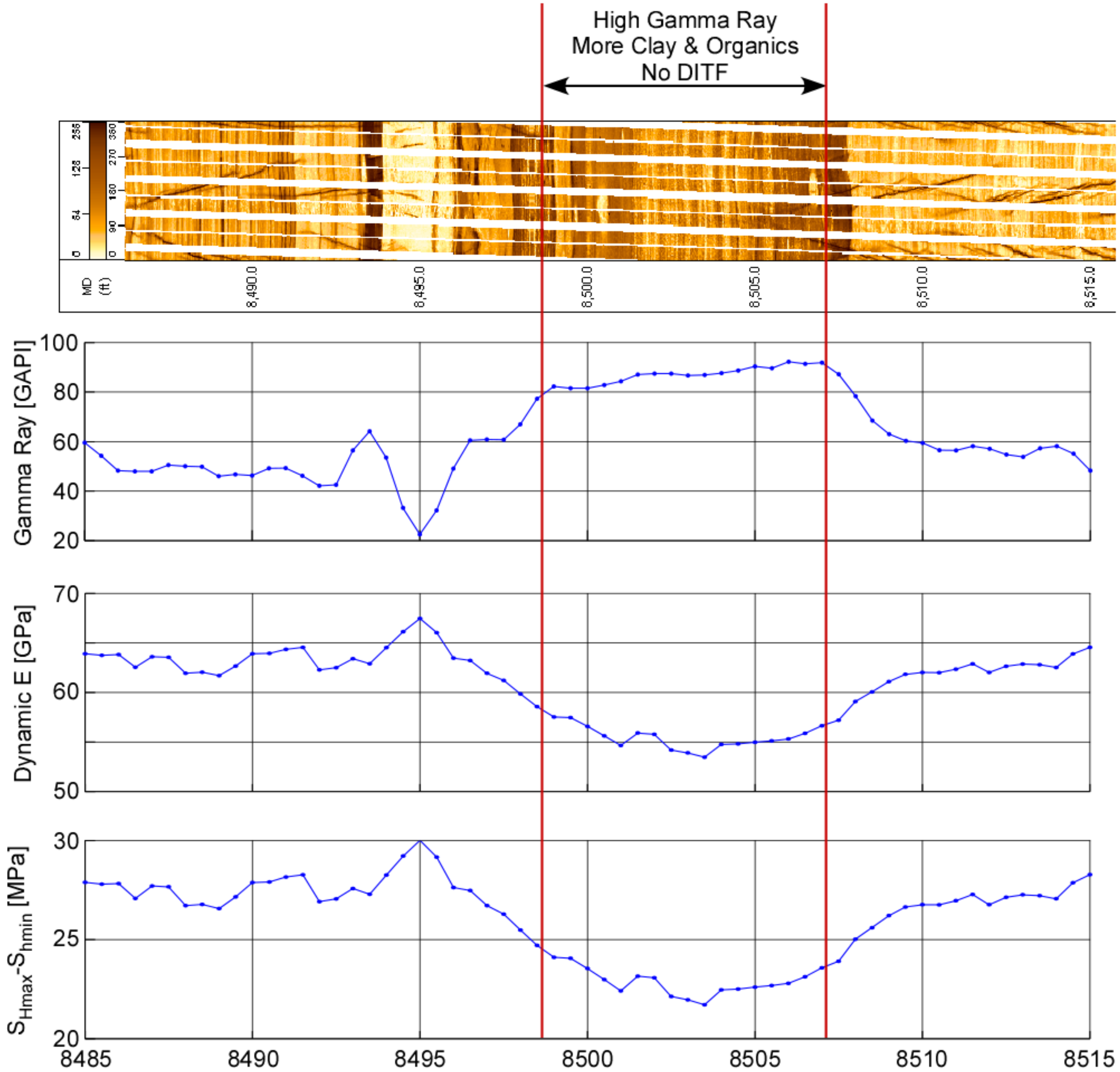


Lab Calibration of "*n*" for the Barnett Shale



- From sonic log data,
  → Dynamic E
  (≈ Static E)
- From empirical trend
  $n \approx 2000/3*B$,
  → constant B
  → constant n
- From viscoelastic theory
  → stress difference

Stress Variations in the Barnett Shale



- Stress analysis predicts lowered differential stress at where DITF is absent
- Transition of DITF presence/absence occurs at somewhere below 25 MPa horiz. stress diff.

Summary

- Organic Rich Shales Creep at Room Temperature

- Clay + Kerogen Content Affects How Much Creep Occurs

- A Power Law Constitutive Law Seems to Describe Creep Behavior

- The Constitutive Law (and Lab-Determined Parameters) Predict Reasonable Values for Stress Anisotropy

- Our Current Research is Focusing on the Creep Behavior of Specific Shales with Mineralogy and Other Factors