PS Effects on Brittleness of Temperature Difference Between Hydraulic Fracturing Fluid and Shale Formation – Study on Woodford Shale*

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Abstract

Objectives: A newly derived fully coupled thermo-hydro-geomechanics one-dimensional simulation is used to study the time-dependent evolution of the fracture aperture during hydraulic fracturing of the anisotropic Woodford Shale. The study aims at quantifying the effects of the spacing of natural fractures and the temperature gradient between the hotter reservoir rock and the colder fracturing fluid on the efficiency of the fracture job. The results can then be used to optimize hydraulic fracturing design for the shale reservoir.

Procedures: It has been observed during geological characterization that many natural fractures exist in the Woodford Shale and they are roughly vertical. During the hydraulic fracturing operation, they may reactivate and join to form fractures with almost parallel branches. Due to the large vertical and lateral extent of the hydraulic fracture, a section sufficiently far from the wellbore, fracture tips, and fracture joints can be modeled using the 1D solution.

Results: It was found that with an average natural fracture spacing of 1.2m, a fracturing fluid with the same temperature as the reservoir rock would create a nominal fracture aperture of 0.84 mm. Furthermore, this fracture will gradually closes due to shale swelling from the fracturing fluid invasion into the formation so proppant transport will gradually degrade. On the other hand, with a fracturing fluid 60°C colder than the rock formation, the fracture will gradually widen due to shale contraction as the cold front penetrates into the formation. At the end of the pumping, the aperture with the colder fracturing fluid is approximately 70% larger than that created with the hotter fluid. It was also found that the fracture aperture monotonically increases with increasing natural fracture spacing.

Conclusions: It is noted that while a wider fracture aperture promotes proppant transport, it requires more fracturing fluid volume to fill the same fracture length. In other words, the same pumped fluid volume will create a shorter hydraulic fracture and the impression of a less brittle formation. Therefore, it is crucial that the natural fracture spacing is taken as an input in the design of hydraulic fracturing jobs. Furthermore,

based on the proppant size and transport characteristics, the temperature of the fracturing fluid must be controlled to optimize both proppant transport and fracturing efficiency.

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Abstract

A newly-derived fully-coupled thermo-hydro-geomechanics one-dimensional simulation is used to study the time-dependent evolution of the fracture width during hydraulic fracturing of the anisotropic Woodford Shale. The study aims at quantifying the effects of the spacing of natural fractures and the temperature gradient between the hotter reservoir rock and the colder fracturing fluid on the efficiency of the fracture job. The results can then be used to optimize hydraulic fracturing design for the shale reservoir.

Overview of Woodford Shale

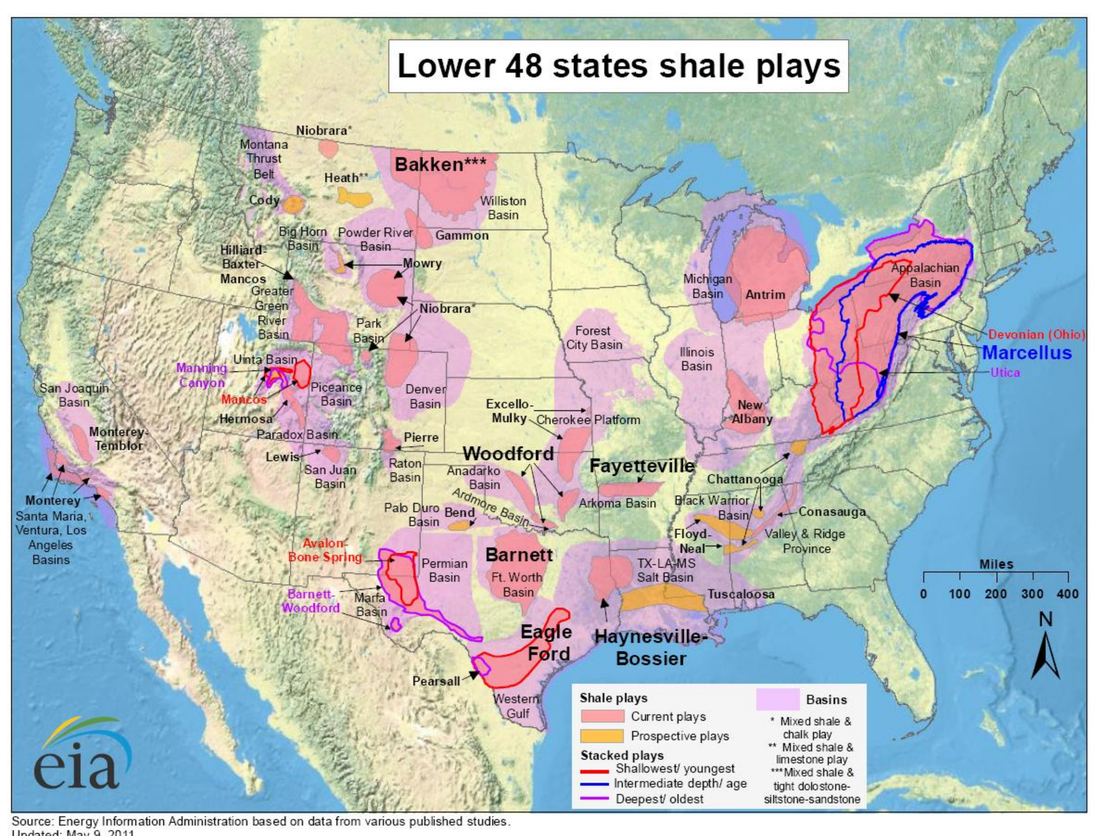


Figure 1. Gas and oil shale plays of the United States (Source: EIA).

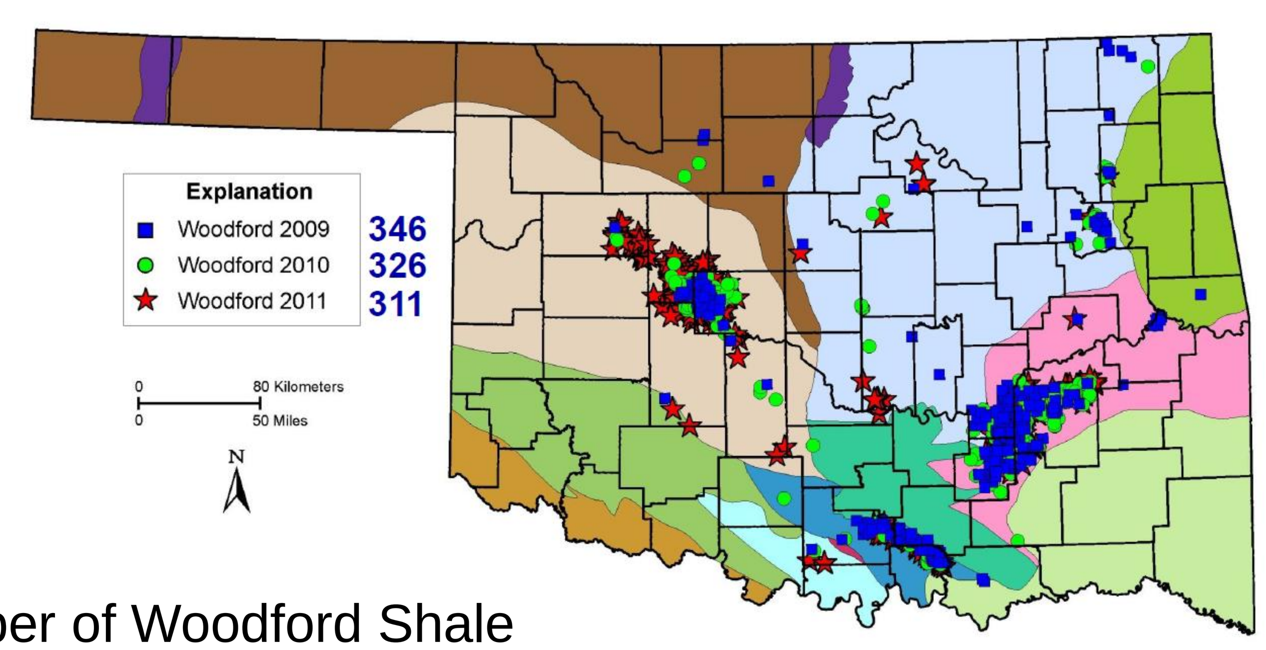


Figure 2. Number of Woodford Shale wells in Oklahoma (Cardott 2012).

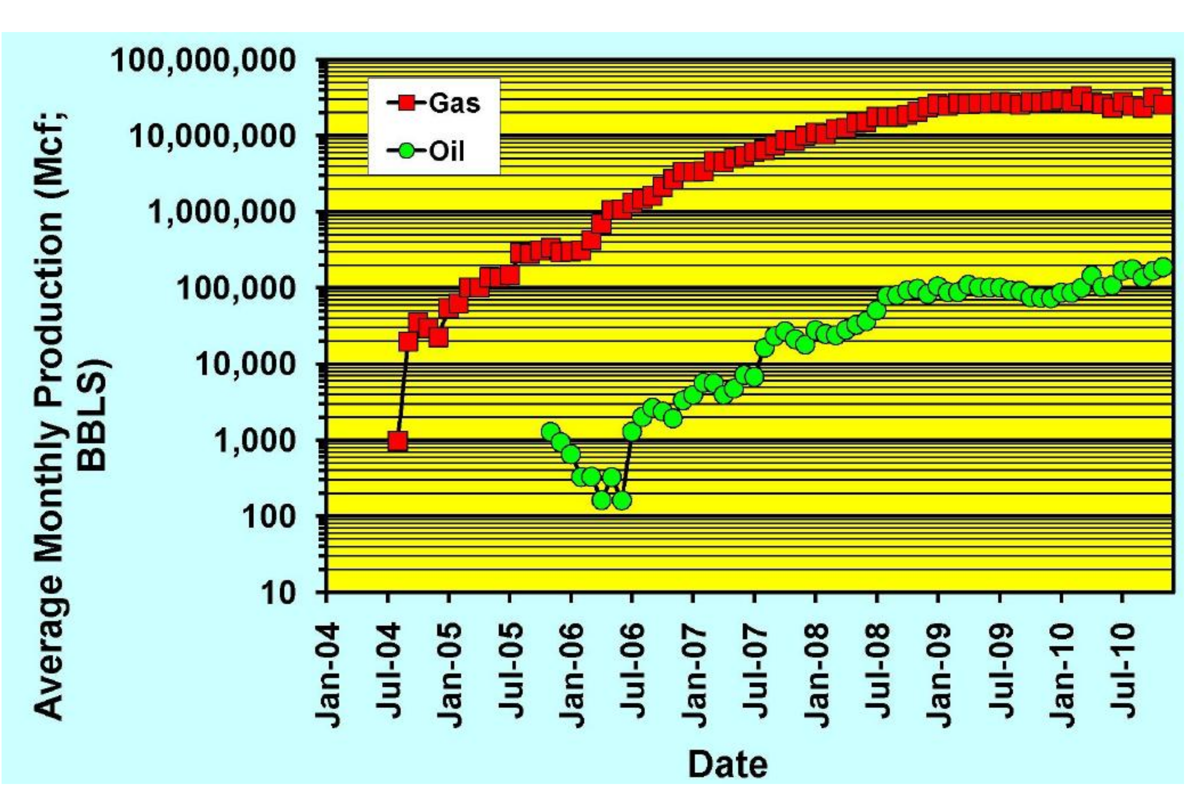


Figure 3. Gas and oil production of Woodford Shale. (Cardott 2012).

Understanding Brittleness

PERCEPTION OF BRITTLENESS

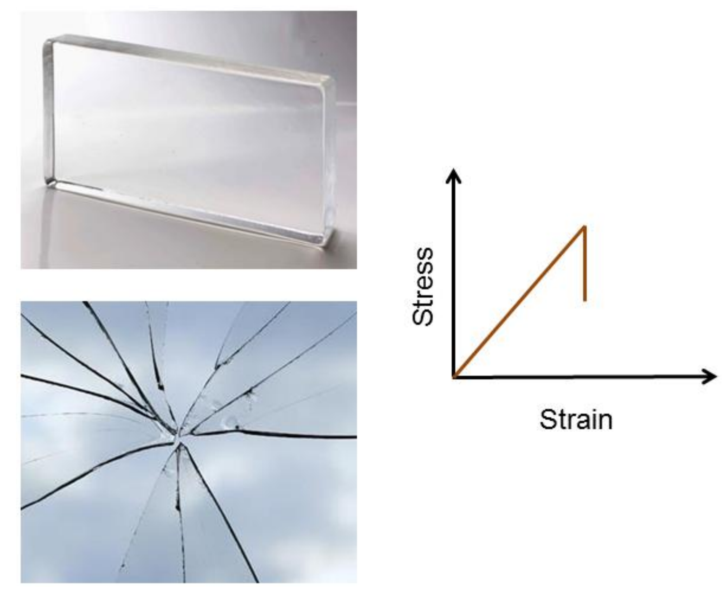


Figure 4. Glass, easy to propagate fractures.

Figure 5. Tire, hard to propagate fractures.

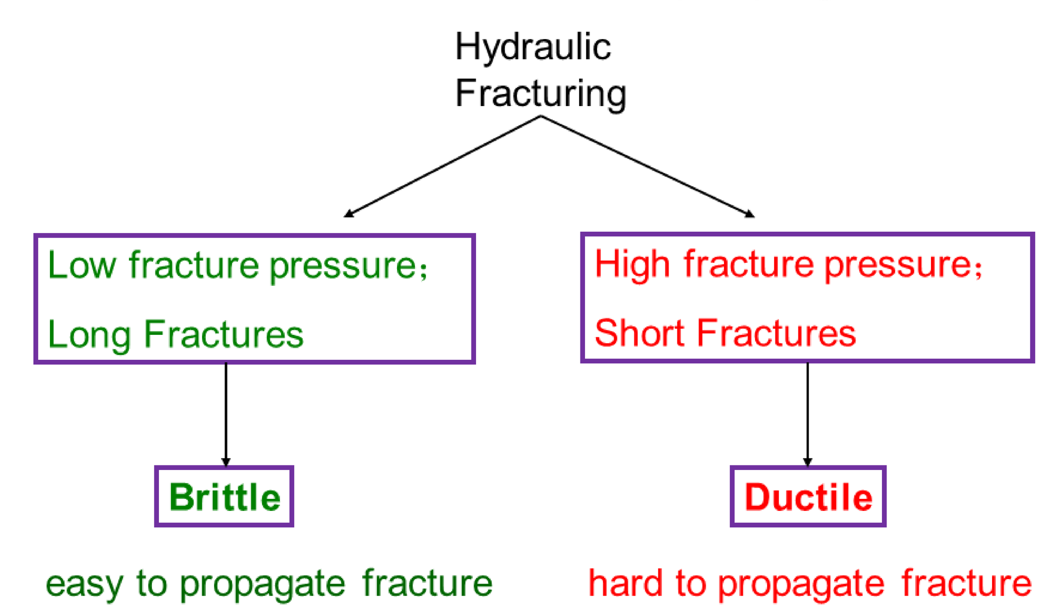
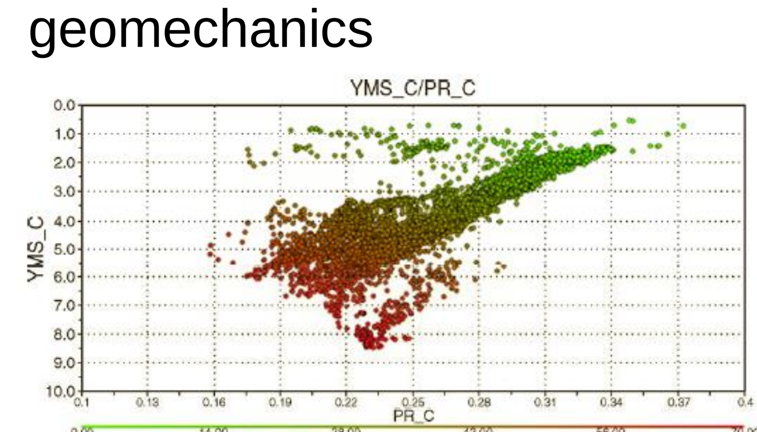


Figure 6. Perception of brittleness of rock.

Early attempts to characterize brittleness – Brittleness Index

$$\mathrm{BI} = \frac{\text{Quartz} + \text{Dolomite}}{\text{Quartz} + \text{Dolomite} + \text{Calcite} + \text{Clays} + \text{TOC}}$$

Figure 7. Mineralogical interpretation (Wang and Gale 2009), easy for log-based implementation, but is not based on geomechanics



$$\mathrm{BI} = \frac{1}{2}\left(\frac{E-1}{8-1} + \frac{\nu - 0.4}{0.15-0.4}\right)\cdot 100\%$$

Figure 8. Empirical interpretation on Barnett Shale (Rickman et al. 2008), easy for log-based implementation, but is not based on geomechanics

$$\mathrm{BI} = \frac{\text{reversible energy } (W_{el})}{\text{total energy } (W_{tot})} = \frac{\text{Area } DCE}{\text{Area } OABCE}$$

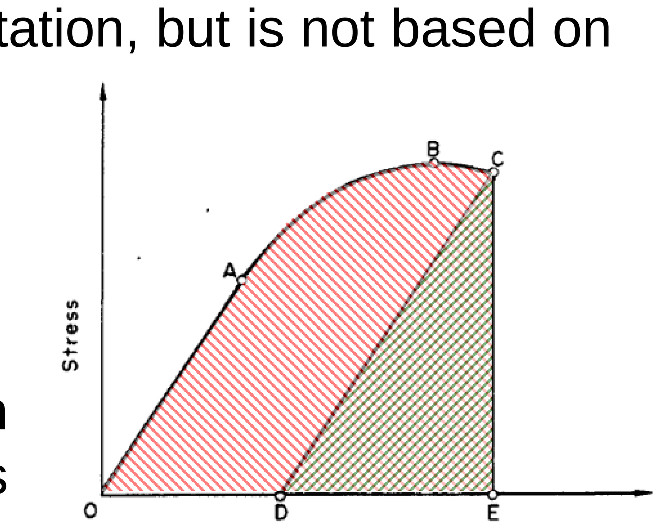
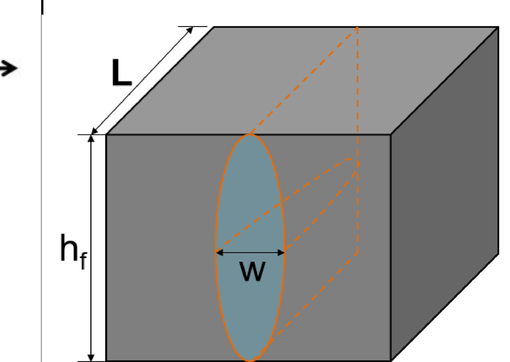


Figure 9. Mechanics interpretation (Hucka and Das 1974), but requires cores and lab testing

Why do Young's modulus and Poisson's ratio influence brittleness?



Poisson's ratio

fracture height

$$w = \frac{(1-\nu^2)}{E} h_f \left(P_{frac} - S_{\mathrm{hmin}}\right)$$

Young's modulus

pump rate

$$L = 0.68\left[\frac{EQ^3}{\mu\left(1-\nu^2\right)h_f^4}\right]^{1/5} t^{4/5}$$

time

fluid viscosity

Figure 10. Fracture width and length formula based on isotropic elasticity (Perkins & Kern 1961 and Nordgren 1972). Young's modulus and Poisson's ratio influence the brittleness of the rock by controlling the width and length of hydraulic fractures. But effects of E are much stronger than ν, they should not be lumped together as in previous approaches.

What about anisotropy?

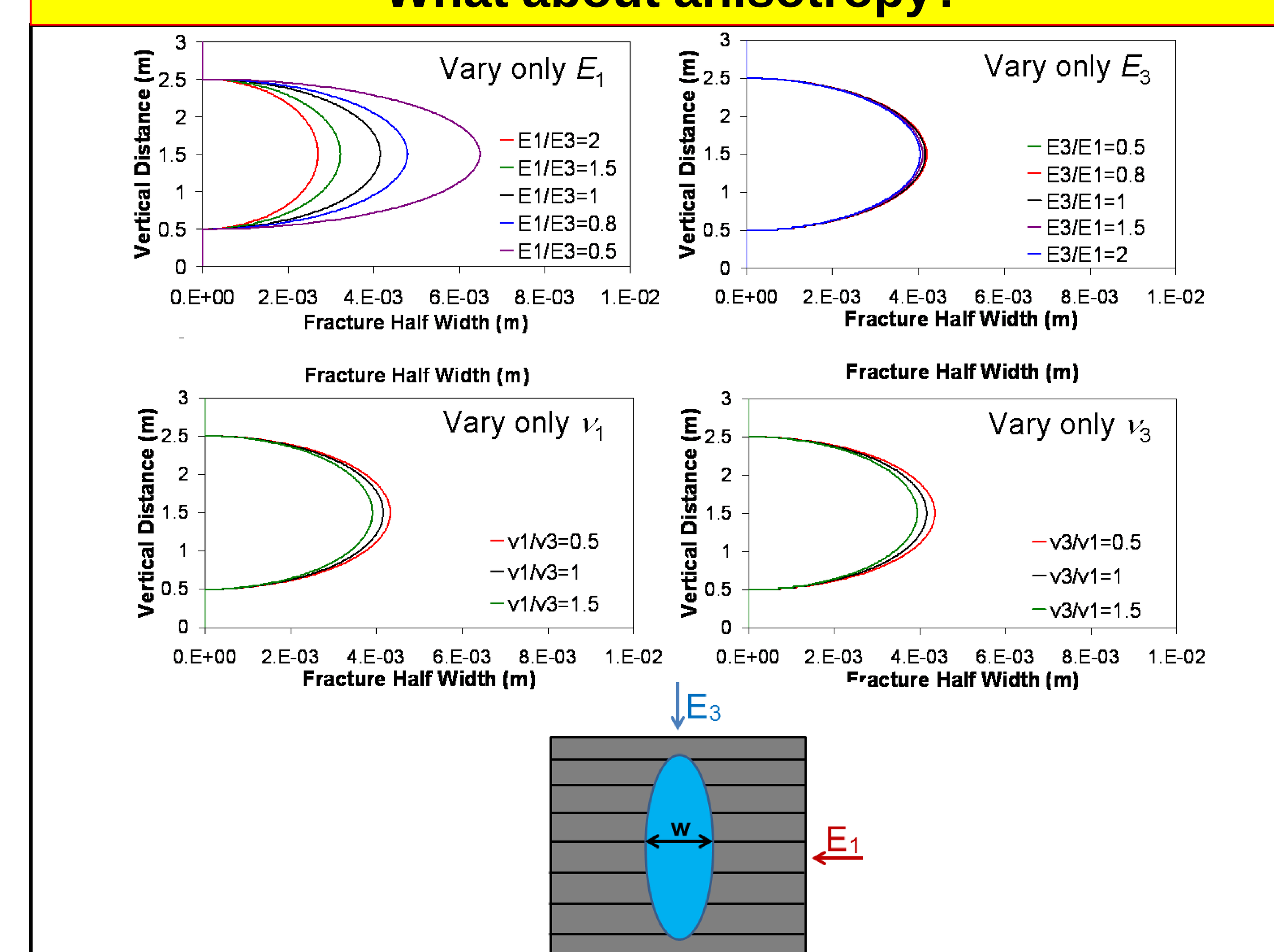


Figure 11. Abaqus simulation shows that fracture width is mainly controlled by Young's modulus E_1 in the lamination direction (Tran et al. 2012).

Does temperature difference between fracturing fluid and shale formation influence brittleness too???

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Natural Fractures

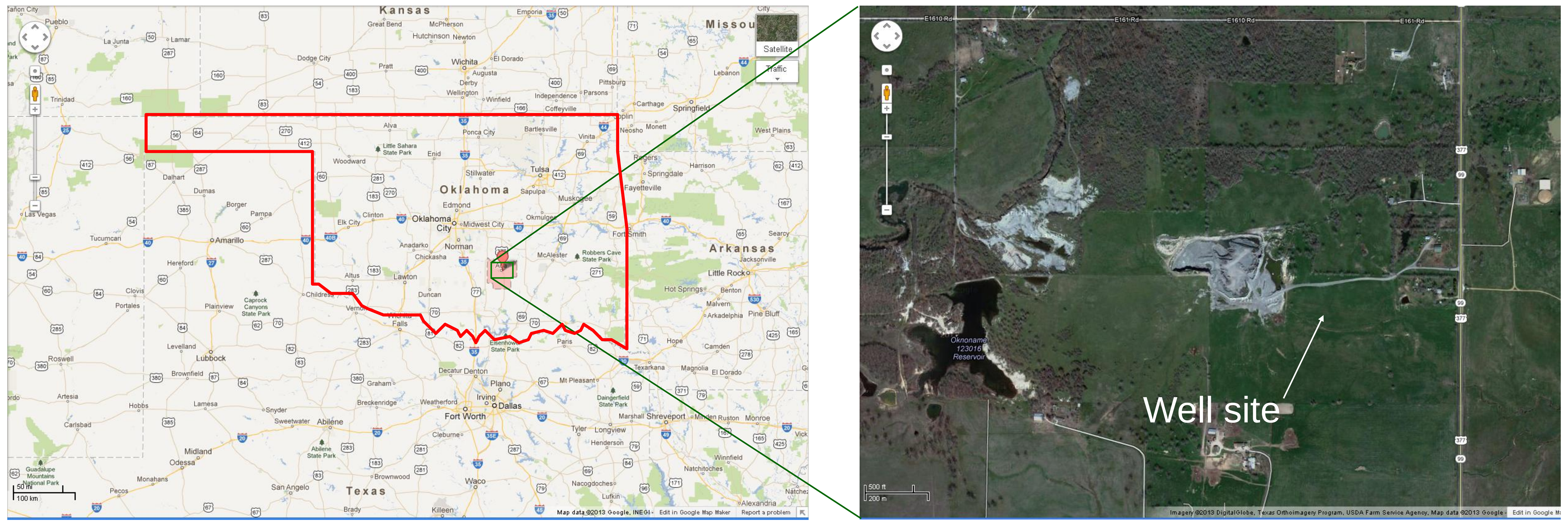
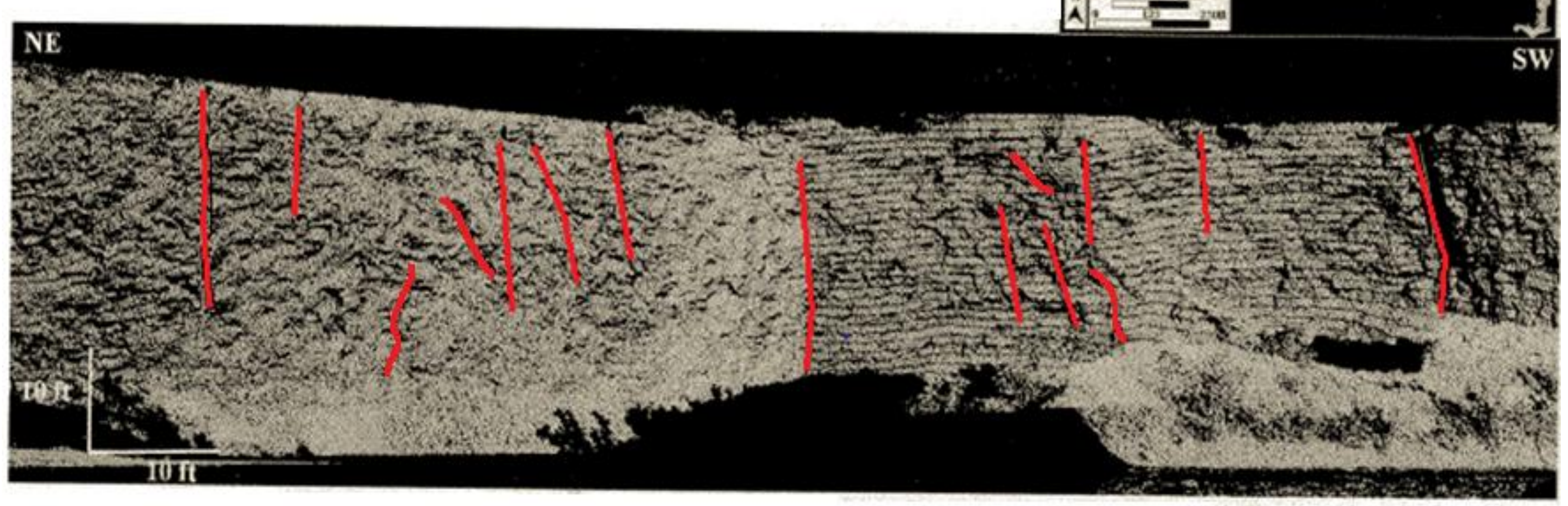


Figure 12. Location of the Wyche Quarry and the drilled well (Google Map).

Figure 13. Natural fractures in the Woodford Shale are almost vertical, with an average distance of 1.2 m between fractures (Portas 2009).



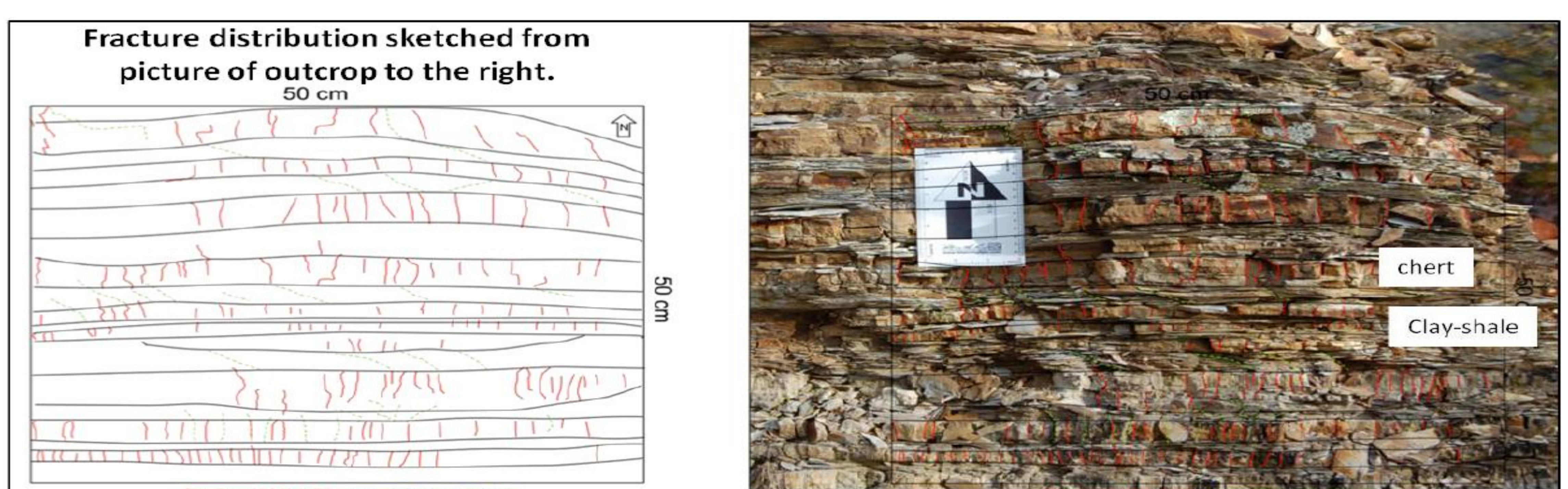
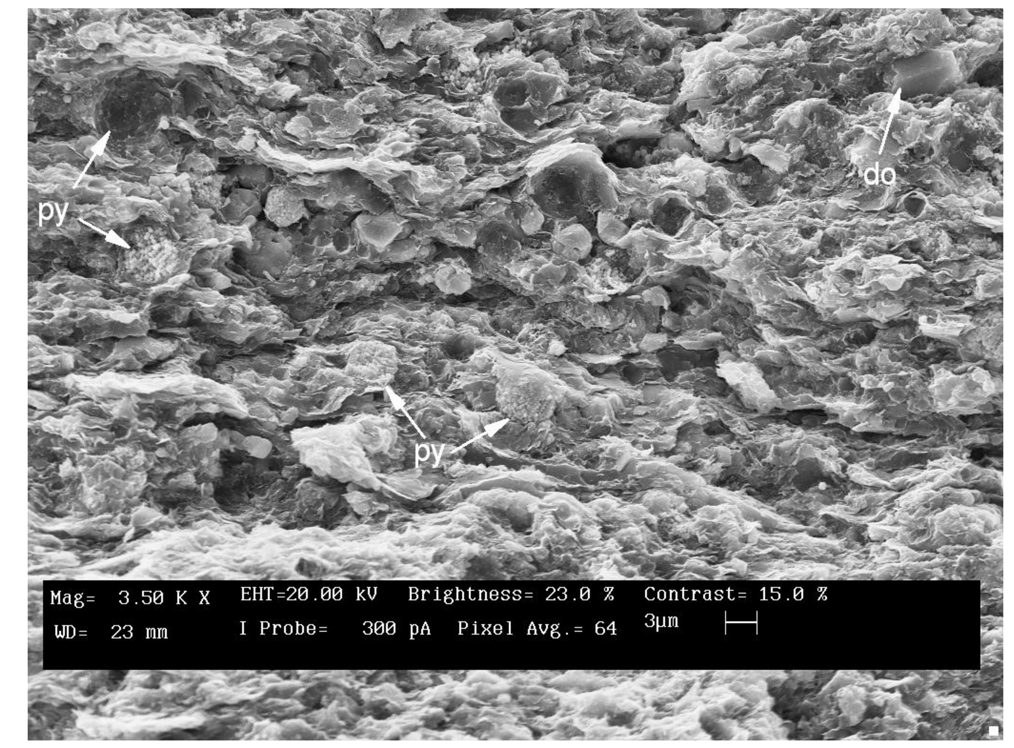
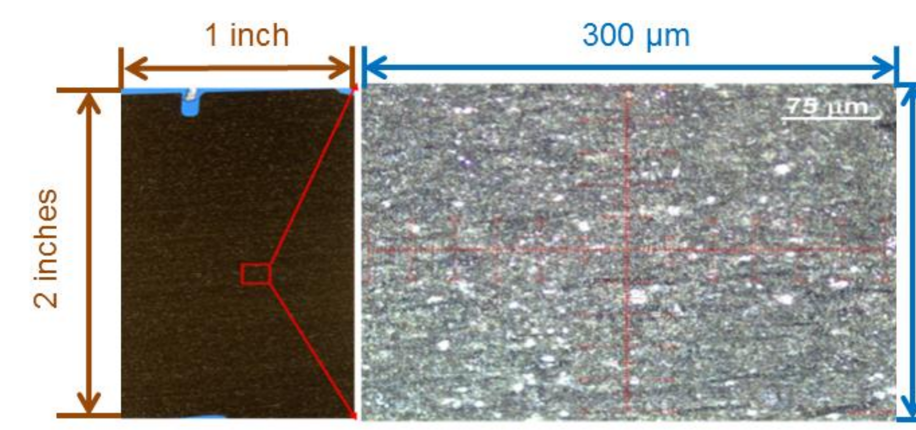


Figure 14. At smaller scales, there are also extensive natural vertical fractures in chert beds between shale layers (Slatt and Abousleiman 2011).

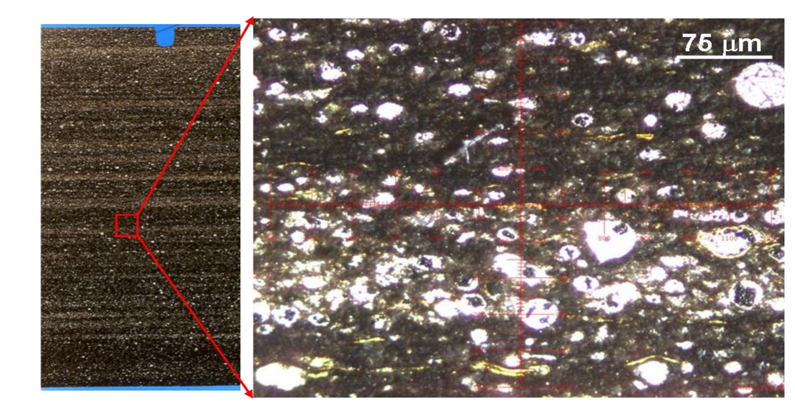
Mechanical Anisotropy of Woodford Shale



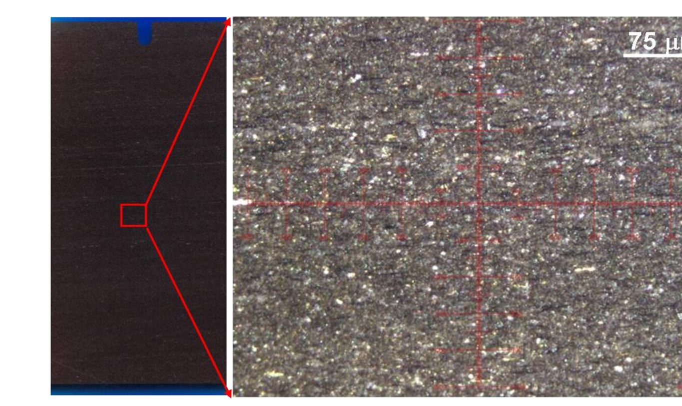
SEM study shows little preferred orientation of clay pallets in Woodford Shale



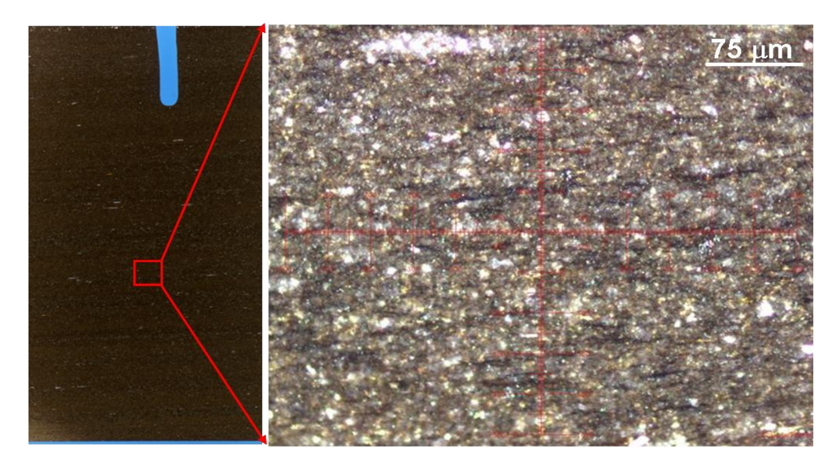
Light gray laminated shale
Depth 33.81 m



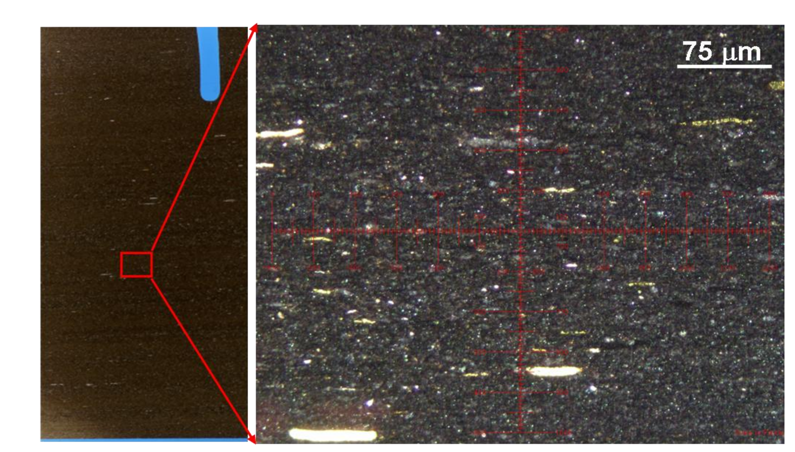
Calcareous laminated shale
Depth 36.86 m



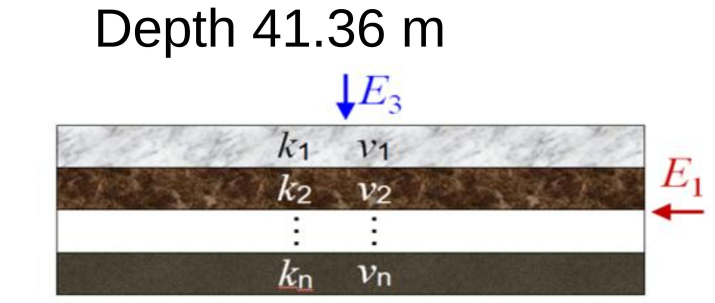
Gray laminated shale
Depth 41.36 m



Gray laminated shale
Depth 44.28 m



Black laminated shale
Depth 36.86 m



k_i: stiffness modulus of the i[th] layer

v_i: volume fraction of the i[th] layer

$$E_1 = v_1 k_1 + v_2 k_2 + \ldots + v_n k_n$$

$$E_3 = 1 \Big/ \left(\frac{v_1}{k_1} + \frac{v_2}{k_2} + \ldots + \frac{v_n}{k_n} \right)$$

$E_1 > E_3$!

Figure 15. SEM study shows only little preferred orientation of clay pallets in Woodford Shale. However, thin section study reveals the laminated nature of Woodford Shale. Schematic model for Young's moduli E_1 in lamination direction and E_3 in transverse direction for a composite of homogeneous isotropic layers. Using Cauchy's inequality it can be shown that E_1 is always greater than or equal to E_3; E_1 is equal to E_3 if and only if all layers are the same.

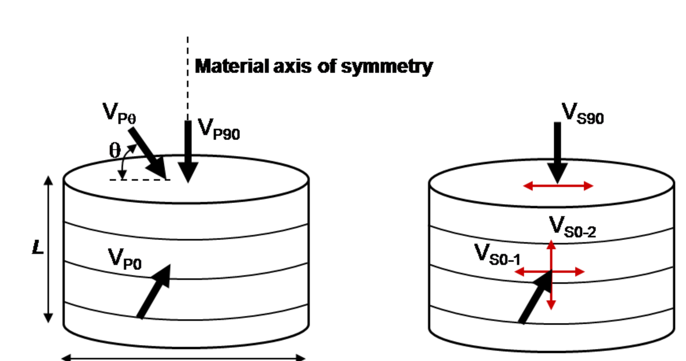


Figure 16. Ultrasonic Pulse Velocity (UPV) setup (Abousleiman et al. 2007).

Depth (m)	Velocities (m/sec)						
	V_{P0}	V_{P90}	$V_{S0\text{-}1}$	$V_{S0\text{-}2}$	V_{S90}	$V_{P\theta}$	θ (°)
33.81	3460	2980	1929	1656	1650	3076	41
36.85	3363	2902	1870	1648	1610	3050	40
41.36	3530	2860	2024	1565	1562	2944	25
44.28	3313	2532	1932	1498	1492	3028	52
50.59	3301	2615	2007	1562	1571	2970	45

Table 1. Measured acoustic velocities confirm the anisotropy of Woodford Shale (Tran 2010).

Depth (m)	E_1 (GPa)	E_3 (GPa)	Difference (%)
33.81	20.3	15.8	22.2
36.85	18.8	13.8	26.6
41.36	22.2	13.5	39.2
44.28	19.6	10.4	46.9
50.59	19.5	10.9	44.1

Table 2. Engineering poroelastic moduli from UPV analysis show the anisotropy in Woodford Shale (Tran 2010).

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Model for Hydraulic Fracturing

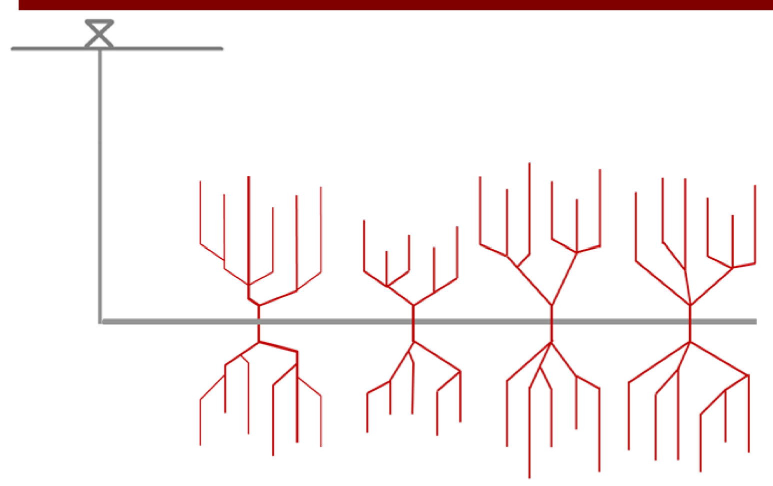

Figure 17. Branching of hydraulic fractures due to the existence of natural fractures.

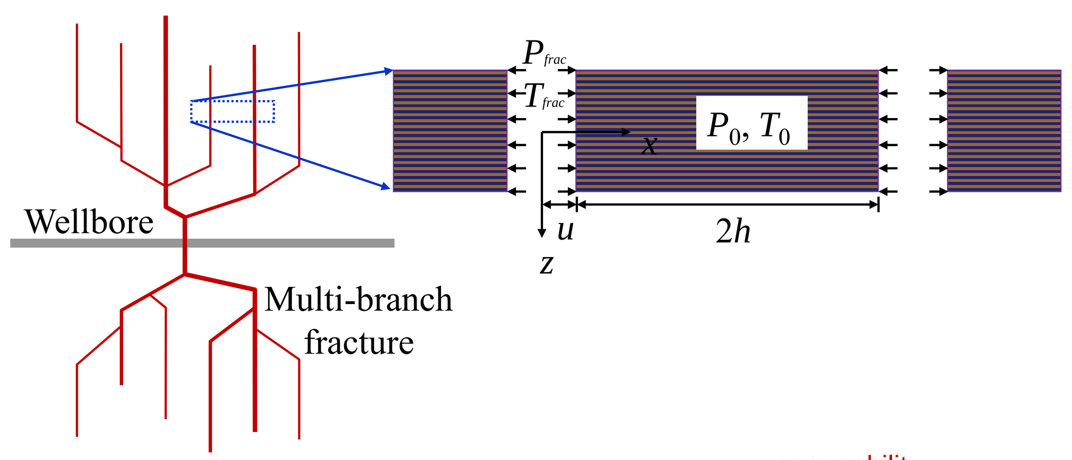

Figure 18. Anisotropic thermo-hydro-geomechanics model for a section of the multi-branch hydraulic fracturing pattern.

Table 3. Properties of the Woodford Shale used in simulation.

	permeability	viscosity	porosity	fluid pressure
Hydraulic	$k = 45nD$	$\mu = 10^{-3} kg/m/s$	$\phi = 0.15$	$P_{frac} = 64MPa$
Thermal	$\alpha_f = 7\times10^{-4} /^{o}C$	$\alpha_s = 2\times10^{-5} /^{o}C$	thermal expansion coefficients of fluid and rock grains	
	$\rho C_v = 2616 kJ/m^3/^{o}C$ heat capacity		$\lambda = 1.4 J/m/s/^{o}C$ heat conductivity	
Mechanical	$E_1, E_2 = 5.6GPa$	$E_3 = 4.6GPa$	Young's moduli	
	$v_{12}, v_{21} = 0.3$	$v_{31}, v_{32} = 0.3$	Poisson's ratios	
In-situ state	Depth = 2500m	$S_{h\min} = 52MPa$	$S_V = 57.5MPa$	
	$T_0 = 90^{\circ}C$	$P_0 = 27.6MPa$		

Thermo-Hydro-Geomechanics Governing Equation

stress in horizontal direction (Pa)

strain in horizontal direction

pore pressure (Pa)

temperature (K)

$$\sigma_{xx} = M_{11}\varepsilon_{xx} + \alpha_1 p + \beta_1^s T$$

thermal factor (Pa/K)

Biot's pore pressure coefficient

stiffness coefficient (Pa)

$$M_{11} = \frac{E_1(E_3 - E_1 v_{13}^2)}{(1+v_{12})(E_3 - E_3 v_{12} - 2E_1 v_{13}^2)}$$

$$\alpha_1 = \alpha_1(E_1, E_3, v_{12}, v_{13}, \cdots)$$

Analytical Solution for Fracture Width

part of fracture width due to stress change

part of fracture width due to pore pressure change

$$w(t) = \boxed{-\frac{2(P_{frac} - S_{h\min})}{M_{11}}h} + \boxed{\frac{2\alpha_1(P_{frac} - P_0)}{M_{11}}h + f(t, P_{frac} - P_0, k_1, \ldots)}$$
$$\boxed{+\frac{2\beta_1^s(T_{frac} - T_0)}{M_{11}}h + g(t, T_{frac} - T_0, \lambda_1, \ldots)}$$

fracture width

part of fracture width due to temperature change

Figure 19. Fracture width as a function of time from fracture opening (Abousleiman et al. 2013).

Effects of Fracturing Fluid Temperature

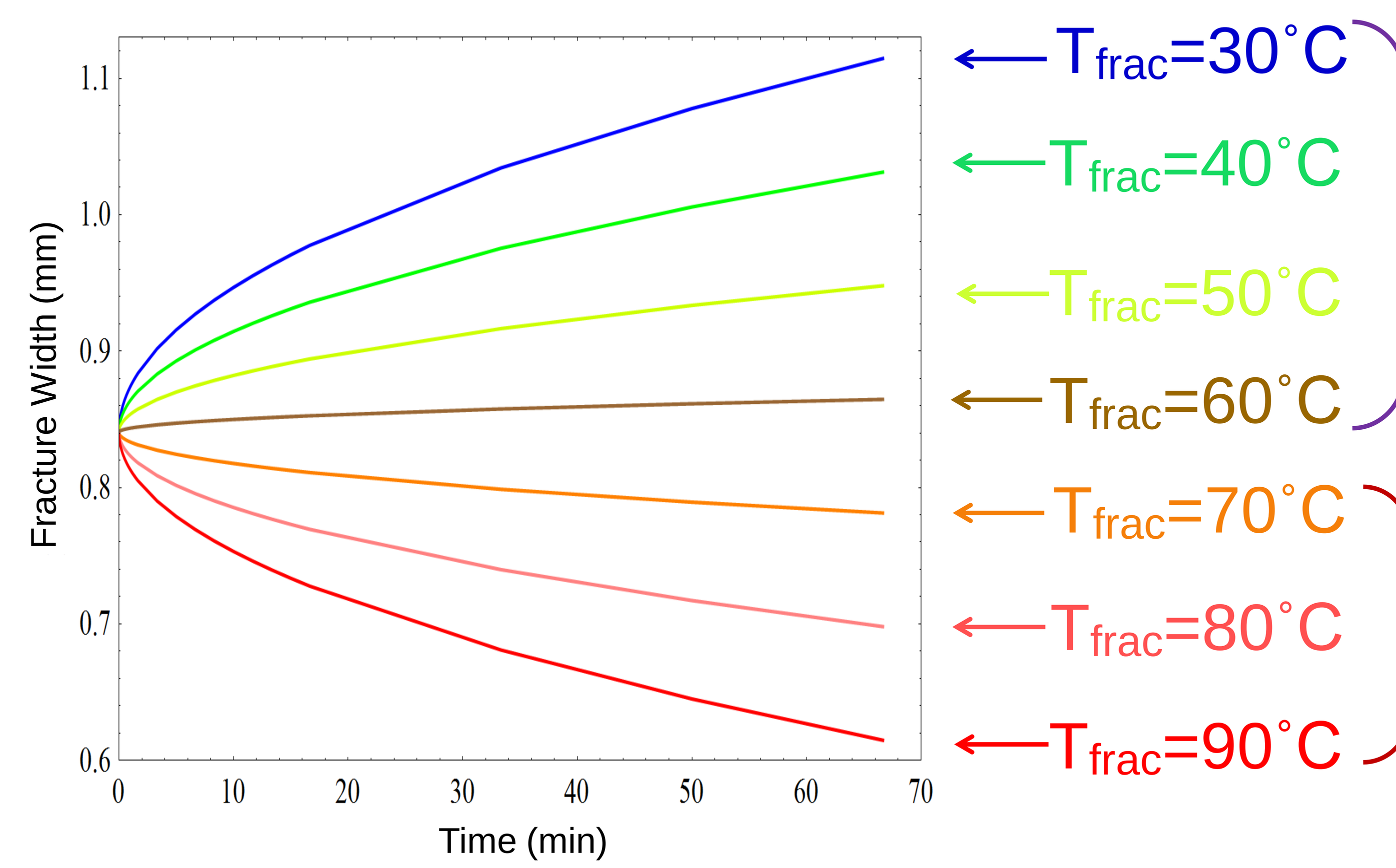

Figure 20. Fracture width evolution with time at different fracturing fluid temperatures

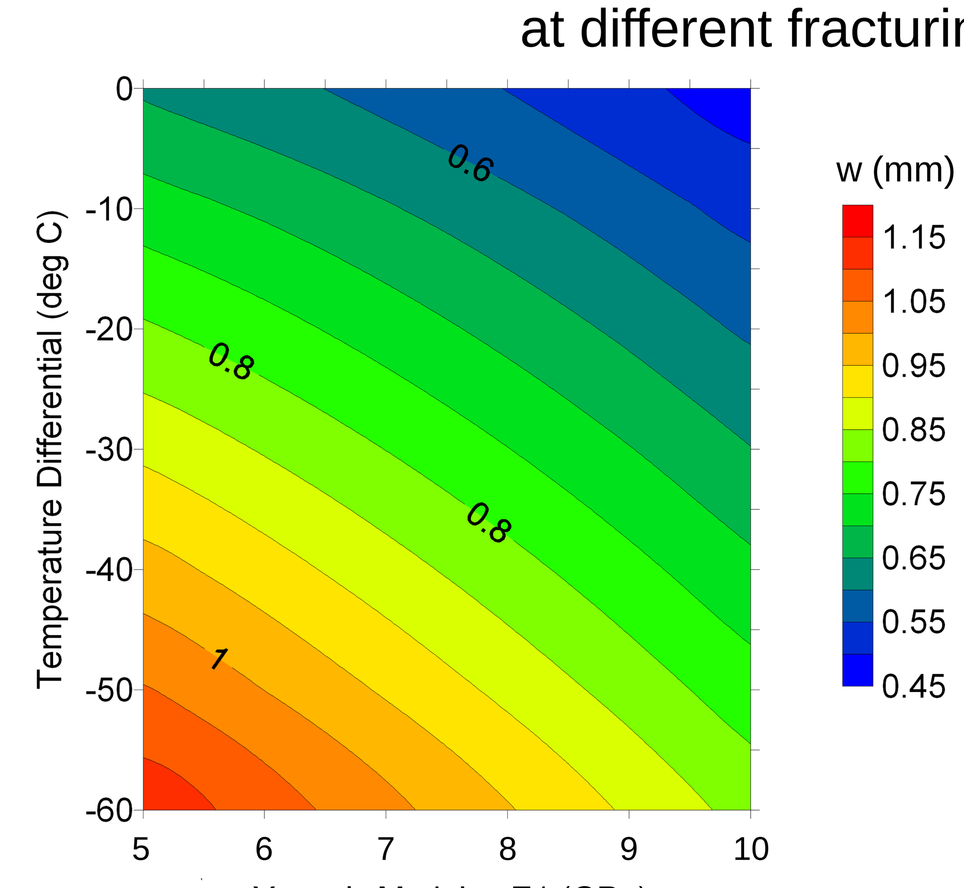

Figure 21. Importance of fracturing fluid temperature on fracture width (time = 1 hour). It can be seen that the effects of temperature is of the same order of magnitude as the effects of the Young's modulus E_1 in lamination direction. E_1 is the main controlling mechanical factor (from Figure 11).

Hydraulic Fracturing Optimization?

1. Temperature difference between fracturing fluid and shale formation significantly influence brittleness.
2. Effects of temperature difference between fracturing fluid and shale formation on fracture width are the same order of magnitude as effects of shale stiffness.
3. Hotter fracturing fluid leads to narrower and longer fracture, or more brittleness.
4. Narrower fracture however can hinder proppant transport and decrease fracture permeability.
5. Fracturing fluid temperature must be accounted for in hydraulic fracturing optimization.