PS The Effects of Lamination/Bedding on the Brittleness for the Woodford Shale Silica-Rich Intervals, From the Wyche-1 Core-Well Analysis, Pontotoc County, Oklahoma*

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Search and Discovery Article #51394 (2017)**
Posted June 26, 2017

*Adapted from poster presentation given at AAPG 2017 Annual Convention and Exhibition, Houston, Texas, April 2-5, 2017

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Abstract

The Woodford Shale (WDS) as many other self-source unconventional rocks is evidently anisotropic. However, anisotropy (lamination/bedding) is not commonly included on defining "fracability". FMI log, Core (Wyche-1), and thin section inspection illustrates that middle and lower WDS brittle intervals are characterized by more frequent and visible laminae, in comparison with the upper Woodford. Thomsen' coefficients ε and γ, obtained from Ultra Pulse Velocities (UPV) analysis, were used to quantify anisotropy and to explore their potential effects on rock "fracability". The intervals that exhibit more laminae (anisotropy) are characterized by higher ε and γ coefficients, which are also characterized by less Fracture Toughness (Kic) and Tensile Strength (T). Fracture Toughness (KIc) is a property which describes the ability of a material containing a crack, to resist fracture. It is one of the most important properties for hydraulic fracturing designs and is a measurement of the energy required to grow a thin crack expressed on MPa $m^{½}$ or $MN/m^{½}$. Tensile Strength (T) is the maximum stress that a material can withstand while being stretched or pulled before failing or breaking. T is defined as a stress, which is measured as force per unit area (Pa or N/m^2) The upper Woodford samples which were characterized by more diffuse and/or less laminae on thin sections and microresistivity logs are also represented by lower values at ε and γ anisotropic coefficients This work also illustrates that more laminae at middle Woodford brittle intervals creates more anisotropy planes of weakness, that may assist in reducing the effective minimum horizontal principal stress and they may response much brittle during hydraulic stimulation.

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1. ABSTRACT

The Woodford Shale as many other self-source unconventional rocks is anisotropic. However, anisotropy (lamination/bedding) is not commonly included when defining "fracability".

FMI log, Core (Wyche-1) and thin section inspection illustrates that middle and lower Woodford Shale brittle intervals are characterized by more frequent and visible laminae, in comparison with the upper Woodford.

Thomsen' coefficients ε and γ, obtained from Ultra Pulse Velocities (UPV) analysis, were used to quantify anisotropy and to explore their potential effects on rock "fracability". The intervals that exhibit more laminae (anisotropy) are characterized by higher ε and γ coefficients, which are also characterized by less Fracture Toughness (*Kic*) and Tensile Strength (*T*).

This work illustrates that more laminae at middle Woodford brittle intervals creates more anisotropy planes of weakness, that may assist in reducing the effective minimum horizontal principal stress. Anisotropy (lamination) makes the rock more brittle during hydraulic stimulation.

2. LOCATION AND DATA SET

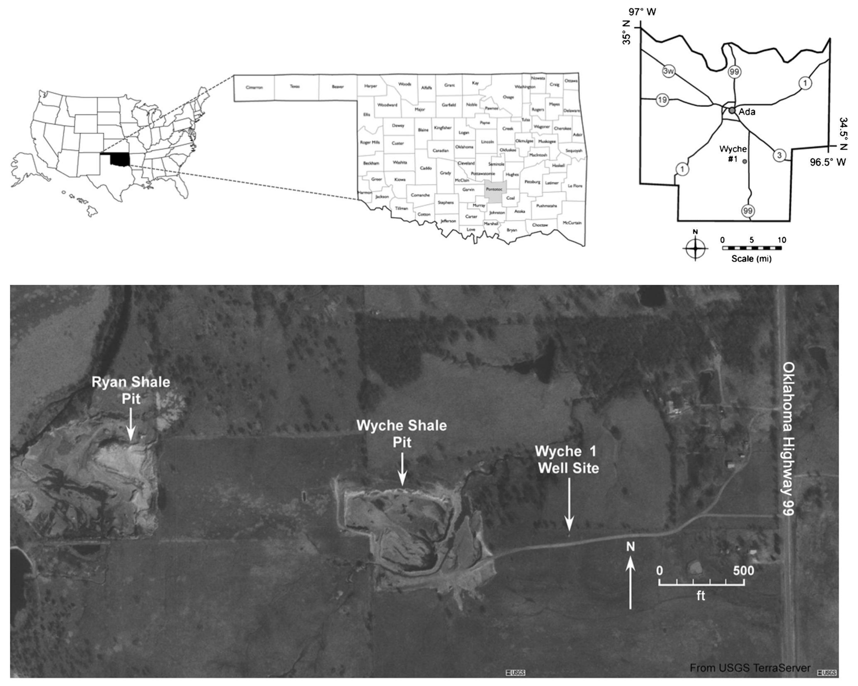


Figure 1. Wyche-1 Core Location

The Wyche-1 well was a research well drilled, cored and logged about 500 feet (~150 m) east of an active quarry in the Wyche shale pit, Pontotoc County, Oklahoma (Figure 1). The core recovery was ~95%, which is equivalent to 180 ft (~54 m). A complete set of well logs was provided by Shlumberger and Devon Energy (Figure 2).

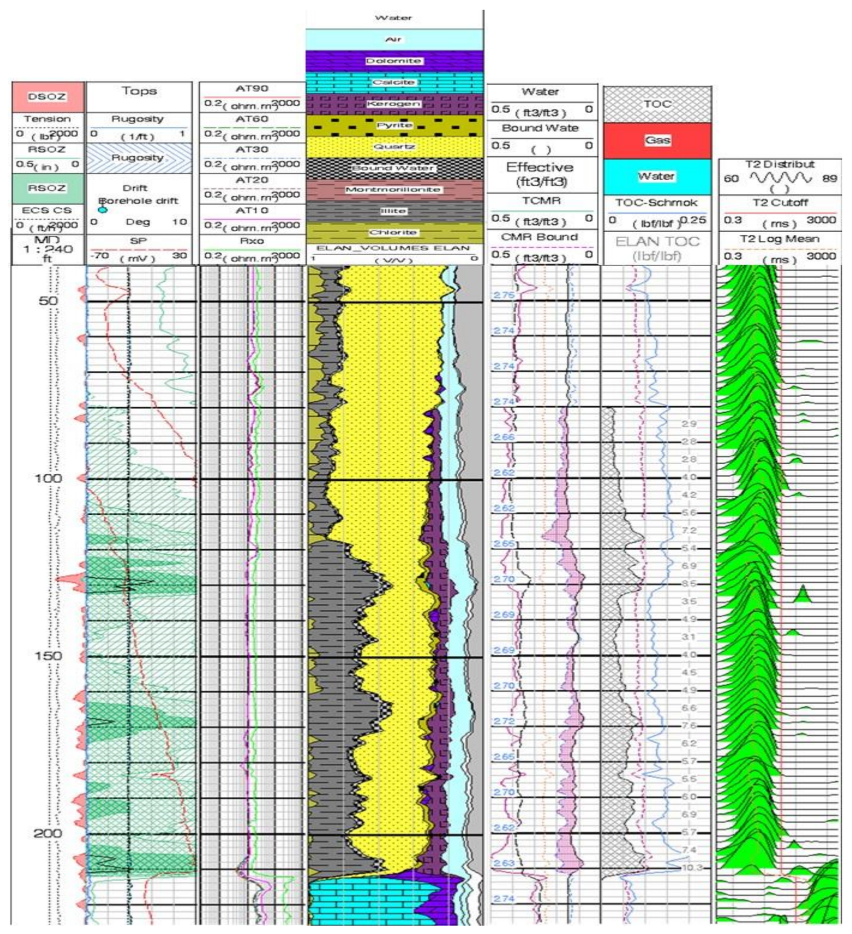


Figure 2. Wyche-1 well log set

4. PROBLEMS AND RESEARCH QUESTIONS

I) In the Woodford Shale (or in other self-sourced shale plays), more than one brittle interval may be characterized by similar acoustic (Impedance) and dynamic geomechanical rock properties (*E*, *v*), calculated from seismic and well log data (Figure 3).

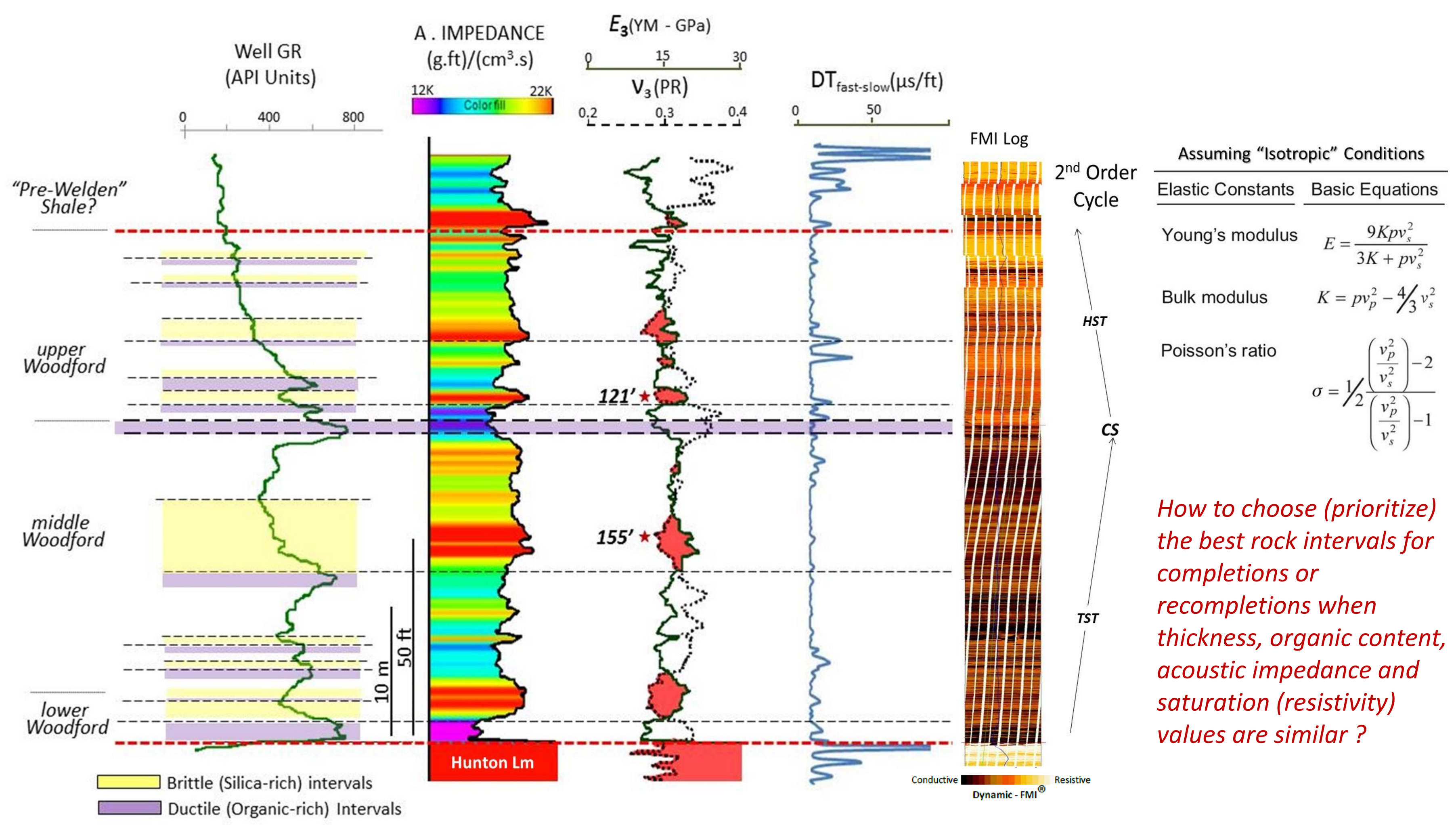


Figure 3. Wyche-1 Gamma Ray (GR) quartz-rich brittle intervals (yellow areas) and organic-rich ductile intervals (purple areas) compared with the Acoustic (A) Impedance, Young's modulus (E_3) and the Poisson's ratio (v_3) calculated from sonic and density well logs. The Woodford brittle intervals are characterized in this well by high acoustic impedances. The intervals characterized by the highest *E* and the lowest ν, define areas of intersection crossover. The differences between fast and slow velocities (DT fast-slow track) are indicating a marked horizontal anisotropy for the Hunton and Pre-Welden Shale intervals. FMI® shows almost horizontal bedding and the absence of fractures and/or maximum vertical stresses. Red Stars highlight two samples located at 121 feet and 155 feet (see Figure 10).

II) Compositional **Brittleness Index** (B.I.) helps to differentiate argillaceous ductile shale intervals, from silica-rich brittle intervals in the Woodford Shale. However, It doesn't explain completely rock "*fracability*" in terms of the Young's Modulus (E) and Poisson's Ratio (v). Under the same stress and (pore) pressure conditions, rocks with similar composition and characterized by the same values of B.I. may display different values of E and v. (Figure 4), and might respond differently during hydraulic stimulation.

What's the role of lamination/bedding (anisotropy) on rock fracability?

How to quantify anisotropy at different scales and without biases?

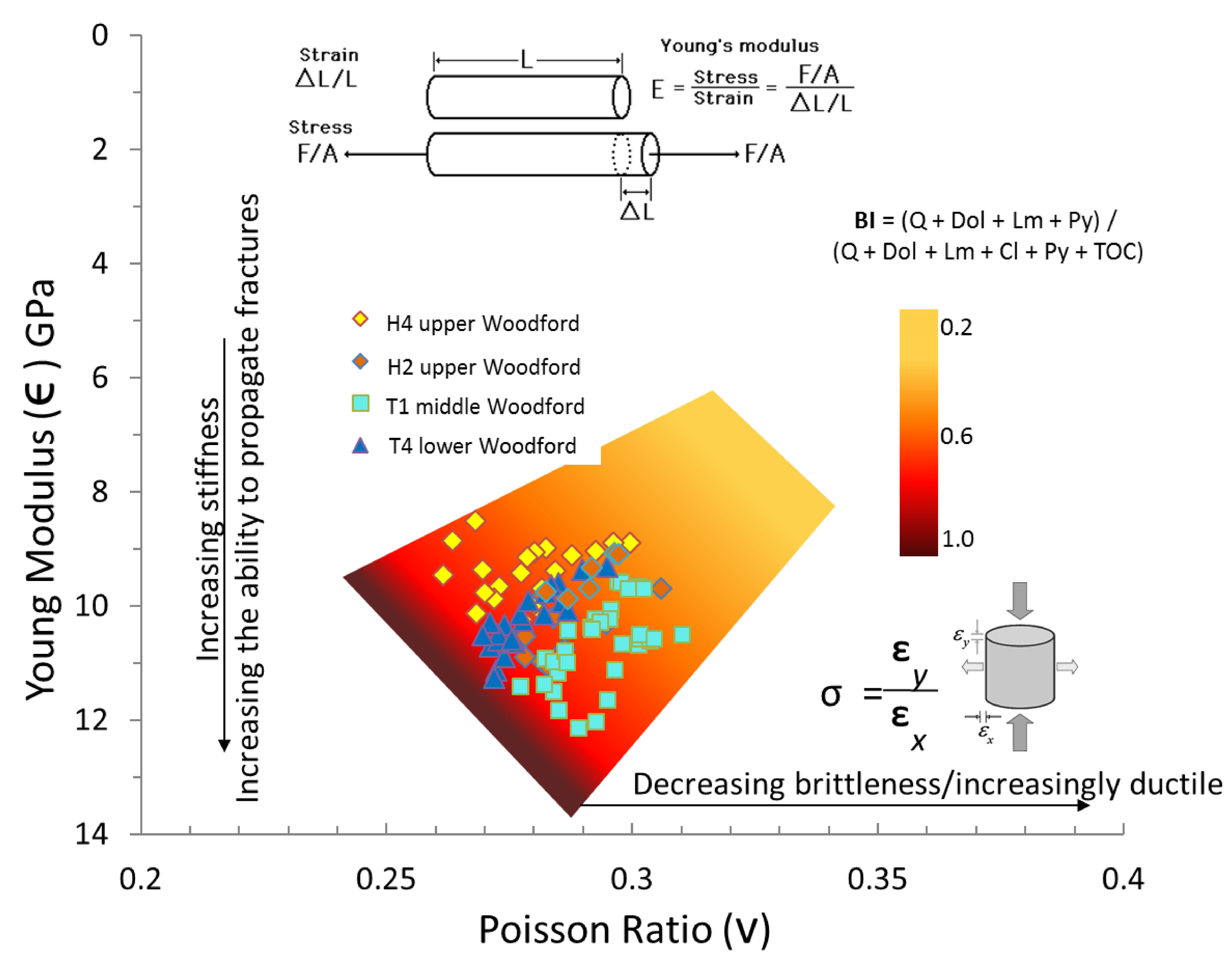


Figure 4. Young's modulus and Poisson's ratio calculated from logs for the crossover intervals, characterized by the highest *E* and the lowest *v* from the Wyche-1 well (Figure 3). The yellow and orange colors represents the brittle intervals associated with the upper Woodford regressive hemicycles and the blue color represent the brittle intervals associated with the lower and middle Woodford regressive hemicycles. BI = Brittle Index; Q = quartz; Dol = dolomite; Cal = Calcite; Py = Pyrite; Cl = Clay minerals; TOC = Total Organic Carbon.

5. VERTICAL TRANSVERSE ISOTROPY (VTI)

In VTI rocks, acoustic and mechanical vertical properties differ from horizontal plane properties. VTI can be generated from nanno- to meso- scales in organic-rich, self-storage unconventional deposits:
I) The finest intrinsic anisotropy is due to the constituent plate-shaped clay particles, normally oriented parallel to each other (Sayers, 2005; Slatt and O'Brien, 2011); the transverse isotropy associated with the small scale lamination is commonly observed in (II) SEM, (III) and thin sections (Slatt and Abousleiman, 2011); and anisotropy is also present, (IV) in the horizontal bedding or layering, typically perceived at outcrop scale (Figure 5).

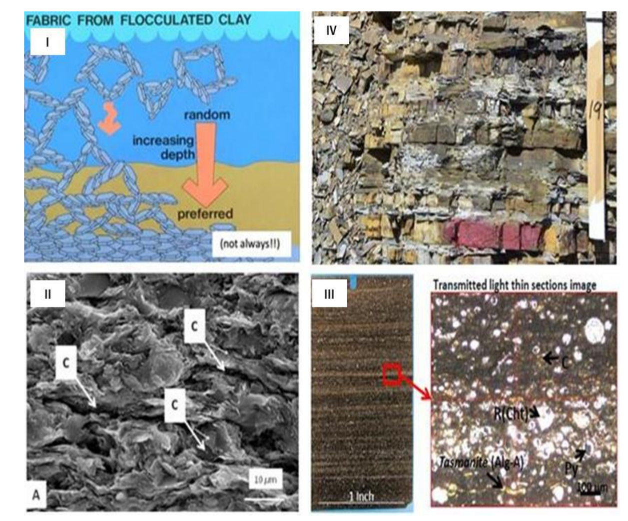


Figure 5. VTI in Woodford Shale samples

Most of the unconventional reservoirs are described as VTI under absence of significant vertical discontinuities (i.e. fractures, faults, cracks, etc). Understanding the anisotropy of Young's Modulus (E) and Poisson's Ratio (v) is important for determining the variation of minimum horizontal stress and for designing hydraulic fracturing

Assuming that the vertical stress σ_V is a principal stress (i.e. Normal and strike – slip stress fields), the minimum σ_h horizontal stresses can be written in terms of the vertical stress σ_V, α_h and α_V poroelastic coefficients and pore pressure *p* as (Sayers, 2010):

$$\sigma_h = \alpha_h p + K_0(\sigma_V - \alpha_V p).$$

VTI layered models needs five independent elastic constants (C_{11}, C_{12} = C_{13}, C_{33}, C_{44}, C_{66}) to fully describe the stiffness (Figure 6):

$$E_1 = \frac{(C_{11} - C_{12})(C_{11}C_{33} - 2C_{13}^2 + C_{12}C_{33})}{C_{11}C_{33} - C_{13}^2}$$

$$E_3 = C_{33} - 2\frac{C_{13}^2}{C_{11} + C_{12}}$$

$$v_1 = \frac{(C_{33}C_{12} - C_{13}^2)}{C_{11}C_{33} - C_{13}^2}$$

$$v_3 = \frac{C_{13}}{C_{11} + C_{12}}$$

$$\mu_1 = C_{66} = \frac{E}{2(1+v)}$$

$$\mu_3 = C_{44}$$

$$Ko^{ISO} = \frac{v}{1-v}$$

$$Ko^{VTI} = \frac{E_1 v_3}{E_3 1 - v_1}$$

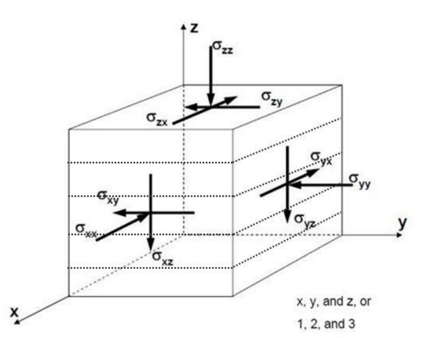
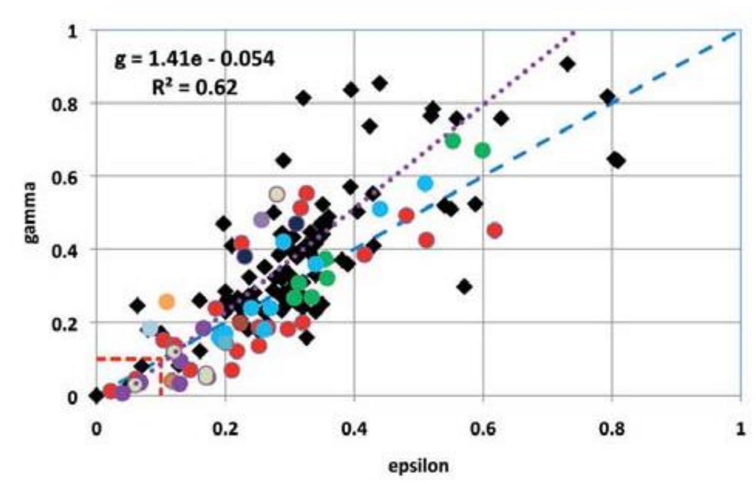


Figure 6a. The elastic constants for the VTI case expressed in terms of the Young's modulus (*E*), Poisson's ratio (ν) and the Shear modulus (μ), along the lamination (E_1, v_1 and μ_1) and perpendicular (E_3, v_3 and μ_3). Ko for the isotropic (ISO) and VTI cases are expressed as a function of *E* and ν rock properties.



$$\varepsilon = \frac{C_{11} - C_{33}}{2C_{33}} = \frac{V_p^2(0°) - V_p^2(90°)}{2V_p^2(90°)}$$

$$\gamma = \frac{C_{66} - C_{44}}{2C_{44}} = \frac{V_{sh}^2(0°) - V_{sh}^2(90°)}{2V_{sh}^2(90°)}$$

Figure 6b. Epsilon (ε) vs gamma (γ) Modified from Sondergeld and Rai 2011)

Thomsen (1986) characterized the *Vp* and *Vs* anisotropic velocities into two coefficients ε and γ. Sondergeld and Rai (2011) plotted epsilon (ε) and gamma (γ) values available from different shales (Figure 6b) and it is evident that in many cases, these rocks are positive (ε - γ > 0) or negatively (ε - γ < 0) anisotropic.

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5. METHODS

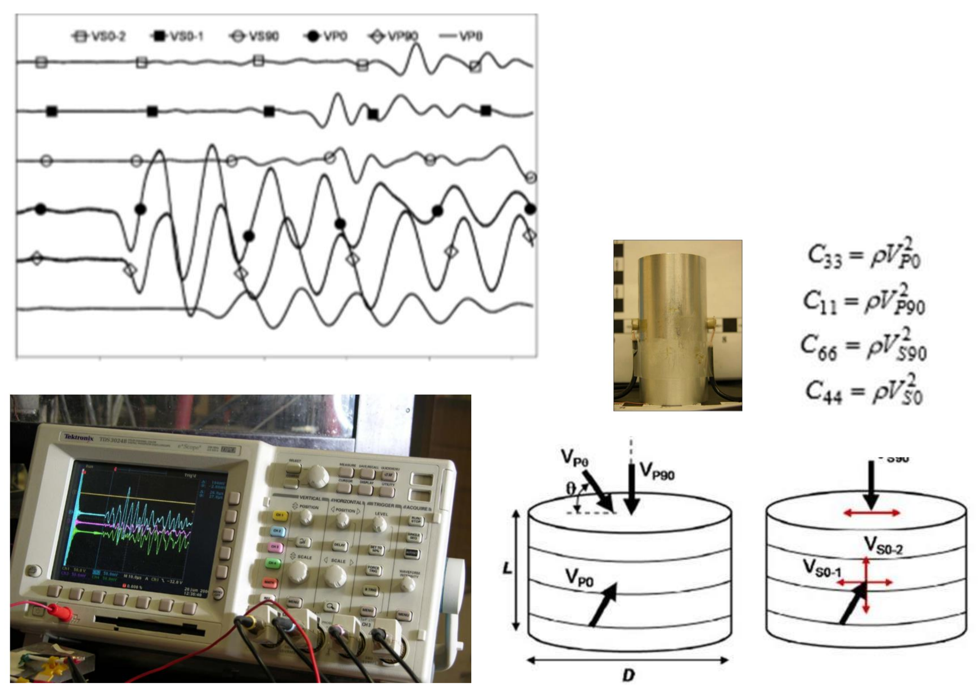

Figure 7. Ultra Pulse Velocity Analysis (UPV).

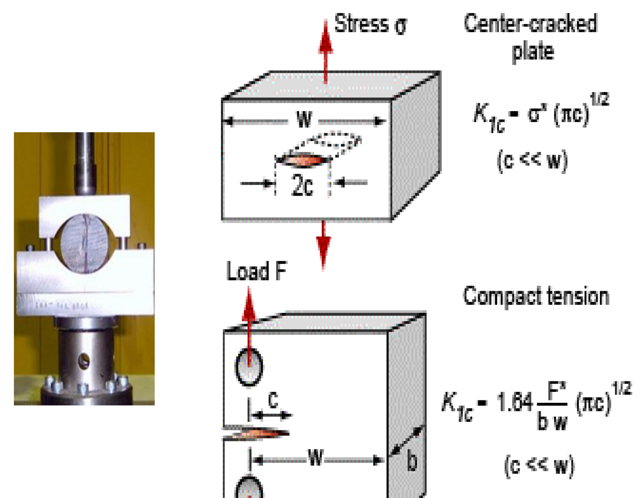

Figure 8. Geomechanic core analysis for Tensile Strength and Fracture Toughness (K*ic*)

The UPV testing equipment normally includes a pulse generation circuit, that consisting of an electronic circuit for triggering pulses and a transducer for transforming that electronic pulse into mechanical pulse. The velocities and sample density are multiplied to obtain the rock stiffness coefficients (Figure 7).

Thomsen's anisotropy coefficients were calculated from UPV core velocities. Epsilon coefficient (ε) is a measurement of the P-wave velocities differences perpendicular and parallel to lamination (anisotropy), while the Gamma coefficient (γ) is a measurement of the S-wave velocities differences perpendicular and parallel to lamination (Figure 6b).

Tensile Strength (*T*) is the maximum stress that a material can resist while being stretched or pulled before failing or breaking. *T* is defined as a stress, which is measured as force per unit area (Pa or N/m^2). Brazilian Test is a lab test for measurement of the tensile strength of rocks. At the failure, the *T* of the rock is calculated as follows. T = 2P/(πDL). P - applied load, D - diameter of the sample (D=2R) L - thickness of the sample (ASTM Standard Test Method D3967-81) (Figure 8).

Fracture Toughness (K*ic*) describes the ability of a material containing a crack, to resist fracture. It is a important properties for hydraulic fracturing designs and is a measurement of the energy required to grow a thin crack expressed on MPa m$^{1/2}$ or MN/m$^{1/2}$ (Sierra et al., 2010).

6. RESULTS

The elastic constants to describe VTI rocks were obtained previously by measuring P- and S- wave velocities from core plugs parallel, perpendicular, and ± 45° to the laminae axis (Figure 7). Thomsen's coefficients were calculated based on those velocities and then compared with the Fracture Toughness (K*ic*) and Tensile Strength (*T*) (Figure 9).

Tensile Strength (*T*) It is the maximum stress that a material can withstand while being stretched before breaking

Depth (ft)	Ten Strength T (Mpa)	Ten Strength II (Mpa)	K*ic*	ε	γ	Bi
111	12.8	6.2	1.17	0.17	0.18	0.62
121	12.7	7.4	1.15	0.17	0.17	0.94
136	11.4	5	0.65	0.26	0.34	0.62
145	11.2	5.1	0.74	0.34	0.31	0.54
166	11.7	4.4	0.74	0.33	0.28	0.51

Table 1. Lab results

Fracture Toughness (K*ic*) Describes the ability of a material containing a crack, to resist fracture

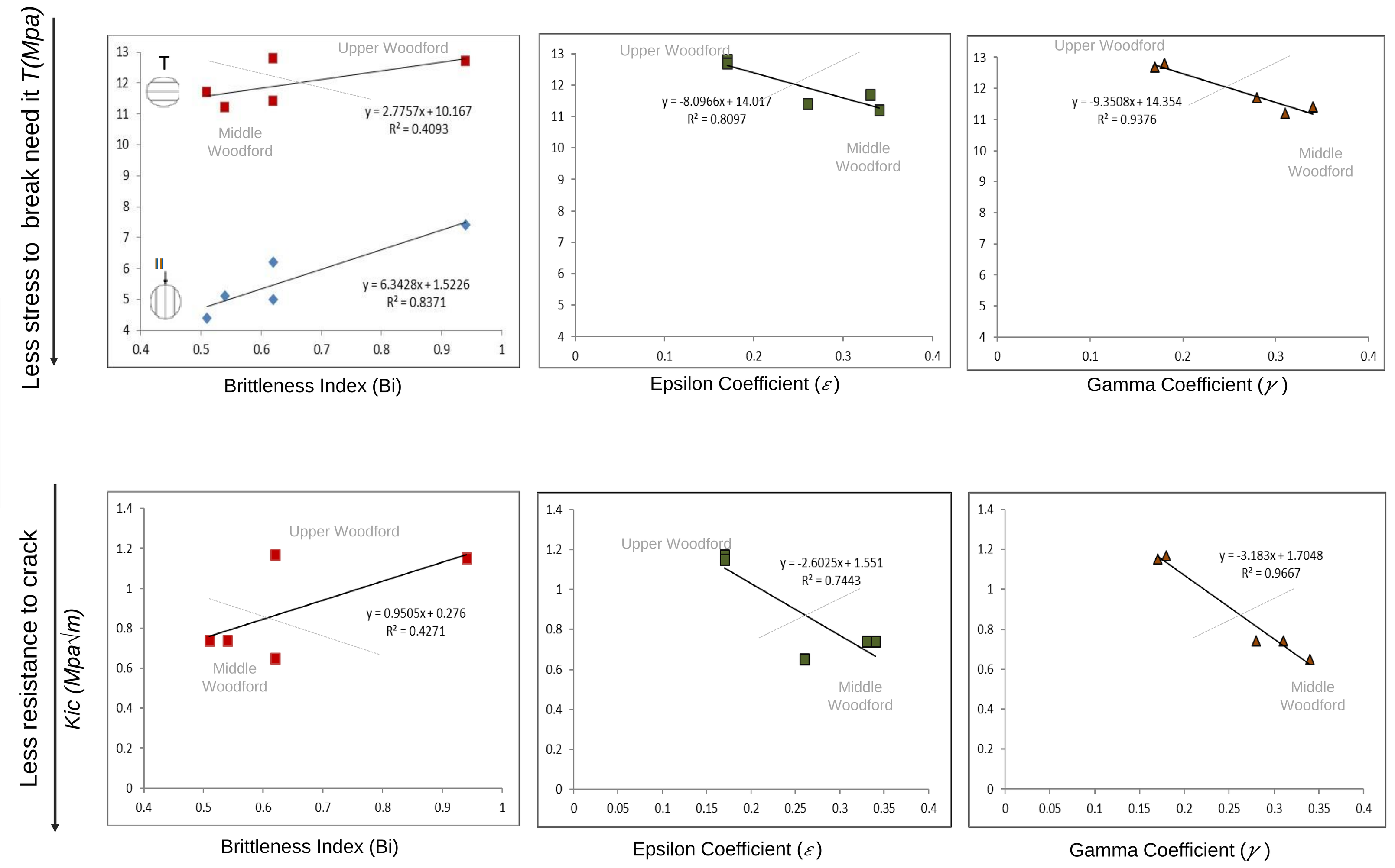

Figure 9. Cross plots between the geomechanic properties Tensile Strength and Fracture Toughness versus Brittleness Index, Epsilon and Gamma Thomsen's Coefficients.

The shale composition doesn't explain completely the rock brittleness variability (Figure 4), because two samples with similar Brittle index (Bi), one from the upper Woodford (111 ft) and the other from the middle Woodford (136 ft), display similar K_{IC} and *T* values (Figures 9). Woodford Shale samples are easier to break parallel (II) than perpendicular (T) to the lamination. Additionally, although we used a limited number of samples, it is evident that the middle Woodford Shale samples that exhibit more laminae (anisotropy), and are marked by higher ε and γ coefficients values, are also characterized by less Fracture Toughness (K_{IC}) and Tensile Strength (*T*) (Table 1).

7. VTI IN WOODFORD SHALE QUARTZ-RICH, BRITTLE INTERVALS

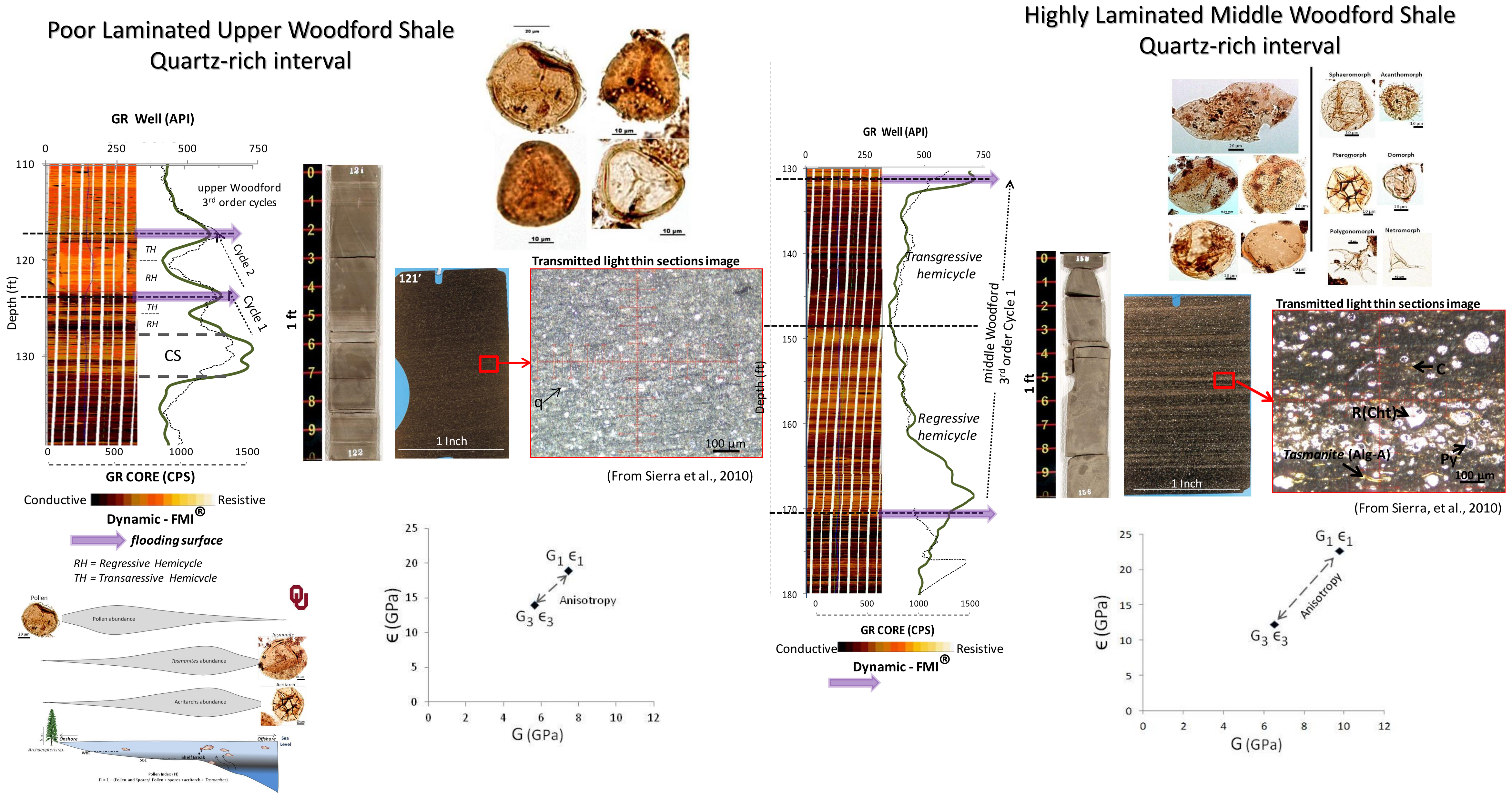

Figure 10. Comparison between Upper and Middle Woodford quarz-rich brittle intervals

A comparison of the Dynamic-FMI® well log, with the gamma ray (GR) well log (green) and the GR core log (dashed gray line) confirm that the upper Woodford Shale is characterized by rocks marked by a reduced lamination (anisotropy), which is also evident in thin section inspection. The upper Woodfors Shale interval is characterized also by a increased detrital and continental input based on palynology assemblages, and thicker 3rd order cycles in comparison with the middle Woodford.
In other hand, the middle Woodford is characterized by more marine palynomorphs and more laminae. The effect of higher anisotropy is reflected in the Young (*E*) and Shear's modulus (G), calculated from core analysis, which are associated with a less minimum horizontal stress (S_h) value for propagating or creating tensile fractures.

8. DISCUSSION

The most laterally continuous, easy to identify, and frequent laminations associated with the middle Woodford samples may be due to the fact that during a rise in base (sea) level, the shoreline is translated landward (i.e. transgression). As a consequence, deposition may be dominated by buoyant plume and lofting depositional process, which may bring continental nutrients to offshore areas and create periodic algae (i.e. *Tasmanites and radiolarian*) blooms (Figure 10). By contrast during HST regressive periods, the seaward movement of the shoreline creates less accommodation space on the continental shelf areas and the shoreline is displaced (i.e. progrades) seaward. As result, offshore accumulation might be affected by the transfer and accumulation of continental sediments, commonly characterized by very thick laminated or structure-less bodies (Figure 10) where some sedimentary features (structures), associated with traction bottom-energy current are commonly observed (O'Brien and Slatt, 1990; Slatt and O'Brien, 2011; Slatt et al., 2012). More laminae in the middle Woodford brittle intervals might assist in reducing the effective minimum horizontal principal stress because laminae can act as planes of weakness during hydraulic fracturing process.

9. CONCLUSIONS

Shales are usually anisotropic and neglecting shale anisotropy may lead to an incorrect estimate of minimum horizontal stress. More laminae in middle Woodford Shale intervals can act as planes of weakness during the tensile fracturing process.

This observation can be useful to prioritize and to select the best intervals for fracking. Those intervals that exhibit more anisotropy (laminae), will be characterized by a lower K_{ic} and *T* and will respond as a more brittle rock to hydraulic stimulation.

Thomsen's coefficient (ε and γ) can be used as an approach to estimate anisotropy and their effect on shale "fracability" under dynamic (well logs, UPV's, seismic) and static conditions (core tests), and also under variable scales scenarios.

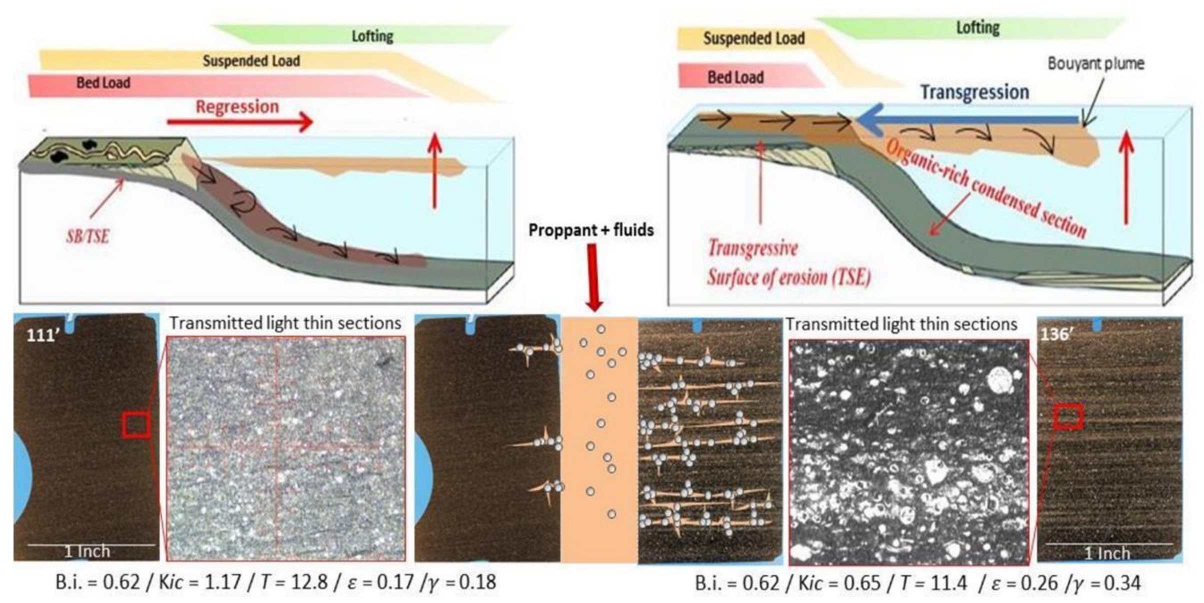

Figure 10. Anisotropy differences between HST and TST Woodford Shale deposits. The sample with less laminae correspond with HST upper Woodford interval (111 ft) and the more laminae with the TST middle Woodford (136 ft). In the middle, a scheme illustrates the hypothetical responds during hydraulic stimulation (Modified from Zavala et al., 2011 and Slatt et al., 2012).

10. REFERENCES

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11. ACKNOWLEDGEMENTS

This material is part of R. Sierra and C. Molinares M.Sc Research Thesis. The authors thanks to Dr. Y. Abousleiman for the assistance and providing the geomechanic core analysis. To Devon Energy and Schlumberger for providing Wyche-1 core and well log data set. To the Woodford Shale Consortium members (Phase III) for their generous support and to the ConocoPhillips School of Geology and Geophysics of The University of Oklahoma.