

Calibration of Brittleness to Elastic Rock Properties via Mineralogy Logs in Unconventional Reservoirs*

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Abstract

To optimally stimulate an unconventional reservoir hydraulically, it is important to identify brittle regions based on knowledge of the geology, petrophysics, mineralogy, and rock mechanics of the area of study. This research reconciles some of the brittleness terminology in the literature and classifies the Barnett Shale in terms of its geomechanical properties, defining the more-brittle regions in Young's modulus and Poisson's ratio crossplots and $\lambda\rho - \mu\rho$ space. These geomechanical properties were defined, calibrated, and computed using specialized logging tools such as: mineralogy, density, and P- and S-wave sonic logs, and calibrated to previous core descriptions and laboratory measurements. With proper calibration these measurements provide a means to geomechanically characterize a reservoir.

In the Barnett Shale, the combination of high concentrations of quartz and calcite gives rise to more brittle rocks, while ductility is controlled primarily by clay content. Contrary to the commonly held understanding, in the Barnett increased kerogen (TOC) does not make the rock more ductile. Further, microseismic event locations from a 3D seismic survey acquired after more than 400 wells have been drilled and hydraulically fractured in the area agree to the predicted brittle regions in the $\lambda\rho - \mu\rho$ crossplot, suggesting that hydraulically induced fractures preferentially populate brittle regions and consequently, produce more gas. Thus, these results are useful to calibrate 3D seismic attribute brittleness estimation.

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CALIBRATION OF BRITTLENESS TO ELASTIC ROCK PROPERTIES VIA MINERALOGY LOGS IN UNCONVENTIONAL RESERVOIRS

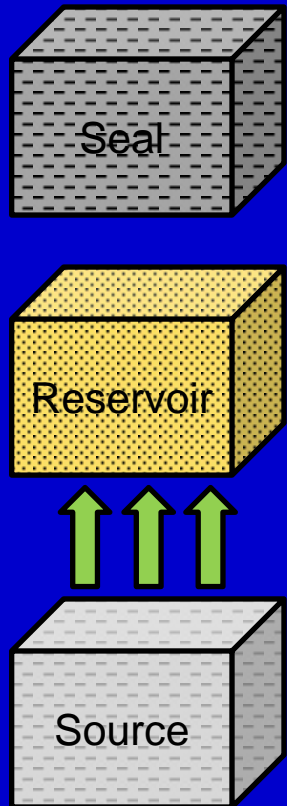
Roderick Perez, Ph.D.

The University of Oklahoma

Transform – Drilling Info

INTRODUCTION

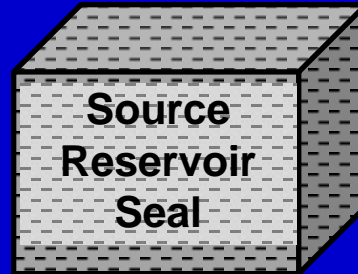
CONVENTIONAL



In a geological sense, in a conventional reservoir the hydrocarbon generated by a kerogen-rich rock migrates naturally and is stored by buoyant forces into the porous space of a reservoir rock, and subsequently is trapped by an impermeable seal. This geological definition of a petroleum system differentiates three rock types: source, reservoir and seal.

UNCONVENTIONAL

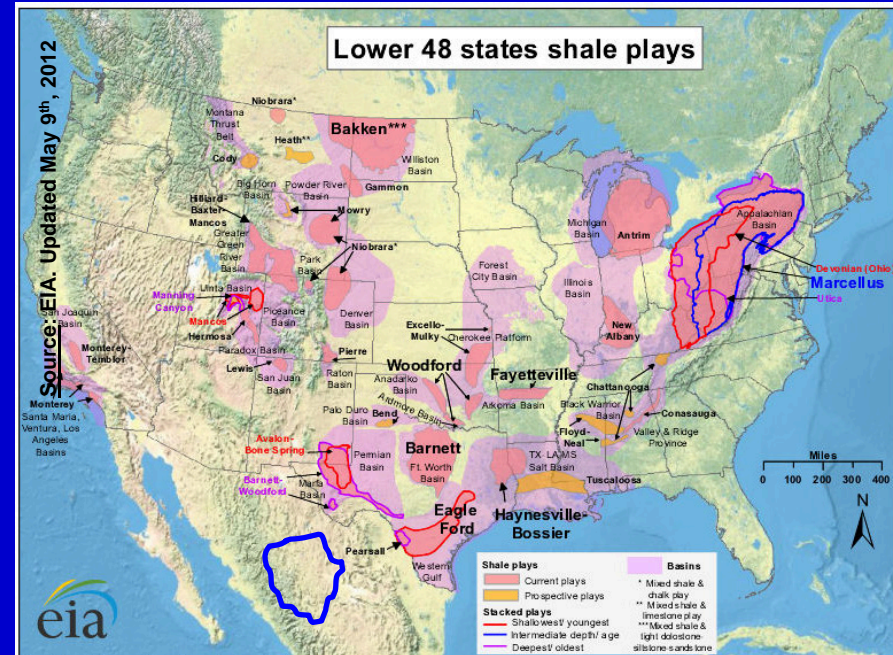
An unconventional reservoir is one where one single rock combines the previous rock characteristics, and the hydrocarbon storage in the rock pores (typically natural gas) does not flow naturally due to the low (> \$ 0.1 mD) rock permeability. Many of these low-permeability rocks are shale and tight sandstone, but currently significant amounts of gas are also produced from low-permeability carbonates and coal bed methane.



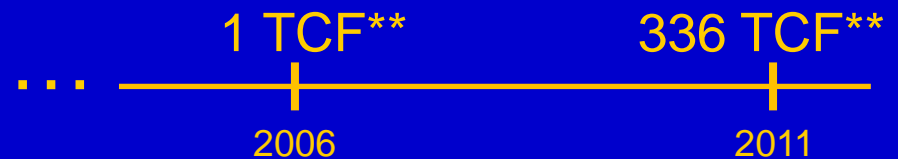
BARNETT SHALE:

Low permeability* (<0.1 mD)
Low porosity* (6%)
High TOC*

*Average values corresponding to the Barnett Shale

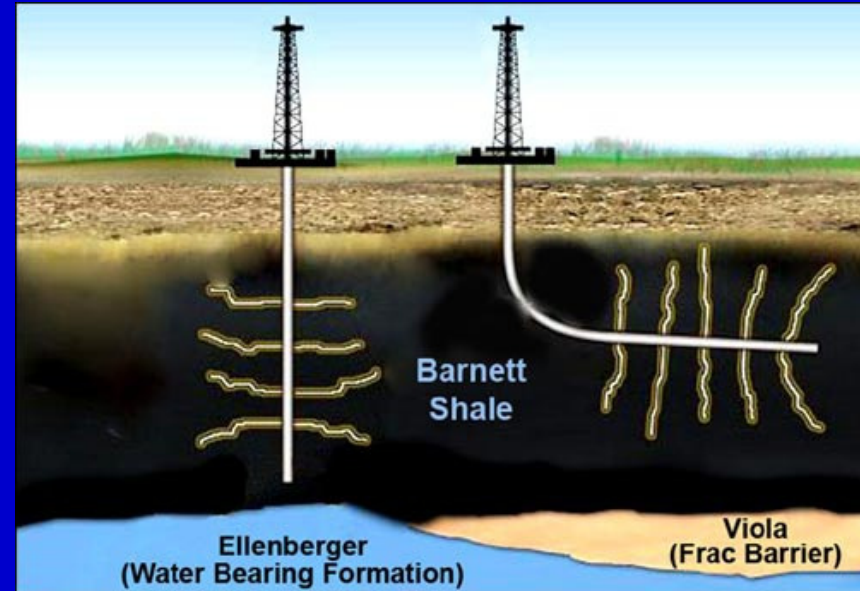
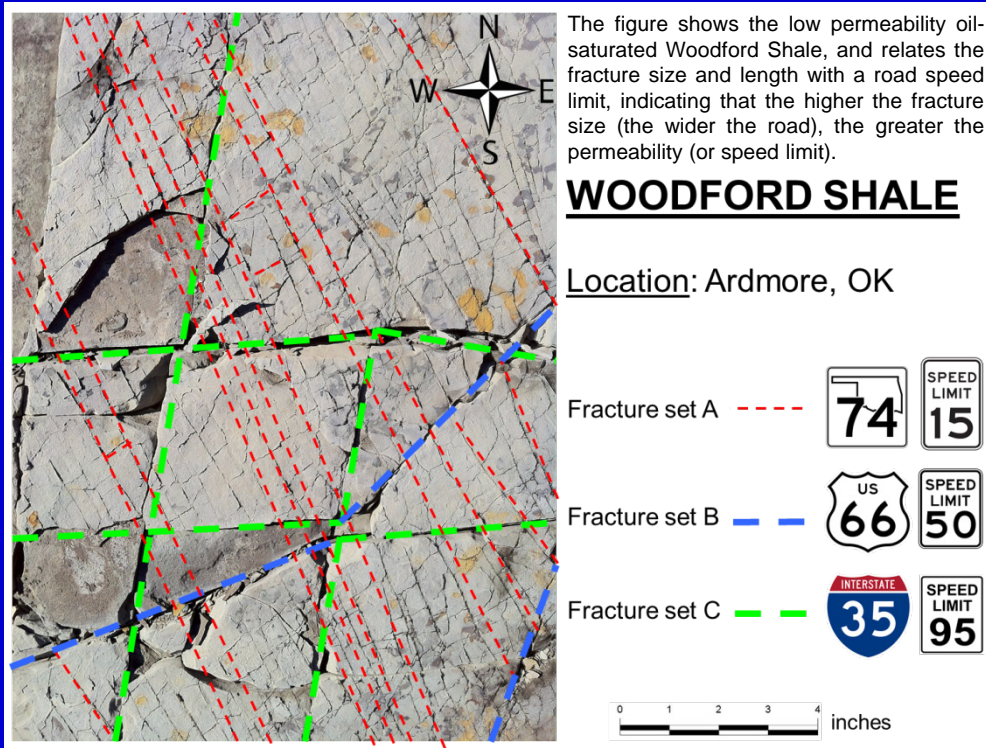


The proliferation of the exploration activity into new shale plays has increased the shale gas resources in the U.S. from 1 TCF in 2006 to 336 TCF in August 2011. In this dissertation we will focus on the Barnett Shale, located in the Fort Worth Basin (Texas).



**Trillion cubic feet

GOAL



Due to the low permeability, it is necessary apply enhanced recovery techniques, such as hydraulic fracture stimulation or steam injection to extract the gas molecules from the rock matrix and achieve gas production.

Finding areas in the shale play that are “**brittle**” is important in the development of a fracture fairway large enough to connect the highest amount of “**rock volume**” during the **hydraulic – fracturing process**.

OUTLINE

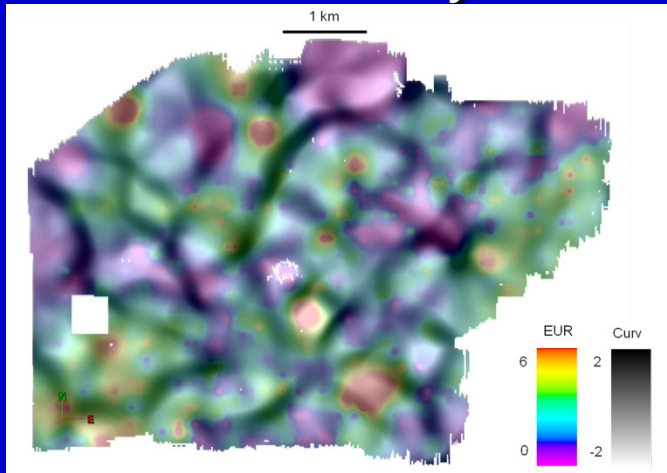
- Introduction
 - Objectives
 - Mineralogy-based brittleness prediction from surface seismic data
 - Surface seismic estimation of hydraulically – fractured rock
 - Microseismic events and flow measured from production logs
 - Conclusions
- Well log calibration
- Seismic rock brittleness quantification
- Calibration to production

OUTLINE

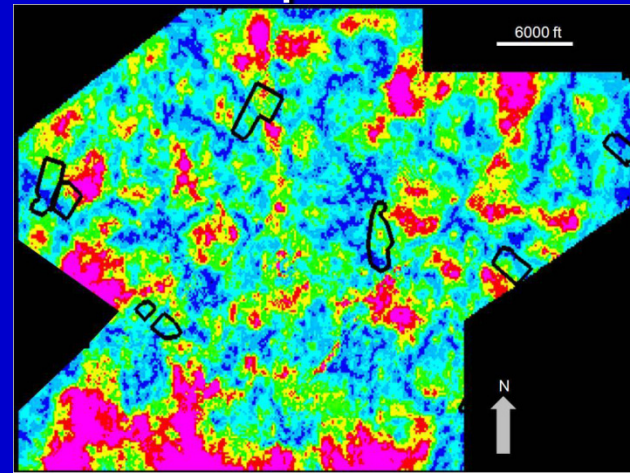
- Introduction
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OBJECTIVES

- Previous work (Thompson, 2010; Zhang, 2010) has shown that seismic impedance, curvature, and other attributes visually correlate with reservoir performance



Relative EUR value co-rendered with most positive curvature (Thompson, 2010)



Anisotropy intensity with polygons of microseismic events from six experiments. Notice the micro-seismic events appear in areas of low anisotropy intensity. (Zhang, 2010)

- Can I link seismic data measurements such as prestack seismic inversion attributes, microseismic event location and magnitude, and most important, EUR, to reservoir performance?

OUTLINE

- Introduction
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WHAT IS BRITTLINESS???

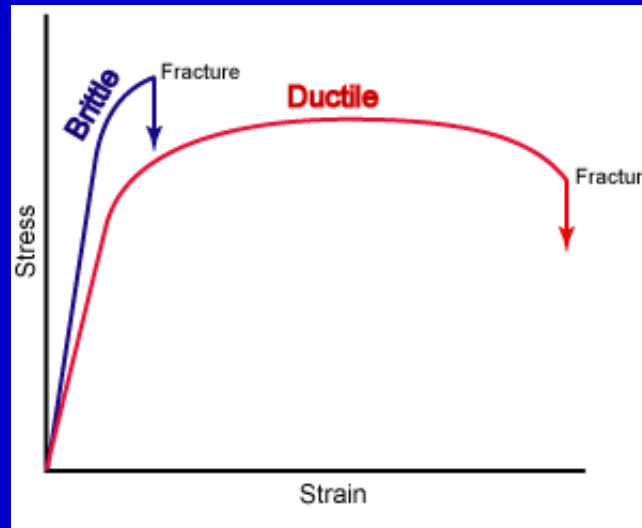
BRITTLE

BRITTLINESS is the measurement of stored energy before failure, and is function of:

- Rock strength
- lithology
- texture
- effective stress
- temperature
- fluid type
- diagenesis
- TOC

BRITTLINESS INDEX (BI) is the most widely used parameter for the quantification of rock brittleness.

$$BI = \frac{\sigma_c}{\sigma_t}$$



Higher the magnitude of the BI, the more brittle the rock is

If the rock has a large region of elastic behavior but only a small region of ductile behavior the rock is considered brittle. In contrast, If the material under stress has a small region of elastic behavior and a large region of ductile behavior, absorbing much energy before failure, it is considered ductile (opposite of brittle).

DUCTILE



BRITTLINESS

How do to quantify brittleness

1) Mineralogy??

2) Elastic parameters??

MINERALOGY

$$BI_{Jarvie(2007)} = \frac{Qz}{Qz + Ca + Cly}$$

$$BI_{Wang(2009)} = \frac{Qz + Dol}{Qz + Dol + Ca + Cly + TOC}$$

BRITTLINESS

Mineralogy

Young's
modulus &
Poisson's
ratio

GEOLOGY

GEOMECHANICAL

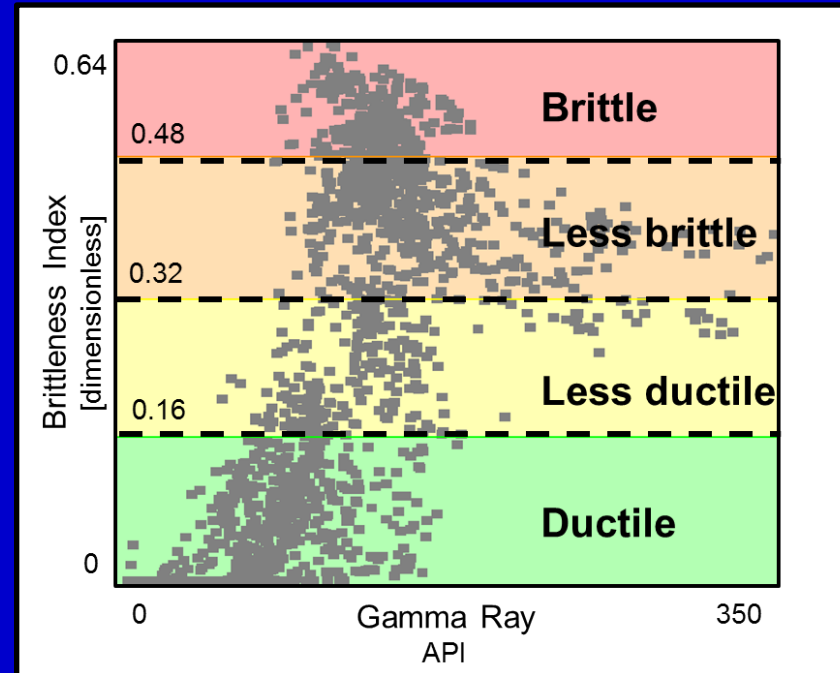
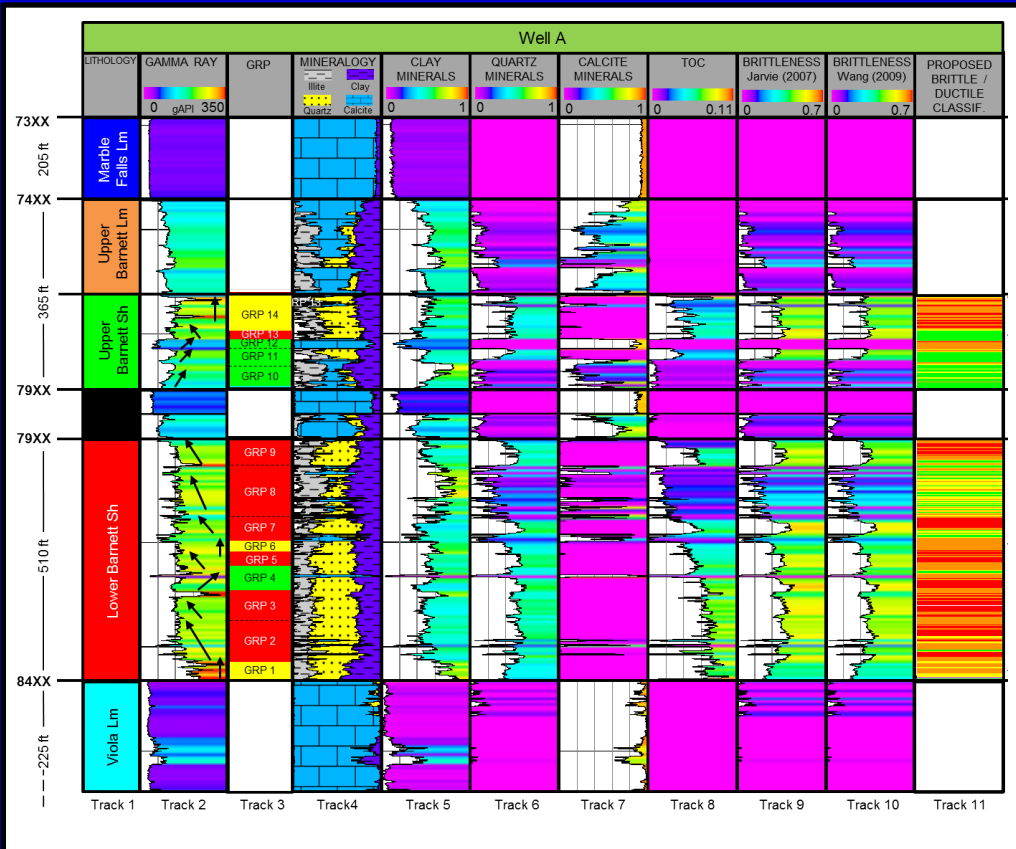
ELASTIC PARAMETERS

$$E_{brittleness} = \frac{E - E_{min}}{E_{max} - E_{min}},$$

$$\nu_{brittleness} = \frac{\nu - \nu_{max}}{\nu_{min} - \nu_{max}},$$

$$Brittleness_{average} = \frac{(E_{brittleness} + \nu_{brittleness})}{2}.$$

BRITTLENESS INDEX (Mineralogy)



$$BI_{Jarvie(2007)} = \frac{Qz}{Qz + Ca + Cly}$$

$$BI_{Wang(2009)} = \frac{Qz + Dol}{Qz + Dol + Ca + Cly + TOC}$$

Qz = Quartz
 Ca = Calcite
 Cly = Clay

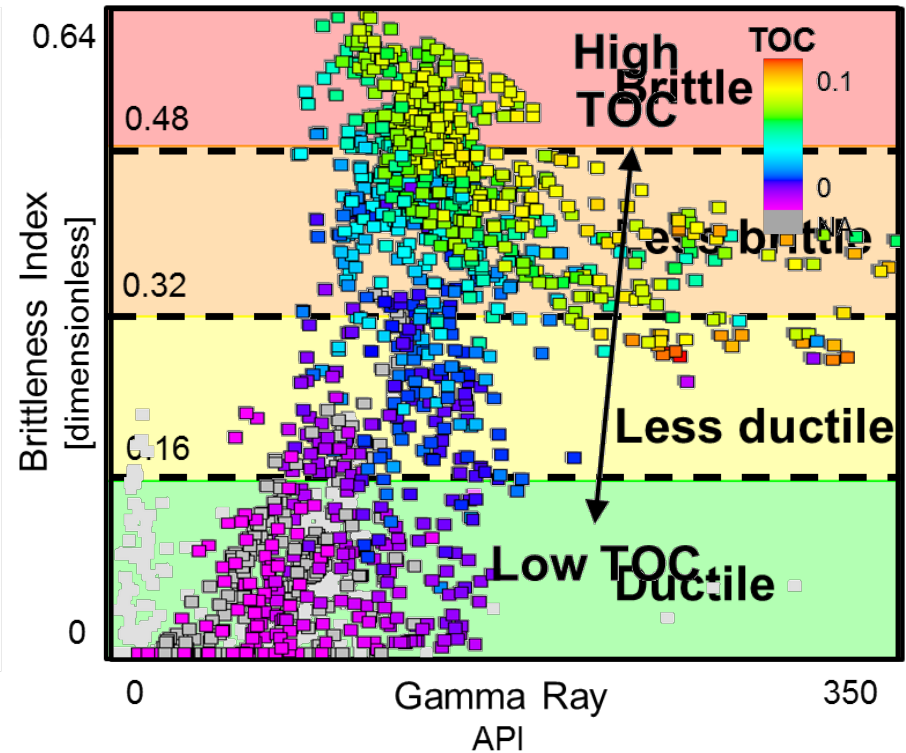
Dol = Dolomite
 TOC = Total Organic Carbon

Gamma ray, GRP, and mineralogy logs corresponding to Well A. The brittleness index logs are calculated using Jarvie et al. (2007) (track 9) and Wang and Gale (2009) (track 10). Track 11 shows the classification results, where brittle (red) and more brittle zones (orange) are associated with high quartz and TOC content zones.

CALIBRATION OF BRITTLINESS TO ELASTIC ROCK PROPERTIES VIA MINERALOGY LOGS

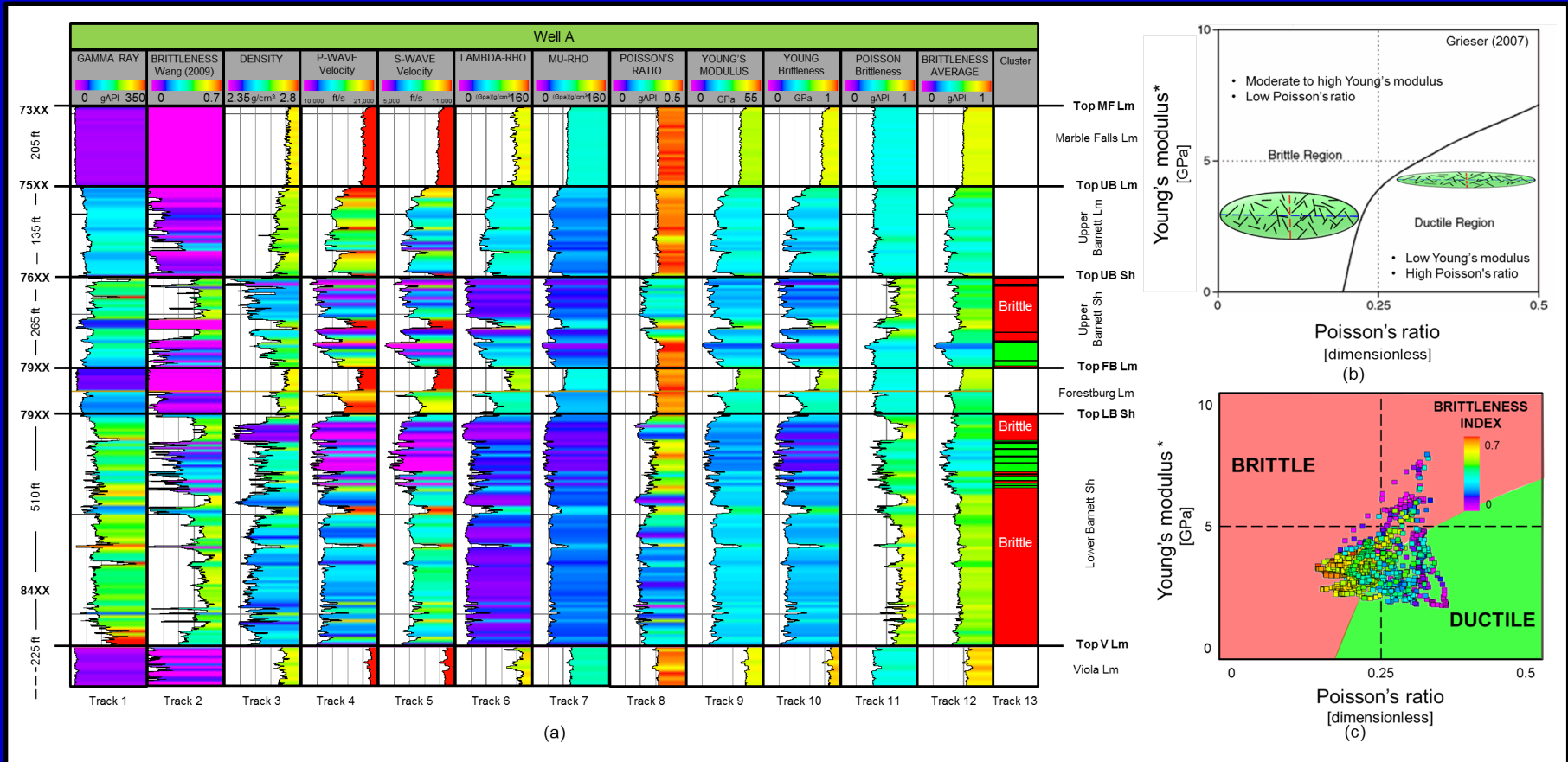
LITHOFACIES		Average TOC (wt%)	Average silica (SiO ₂) %
<i>In situ</i> phosphatic deposit	Increase in organic richness ↑ ↓ Decrease in bottom water oxygen	6	10 - 15
Siliceous, non calcareous mudstone		4.5	30
Siliceous, calcareous mudstone		3.5	-
Calcareous laminae		3.5	-
Micritic / limy mudstone		1.2	10
Reworked shelly deposit		2.6	2 - 10
Silty shelly (wavy) interlaminated deposit		-	20

Singh (2008)



Gamma ray (GR) vs. brittleness index (BI) corresponding to Well A (using Wang and Gale's (2009) equation color-coded by total organic carbon (TOC) content, and Singh (2008) Barnett Shale lithofacies definition ranked in relation to interpreted relative bottom oxygenation and organic richness. Brittle (red), less brittle (orange), less ductile (yellow), and ductile (green) classification proposed (classification results are shown in track 11 on previous slice.

BRITTLINESS AVERAGE (Elastic parameters)



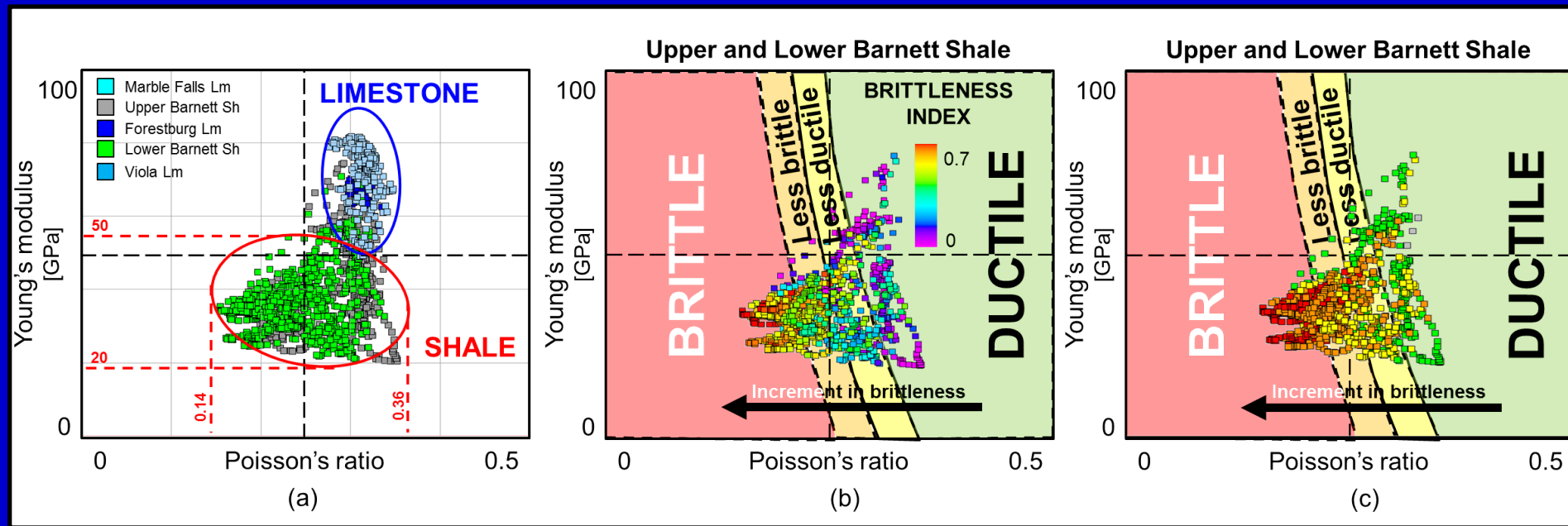
$$E_{\text{brittleness}} = \frac{E - E_{\min}}{E_{\max} - E_{\min}}$$

$$\nu_{\text{brittleness}} = \frac{\nu - \nu_{\max}}{\nu_{\min} - \nu_{\max}}$$

$$\text{Brittleness}_{\text{average}} = \frac{(E_{\text{brittleness}} + \nu_{\text{brittleness}})}{2}$$

a) Set of elastic logs corresponding to Well A, b) Poisson's ratio vs. Young's modulus crossplot indicating empirically defined ductile-brittle regions, and the expected fracture pathway geometry (modified from Grieser and Bray, 2007), (c) the Poisson's ratio vs. Young's modulus values corresponding to formations in Well A overplotted by Grieser and Bray's (2007) ductile (green)-brittle (red) regions color-coded with brittleness index from ECS mineralogy analysis. Classification results are shown in track 13.

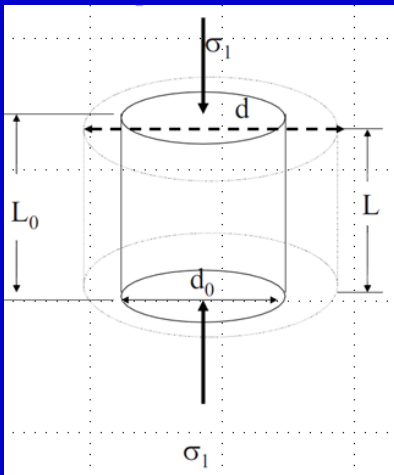
CALIBRATION OF BRITTLINESS TO ELASTIC ROCK PROPERTIES VIA MINERALOGY LOGS



Poisson's ratio vs. Young's modulus crossplot (a) corresponding to each formation in the study area. (b) Poisson's ratio vs. Young's modulus crossplot corresponding to Upper and Lower Barnett Shale color-coded by brittleness index (BI), overlapped by a proposed brittle/ductile classification, and (c) the proposed classification.

CALIBRATION OF BRITTLINESS TO ELASTIC ROCK PROPERTIES VIA MINERALOGY LOGS

Young's Modulus



$$E = \frac{\mu(3\lambda + 2\mu)}{(\lambda + \mu)}$$

$$V_p = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

P-wave
Velocity

$$V_s = \sqrt{\frac{\mu}{\rho}}$$

S-wave
Velocity

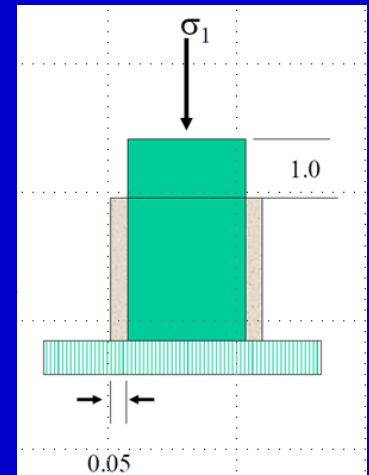
$$M = \lambda + 2\mu$$

P-wave Modulus

$$\frac{E}{1 + \nu} = 2\mu$$

Young - Poisson Relation

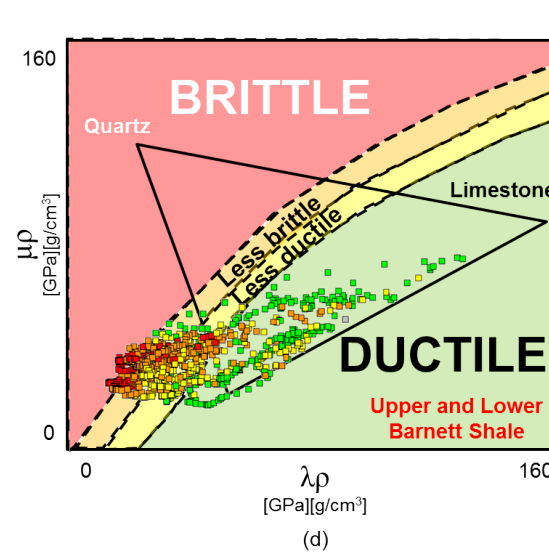
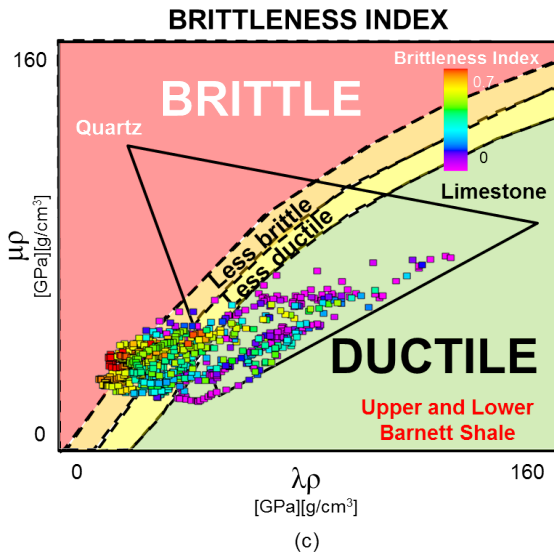
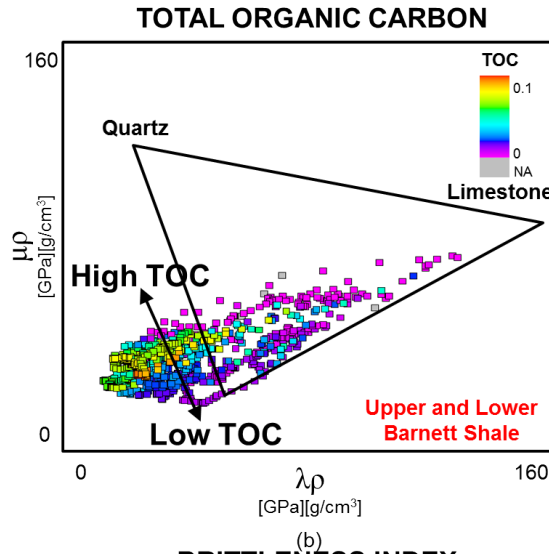
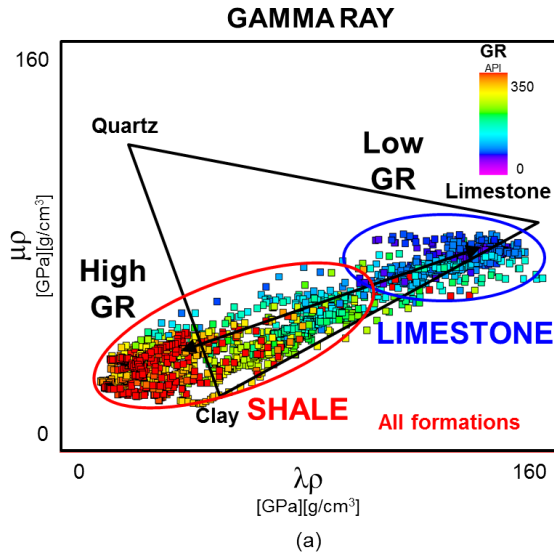
Poisson's ratio



$$\nu = \frac{\lambda}{(2\lambda + 2\mu)}$$

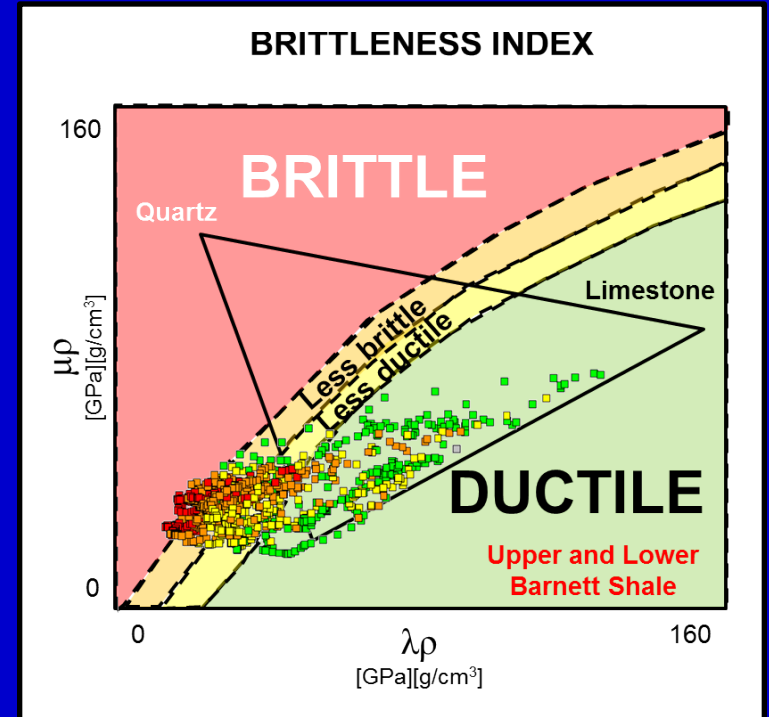
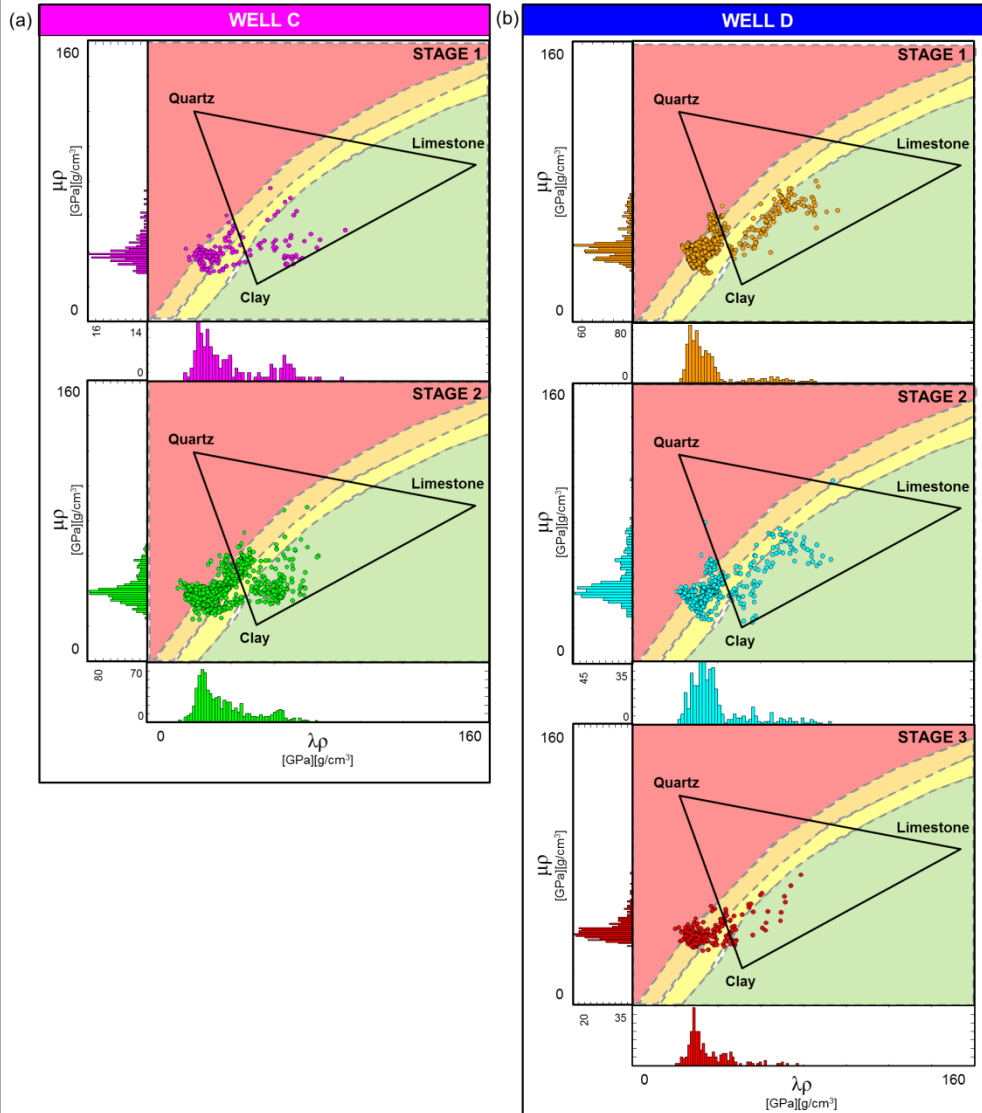
Mu (Lame moduli) - rigidity and Lambda allow the fundamental parametrization of seismic waves used to extract information about rocks in the earth. These parameters link many fields of earth science, from petroleum exploration to earthquake seismology. Some contradictions are removed by restating equations using Lame parameters.

CALIBRATION OF BRITTLINESS TO ELASTIC ROCK PROPERTIES VIA MINERALOGY LOGS



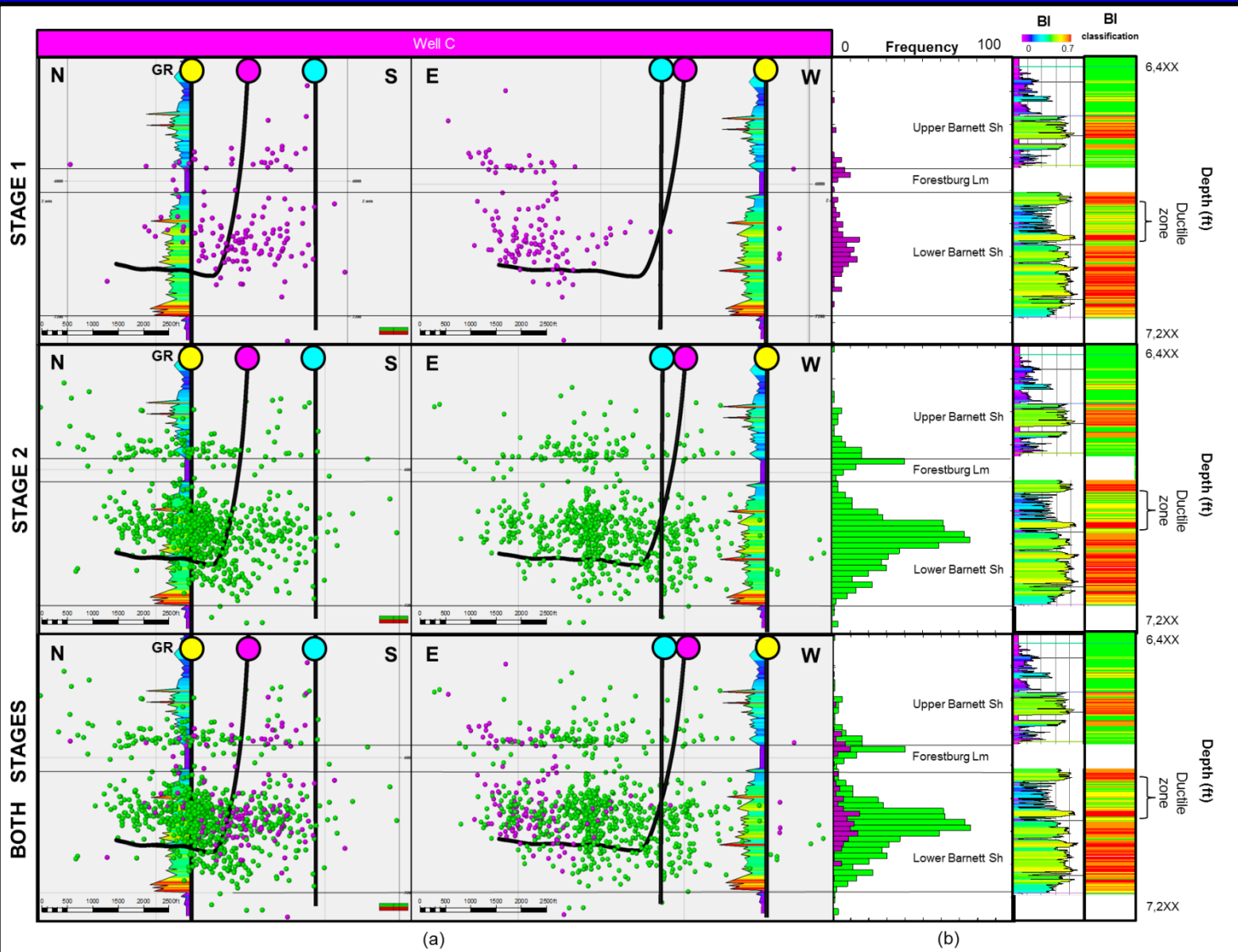
λ - μ crossplot (a) color-coded by gamma ray, (b) color-coded by TOC, (c) color-coded by brittleness index (extracted from mineralogy) overplotted by a proposed brittle/ductile classification, and (d) the proposed BI classification.

CALIBRATION OF BRITTLINESS TO ELASTIC ROCK PROPERTIES VIA MINERALOGY LOGS



Extracted $\lambda - \mu$ from each microseismic event location corresponding to (a) Well C and (b) Well D. (c) $\lambda - \mu$ crossplot from the area around the well. Comparing the microseismic events distribution to those in (a) and (b) shows that the majority of microseismic events occurs in the area that I define as brittle (red) and less brittle (orange).

CALIBRATION OF BRITTLINESS TO ELASTIC ROCK PROPERTIES VIA MINERALOGY LOGS

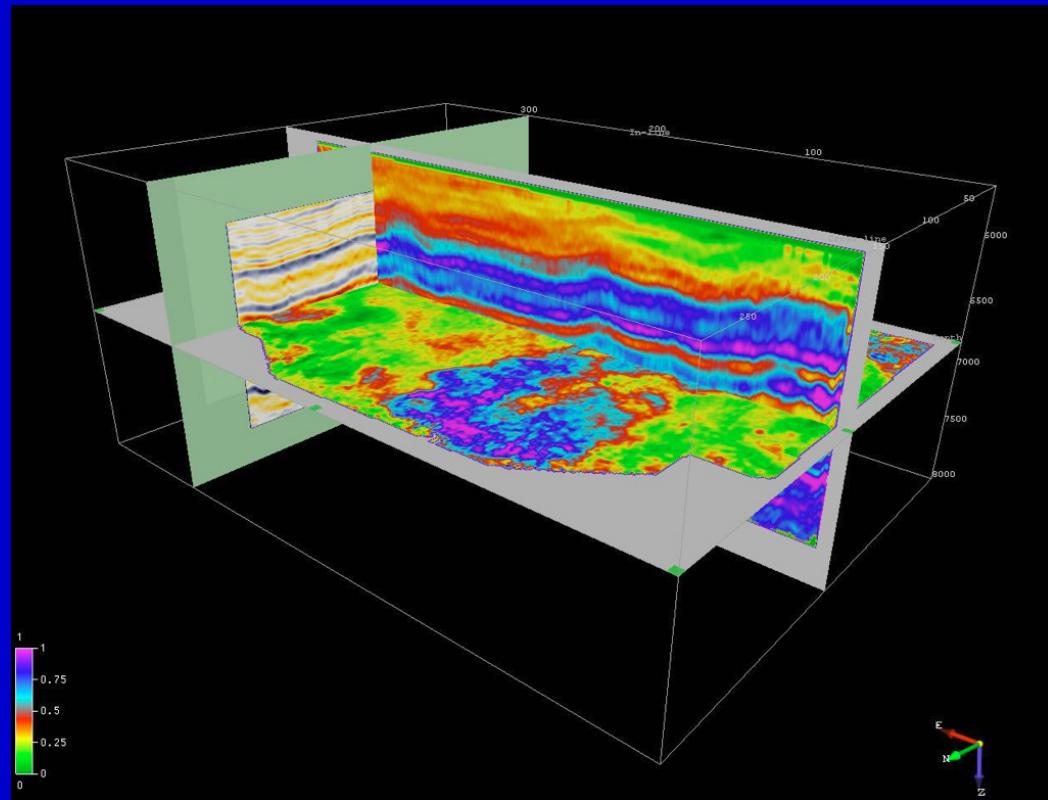
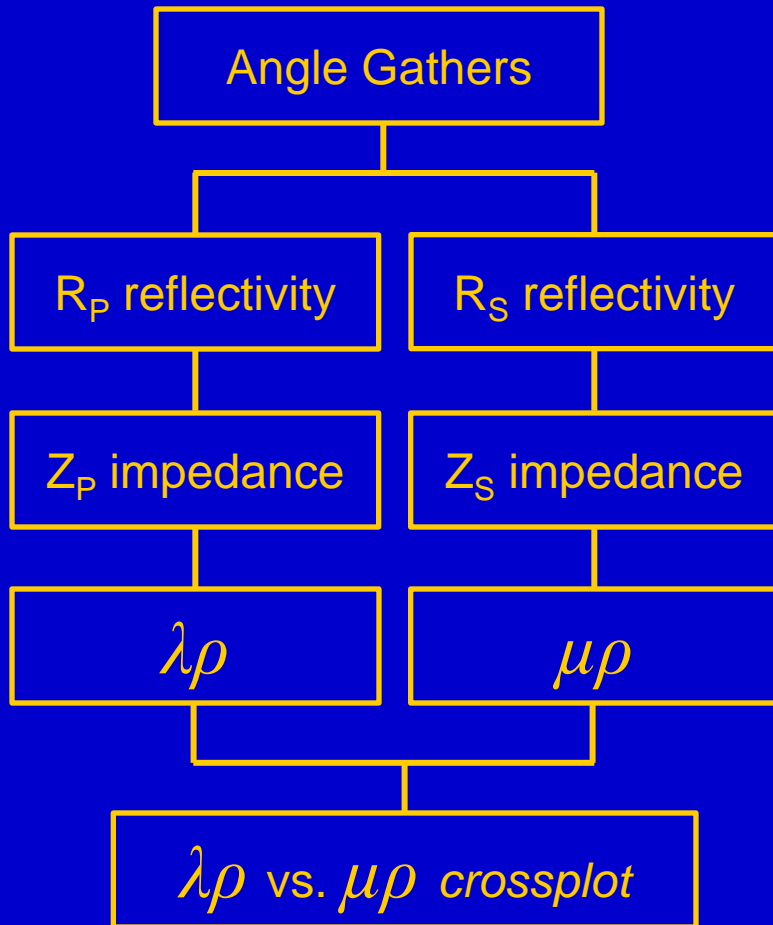


(a) Lateral view and (b) microseismic vertical (depth) histograms, gamma ray, brittleness index log, and BI classification (brittle (red), less brittle (orange), less ductile (yellow), and ductile (green)) corresponding to individual stages of microseismic event locations corresponding to Well C. Vertical histogram shows a decrease in events recorded in the upper section of the Lower Barnett Shale toward the Forestburg Limestone, possibly due to the increment in clay minerals and therefore ductility, creating a ductile zone.

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- Conclusions

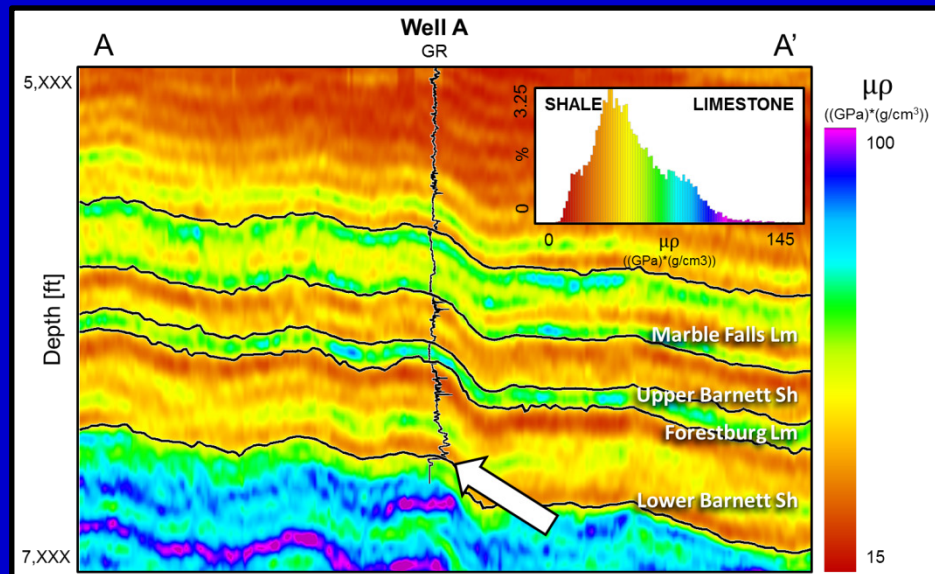
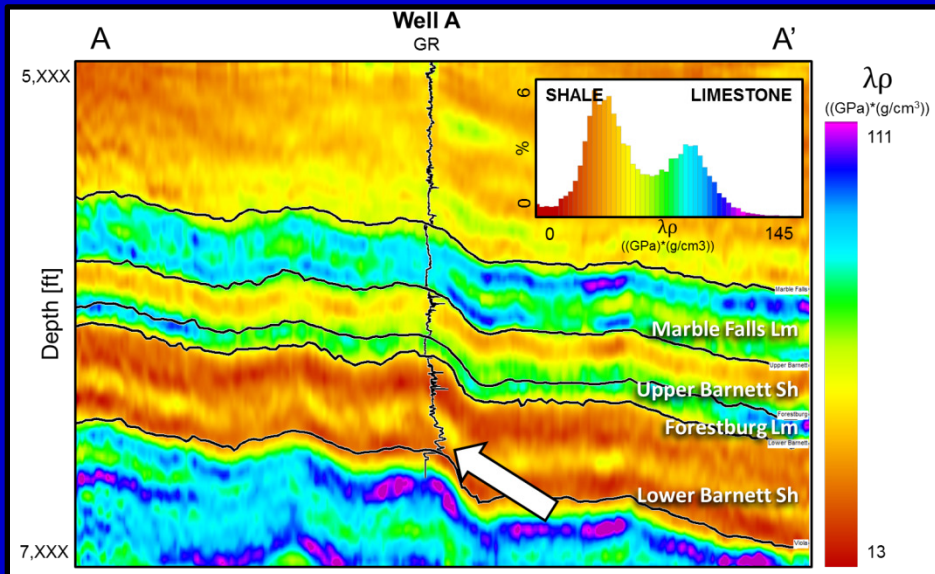
SURFACE SEISMIC ESTIMATION OF HYDRAULICALLY – FRACTURED ROCK



$$\lambda\rho = (\rho V_P)^2 - 2(\rho V_S)^2.$$

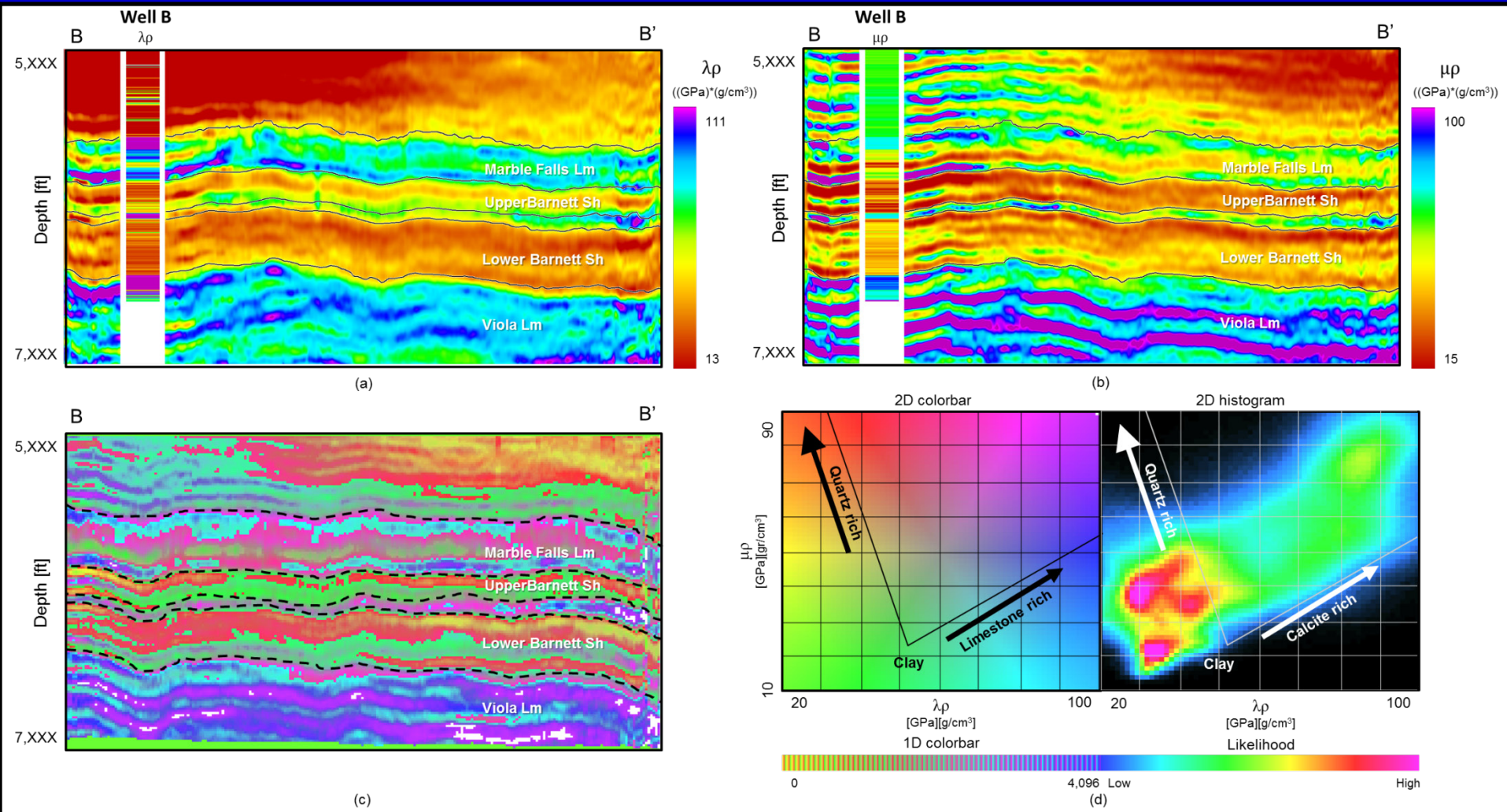
$$\mu\rho = (\rho V_S)^2$$

SURFACE SEISMIC ESTIMATION OF HYDRAULICALLY – FRACTURED ROCK



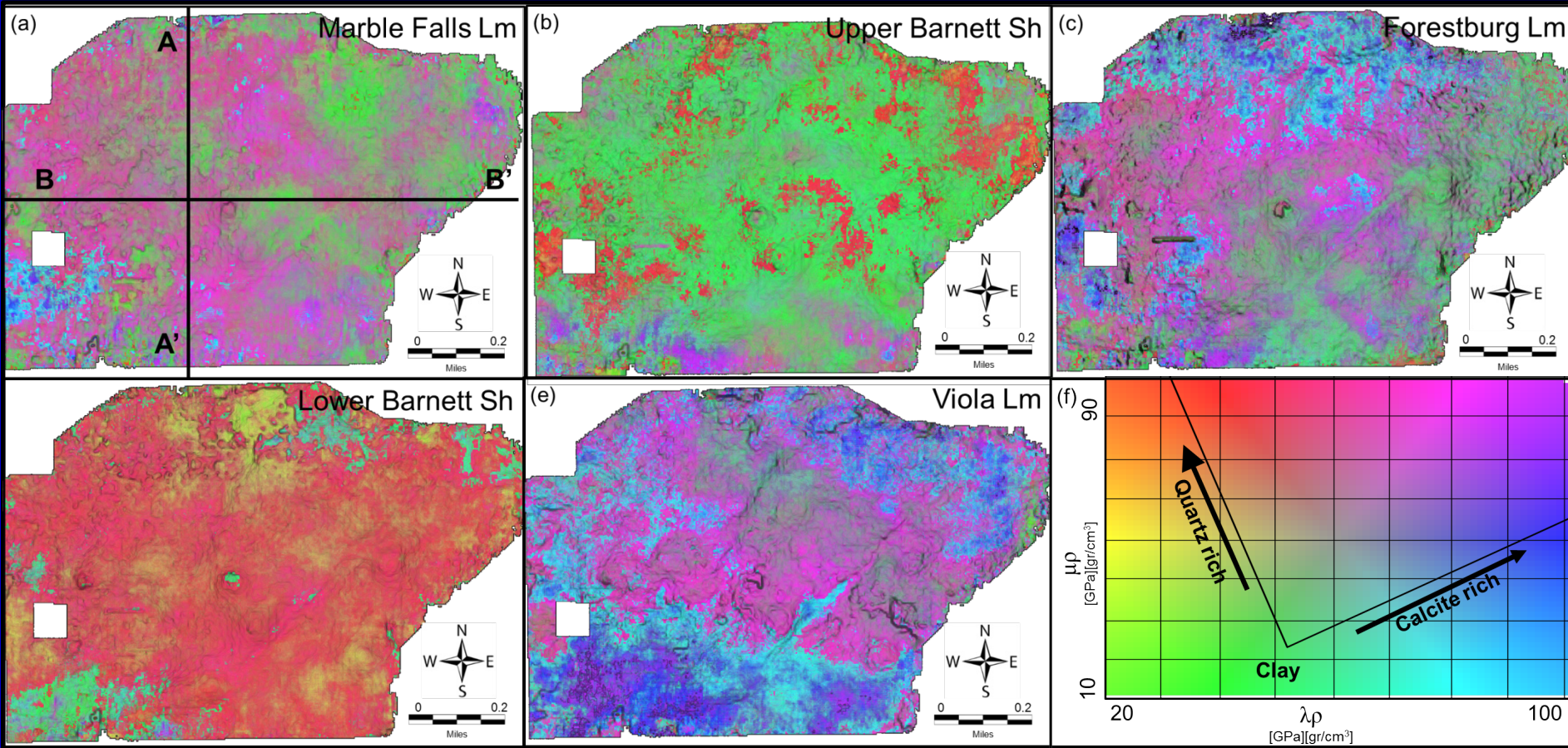
Vertical slices A - A' through (a) λ and (b) μ seismic volumes and their corresponding histograms. Notice that the shale formations exhibit lower values of λ and μ (red and yellow) than the limestone formations (cyan and blue). Location of the line is shown in slice 22. (c) $\lambda - \mu$ crossplot color-coded by gamma ray from logs indicating that shale formations exhibit low λ and low μ . (d) Gamma ray vs. brittleness index indicating that in the Barnett Shale high gamma ray values represent high brittleness and TOC, confirming the core analysis by Singh (2008).

SURFACE SEISMIC ESTIMATION OF HYDRAULICALLY – FRACTURED ROCK



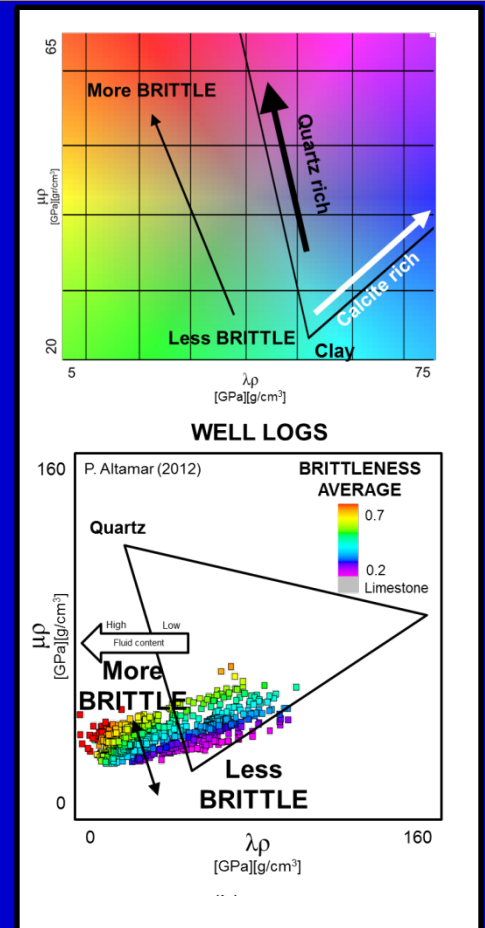
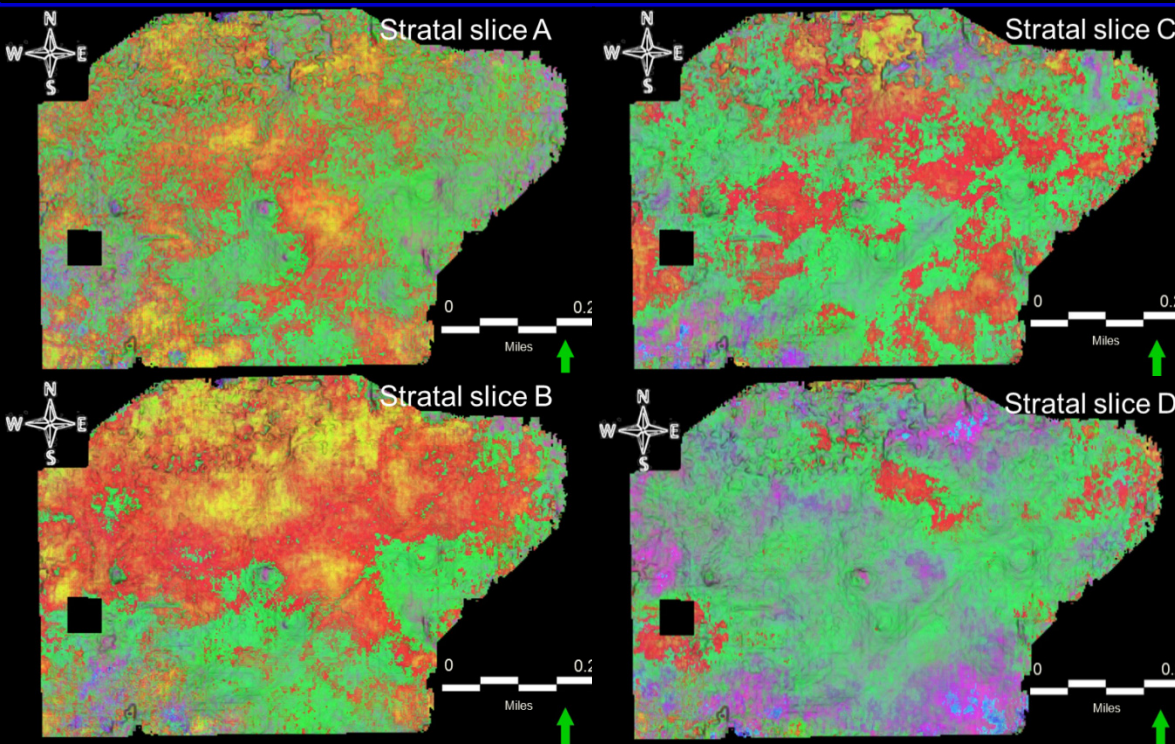
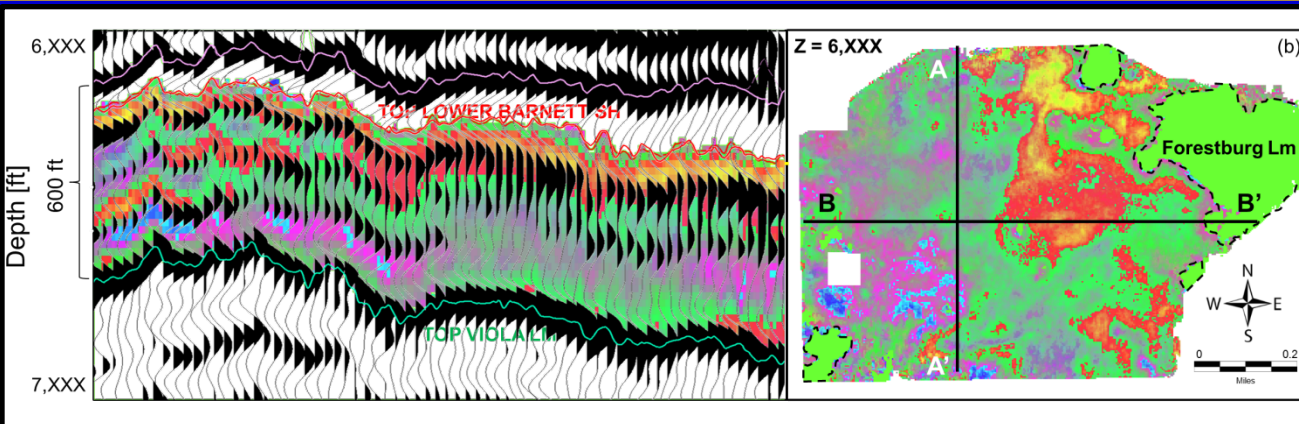
Vertical slices B - B' through (a) λ and (b) μ seismic volumes and (c) through the crossplotted λ vs. μ volumes using a (d) 2D colorbar (location of line B - B' is shown in next slice). The range of the 2D colorbar enhances the differences between quartz- (yellow and red), clay (green), and limestone (magenta, blue, and purple) -rich formations, providing an estimate of lithology and geomechanical behavior.

SURFACE SEISMIC ESTIMATION OF HYDRAULICALLY – FRACTURED ROCK



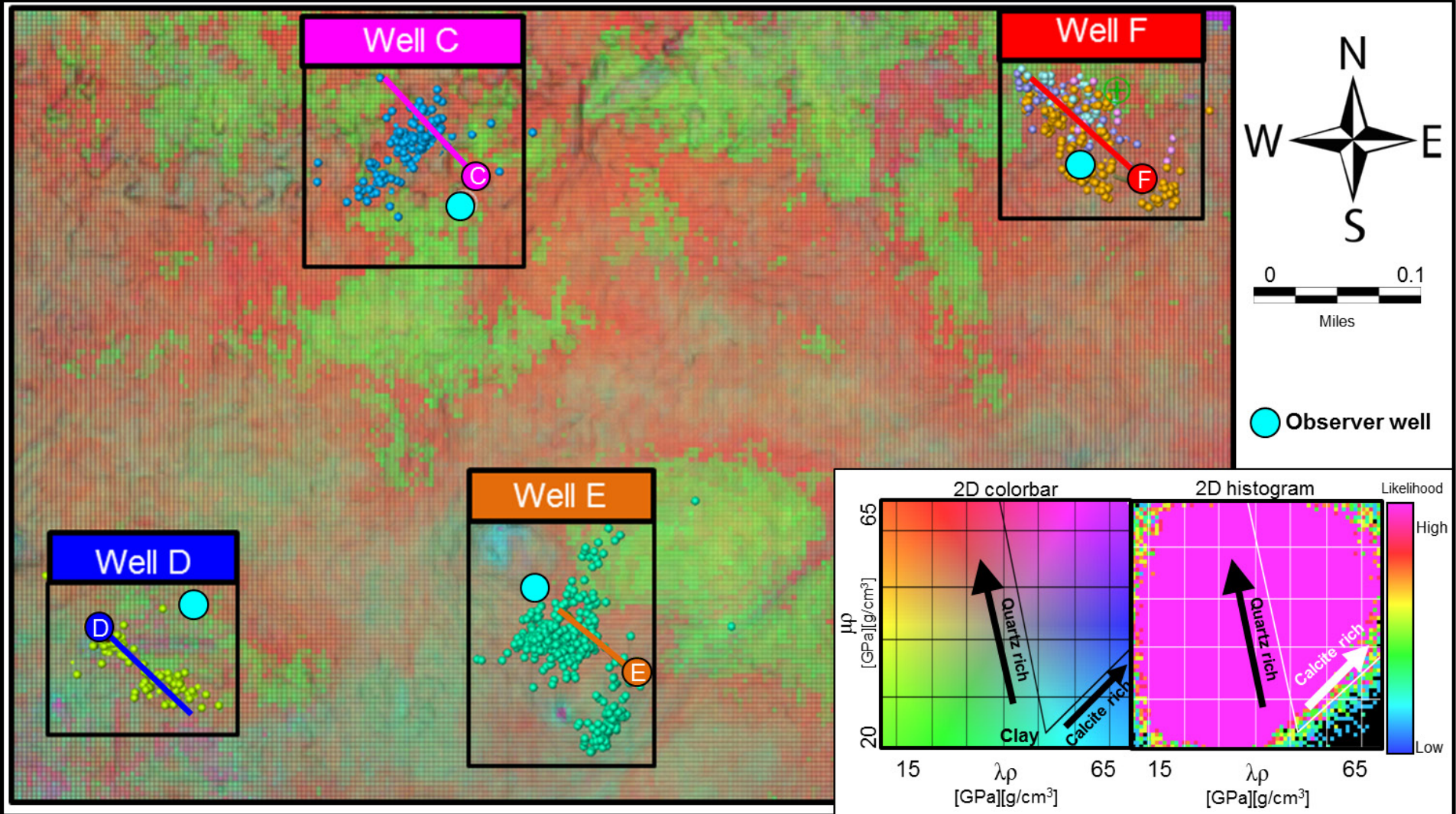
Stratal slices through λ vs. μ crossplot volumes corresponding to (a) Marble Falls, (b) Upper Barnett Shale, (c) Forestburg Limestone, (d) upper Lower Barnett Shale, (e) lower Lower Barnett Shale, and (f) Viola Limestone using the 2D colorbar. Limestones appear as magenta, blue, and purple, while quartz-rich shales appear as yellow and red, and clay-rich shales appear as green.

SURFACE SEISMIC ESTIMATION OF HYDRAULICALLY – FRACTURED ROCK



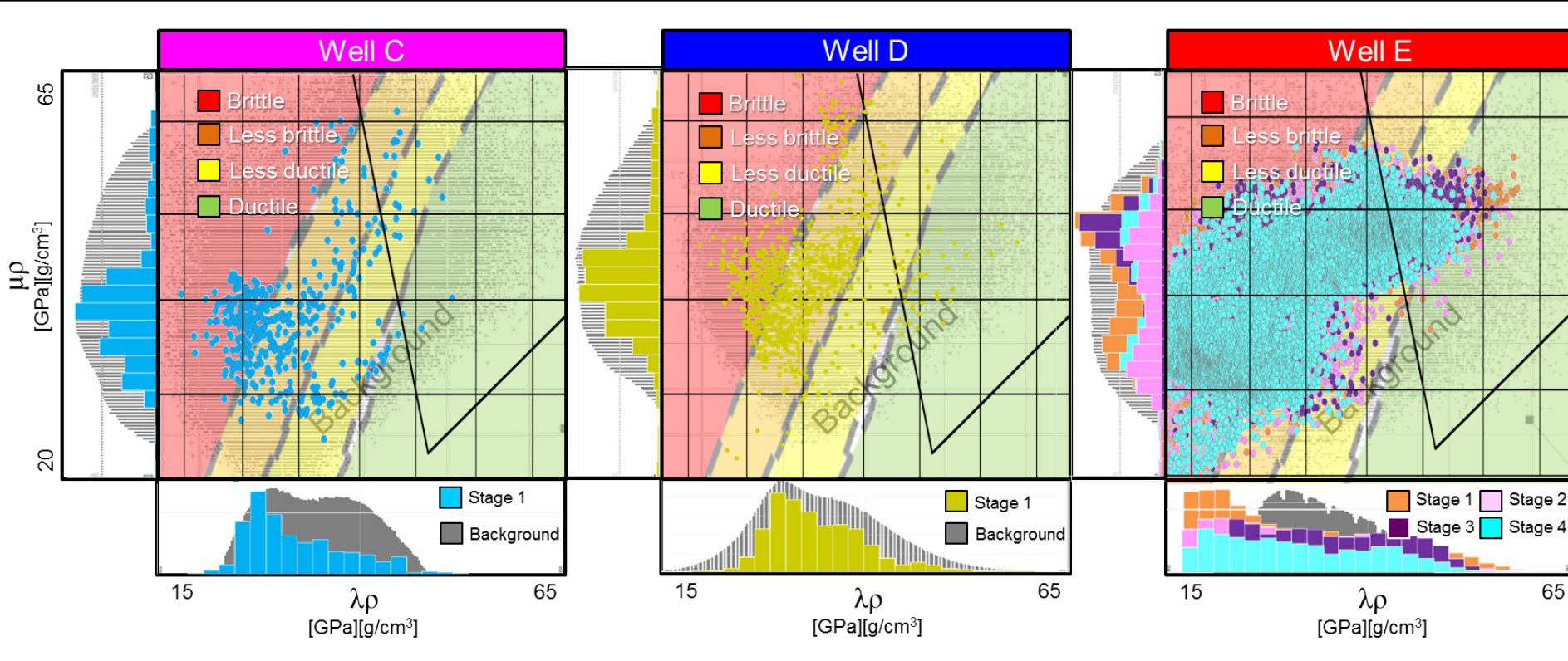
Four stratal slices corresponding to the Lower Barnett Shale indicating the location of the calcite rich (magenta and blue), quartz-rich (yellow and red), and clay-rich shales (green) regions using the 2D colorbar.

PRODUCTION LOGGING COMBINED WITH 3D SURFACE SEISMIC IN UNCONVENTIONAL PLAYS CHARACTERIZATION



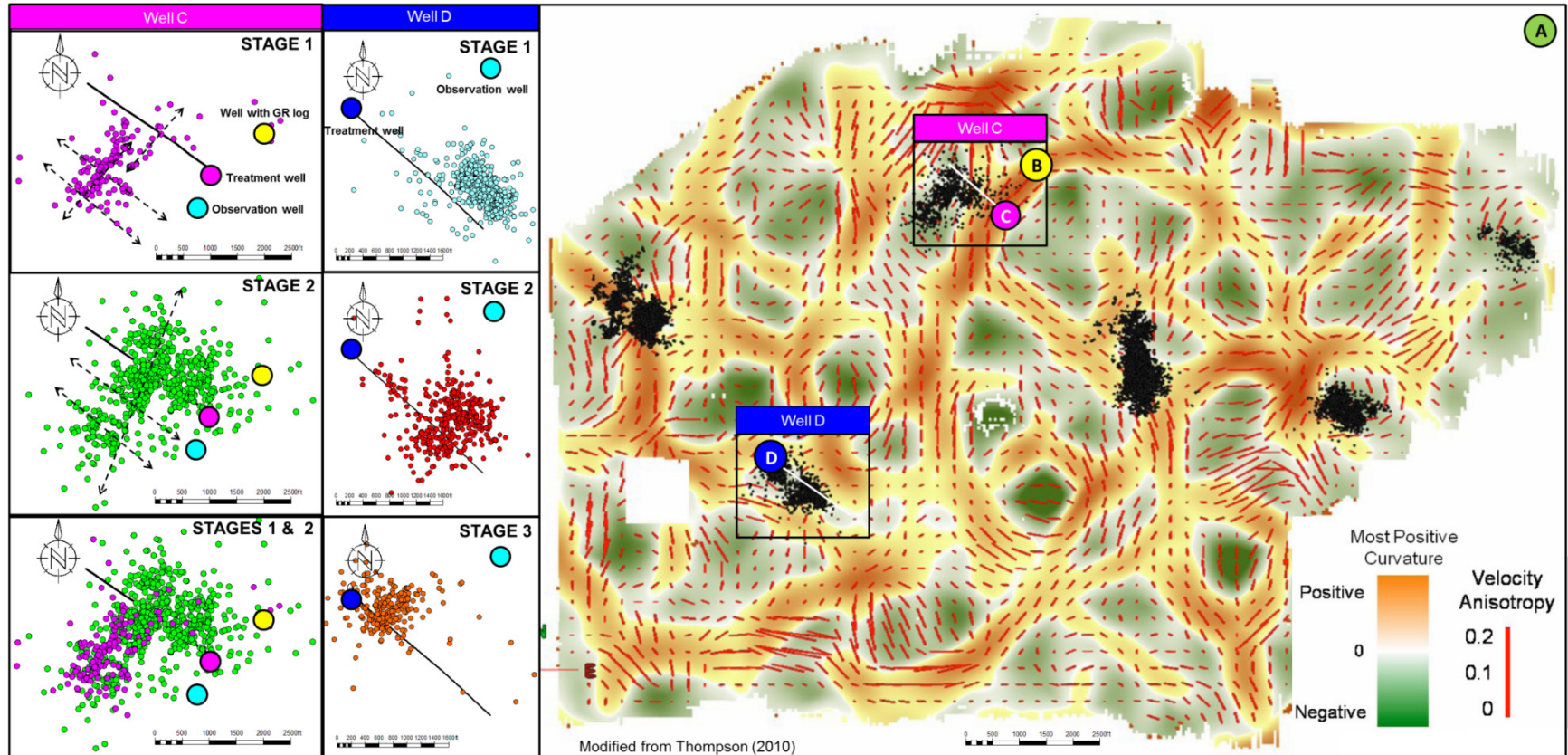
Microseismic events trend towards quartz rich areas, avoiding clay rich zones (green).

PRODUCTION LOGGING COMBINED WITH 3D SURFACE SEISMIC IN UNCONVENTIONAL PLAYS CHARACTERIZATION



Crossplot in gray of $\lambda - \mu$ of falling voxels within boxes shown in slide 24 for the Lower Barnett Shale.

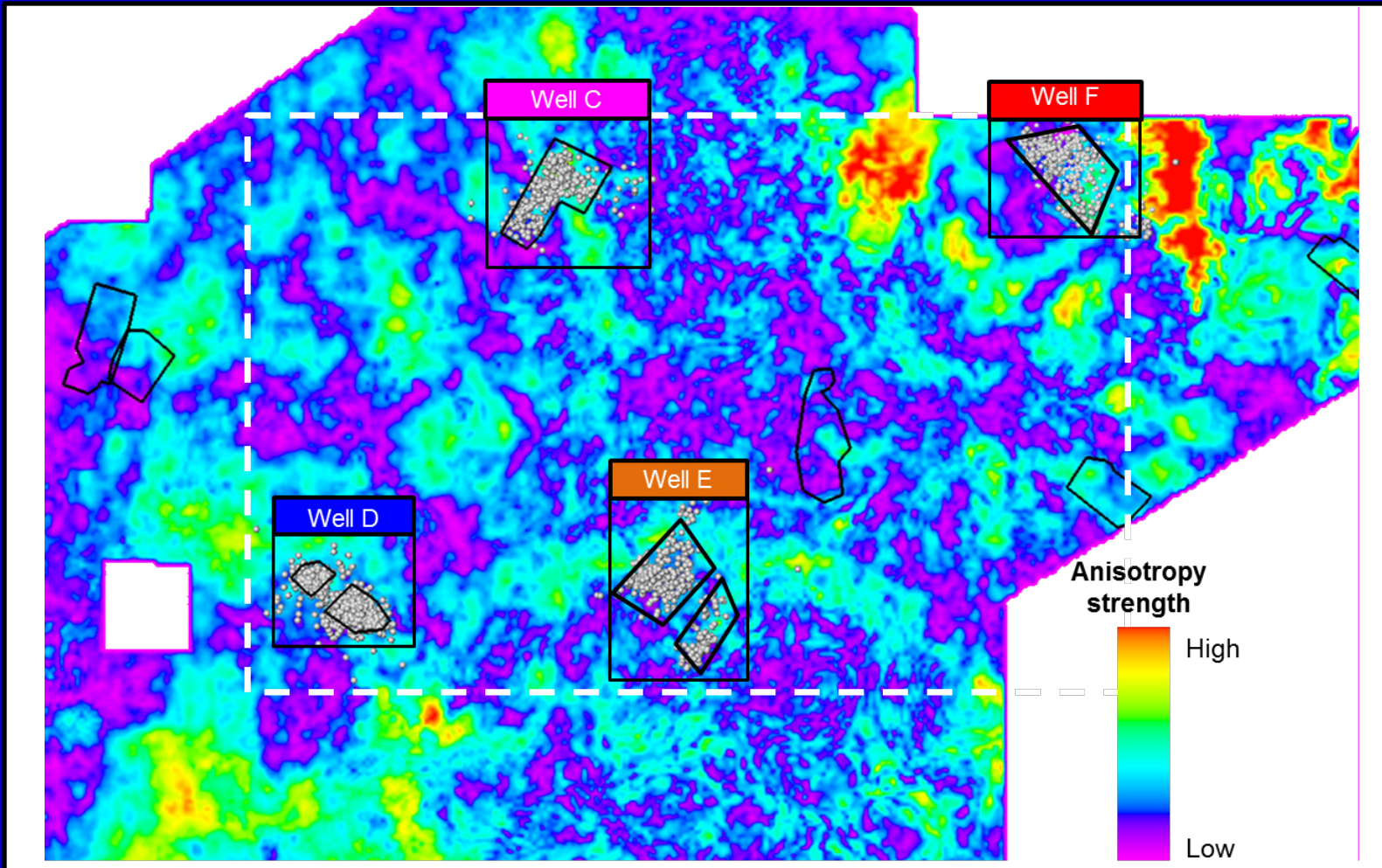
PRODUCTION LOGGING COMBINED WITH 3D SURFACE SEISMIC IN UNCONVENTIONAL PLAYS CHARACTERIZATION



Map view of microseismic event locations corresponding to (a) Well C and (b) Well D the orientation of the fracture lineaments formed by the microseismic events align with the current maximum horizontal stress direction in the Fort Worth Basin (NE-SW). (c) Horizon slice along the top Viola Limestone through the most positive curvature seismic attribute volume. The majority of the microseismic event locations fall into the areas with negative curvature values (bowl shapes). Red vectors indicate velocity anisotropy where the length of the vector is proportional of the degree of anisotropy while the direction indicates the azimuth of maximum anisotropy (modified from Thompson, 2010). The seismic data were acquired after 400 wells stimulated, such that the velocity anisotropy represents the post-frack stress regime.

Microseismic events trend towards negative curvature values (green) avoiding the most positive curvature zones (orange) and follow the velocity anisotropy trend, previously described by Thompson (2010) and Browning (2006).

PRODUCTION LOGGING COMBINED WITH 3D SURFACE SEISMIC IN UNCONVENTIONAL PLAYS CHARACTERIZATION



The majority of the microseismic events are located in zone of low anisotropy strength, suggesting that the rock “relax” after being fractured.

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CONCLUSIONS

- Well calibration is key to have a accurate interpretation of the rock brittleness.
- 2D color-bars are very useful to visualize cross-plot volumes.
- Microseismic is an indirect method to evaluate the hydraulic stimulation in the reservoir.
- Microseismic events
 - trend towards quartz rich areas, avoiding clay rich zones.
 - trend towards negative curvature values (green) avoiding the most positive curvature zones (orange) and follow the velocity anisotropy trend.
 - are located in zone of low anisotropy strength, suggesting that the rock “relax” after being fractured.

ACKNOWLEDGEMENTS

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