Integration of Surface and Subsurface Tools in The Reservoir Characterization of Unconventional Plays*

Roderick Perez[1]

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[1]Transform Software and Services – Drillinginfo (roderick.perez@transformsw.com; roderick.perez@drillinginfo.com)

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 λρ - μρ space. These geomechanical properties were defined, calibrated, and computed using specialized logging tools such as: mineralogy, density, and P- and Swave 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 λρ - μρ crossplot, suggesting that hydraulically induced fractures preferentially populate brittle regions and, consequently, produce more gas. Thus, these results are useful to calibrate estimation of 3D seismic attribute brittleness.

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This work is part of my dissertation research:
Perez, R., 2013, *Brittleness Estimation from Seismic Measurements in Unconventional Reservoirs: Application to the Barnett Shale*: Ph.D. Dissertation, ConocoPhillips School of Geology and Geophysics: The University of Oklahoma.

INTEGRATION OF SURFACE AND SUBSURFACE TOOLS IN THE RESERVOIR CHARACTERIZATION OF UNCONVENTIONAL PLAYS

Roderick Perez, Ph.D.

The University of Oklahoma

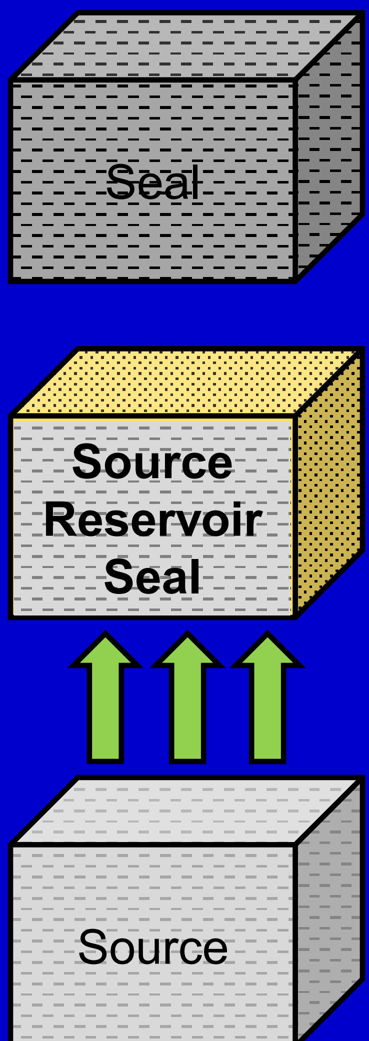
Transform – Drillinginfo

RoderickPerezAltamar@gmail.com
Roderick.Perez@transformsw.com
Roderick.Perez@drillinginfo.com

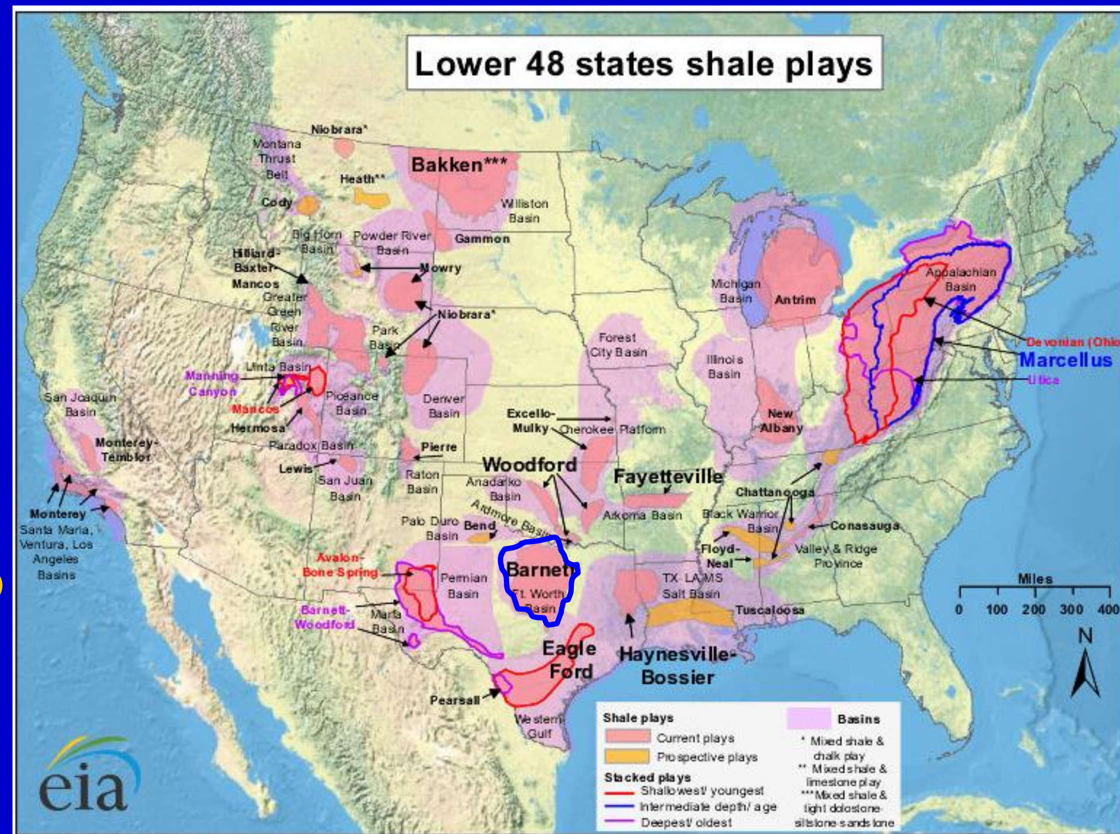
http://www.rockphysicsapplications.com

September 9th, 2013

UNCONVENTIONAL
CONVENTIONAL



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



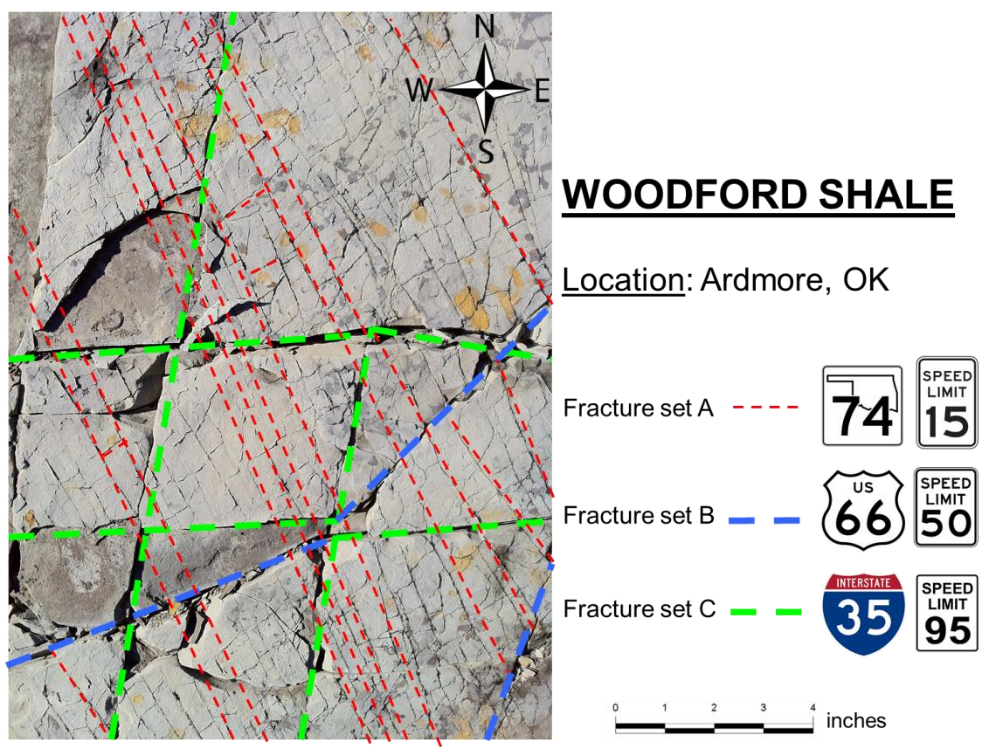
<u>Source</u>: EIA. Updated May 9th, 2011

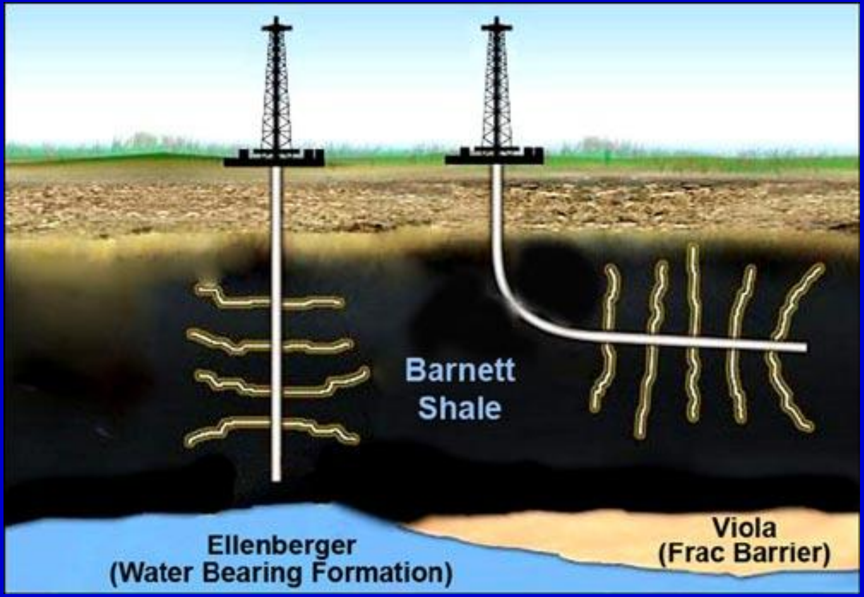
. . . 1 TCF** (2006) — 336 TCF** (2011)

**Trillion cubic feet

*Average values corresponding to the Barnett Shale

GOAL





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

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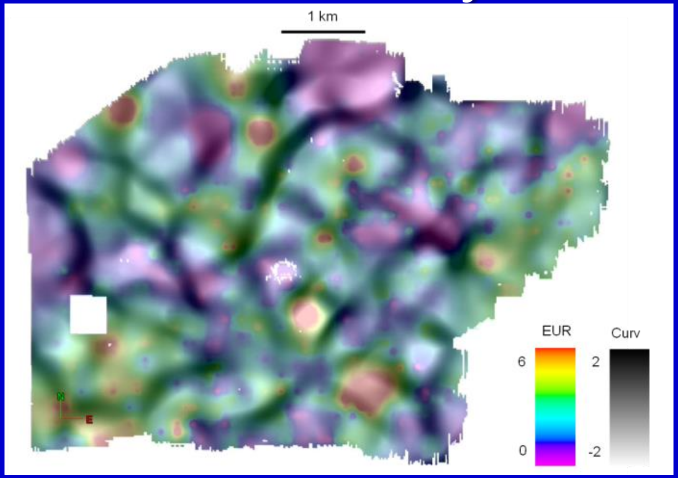
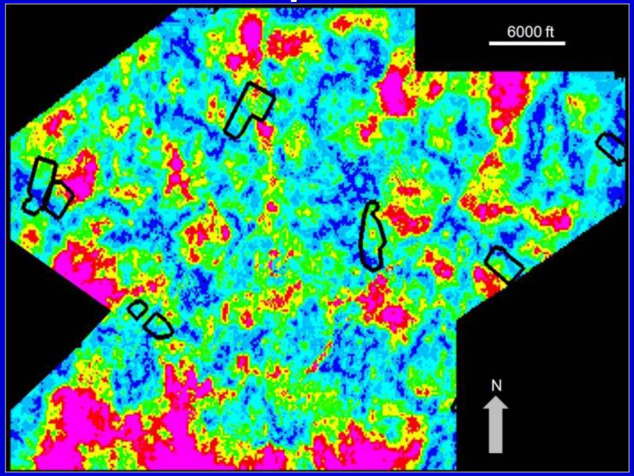
OBJECTIVES

- 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?

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WHAT IS BRITTLENESS???

BRITTLE

DUCTILE

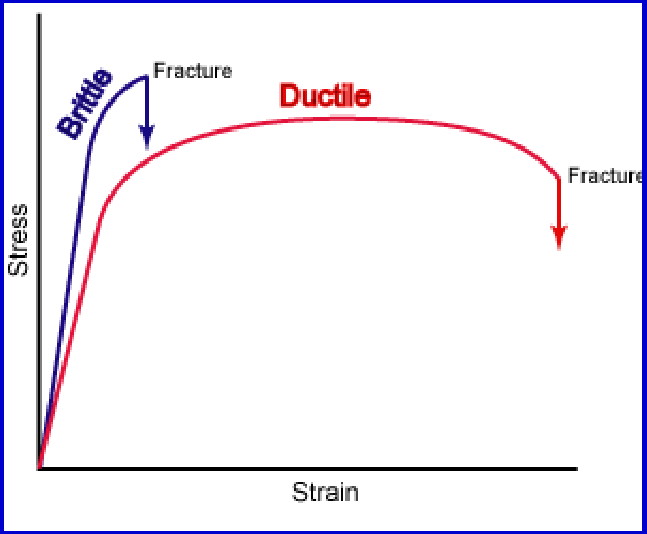
BRITTLENESS is the measurement of stored energy before failure and is function of:

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

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

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

σ_c = Compressive strength
σ_t = Tensile strength



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

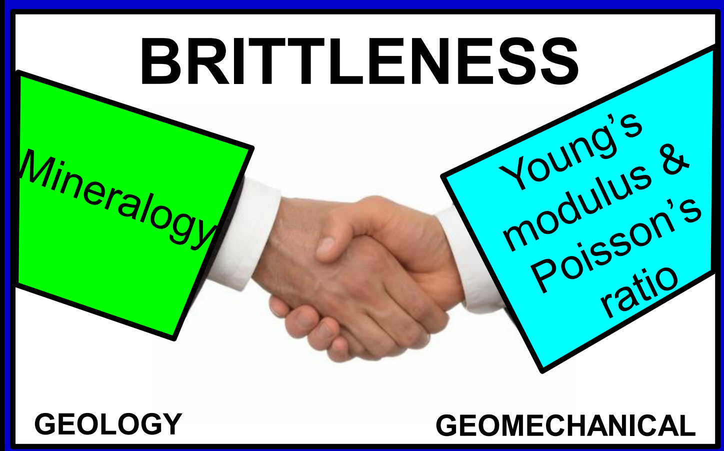
BRITTLENESS

- How do to quantify brittleness
  1) Mineralogy??
  2) Elastic parameters??

MINERALOGY

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

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



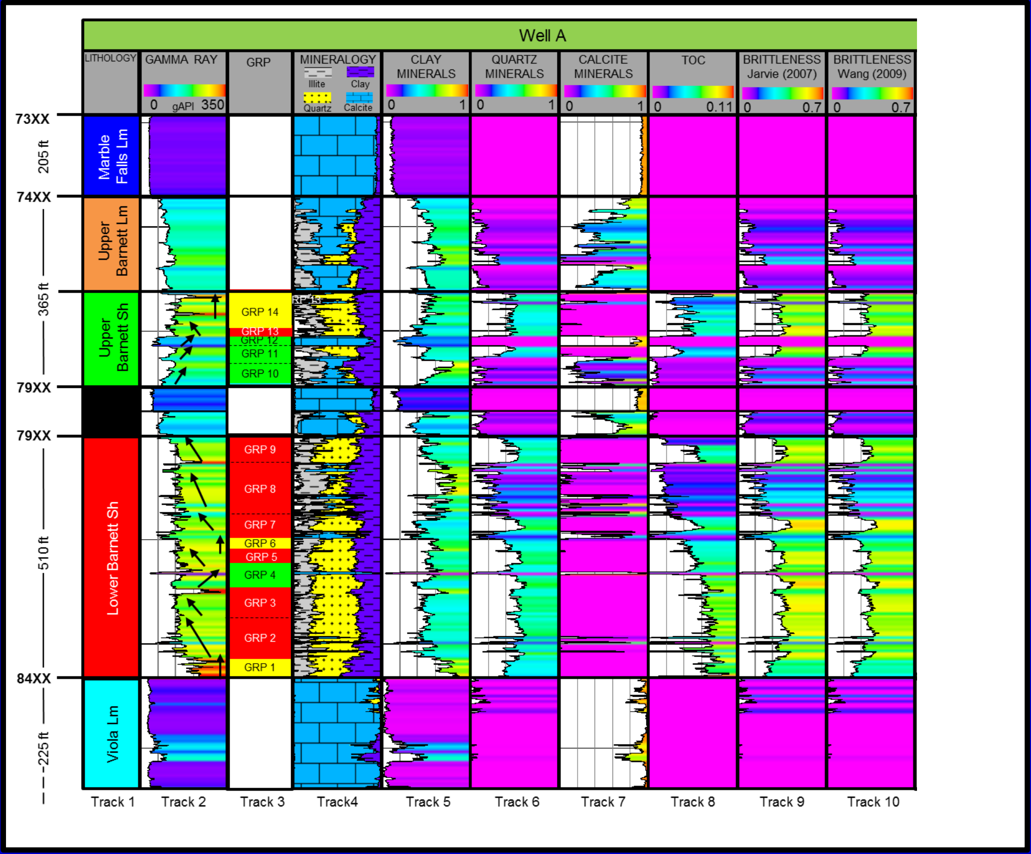
ELASTIC PARAMETERS

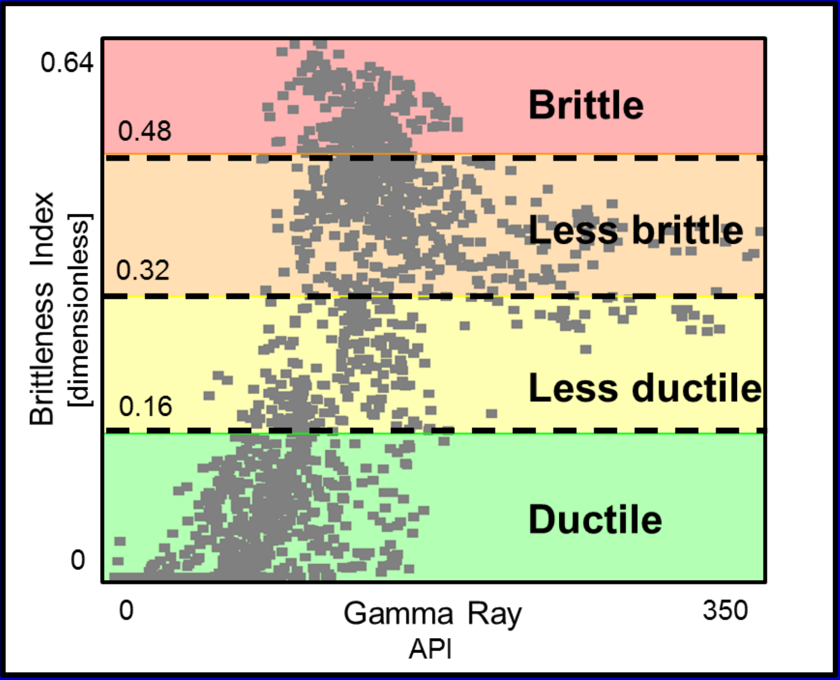
$$E_{brittleness} = \frac{E - E_{min}}{E_{max} - E_{min}},$$

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

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

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

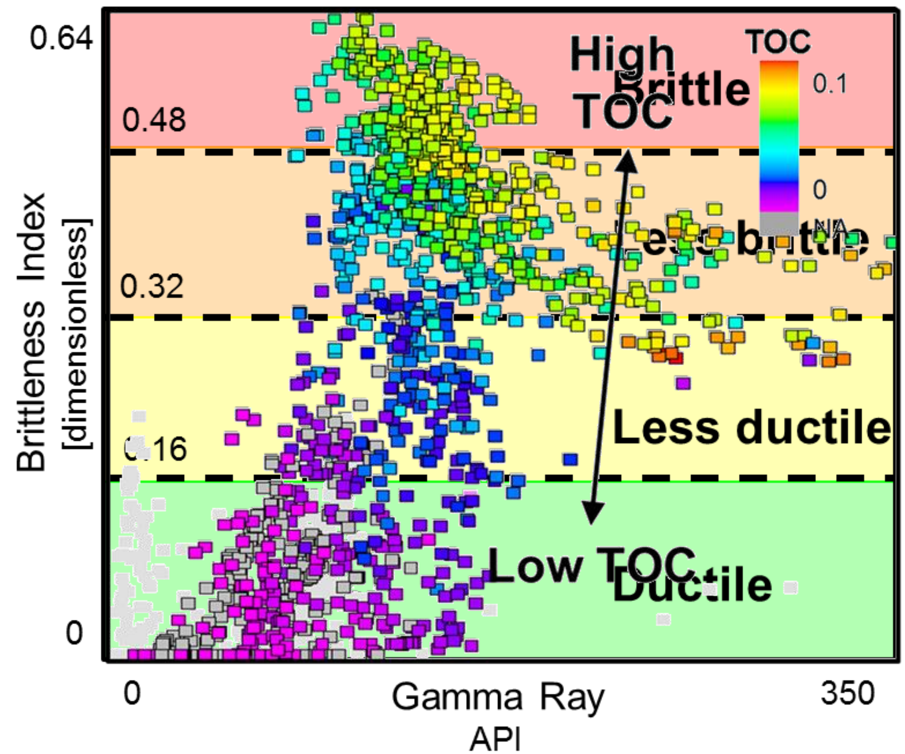
CALIBRATION OF BRITTLENESS TO ELASTIC ROCK PROPERTIES VIA MINERALOGY LOGS

LITHOFACIES	Average TOC (wt%)	Average silica (SiO_2) %
In situ phosphatic deposit	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

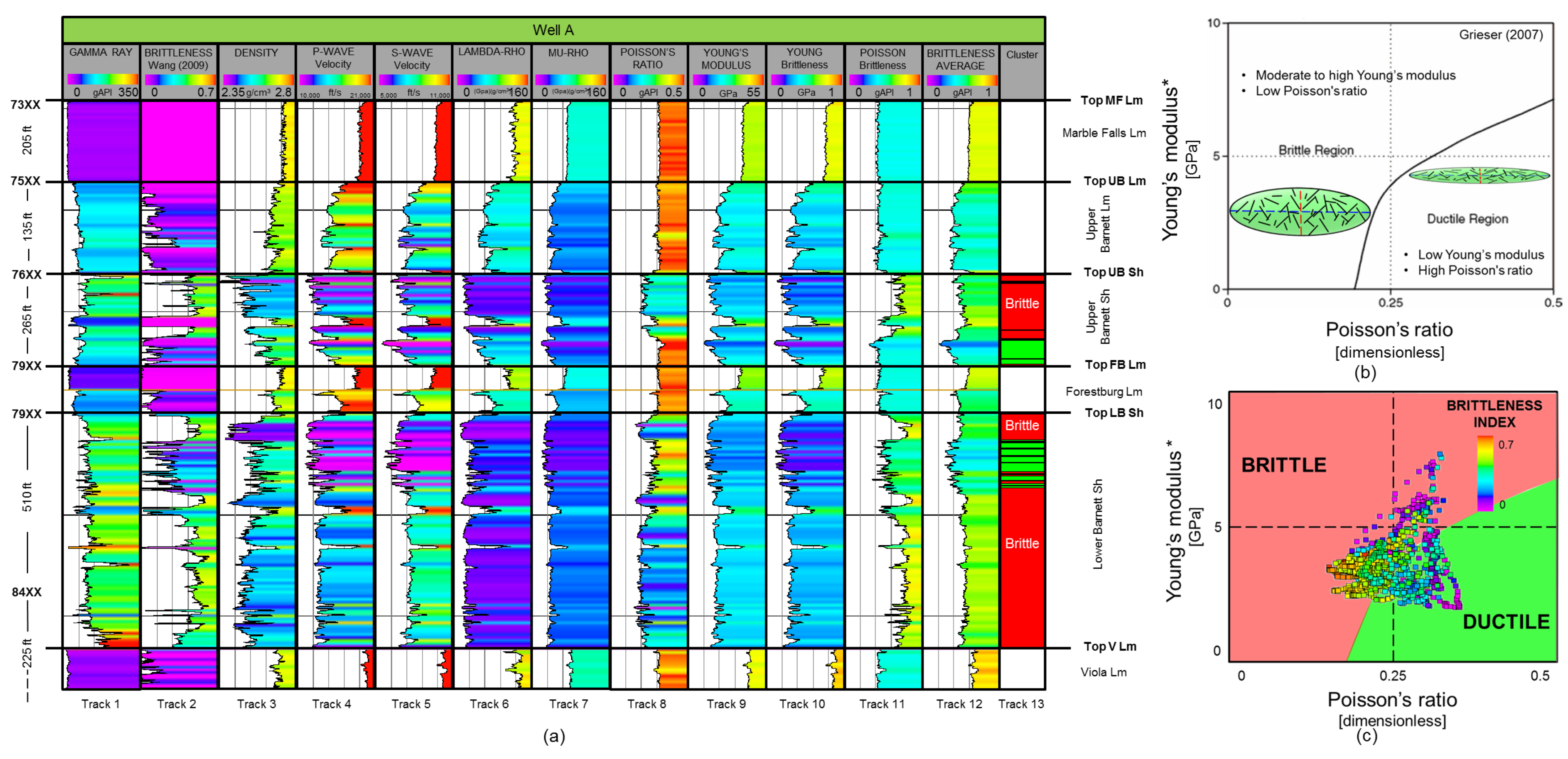
Increase in organic richness

Decrease in bottom water oxygen

Singh (2008)



BRITTLENESS AVERAGE (Elastic parameters)



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

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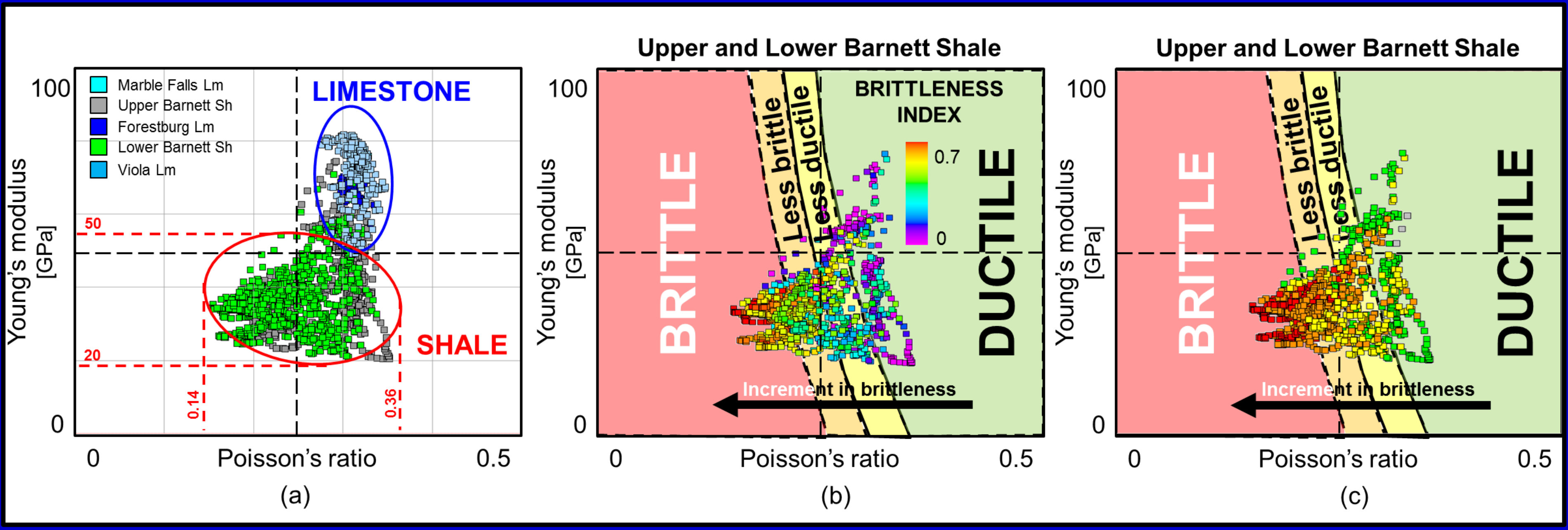
$$Brittleness_{average} = \frac{(E_{brittleness} + \nu_{brittleness})}{2}.$$

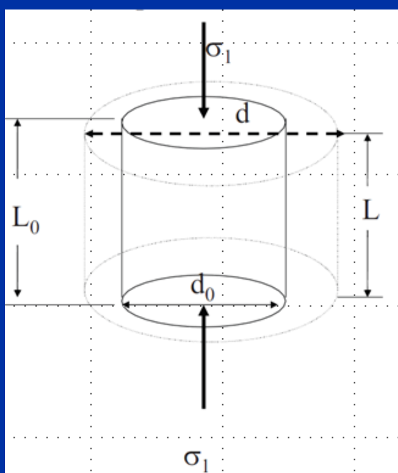
CALIBRATION OF BRITTLENESS TO ELASTIC ROCK PROPERTIES VIA MINERALOGY LOGS



CALIBRATION OF BRITTLENESS TO ELASTIC ROCK PROPERTIES VIA MINERALOGY LOGS

Young's Modulus

Poisson's ratio



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

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

P-wave Velocity

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

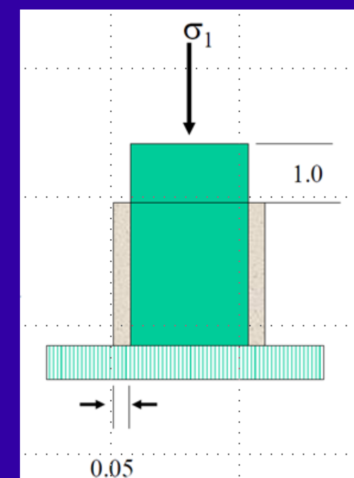
S-wave Velocity

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

P-wave Modulus

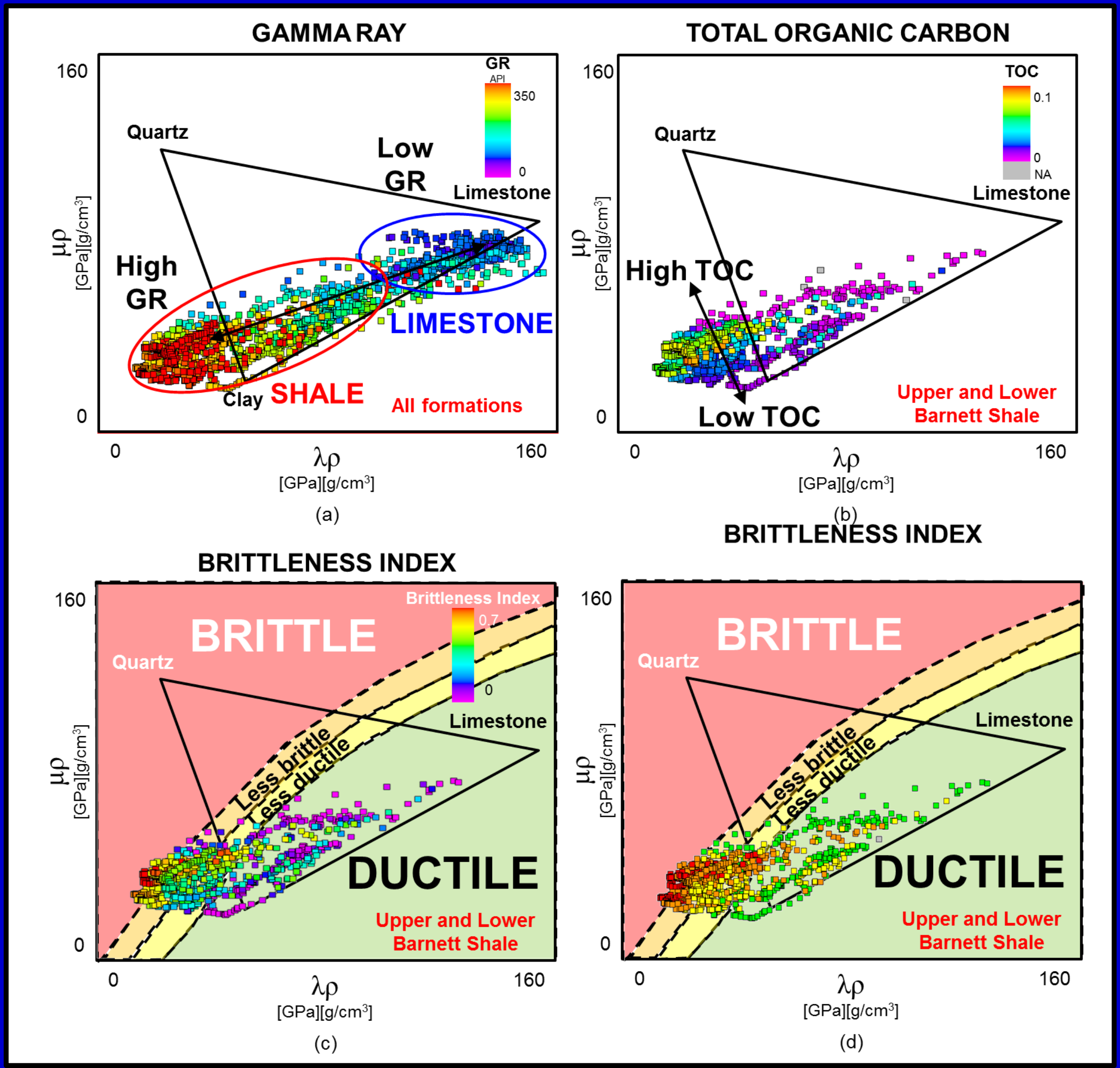
$$\frac{E}{1 + \nu} = 2\mu$$

Young - Poisson Relation



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

CALIBRATION OF BRITTLENESS TO ELASTIC ROCK PROPERTIES VIA MINERALOGY LOGS



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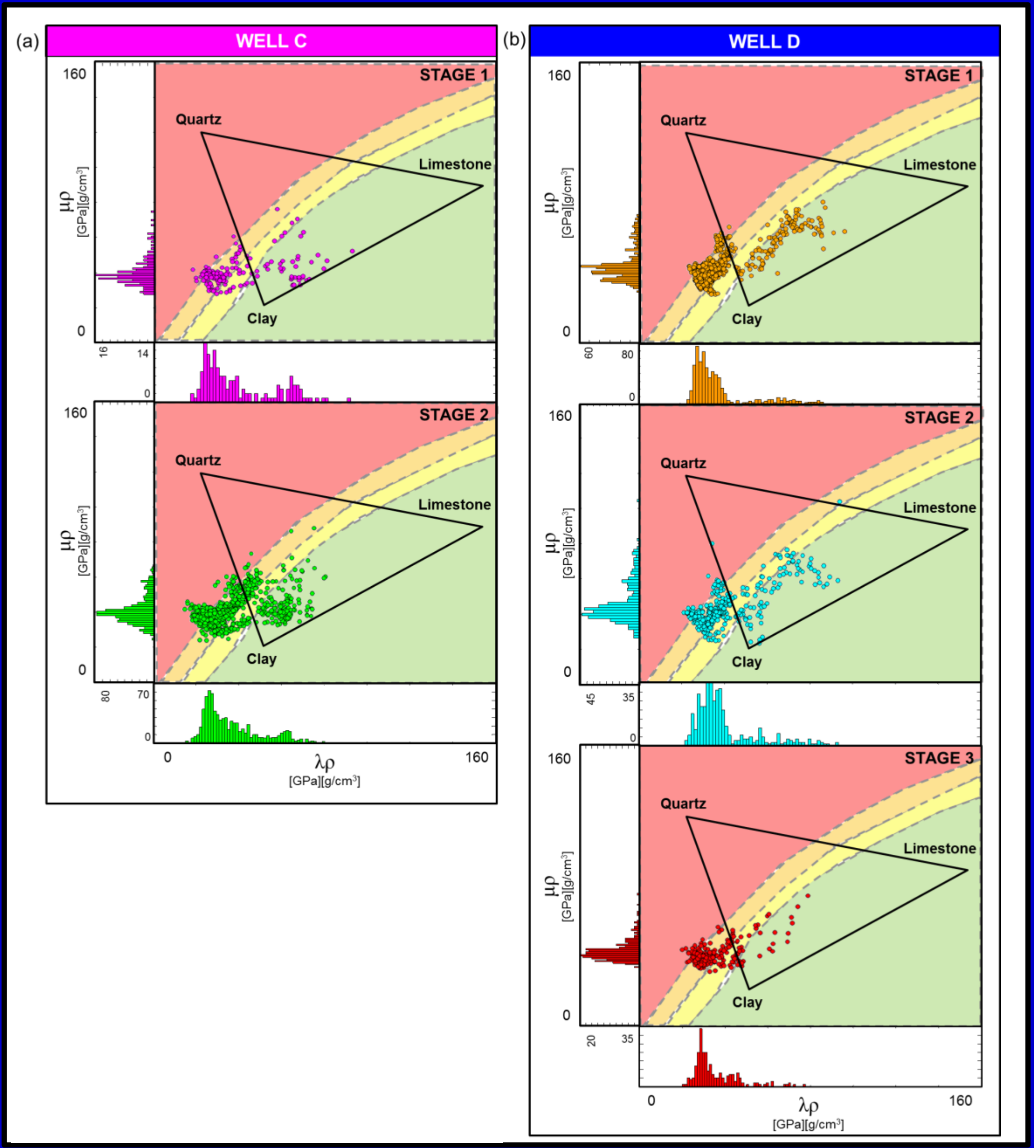
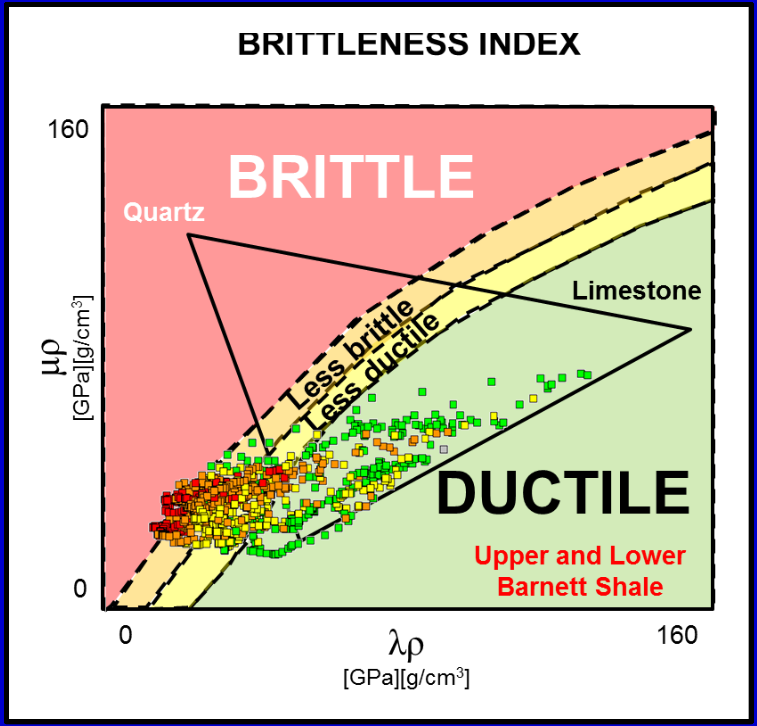
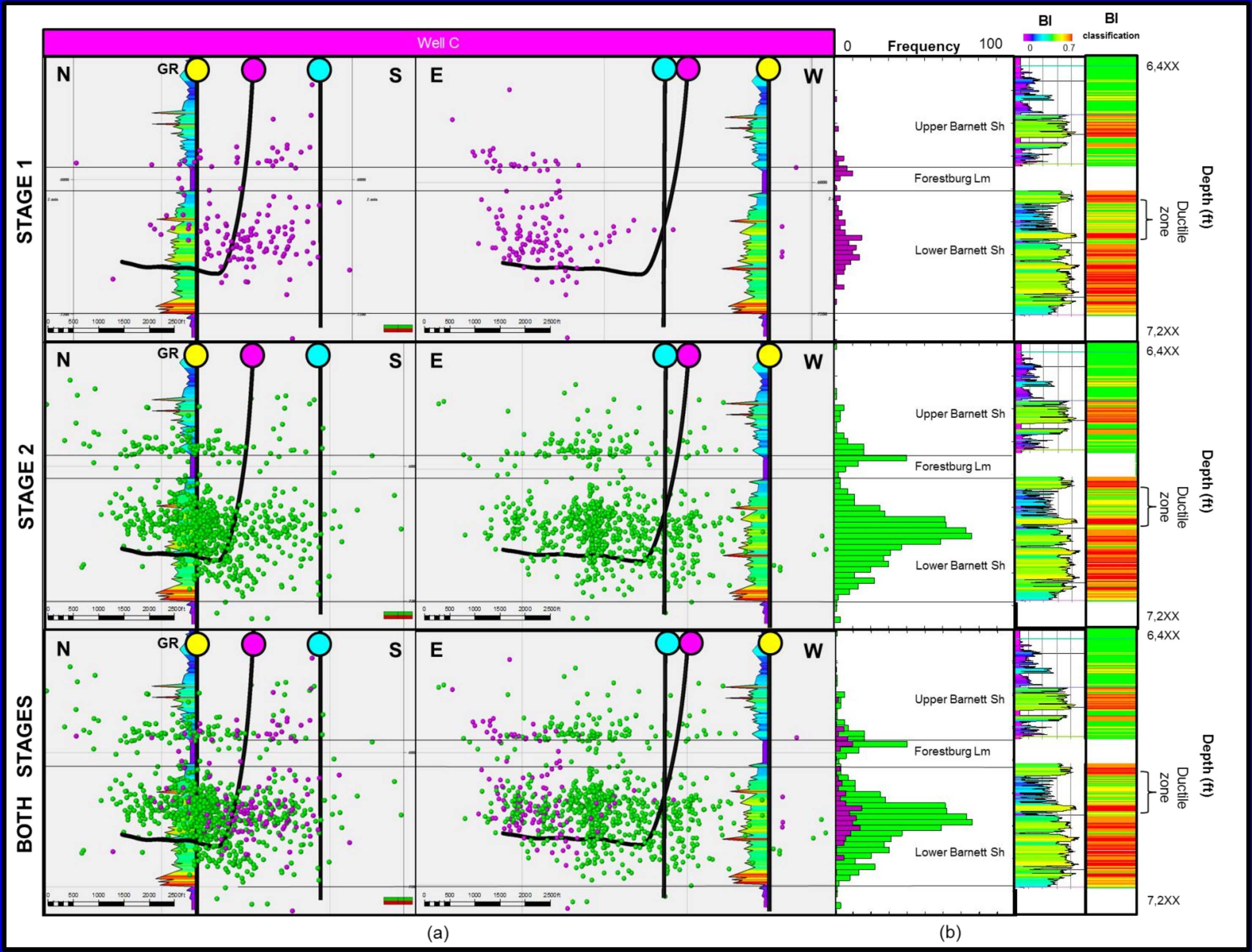




CALIBRATION OF BRITTLENESS TO ELASTIC ROCK PROPERTIES VIA MINERALOGY LOGS



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SURFACE SEISMIC ESTIMATION OF HYDRAULICALLY FRACTURED ROCK

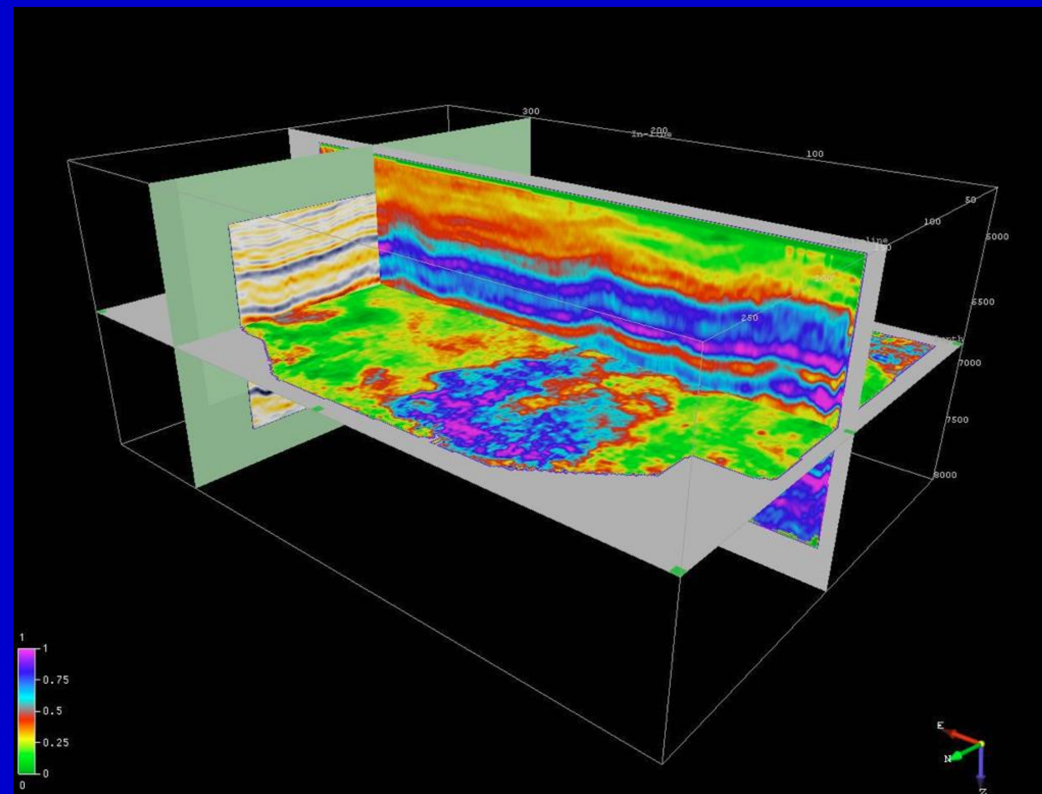
Angle Gathers

R_P reflectivity | R_S reflectivity

Z_P impedance | Z_S impedance

$\lambda\rho$ | $\mu\rho$

$\lambda\rho$ vs. $\mu\rho$ *crossplot*

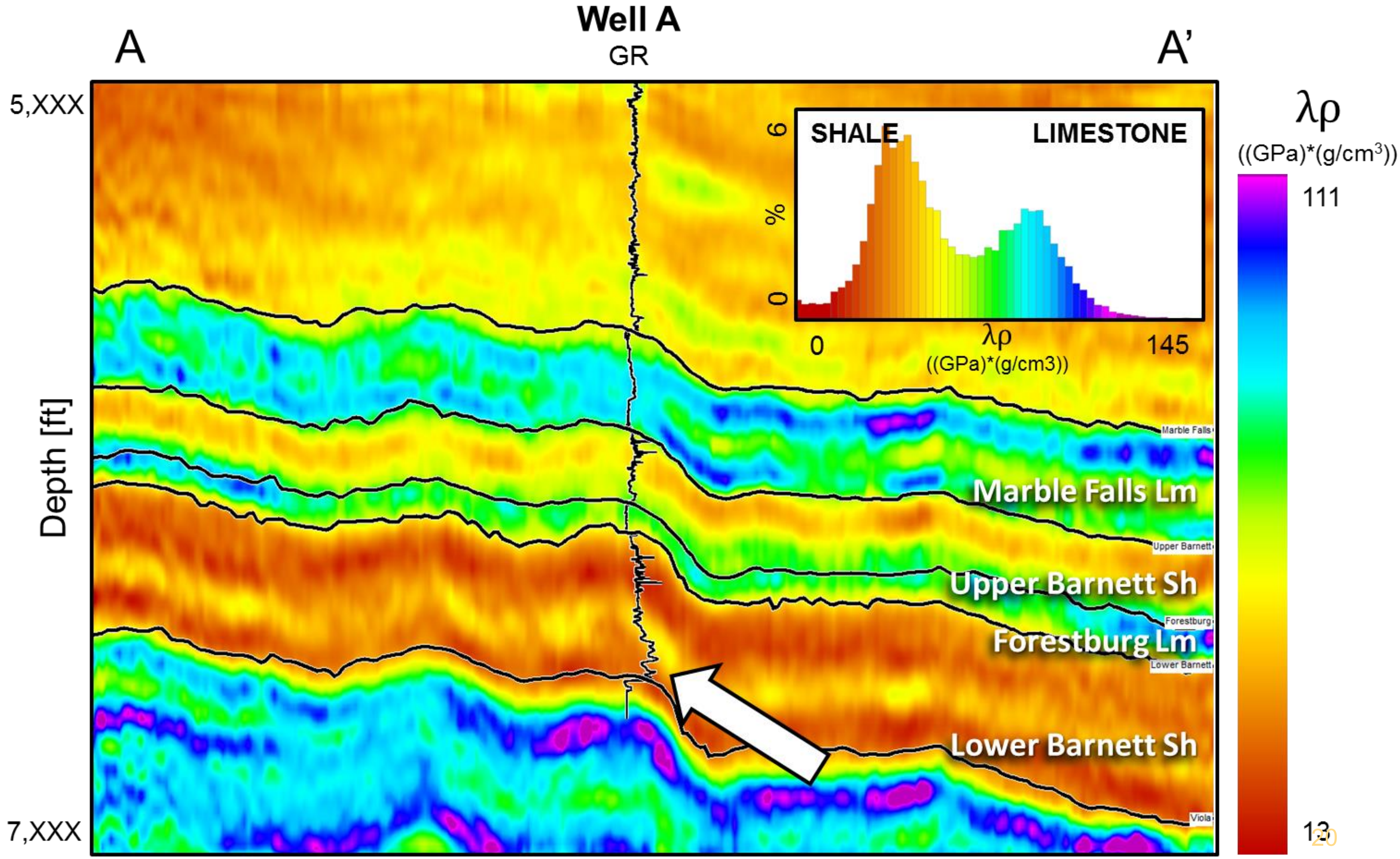


$$\lambda\rho = (\rho V_P)^2 - 2(\rho V_S)^2.$$

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

Goodway (2007)

SURFACE SEISMIC ESTIMATION OF HYDRAULICALLY FRACTURED ROCK



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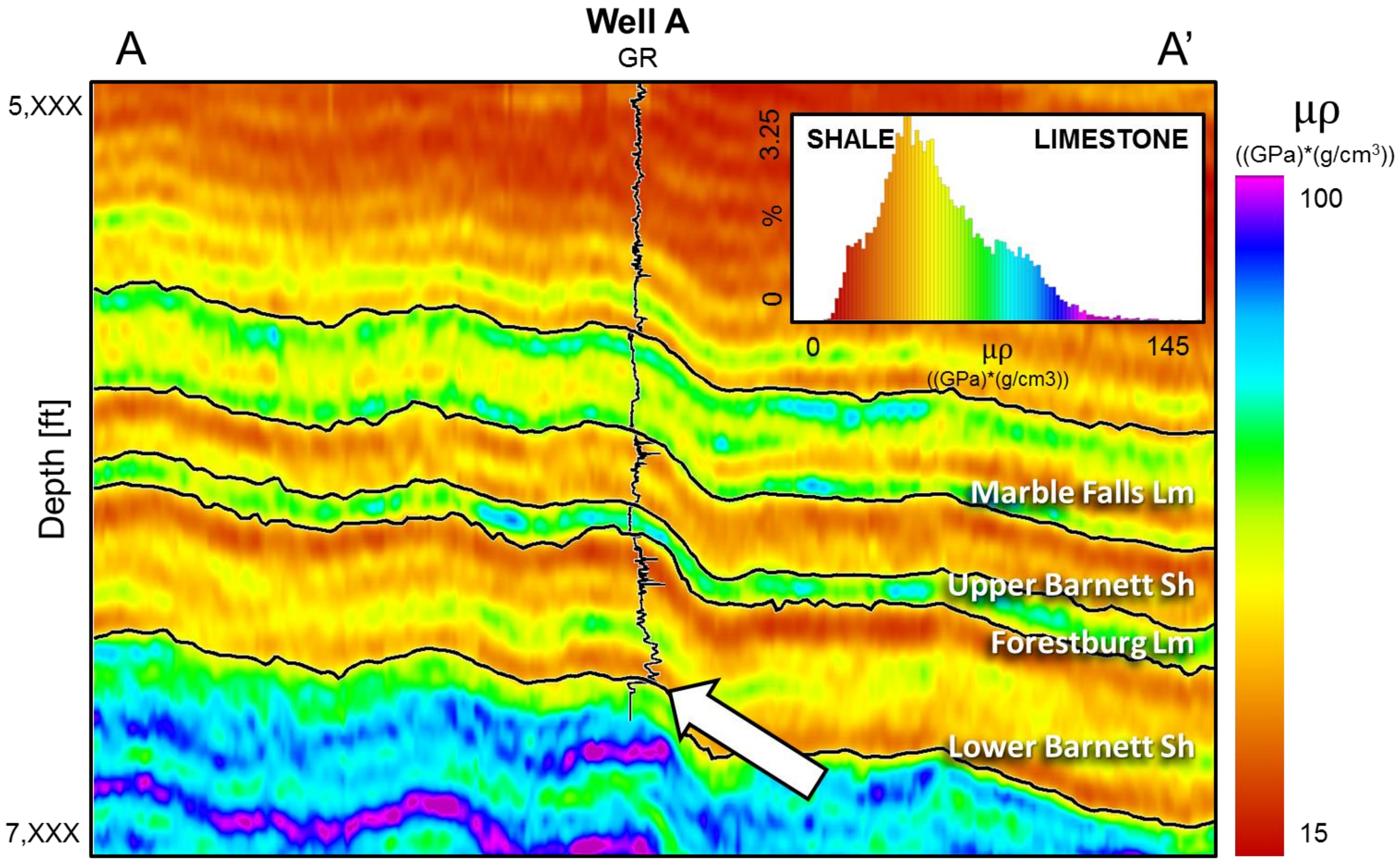

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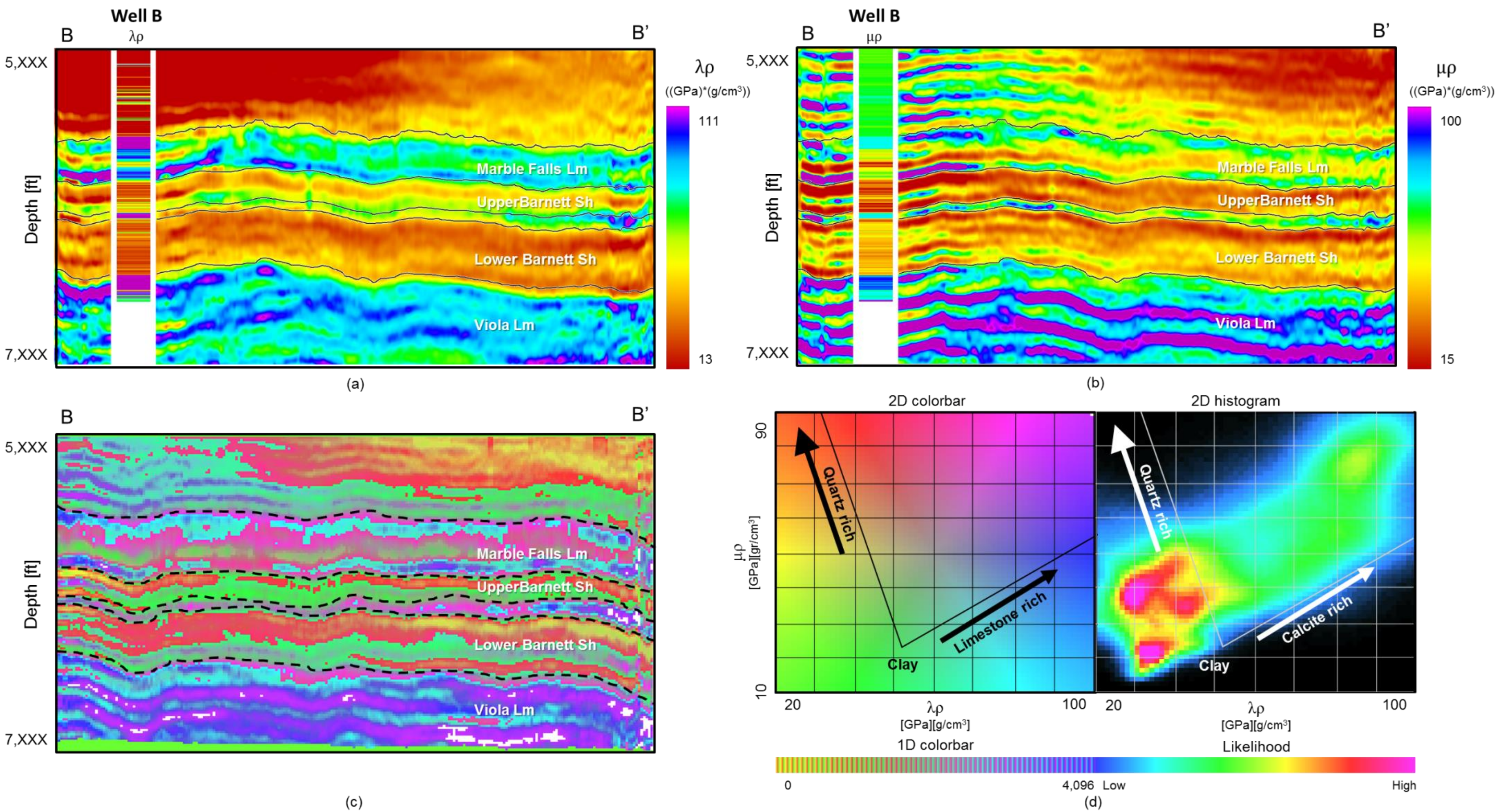

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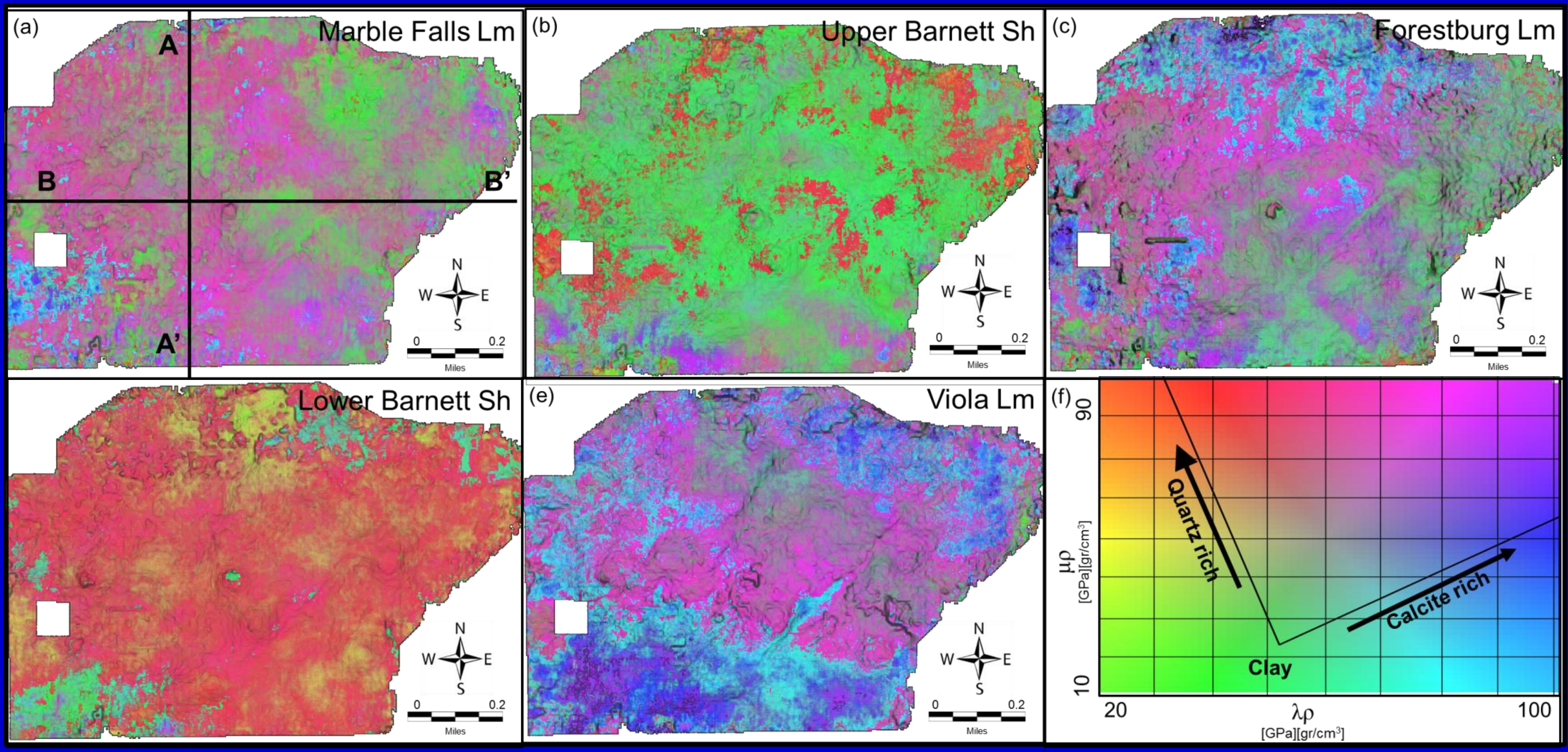

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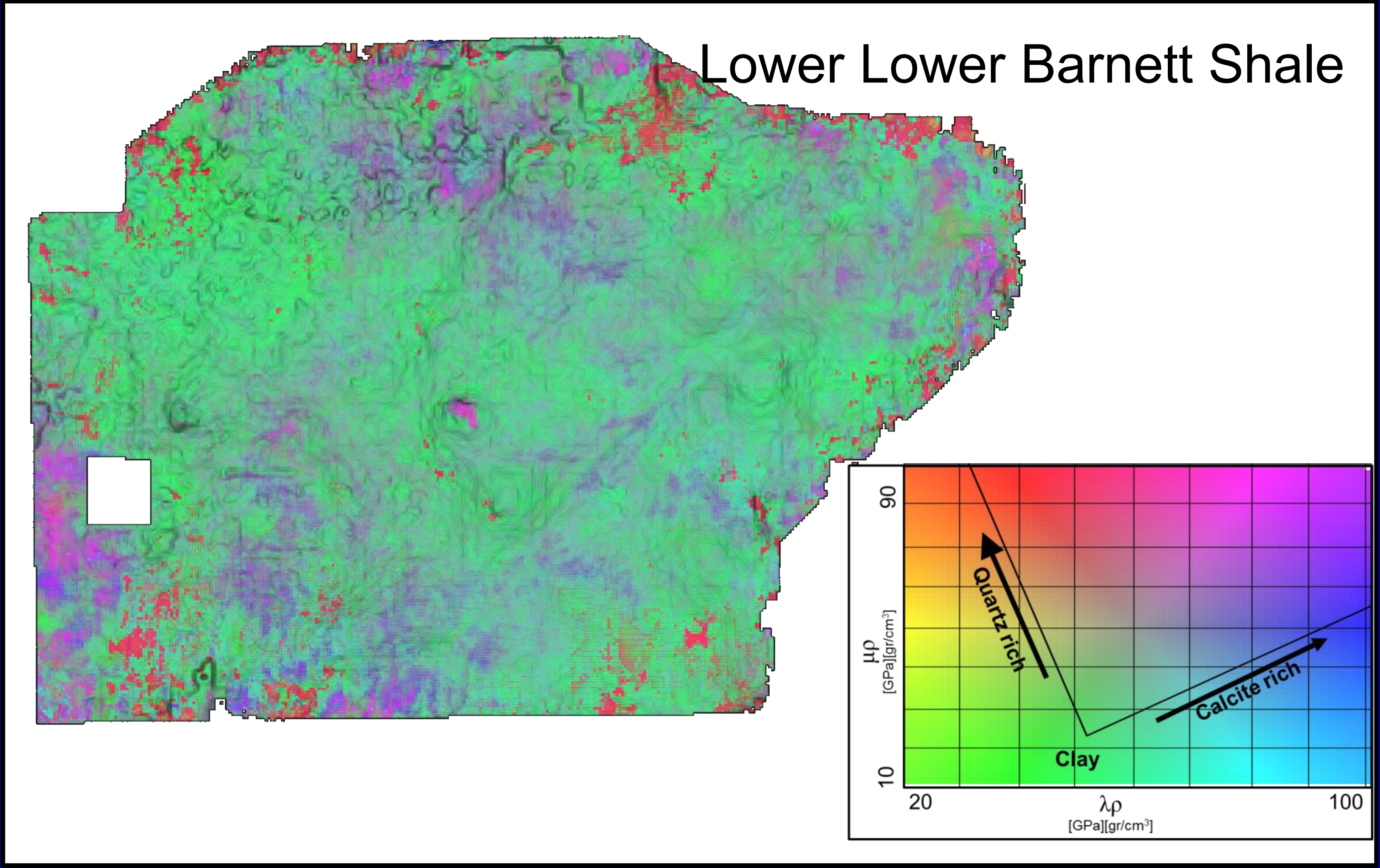

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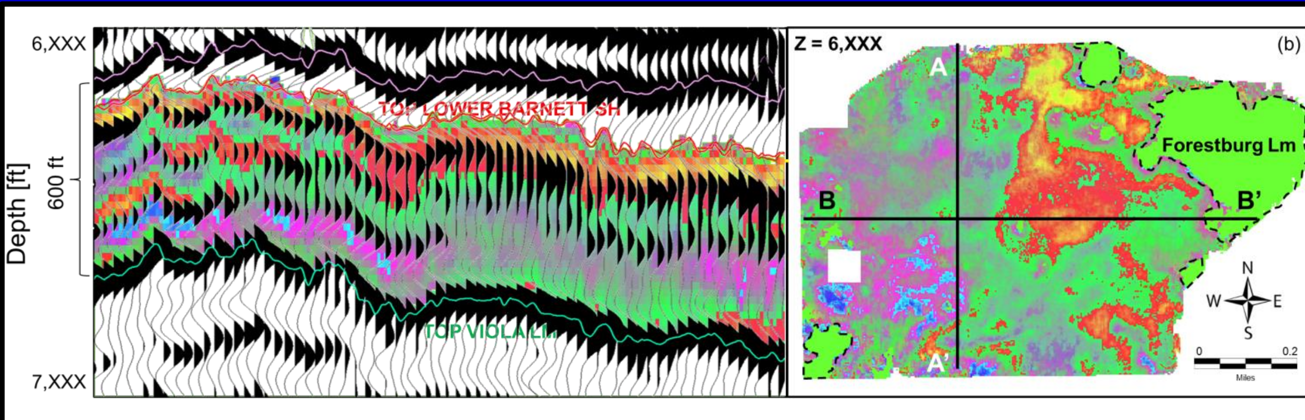
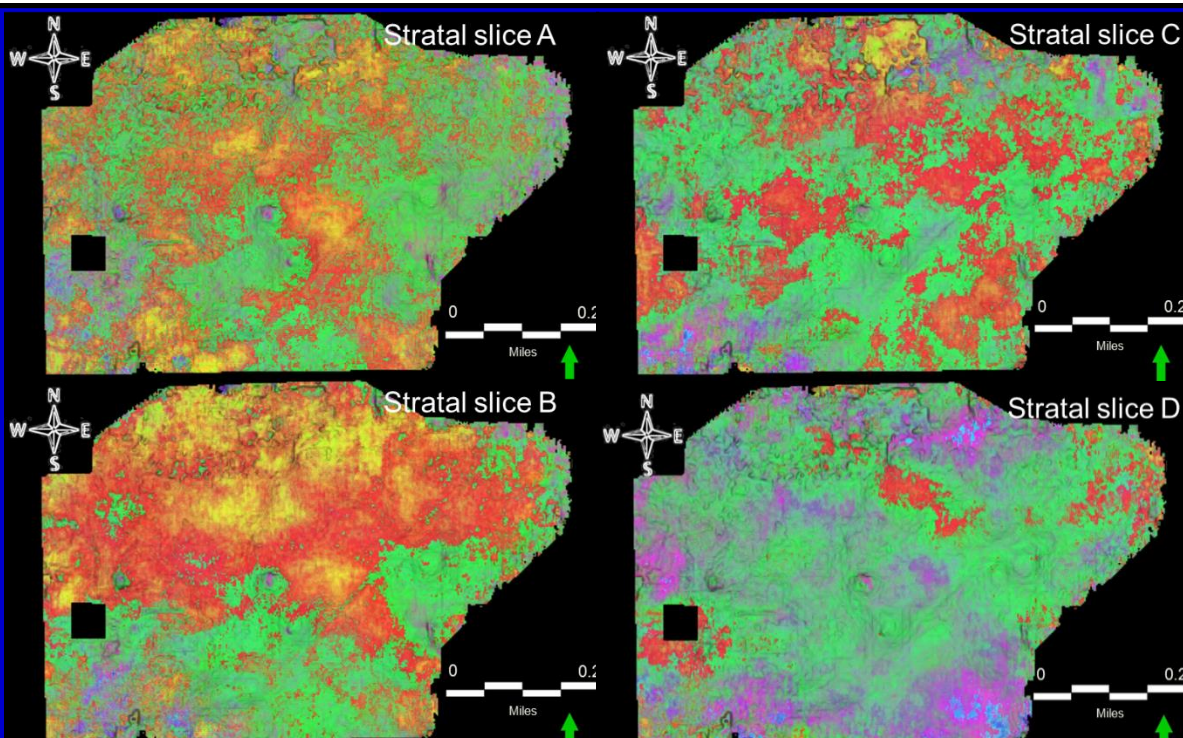
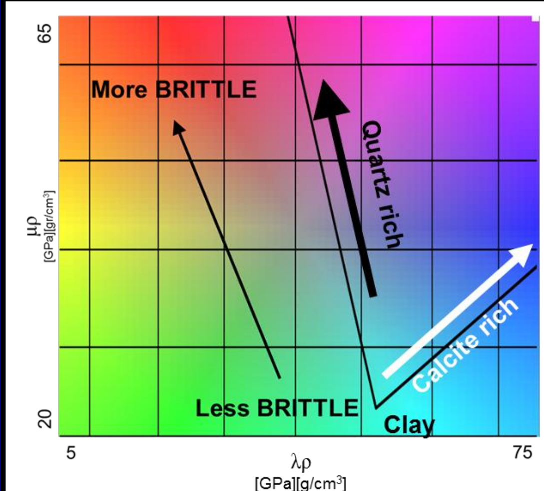
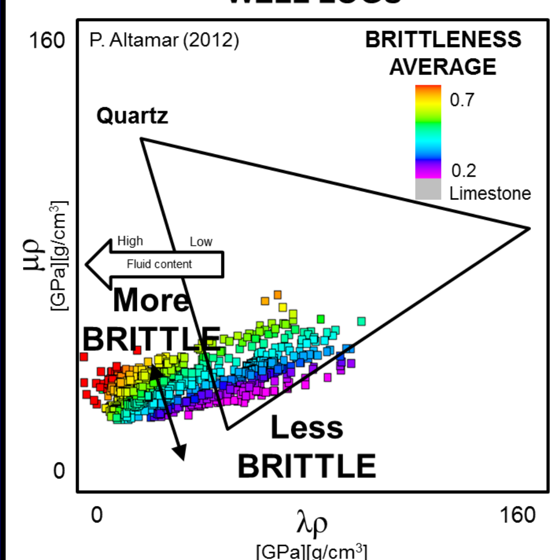


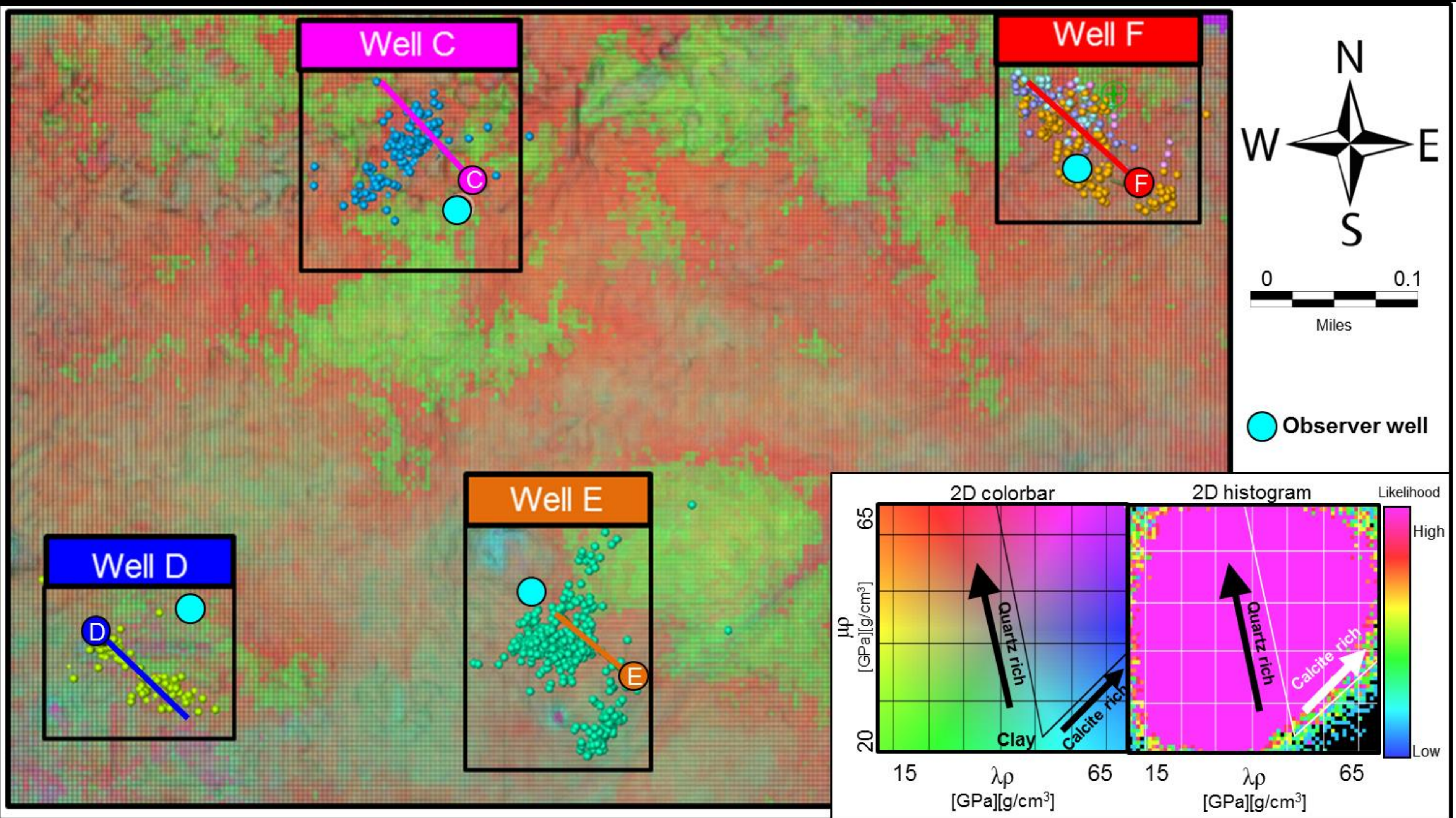




WELL LOGS

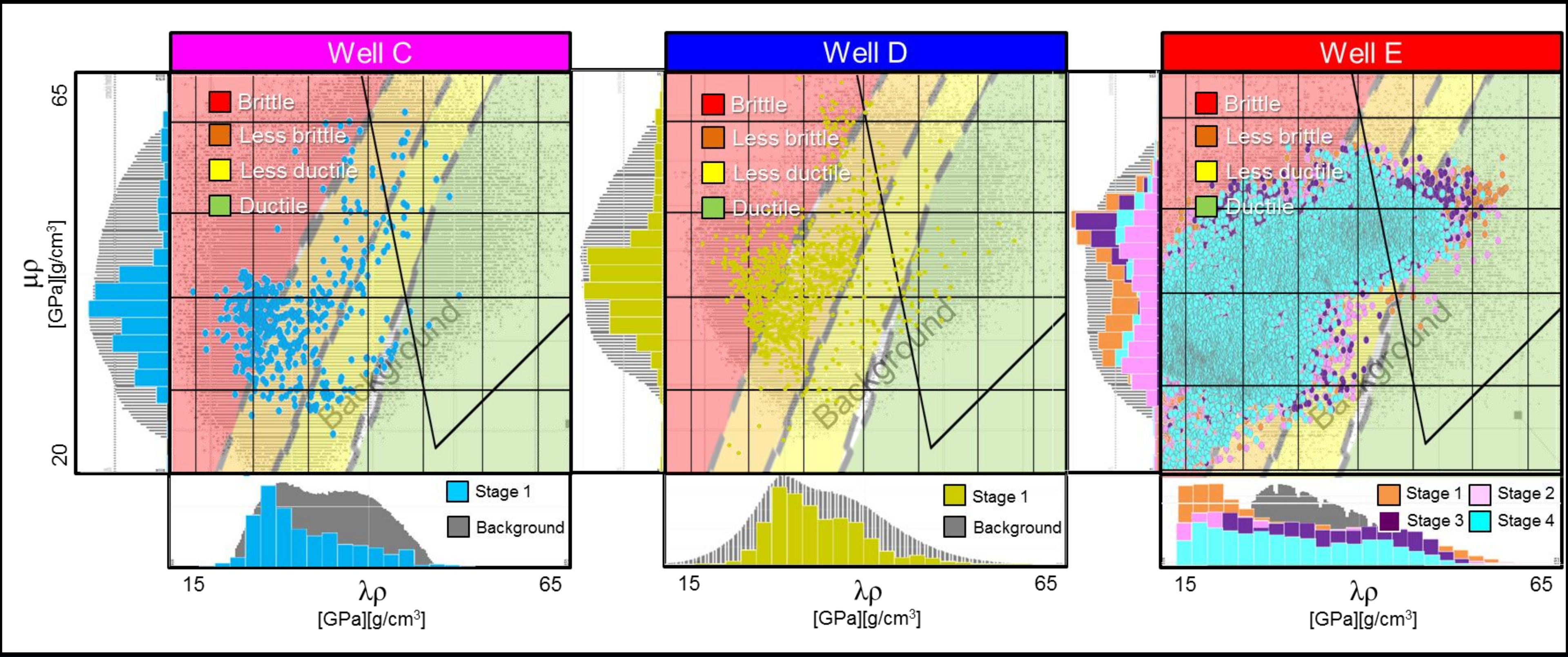


PRODUCTION LOGGING COMBINED WITH 3D SURFACE SEISMIC IN UNCONVENTIONAL PLAYS CHARACTERIZATION



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

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



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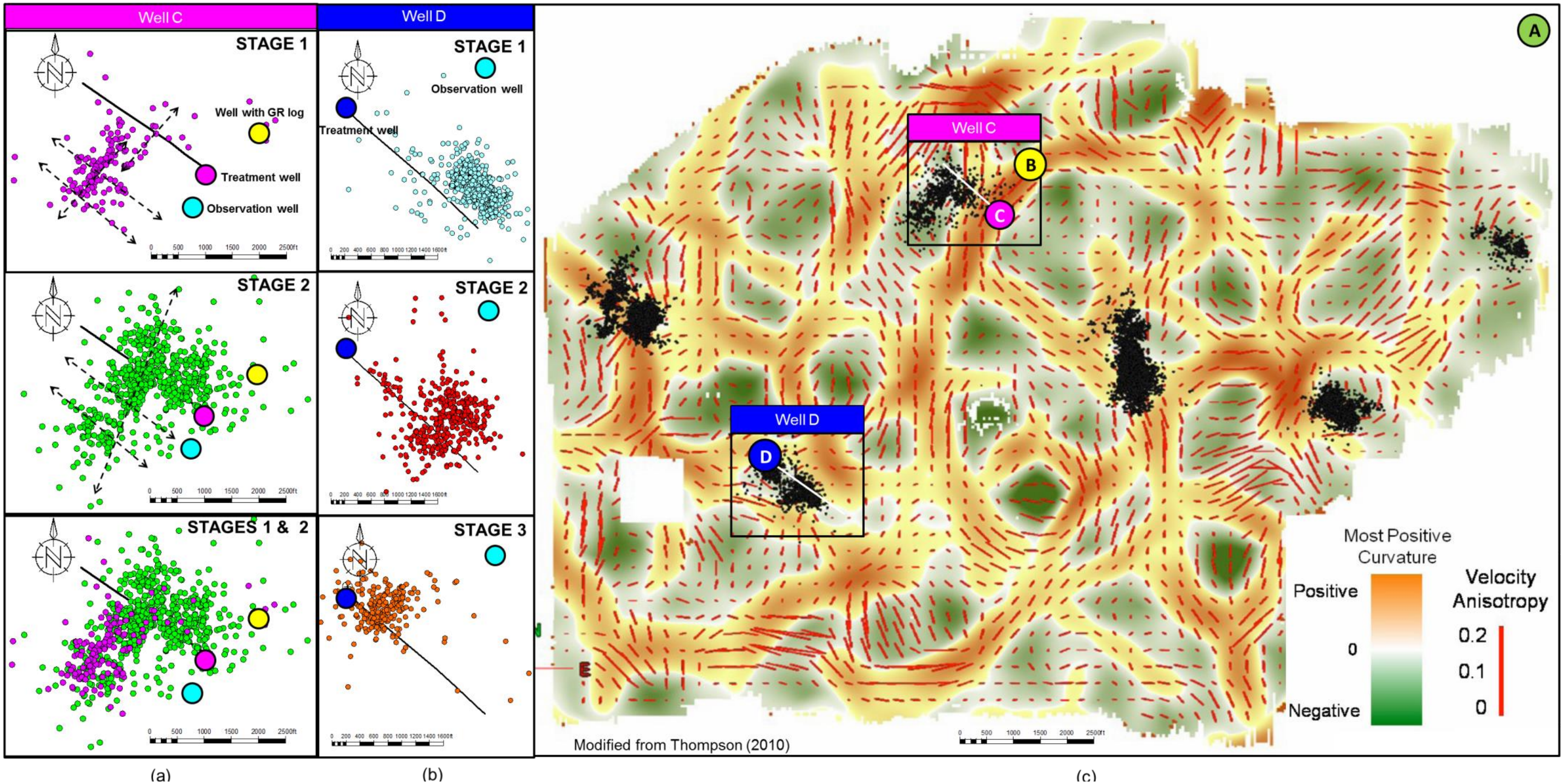
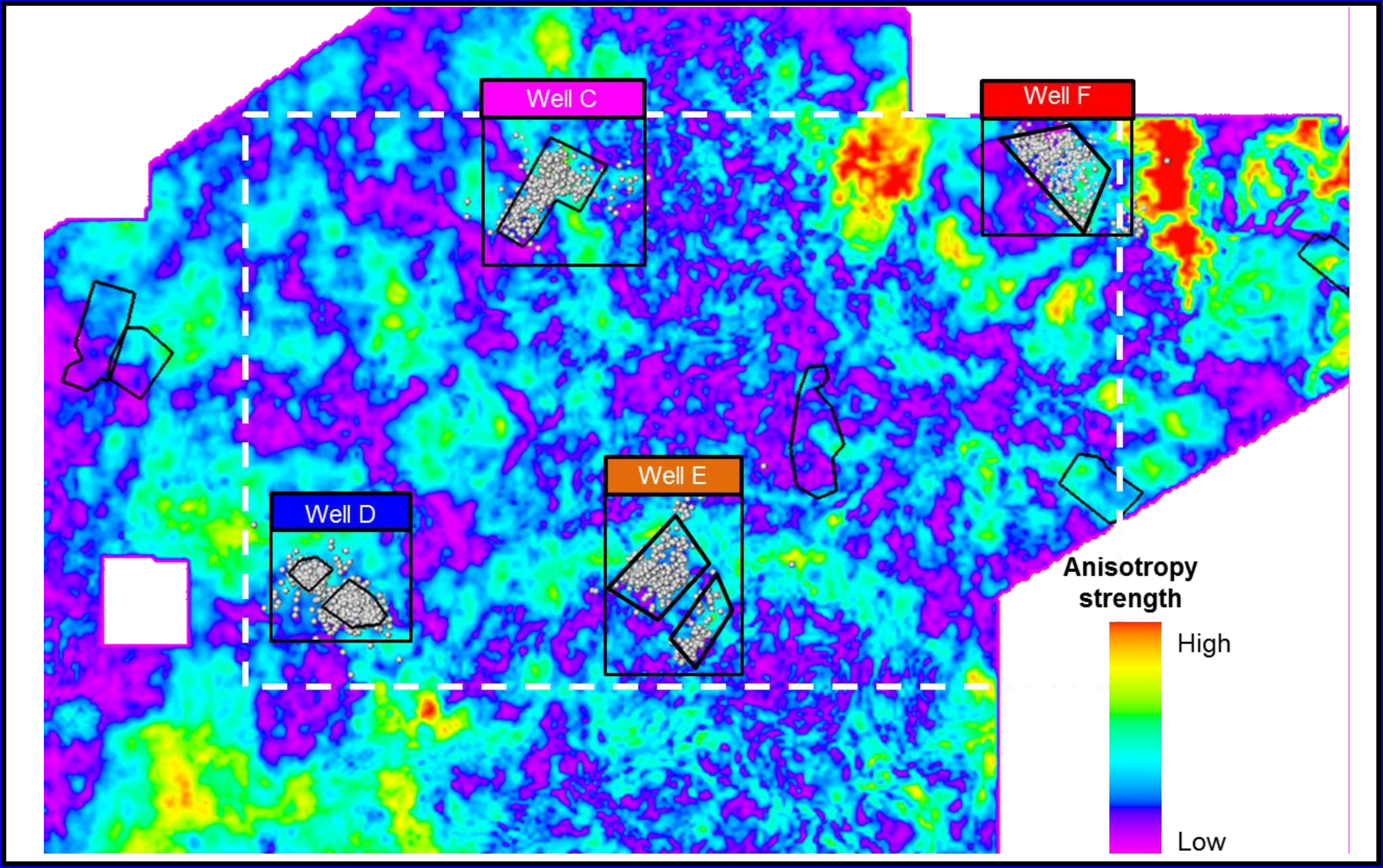


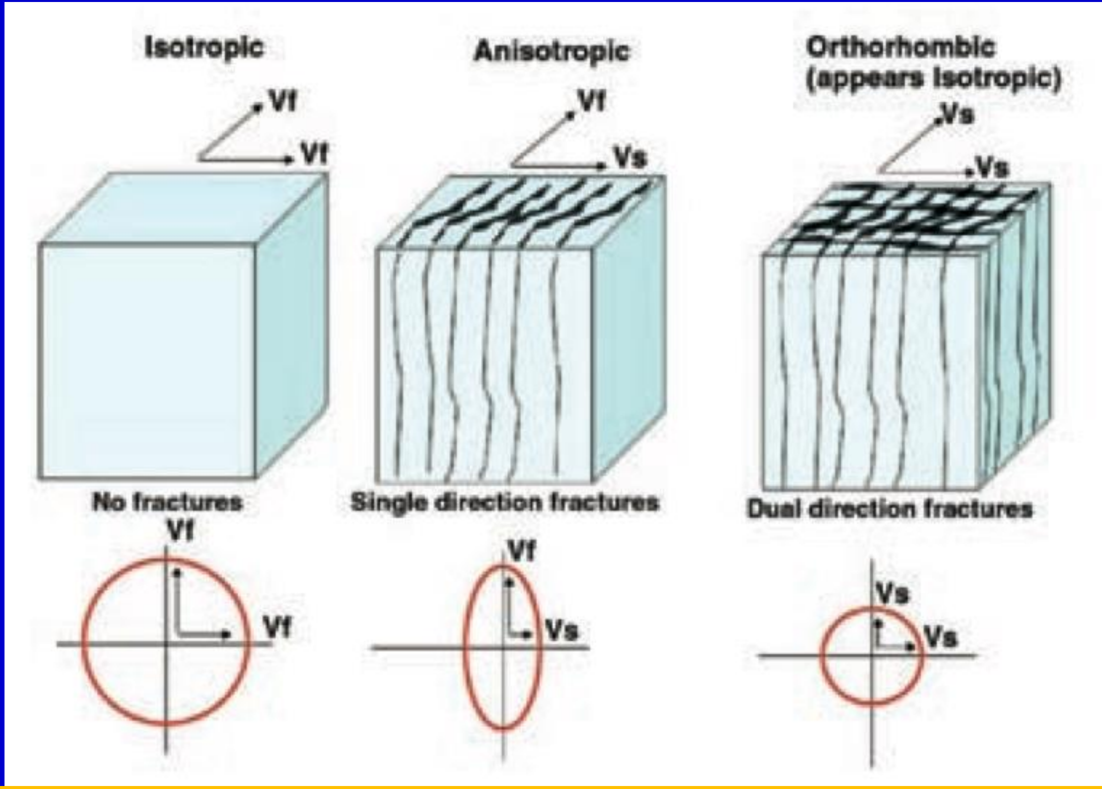
Microseismic events trend towards negative curvature values (green) avoiding the most positive curvature zones (orange) and follow the velocity anisotropy trend, previously described by Thompson (2010) and Browning (2006).

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 rock “relax” after being fractured.

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



Fabric related observation

Tinnin et al. (2008)

Seismic wave propagation is minimally affected parallel to the dominant fracture trend in rocks that have a simple one-directional fracture system (the "fast direction," V_{fast}), but a maximum velocity reduction (the "slow direction," V_{slow}) is aligned perpendicular to the oriented fractures. With multiple sets of fractures, such as the third orthorhombic case, velocity is reduced in all directions, and V_{fast} approaches V_{slow}, resulting in this type of fractured volume appearing to be an isotropic medium. This model implies multidirectional, interconnected fracture sets should be located in areas where there are smaller amounts of anisotropy.

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CONCLUSIONS

- I propose a new (alternative) template, but it isn't unique!!!
- Brittleness definition doesn't take into account rock fabric
- Well calibration is key to having an accurate interpretation of the rock brittleness.
- 2D color-bars are very useful to visualize cross-plot volumes.
- Microseismic events are an indirect way to understand the reservoir and:
  - trend towards quartz-rich areas, avoiding clay-rich zones.
  - trend towards negative curvature values (green) avoiding the most positive curvature zones (orange) and following the velocity anisotropy trend.
  - are located in zone of low anisotropy strength, suggesting that the rock "relaxed" after being fractured.

ACKNOWLEDGEMENTS

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