Seismic Brittleness Index Volume Estimation from Well Logs in Unconventional Reservoirs*

Roderick Perez[1]

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Abstract

Brittleness is a key rock property for effective reservoir stimulation in unconventional reservoirs. Differentiating brittle from ductile rocks is key to perform an efficient well location and completion. I calculate a brittleness index (BI) volume from surface seismic data calibrated by well logs in the Barnett Shale. Completion effectiveness is function of the interaction between multiple engineering variables (length of the horizontal wells, number of stages, number and size of the hydraulic fracture treatments in a multistage completion, volume of proppant placed, proppant concentration, total perforation length, and number of clusters) and the spatial variation between geological factors (permeability, porosity, maximum stress field, among others) in shale gas reservoirs. I correlate a BI log from a well with core descriptions and mineralogy log information with lithological (gamma ray) and geomechanically-related well logs building a non-linear relationship between these variables. Using prestack simultaneous inversion, I derived geomechanical seismic attributes and seismic volumes and I used them to predict lithology and geomechanical behavior in the reservoir. Additionally, I generated a pseudo gamma ray (GR) seismic cube using probabilistic neural network (PNN). I combined these seismic attributes using the non-linear relationship developed from well logs to generate a pseudo BI seismic cube. I propose a methodology to integrate well logs and seismic derived attributes using non-linear relationships to highlight and identify brittle zones in unconventional reservoirs. Finally, I correlated the resulting BI seismic volume with production and volume of proppant placed into the reservoir validating the effectiveness of this technique.

Selected References

Perez, R., 2013, Brittleness estimation from seismic measurements in unconventional reservoirs: Application to the Barnett Shale: Ph.D. Dissertation, The University of Oklahoma.

Perez. R., and K. Marfurt, 2014, Mineralogy-Based Brittleness Prediction from Surface Seismic Data: Application to the Barnett Shale: Interpretation (in press).

Verma, S., A. Roy, R. Perez, and K. Marfurt, Finding high frackability and high TOC zones in Barnet shale with supervised: Probabilistic Neural Network and unsupervised: multi-attribute Kohonen SOM, SEG Abstract, 2012.

SEISMIC BRITTLENESS INDEX VOLUME ESTIMATION FROM WELL L,OGS IN UNCONVENTIONAL RESERVOIRS

Roderick Perez A., Ph.D.

Houston, TX / 2014

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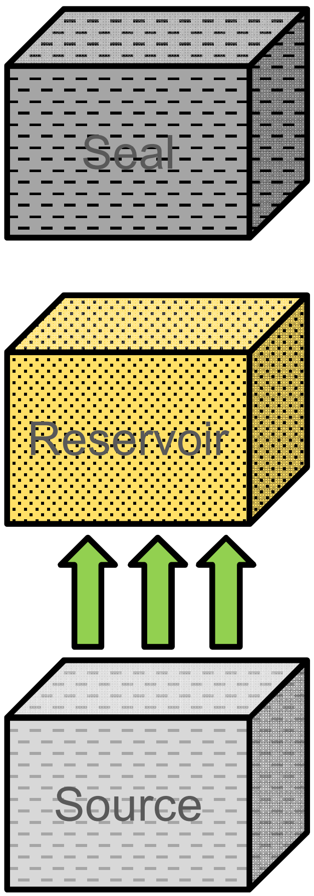
INTRODUCTION

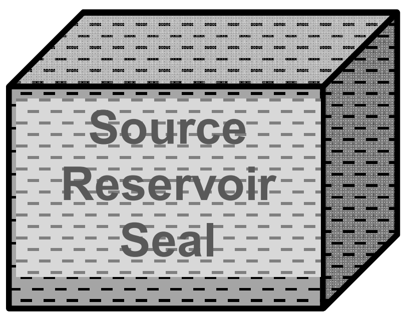
CONVENTIONAL*



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*

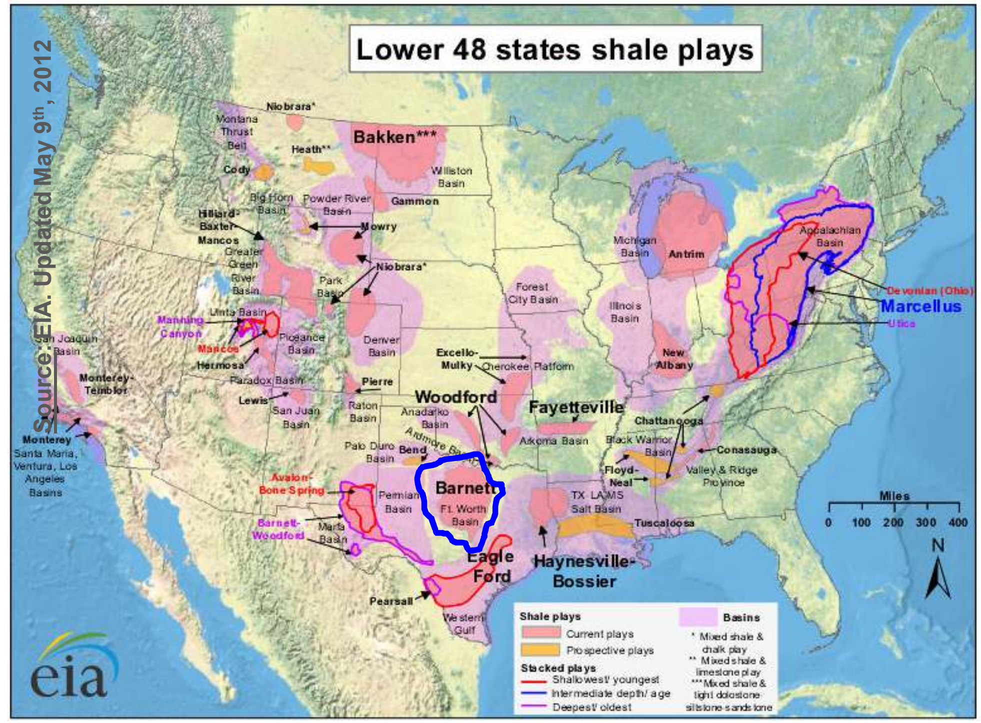
An unconventional reservoir is one where one single rock combines the previous rock characteristics, and the hydrocarbon storage in the rock pores (typically natural gas) does not flow naturally due to the low (> $ 0.1 mD) rock permeability. Many of these low-permeability rocks are shale and tight sandstone,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



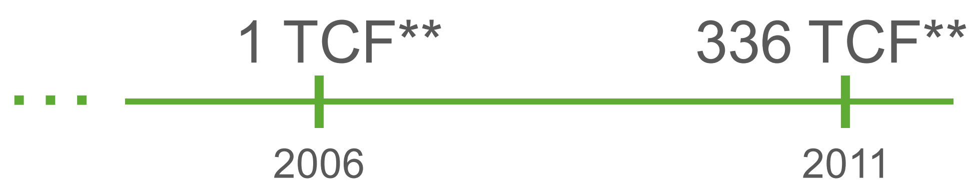
<u>**BARNETT SHALE**</u>:
Low permeability* (<0.1 mD)
Low porosity* (6%)
High TOC*

*Average values corresponding to the Barnett Shale

***Geological**



The proliferation of the exploration activity into new shale plays has increased the shale gas resources in the U.S. from 1 from 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

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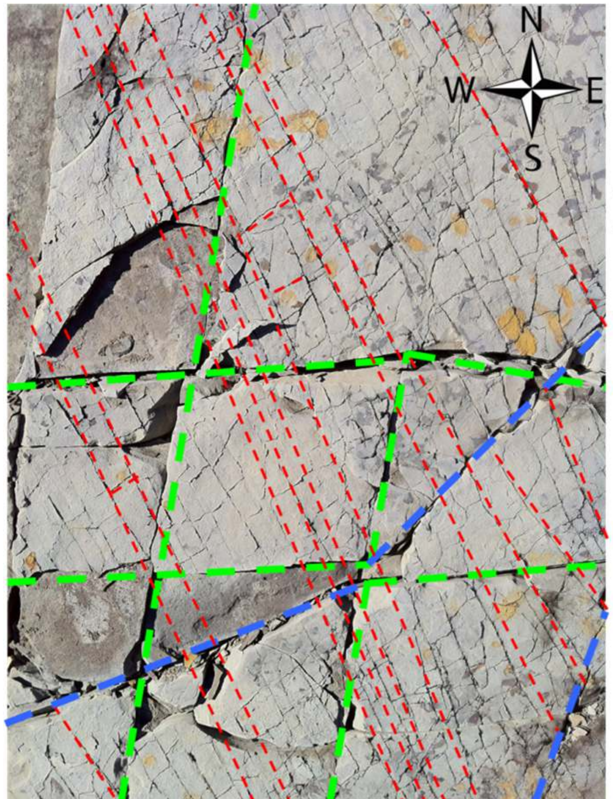
OBJECTIVE



The figure shows the low permeability oil-saturated Woodford Shale, and relates the fracture size and length with a road speed limit, indicating that the higher the fracture size (the wider the road), the greater the permeability (or speed limit).

WOODFORD SHALE

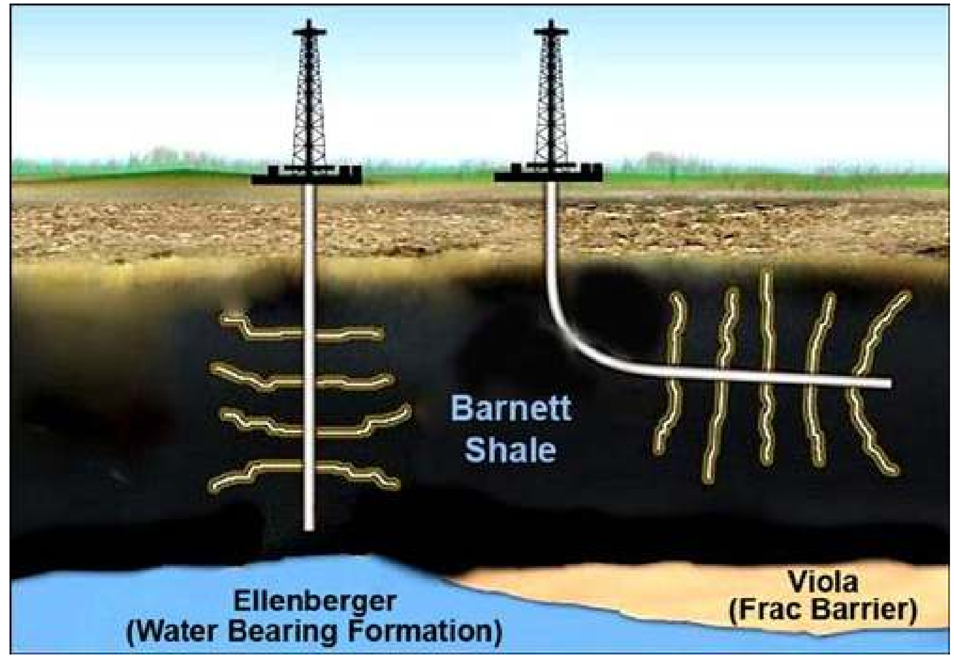
Location: Ardmore, OK

Fracture set A

Fracture set B

Fracture set C

0 1 2 3 4 inches



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**.

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OUTLINE

- Introduction
- Objectives
- Review Brittleness Index (BI)
- BI estimation from logs
  - Linear correlation
  - Non – linear correlation
- Seismic attributes
  - $\lambda\rho, \mu\rho$ (Geomechanical)
  - Pseudo – GR (Geological)
- Conclusions

WHAT IS BRITTLENESS?

BRITTLE

DUCTILE

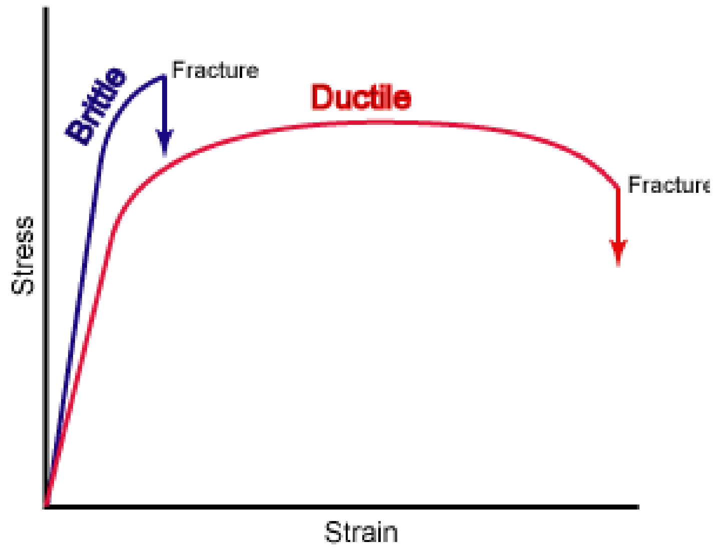
BRITTLENESS is the measurement of stored energy before failure, and is function of:

- 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.

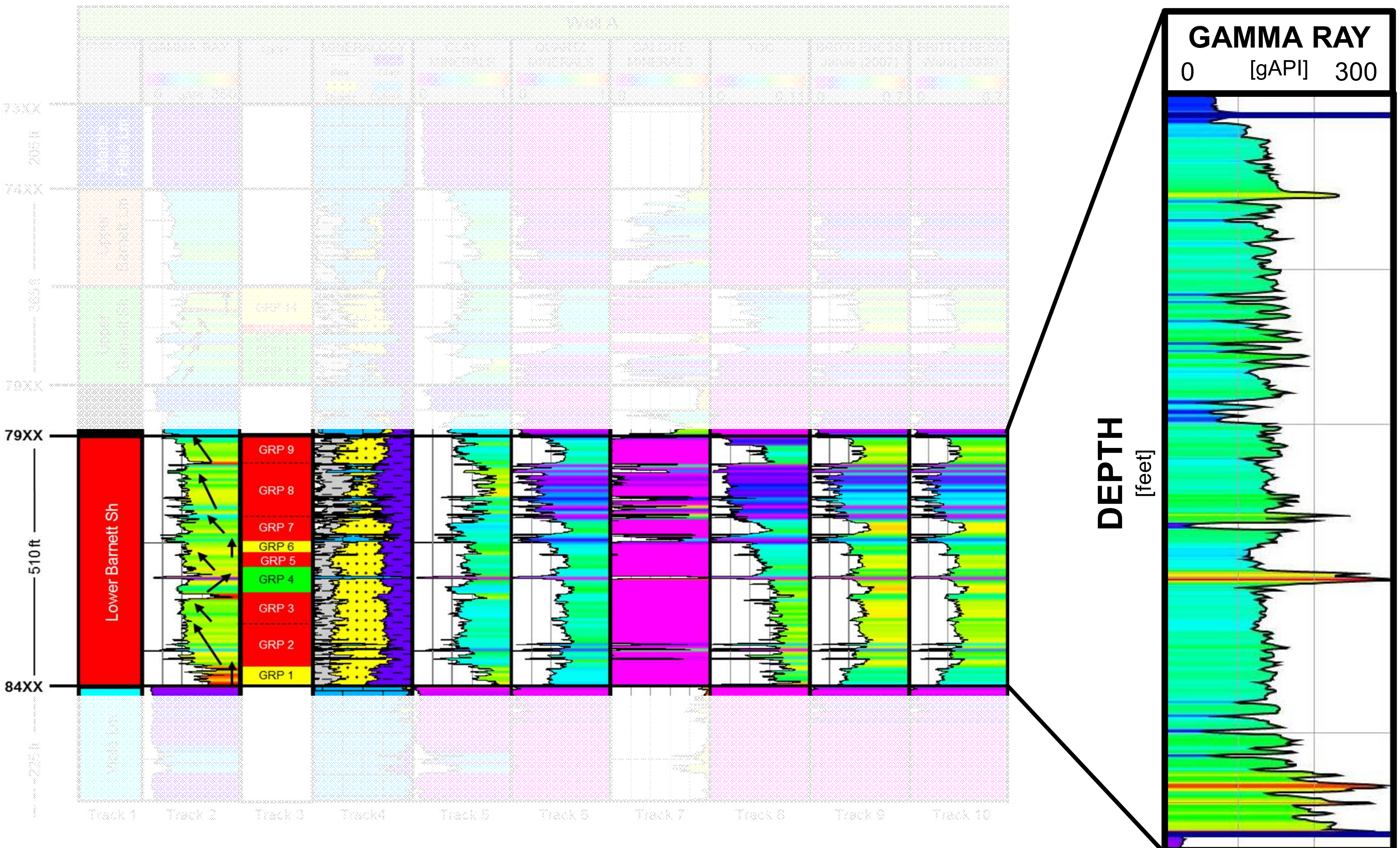
$$BI = \frac{\sigma_c}{\sigma_t}.$$

σ_c = Compressive strength
σ_t = Tensile strength



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

BRITTLENESS INDEX FROM LOGS



$$BI_{Jarvie(2007)} = \frac{Qz}{Qz + Ca + Cly} \quad BI_{Wang(2009)} = \frac{Qz + Dol}{Qz + Dol + Ca + Cly + TOC}$$

Qz = Quartz
Ca = Calcite
Cly = Clay
Dol = Dolomite
TOC = Total Organic Carbon

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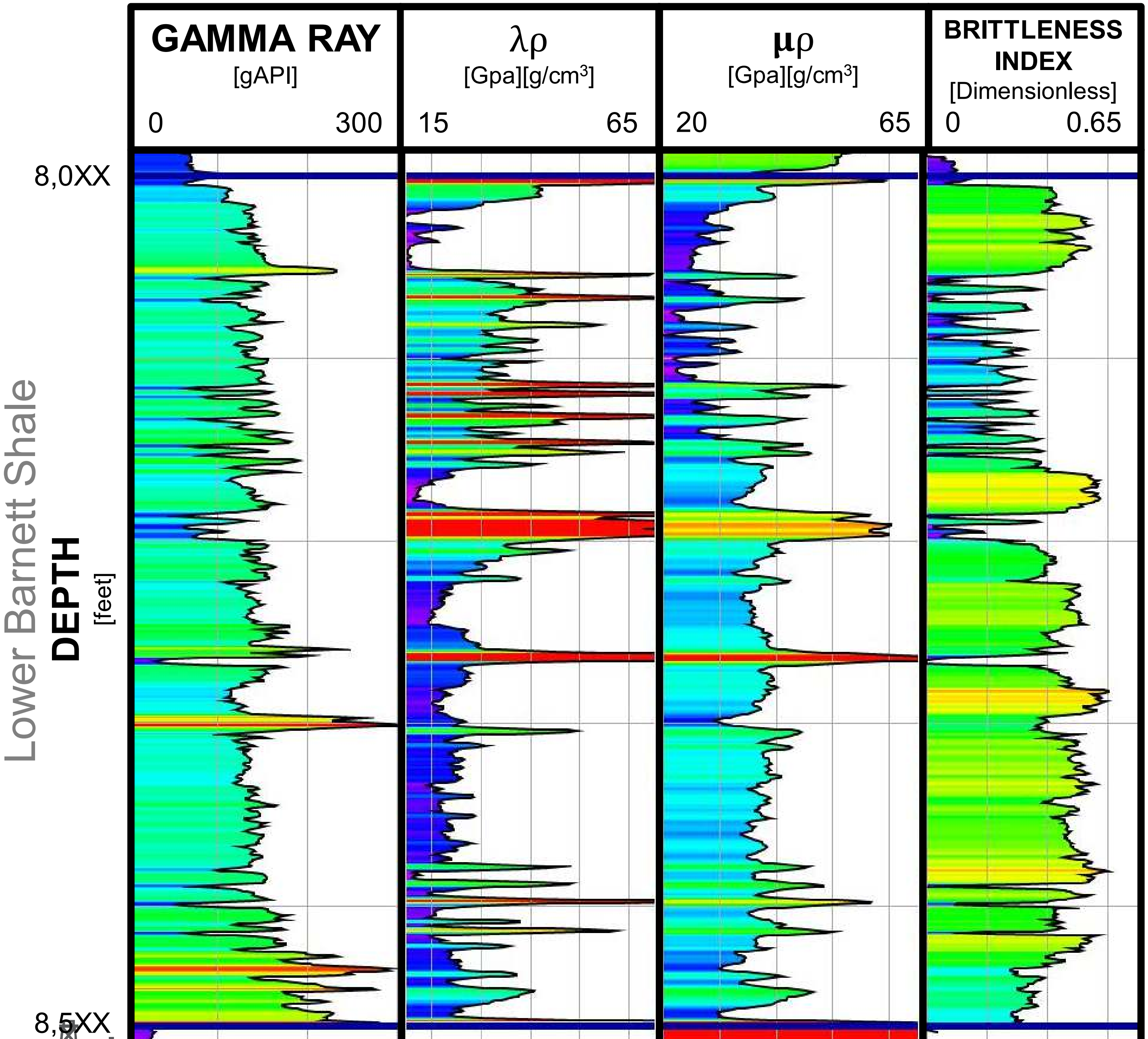
BRITTLENESS INDEX FROM LOGS

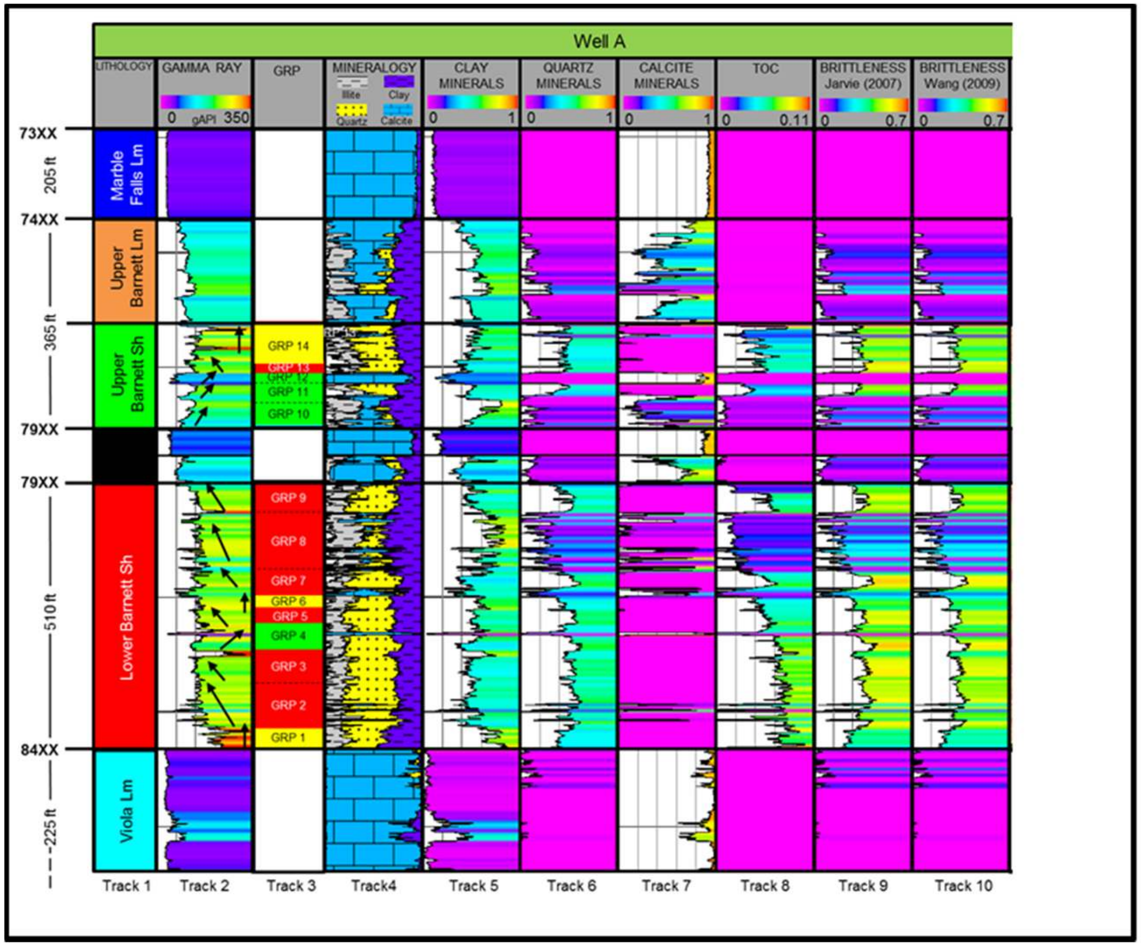


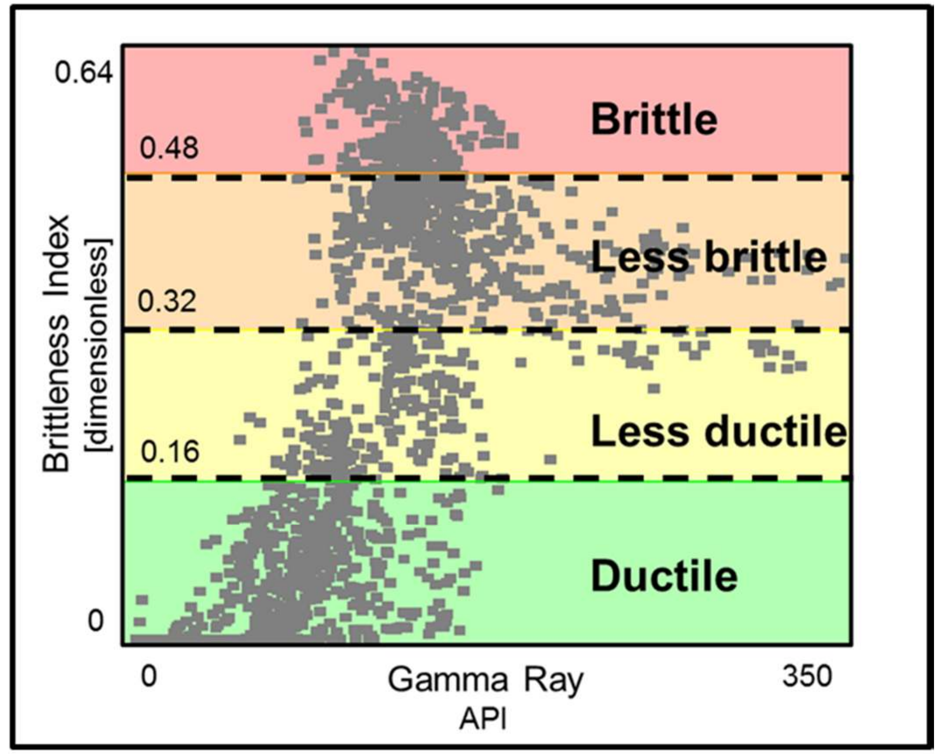
$$f_{BI}(\lambda\rho, \mu\rho, GR)$$

Brittleness Index:

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

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
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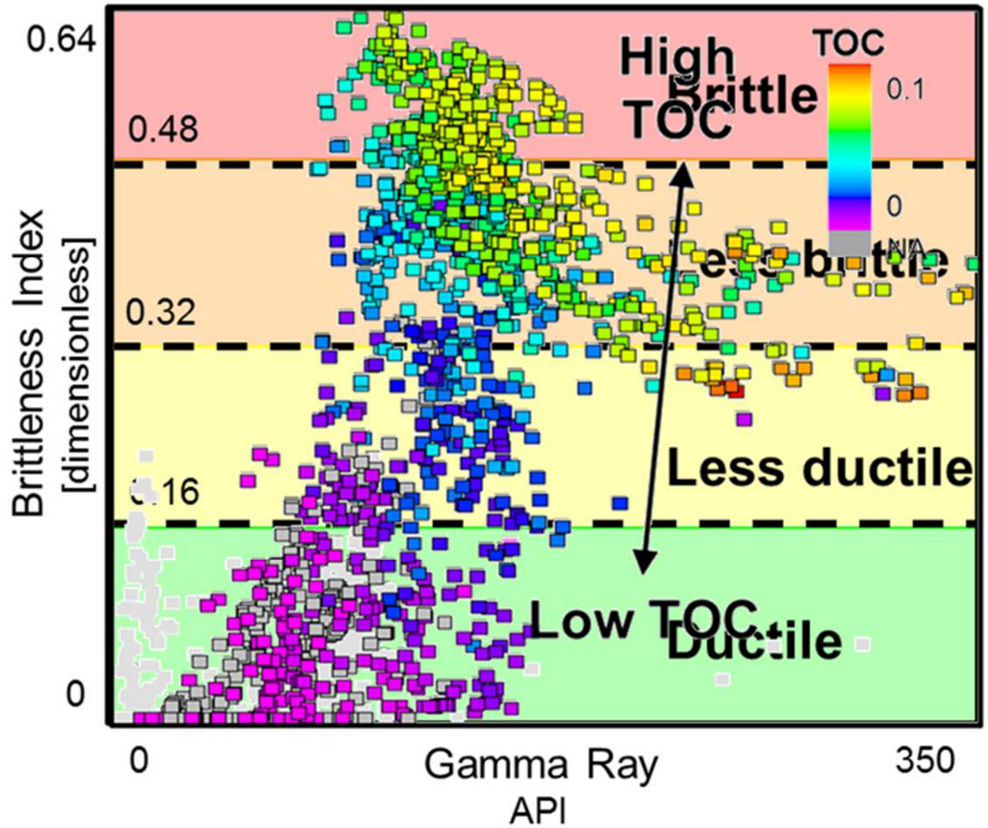
BRITTLENESS INDEX (Mineralogy)

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

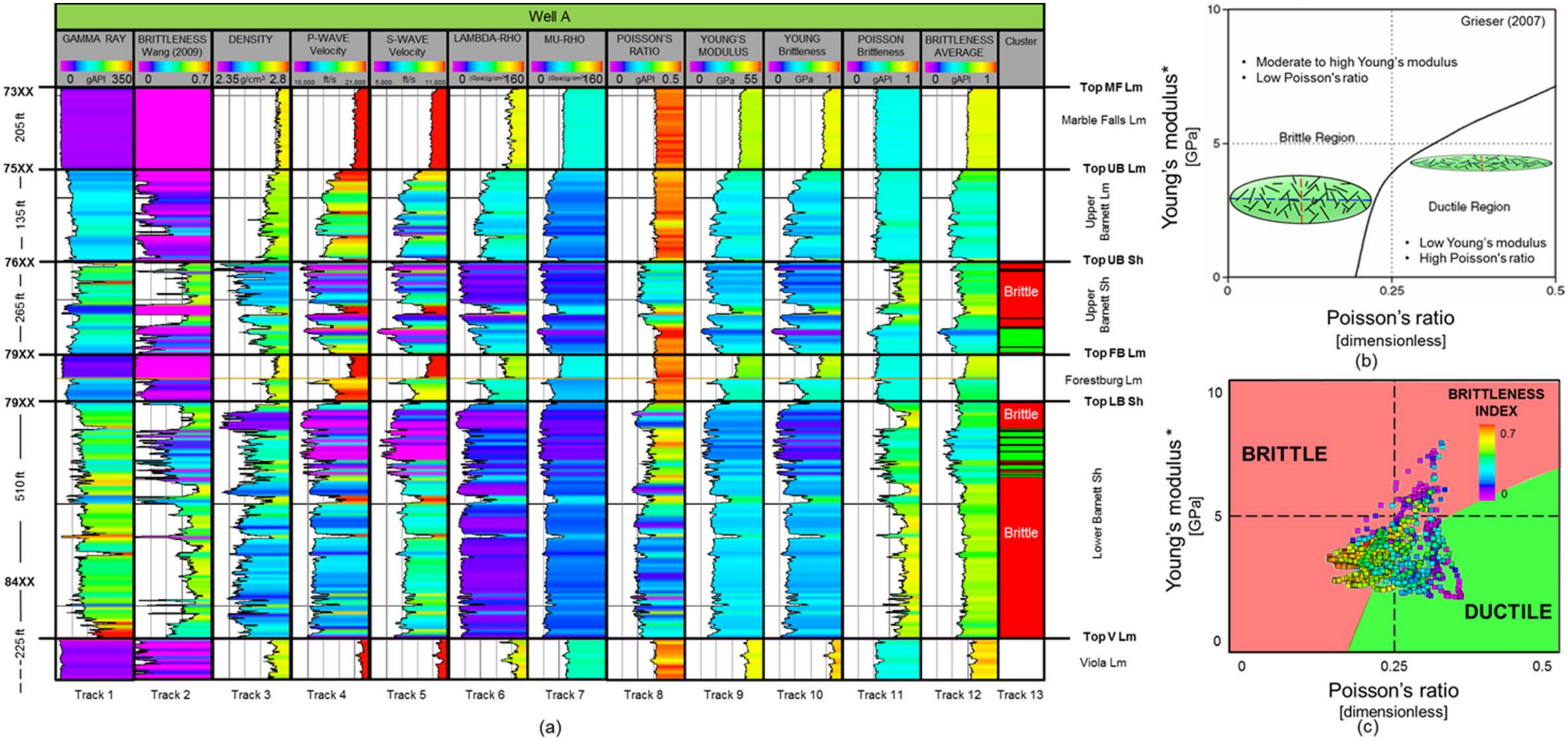
Increase in organic richness ↑

Decrease in bottom water oxygen ↑

Singh (2008)



BRITTLENESS AVERAGE (Elastic parameters)



$$E_{brittleness} = \frac{E - E_{min}}{E_{max} - E_{min}}, \qquad \nu_{brittleness} = \frac{\nu - \nu_{max}}{\nu_{min} - \nu_{max}}, \qquad Brittleness_{average} = \frac{(E_{brittleness} + \nu_{brittleness})}{2}.$$

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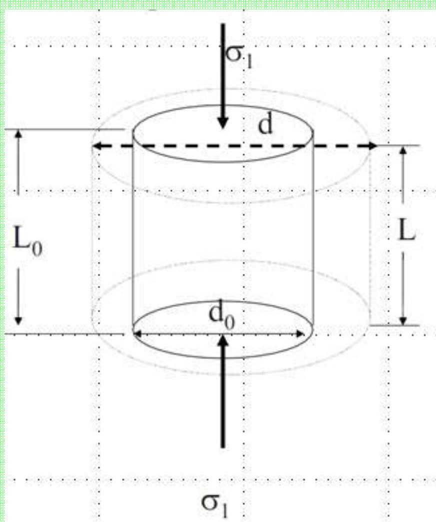
ROCK PHYSICS REVIEW

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

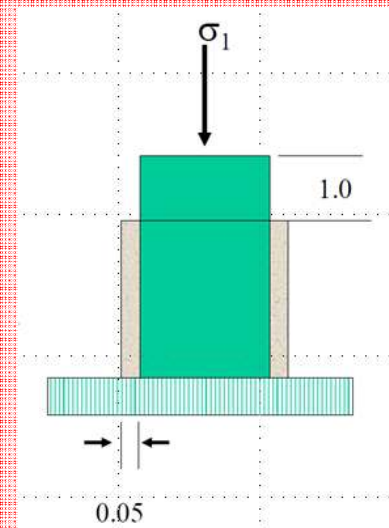
$$M = \lambda + 2\mu$$

P-wave Modulus

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

Young - Poisson Relation

Poisson's ratio



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

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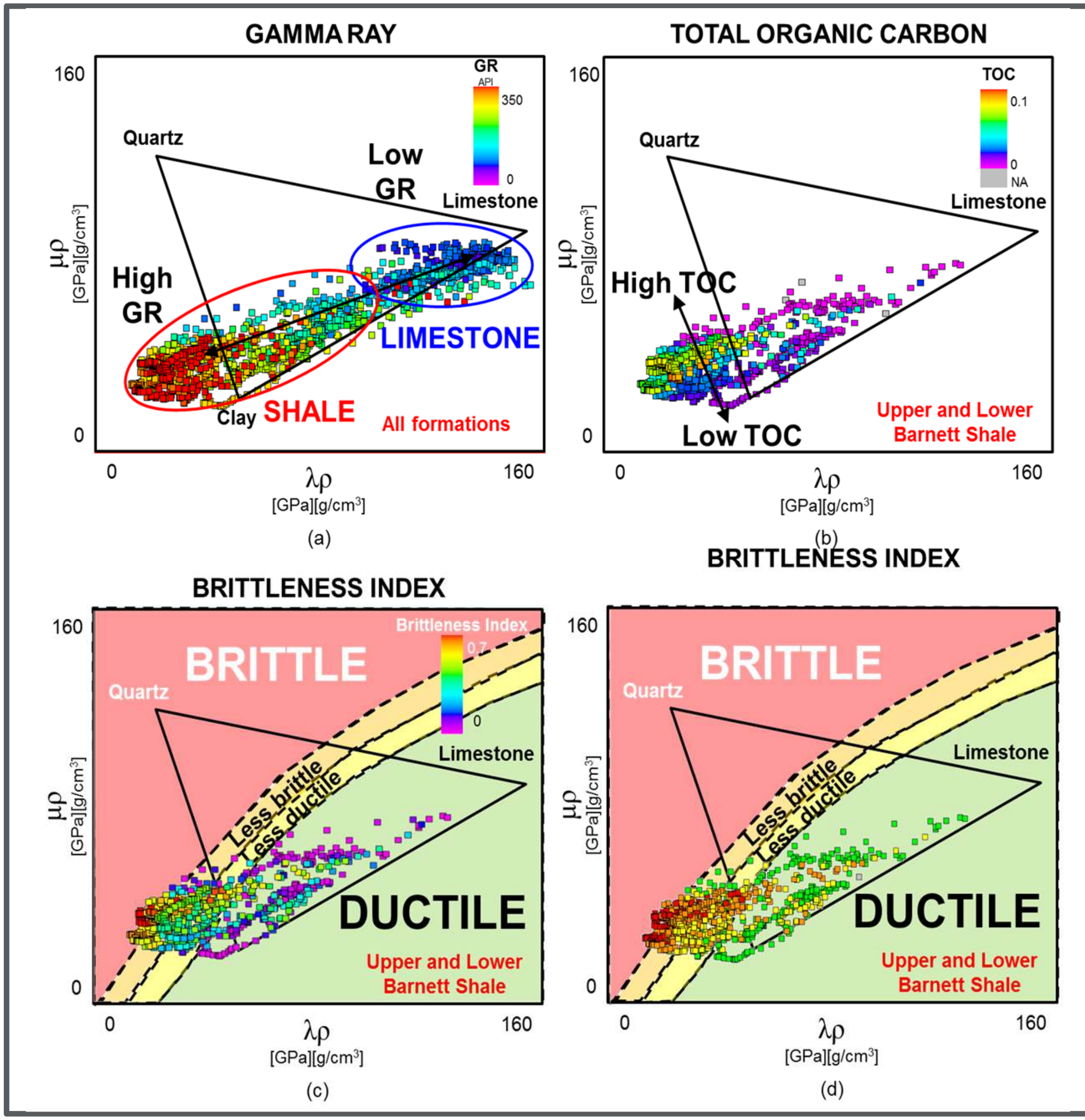
CALIBRATION GEOLOGIC AND GEOMECHANICAL PARAMTERS



- Perez, 2013, Brittleness estimation from seismic measurements in Unconventional reservoirs: Application to the Barnett Shale: Ph.D. Dissertation, The University of Oklahoma.
- Perez, R. and K. Marfurt, 2014, Mineralogy-Based Brittleness Prediction from Surface Seismic Data: Application to the Barnett Shale (Manuscript ID: INT-2013-0161)

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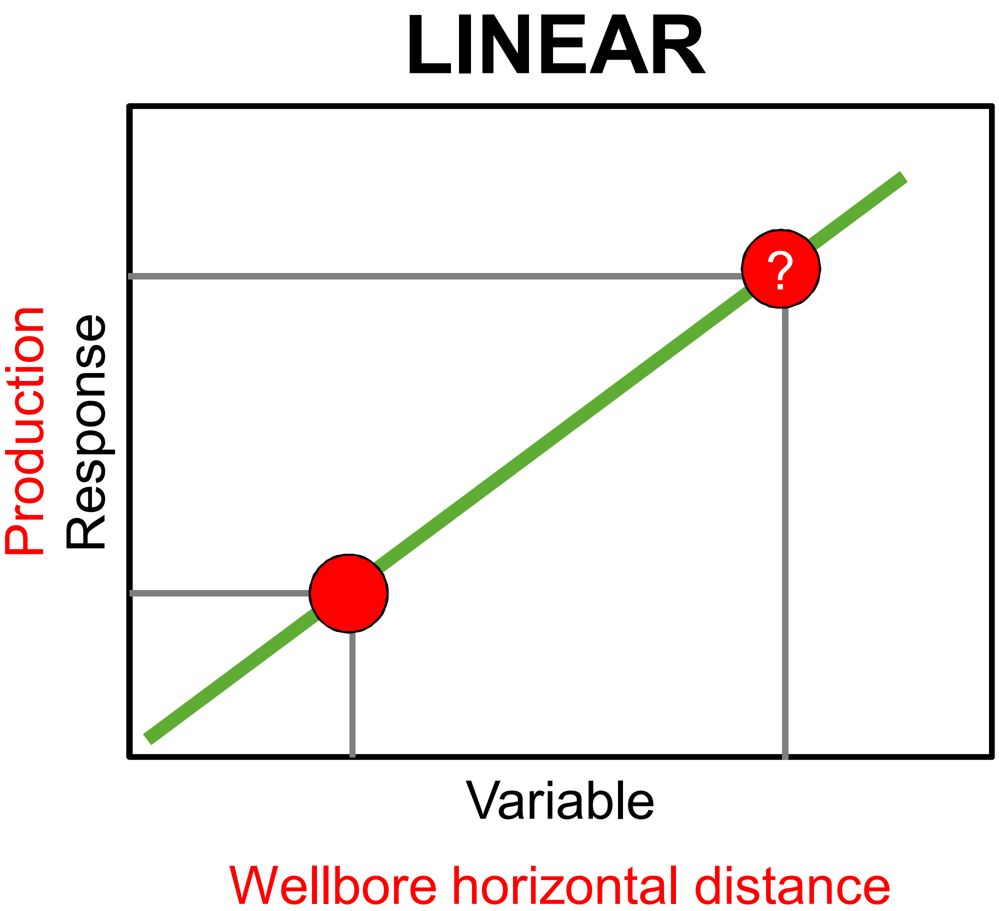
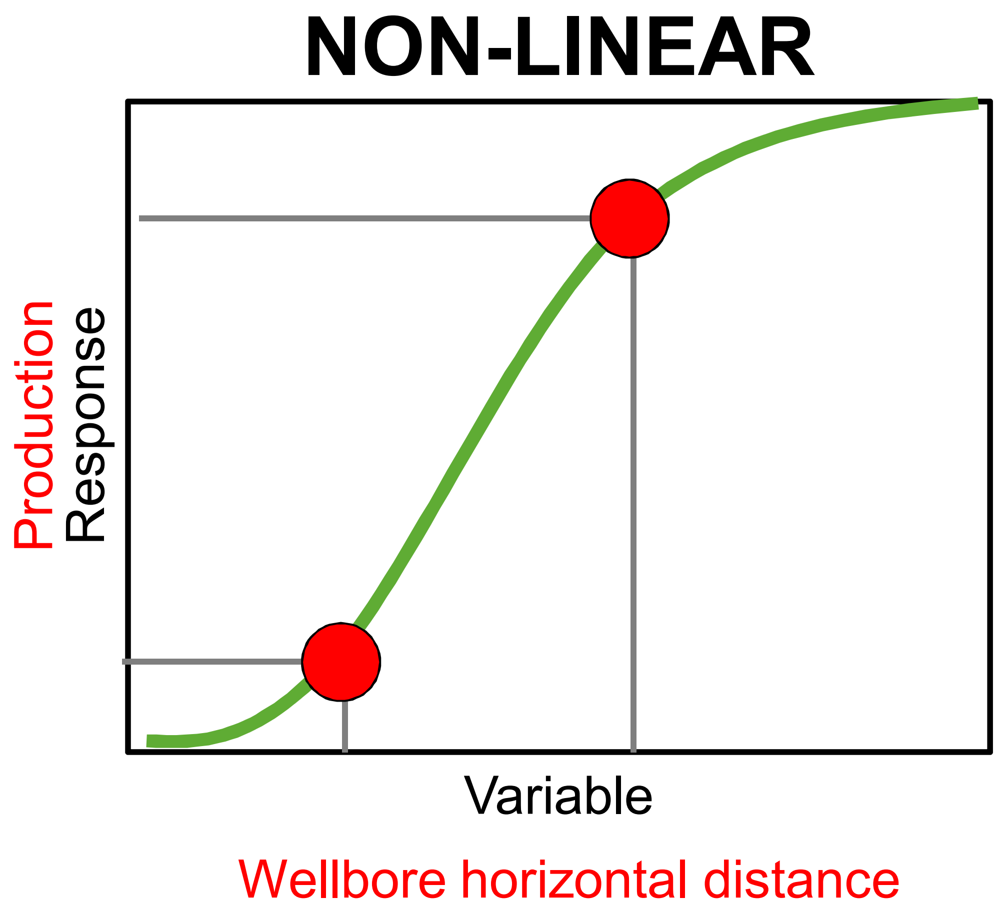
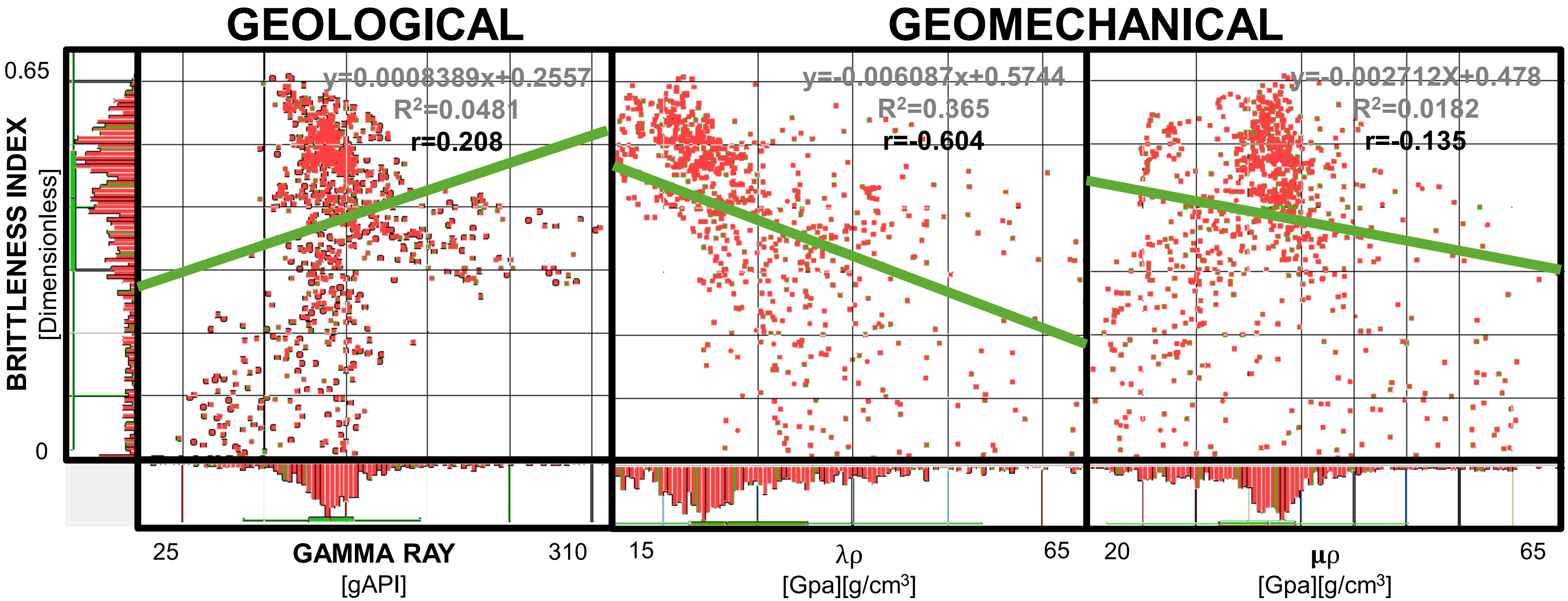
LINEAR vs. NON-LINEAR CORRELATION





LINEAR CORRELATION



	Brittlene...	GR (Gam...	Lambda_...	Mu_Rho ...
Brittleness_...	1.0	0.208	-0.604	-0.135
GR (Gamm...	0.208	1.0	-0.259	-0.343
Lambda_R...	-0.604	-0.259	1.0	0.603
Mu_Rho (P...	-0.135	-0.343	0.603	1.0

Correlation coefficient

	Brittlene...	GR (Gam...	Lambda_...	Mu_Rho ...
Brittleness_...	1.0	0.015	-0.732	-0.036
GR (Gamm...	0.015	1.0	-0.142	-0.34
Lambda_R...	-0.732	-0.142	1.0	0.419
Mu_Rho (P...	-0.036	-0.34	0.419	1.0

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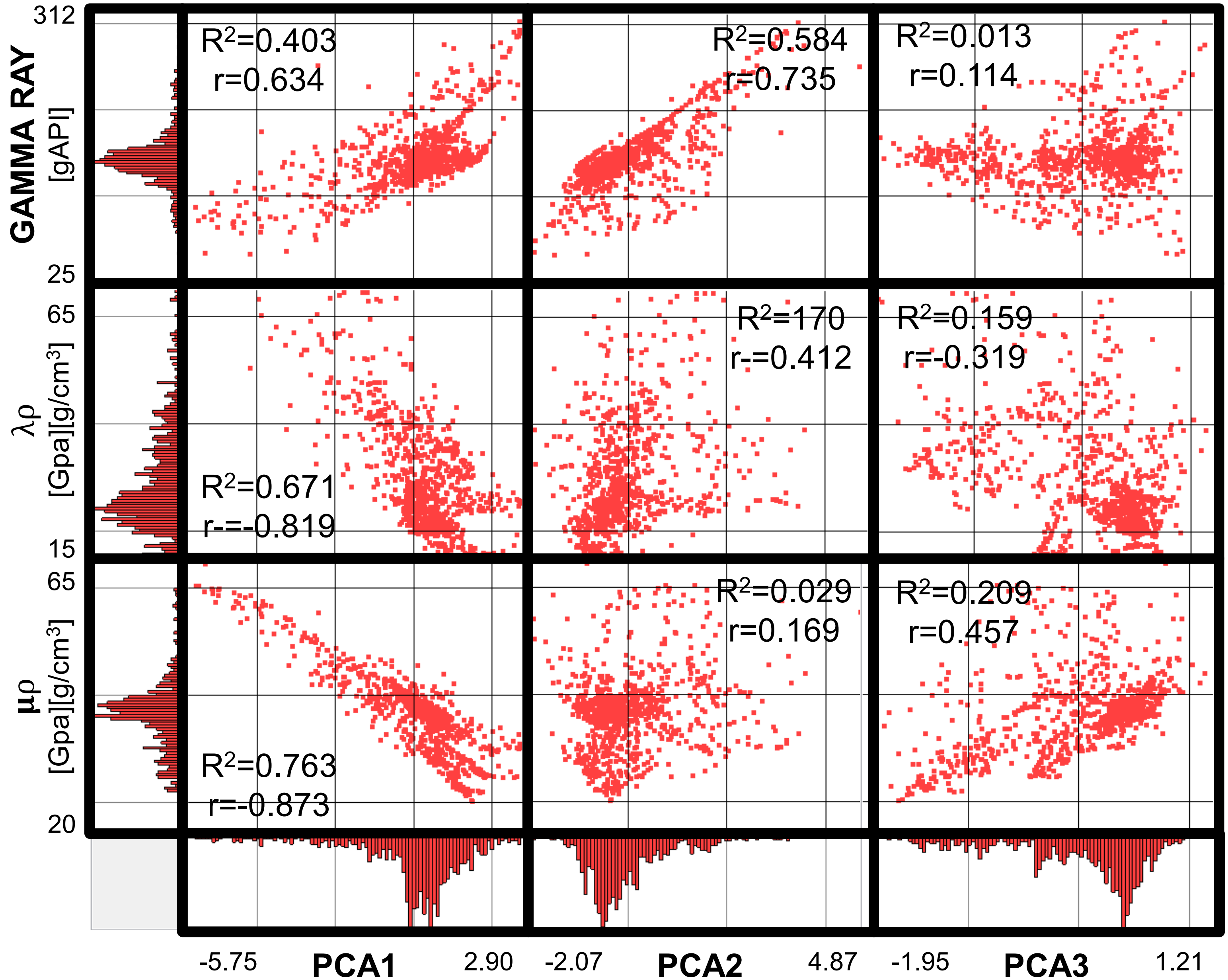
PRINCIPAL COMPONENT ANALYSIS



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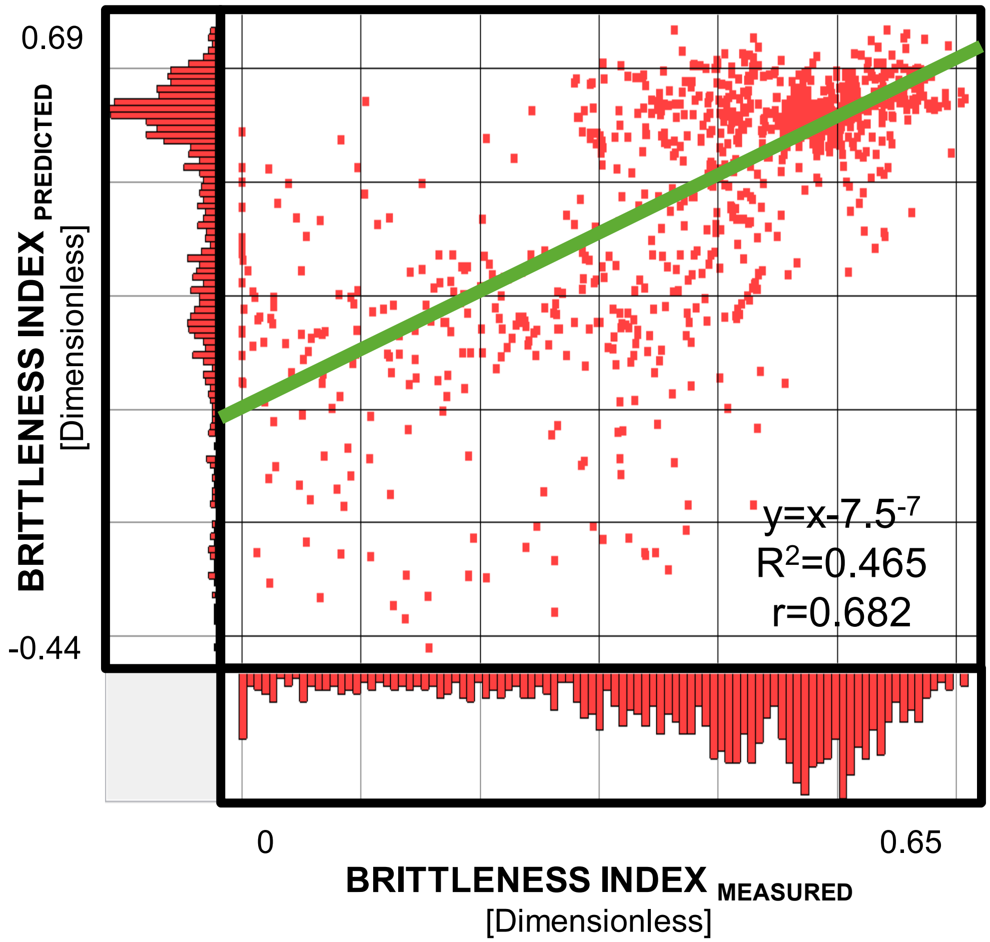
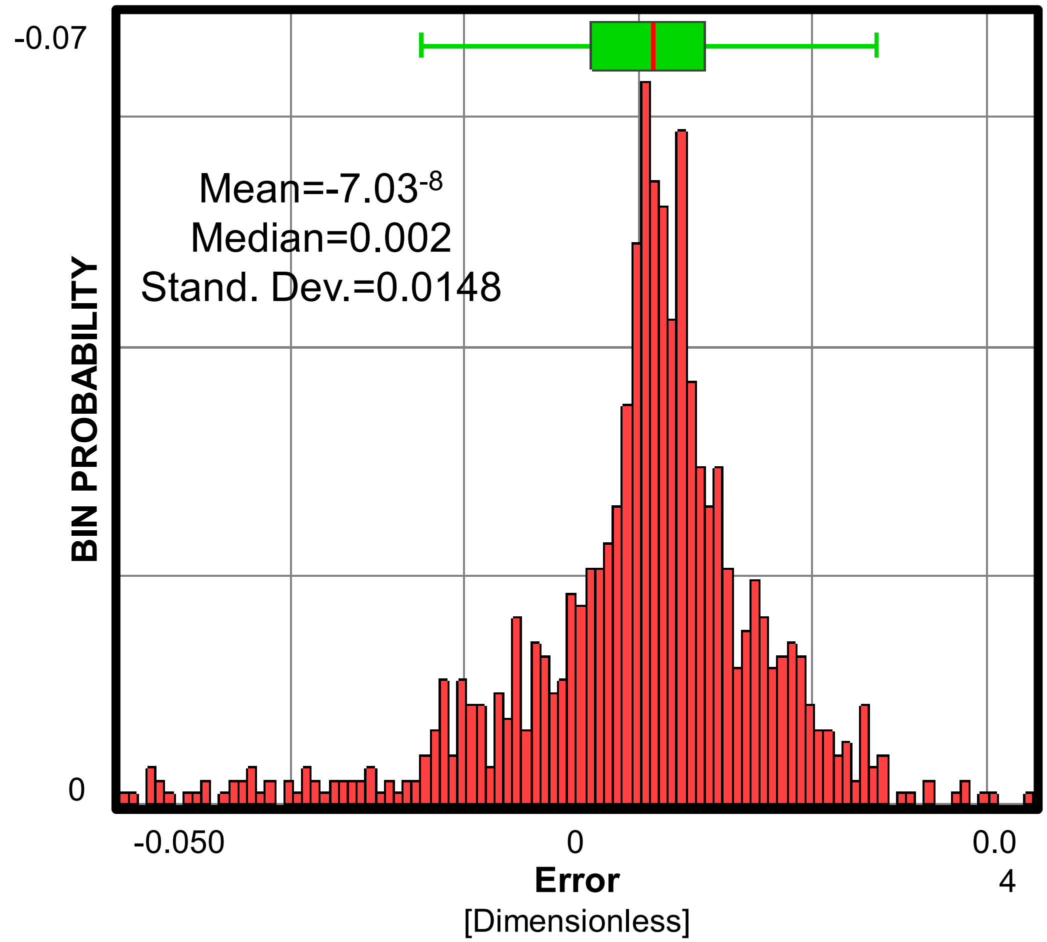
LINEAR REGRESSION RESULTS





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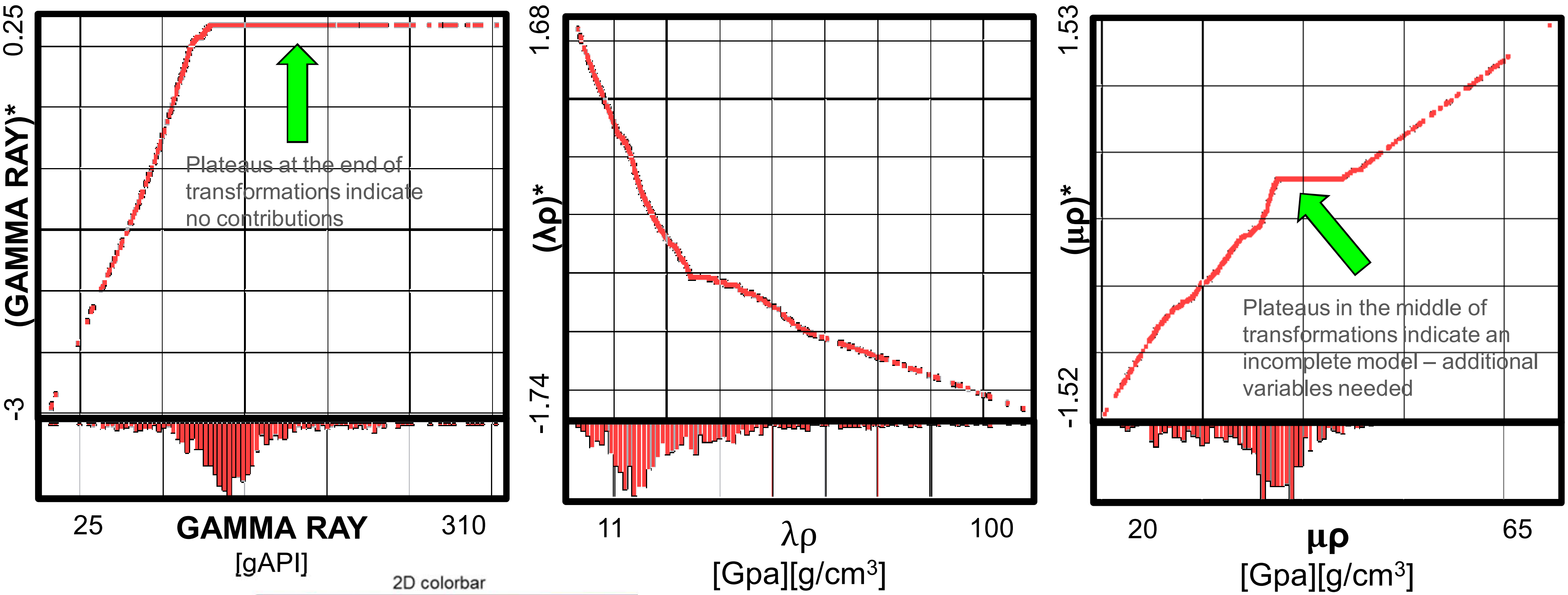
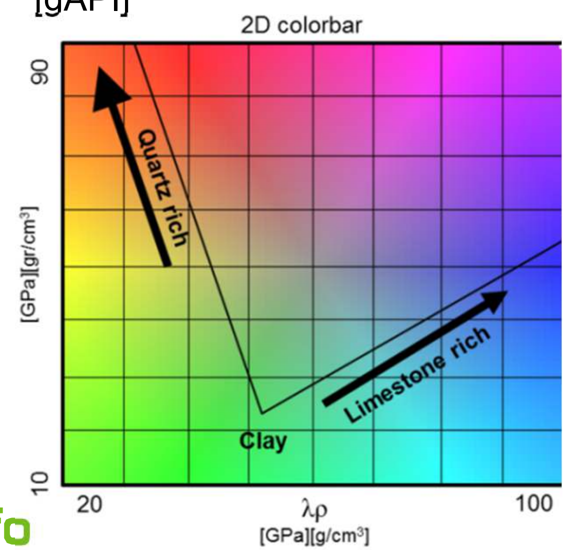
NON-LINEAR REGRESSION RESULTS





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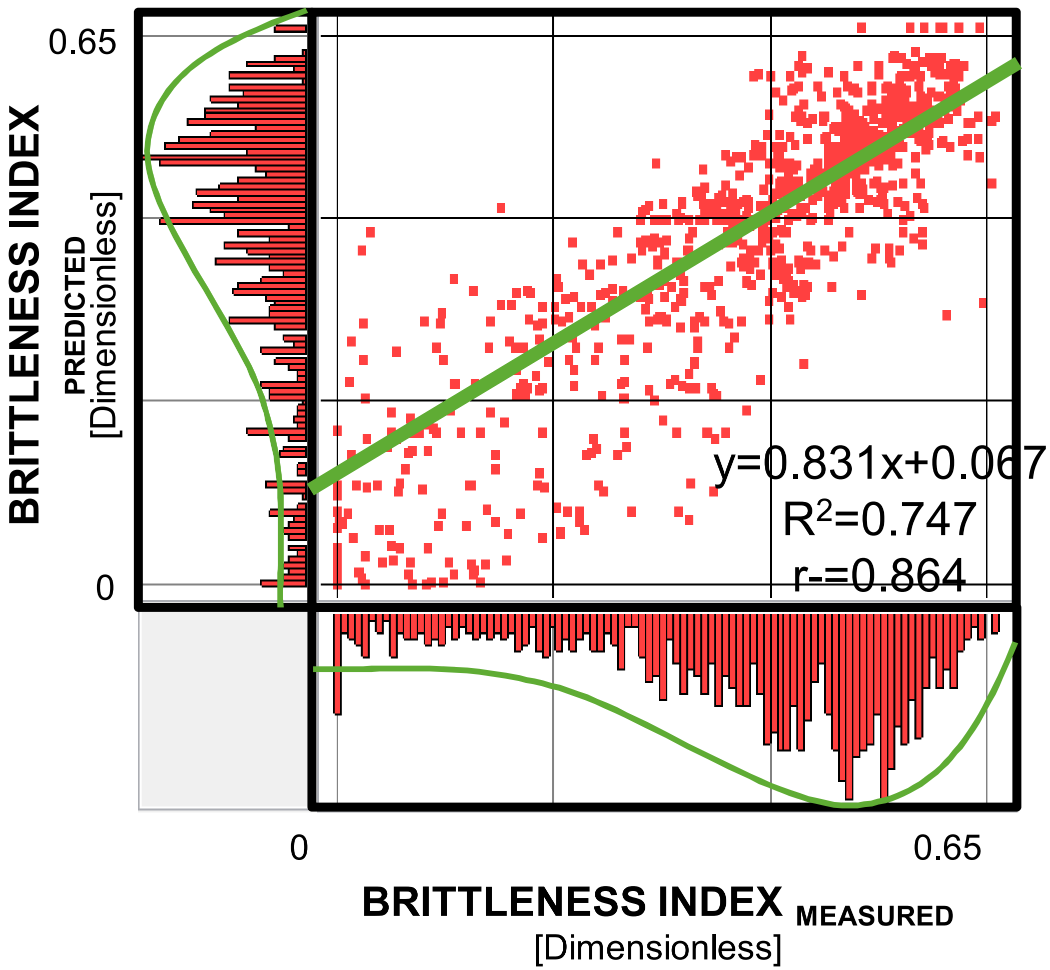
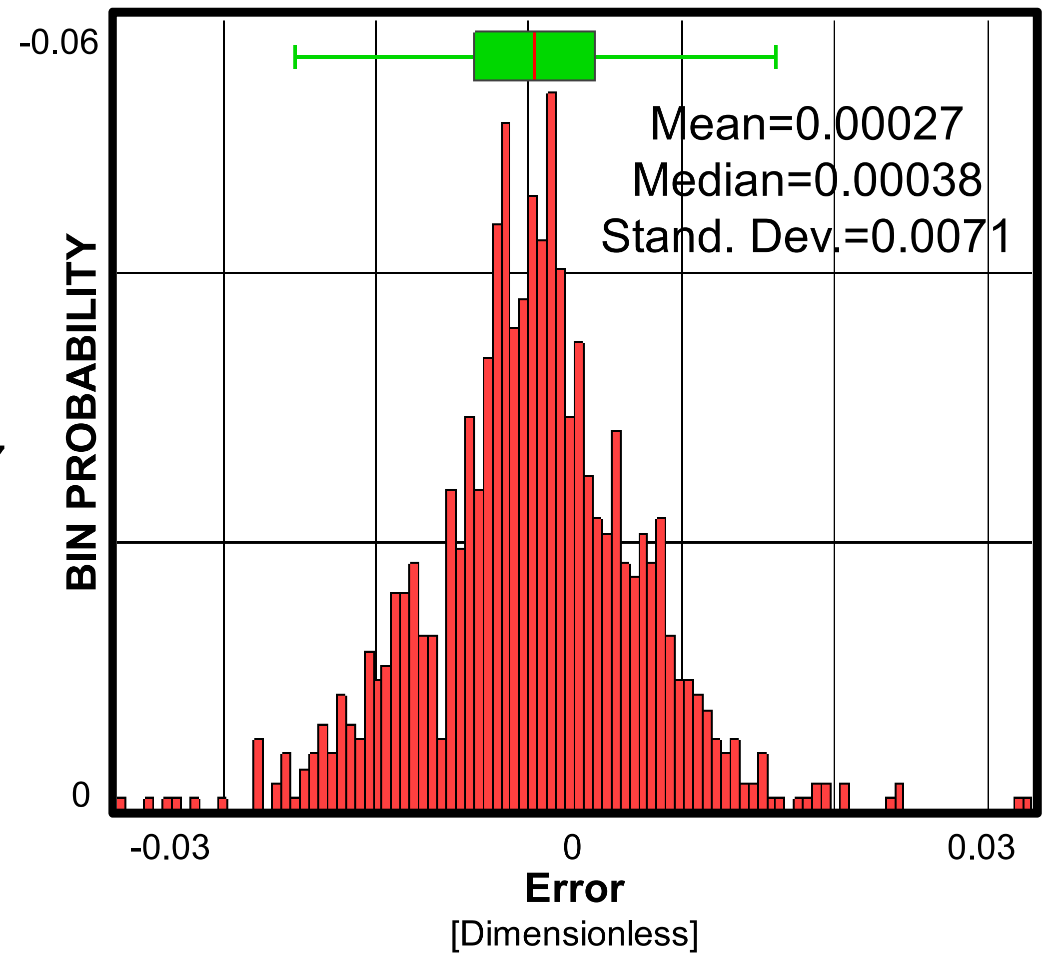
NON-LINEAR REGRESSION RESULTS





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SEISMIC PROCESSING

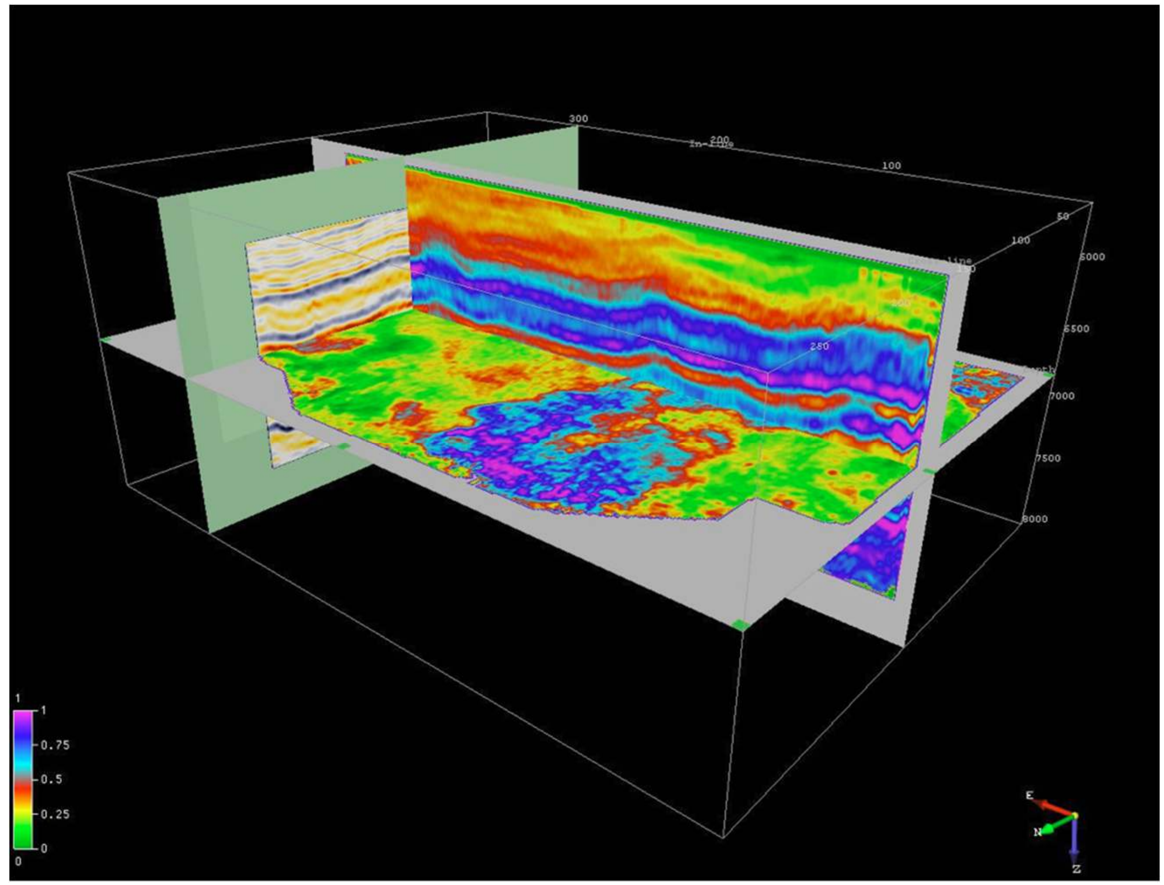
Angle Gathers

R_P reflectivity | R_S reflectivity

Z_P impedance | Z_S impedance

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

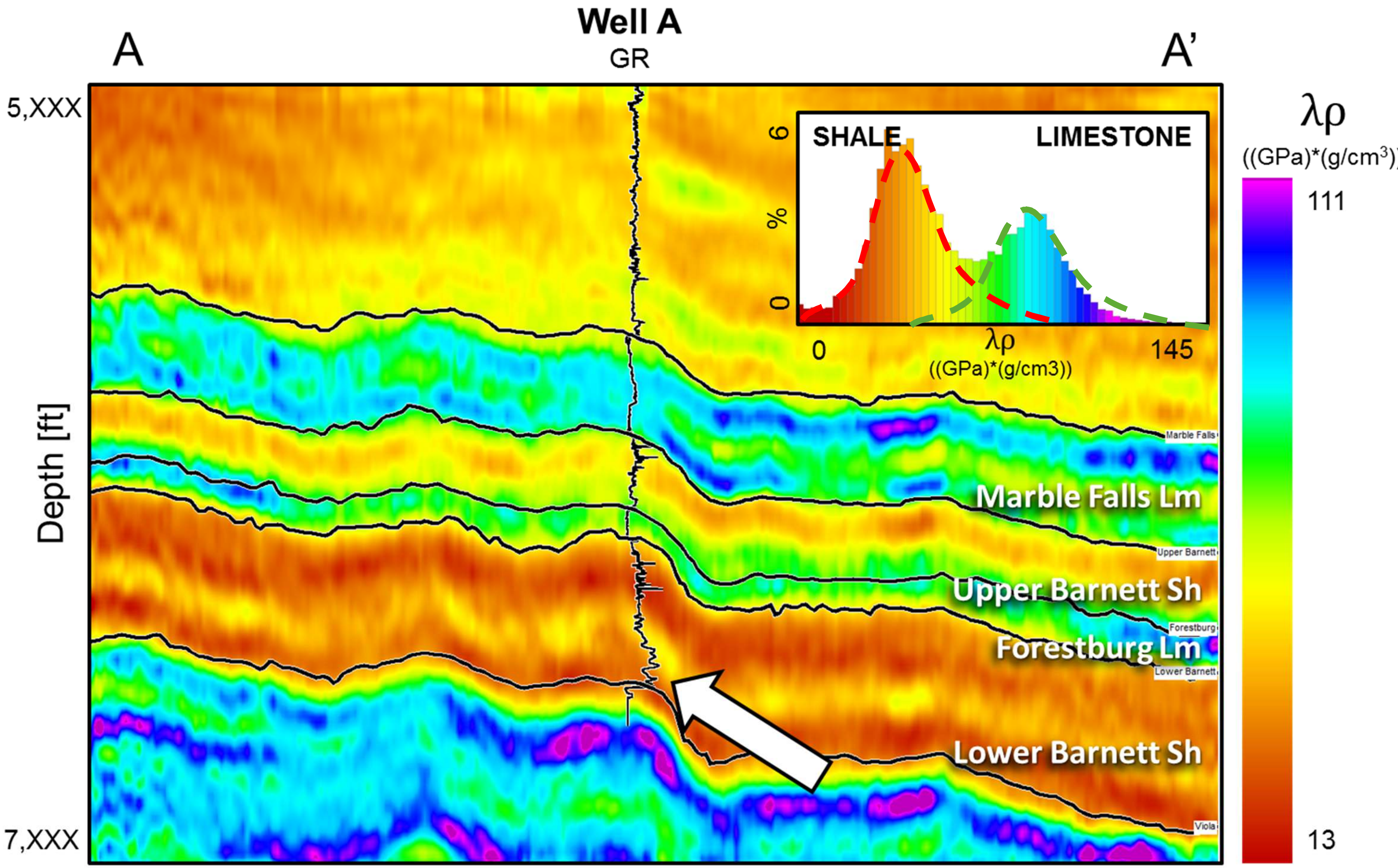
$\lambda\rho$ vs. $\mu\rho$ *crossplot*



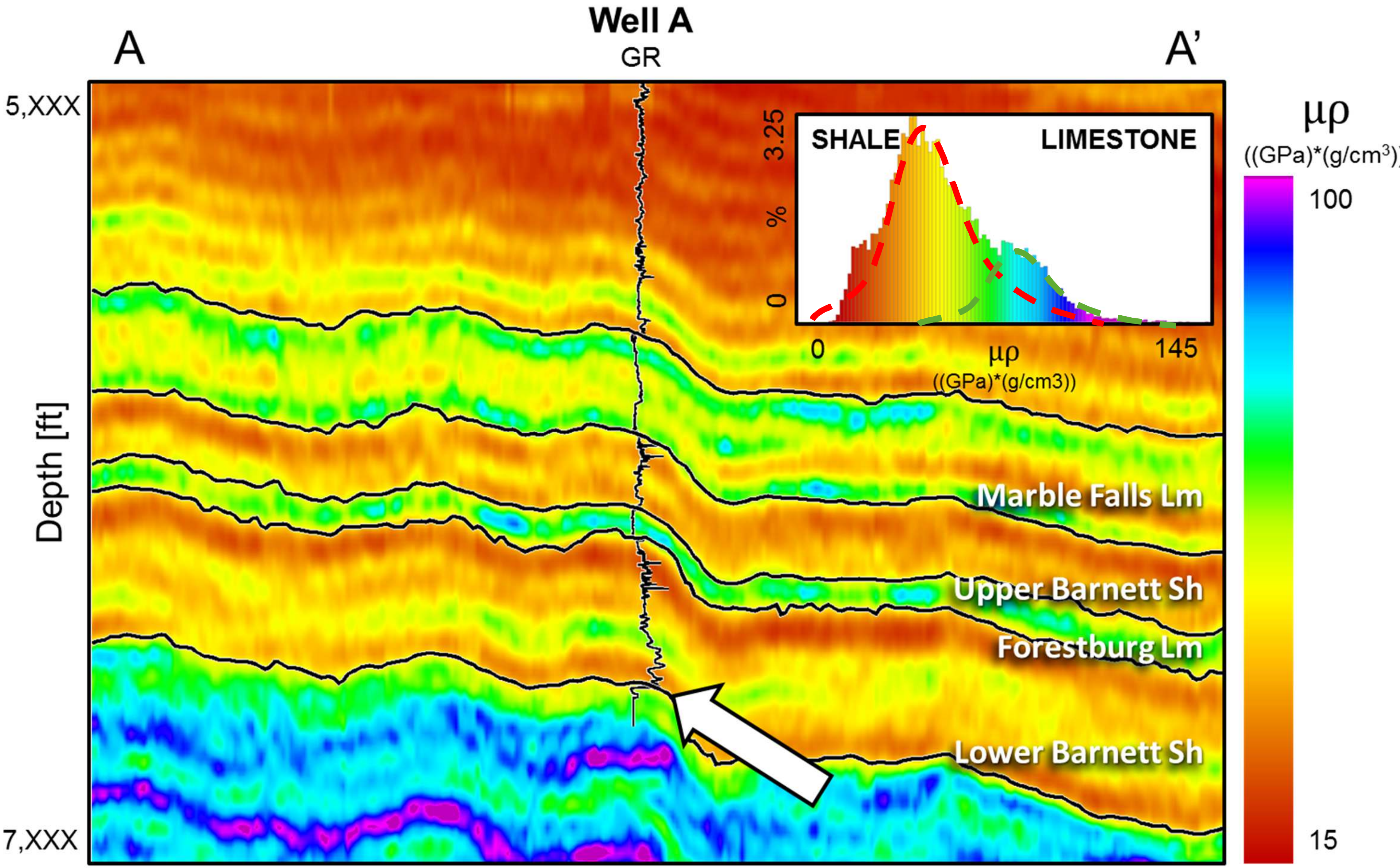
$$\lambda\rho = (\rho V_P)^2 - 2(\rho V_S)^2. \qquad \mu\rho = (\rho V_S)^2$$

Goodway (2007)

λρ SLICE


Well A
GR
A
A'
5,XXX
7,XXX
Depth [ft]
SHALE
LIMESTONE
%
0
6
0
λρ
145
((GPa)*(g/cm3))
Marble Falls
Marble Falls Lm
Upper Barnett
Upper Barnett Sh
Forestburg
Forestburg Lm
Lower Barnett
Lower Barnett Sh
Viola
λρ
((GPa)*(g/cm³))
111
13

$\mu\rho$ SEISMIC SLICE



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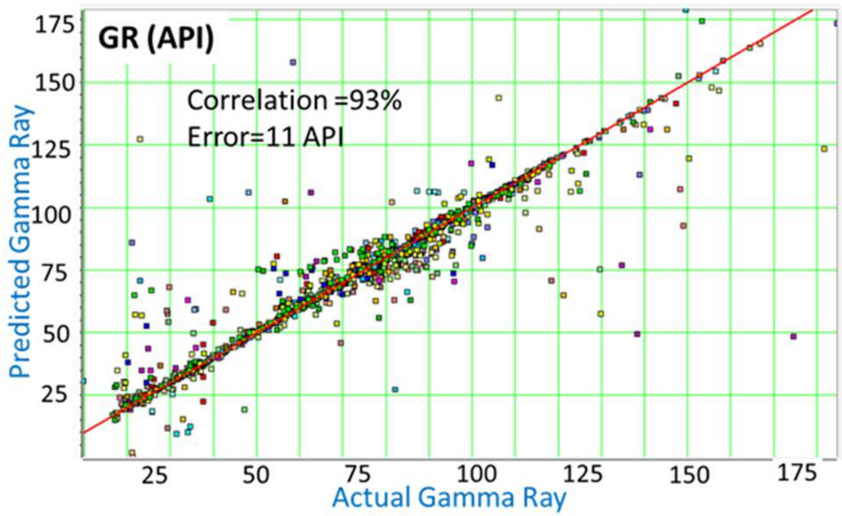
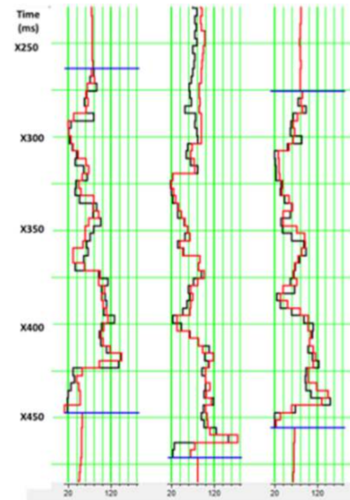
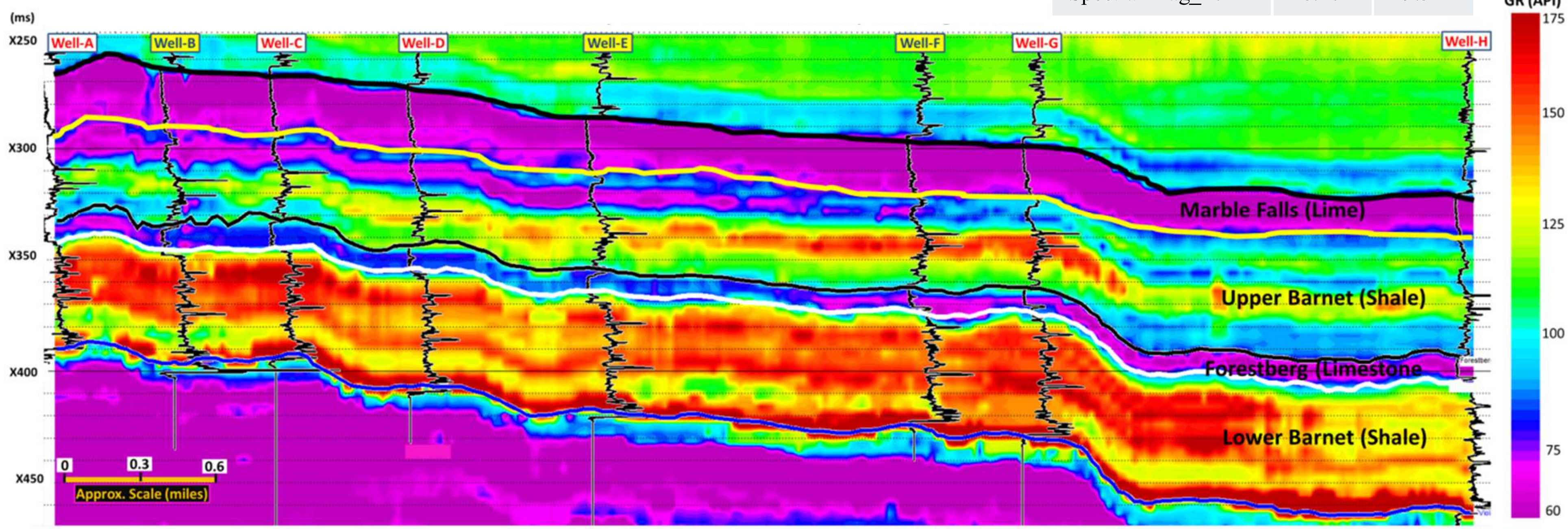
GR SEISMIC VOLUME



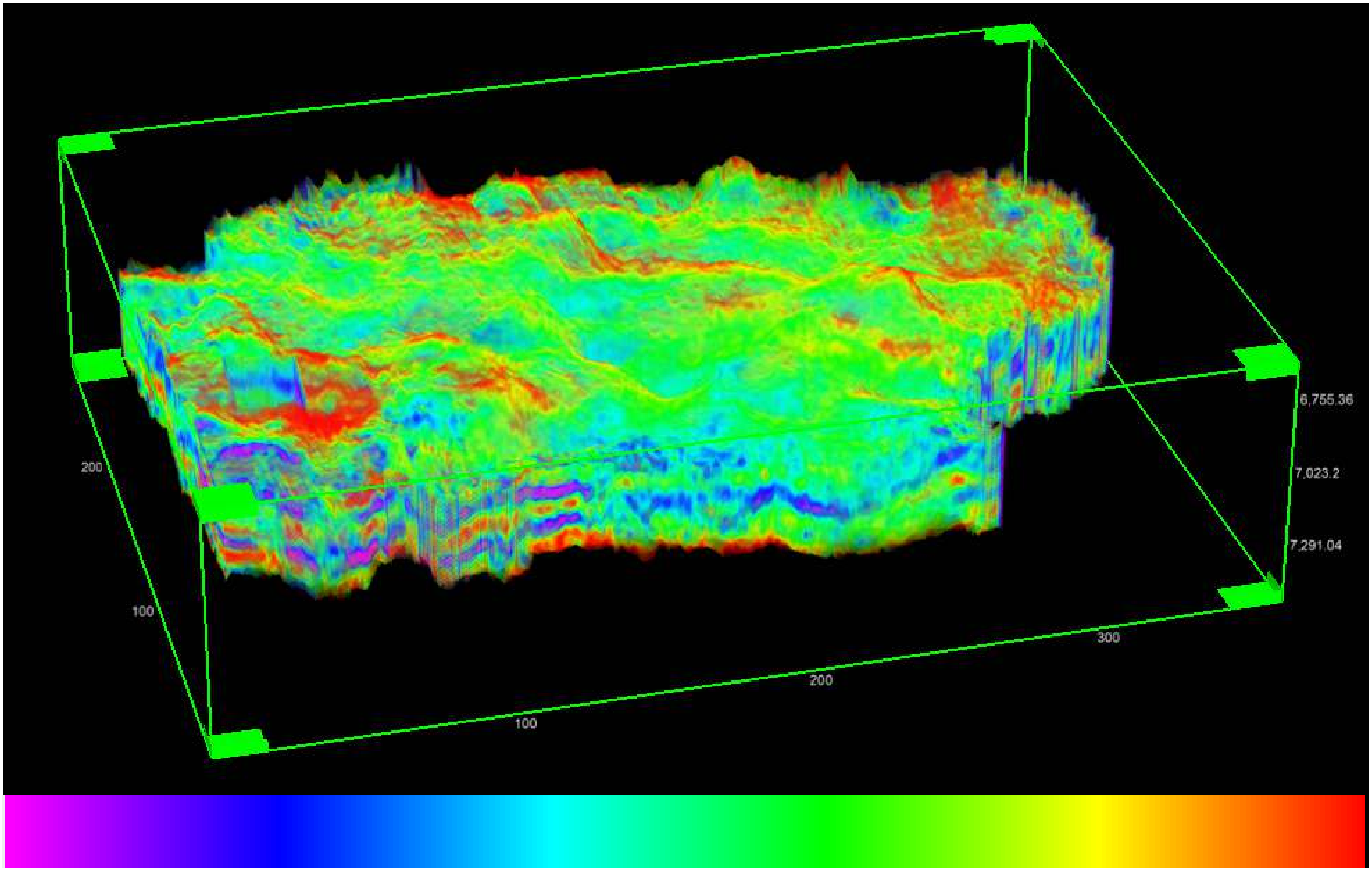


Final Attribute Operat. length: 9	Train. Error	Valid. Error
(Zp)**2	22.15	22.48
RAI	20.57	21.00
Sweetness	19.98	22.55
(Quadrature)**2	19.47	20.20
1/Zs	19.16	20.10
Vs/Vp	18.51	19.46
Coherent Energy	18.20	19.27
Spectral Mag_20Hz	18.10	19.34

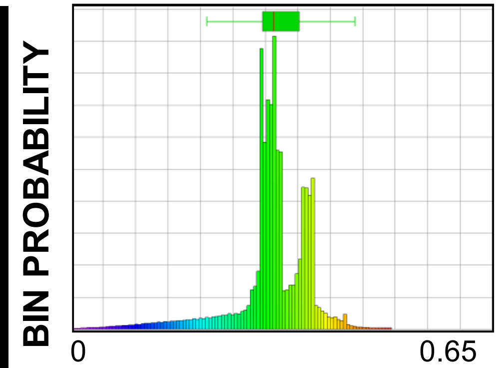


Verma, S., Roy, A., Perez, R., and Marfurt, Finding high frackability and high TOC zones in Barnet shale with supervised: Probabilistic Neural Network and unsupervised: multi-attribute Kohonen SOM, SEG Abstract, 2012.

BRITTLENESS INDEX SEISMIC VOLUME



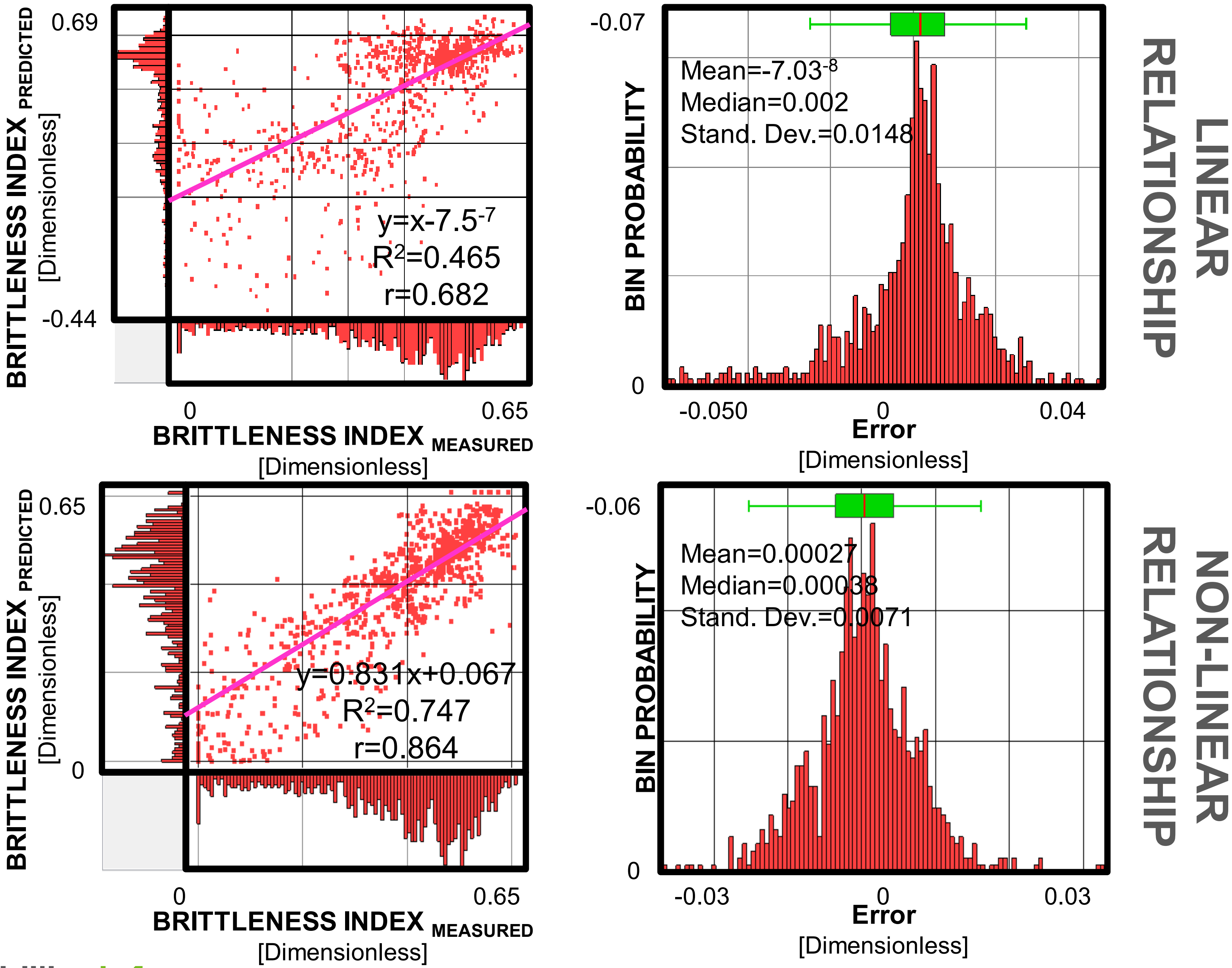
0 **BRITTLENESS INDEX** 0.65
[Dimensionless]



BRITTLENESS INDEX
[Dimensionless]

Num Points	1823034
Minimum	0.00
Maximum	0.494
Mean	0.310
Mean Absolute	0.310
Median	0.313
Std Deviation	0.0636
Skewness	-1.67
Kurtosis	4.67
25th %	0.296
75th %	0.353

SUMMARY



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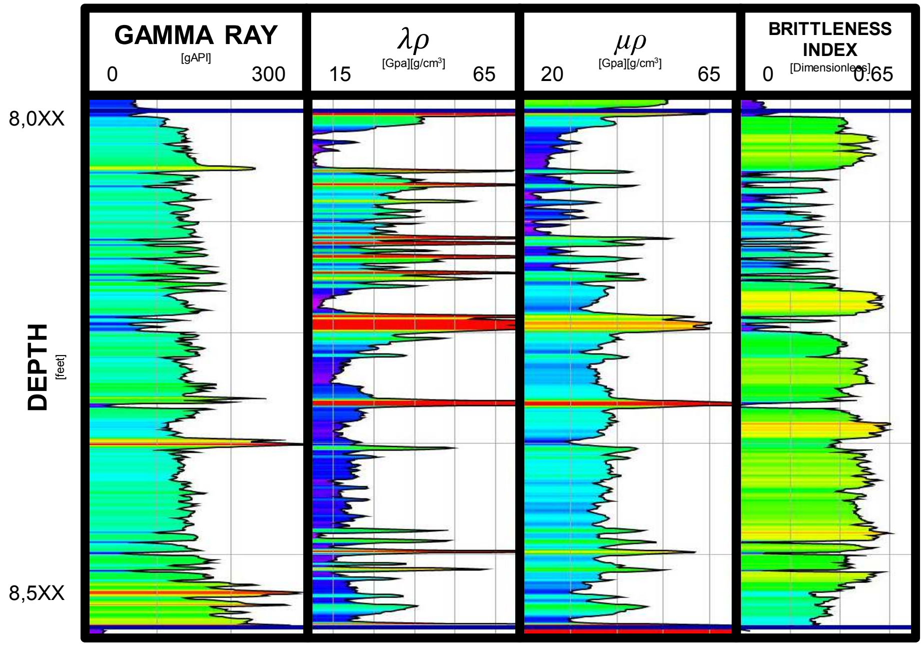
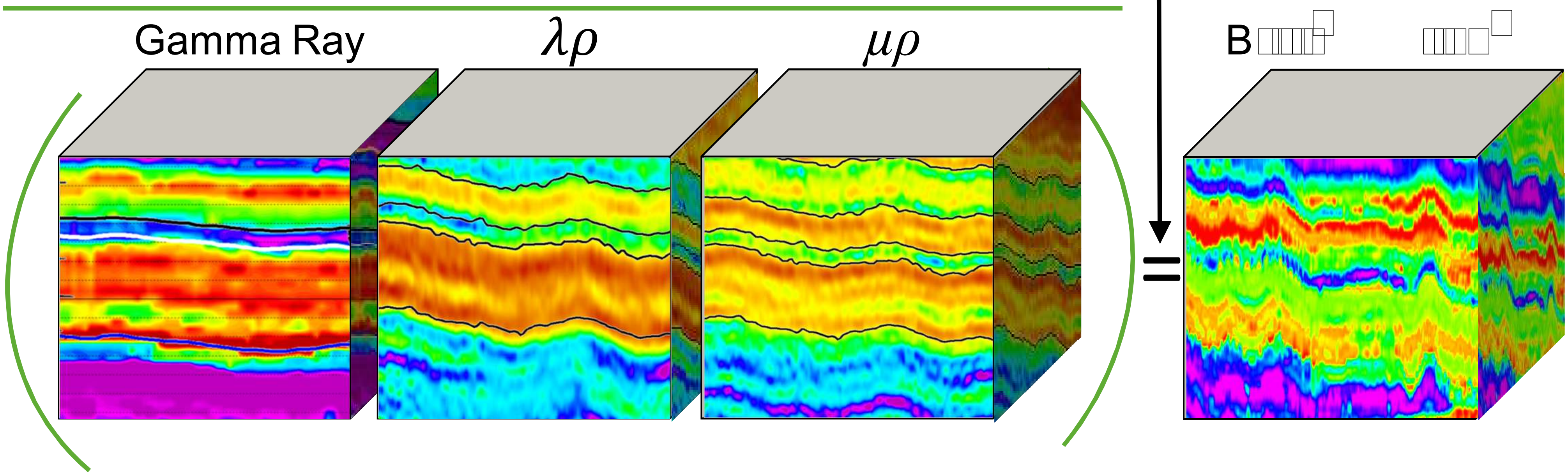
SUMMARY



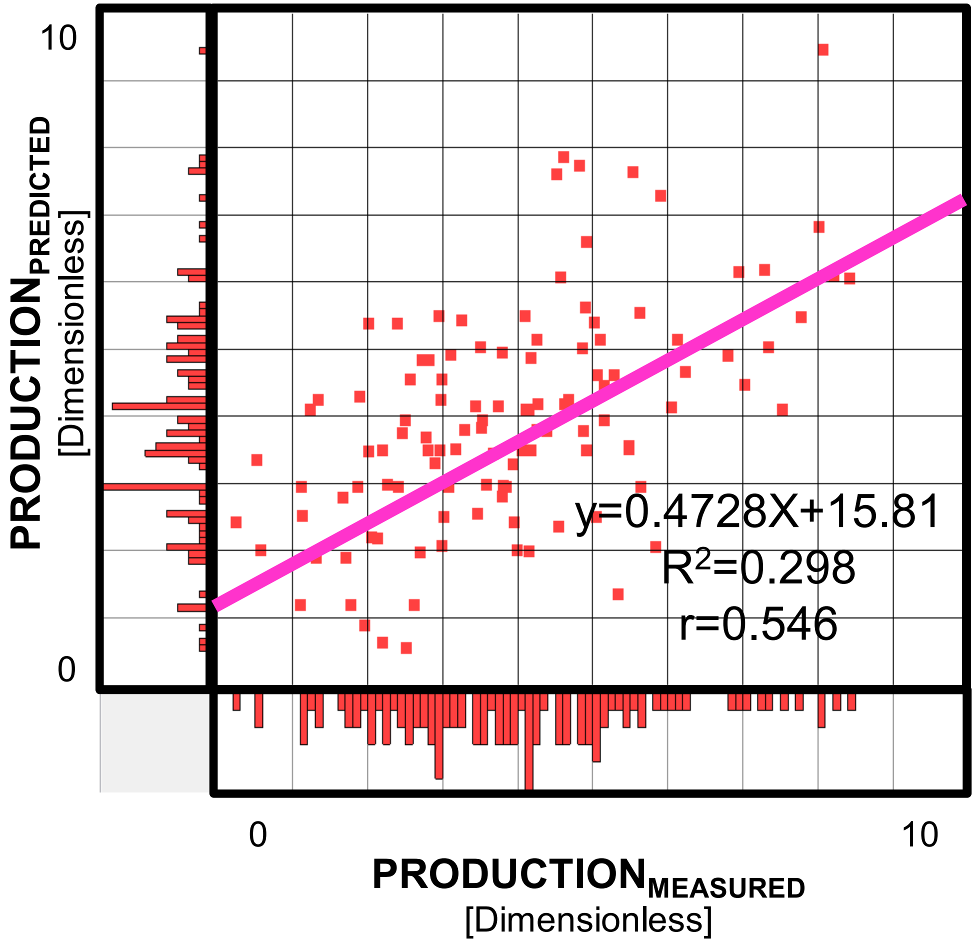
$$f_{BI}(\lambda\rho, \mu\rho, GR)$$

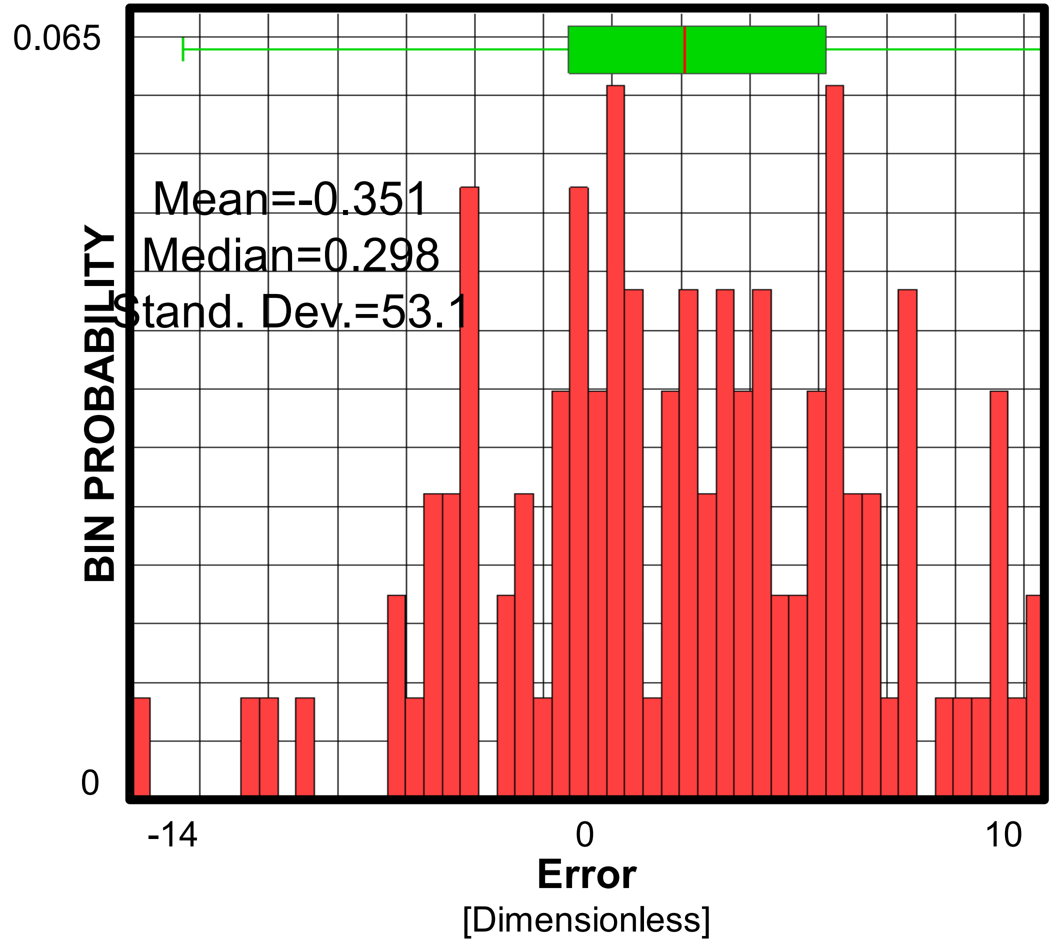


CORRELATION TO PRODUCTION

- **RESPONSE**: Relative EUR
- **VARIABLES**:

Engineering variables
  - Horizontal length
  - Azimuth
  - Number of stages
  - Total stage length





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CORRELATION TO PRODUCTION

- **RESPONSE:** Relative EUR
- **VARIABLES:**
  - Engineering variables
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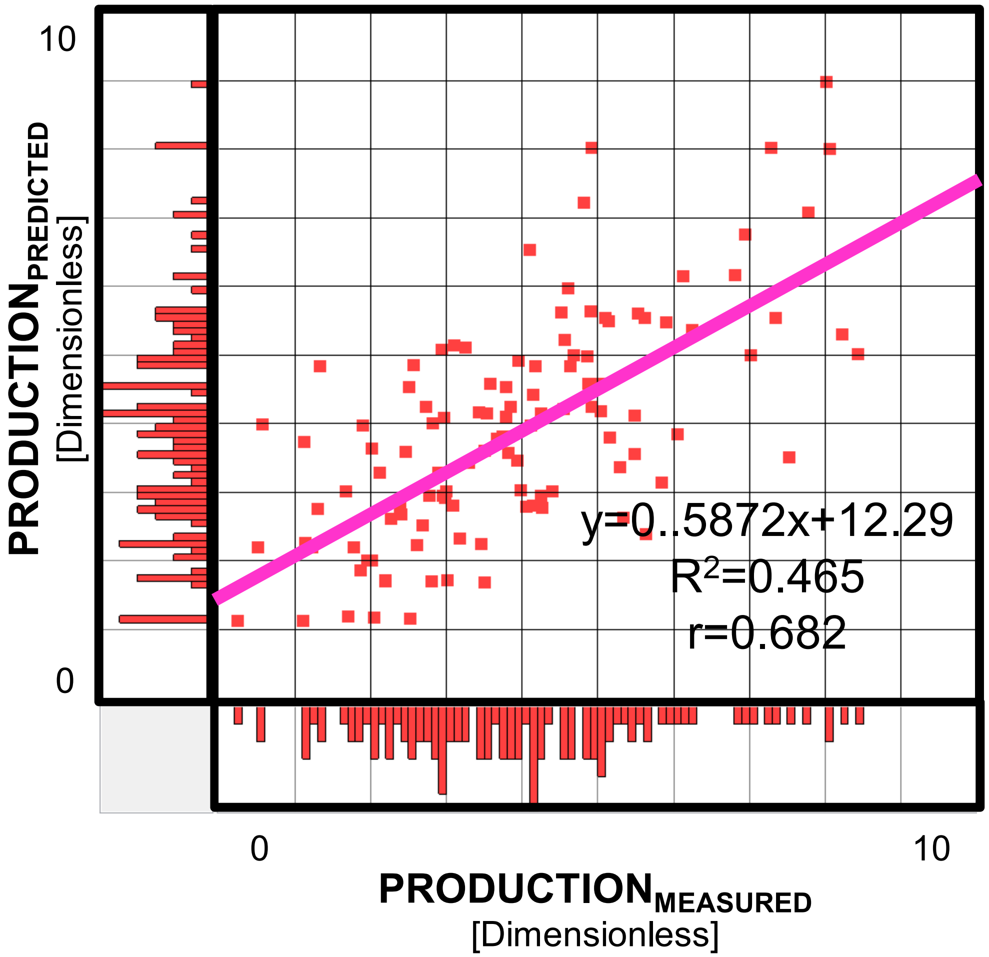
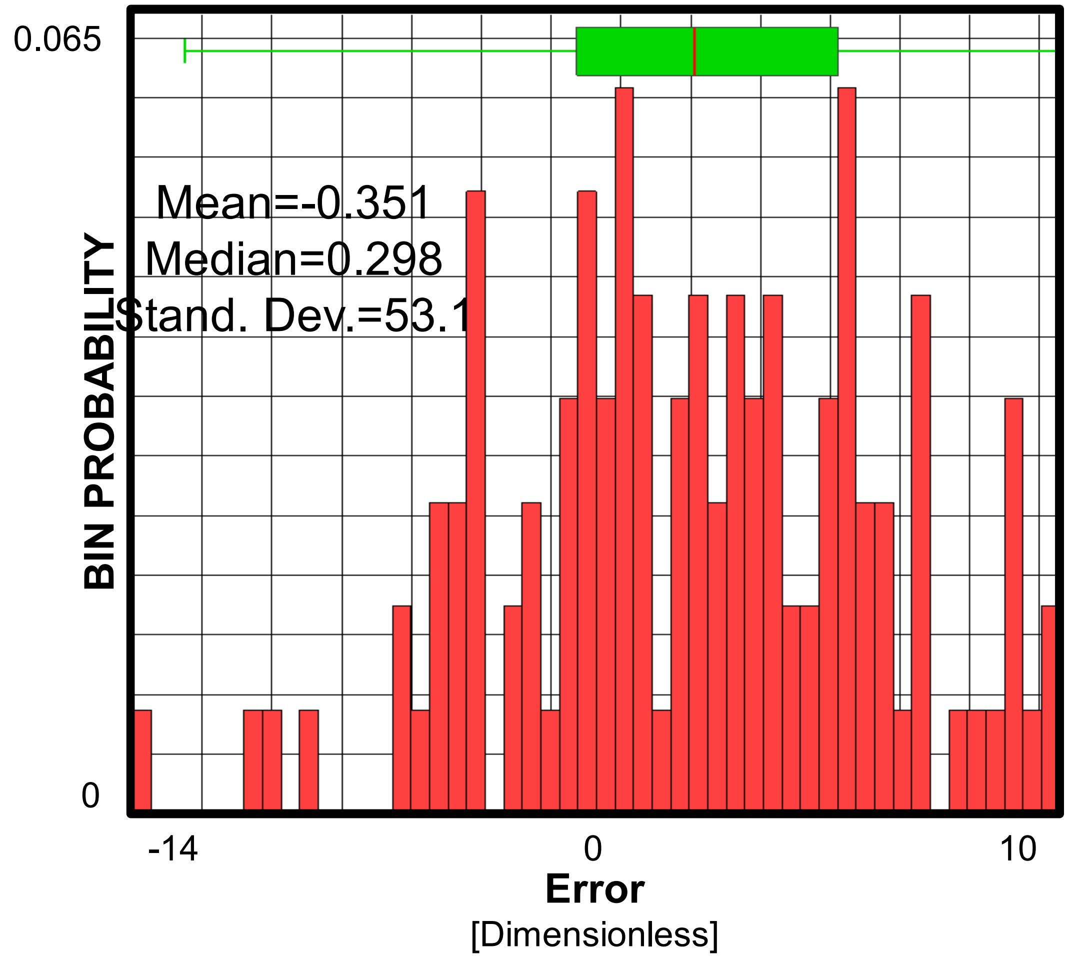
    - Azimuth
    - Number of stages
    - Total stage length
  - Geological variables
    - GR
    - LambdaRho
    - MuRho





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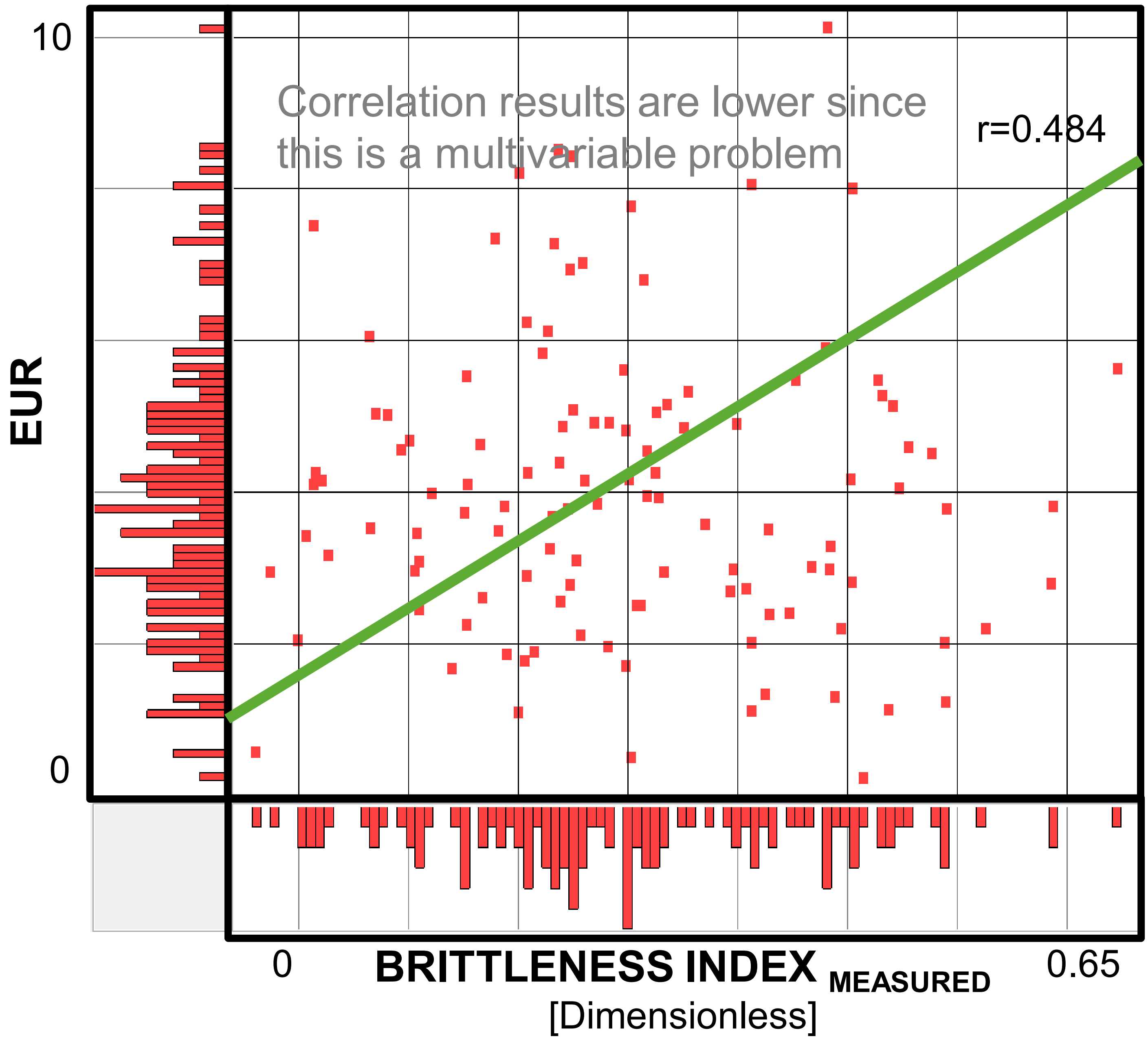
CORRELATION TO PRODUCTION



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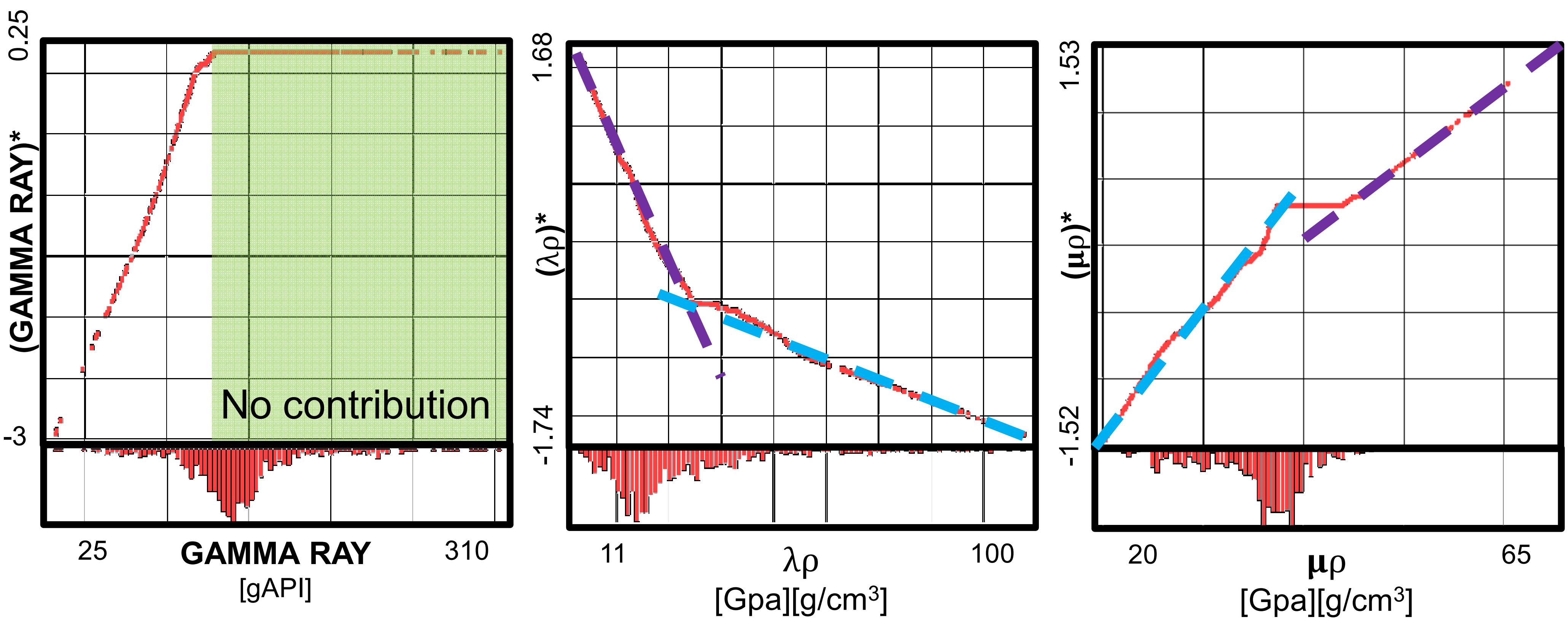
REFINING NON-LINEAR REGRESSION RESULTS
Facies Dependent Brittleness



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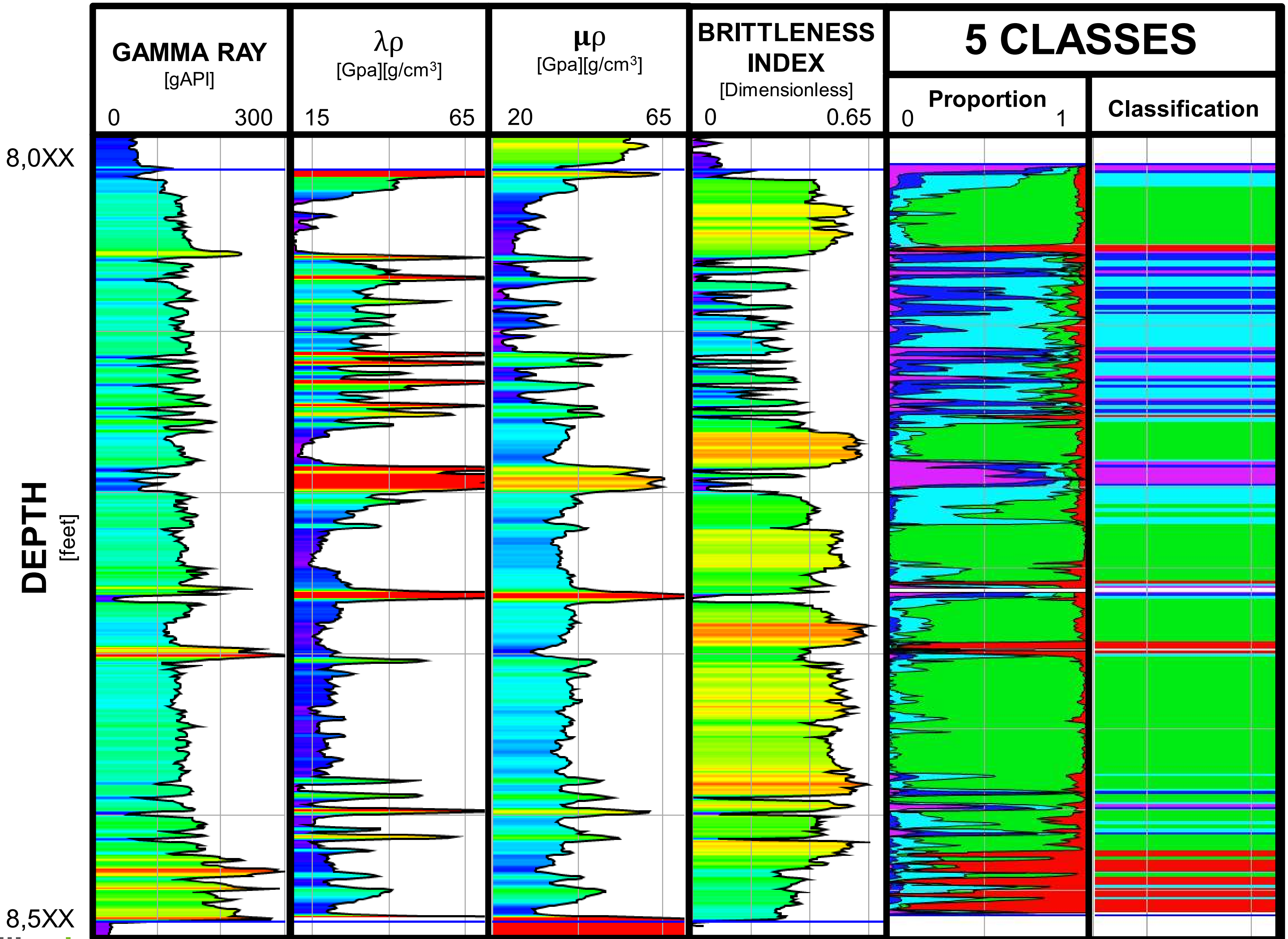
REFINING NON-LINEAR REGRESSION RESULTS



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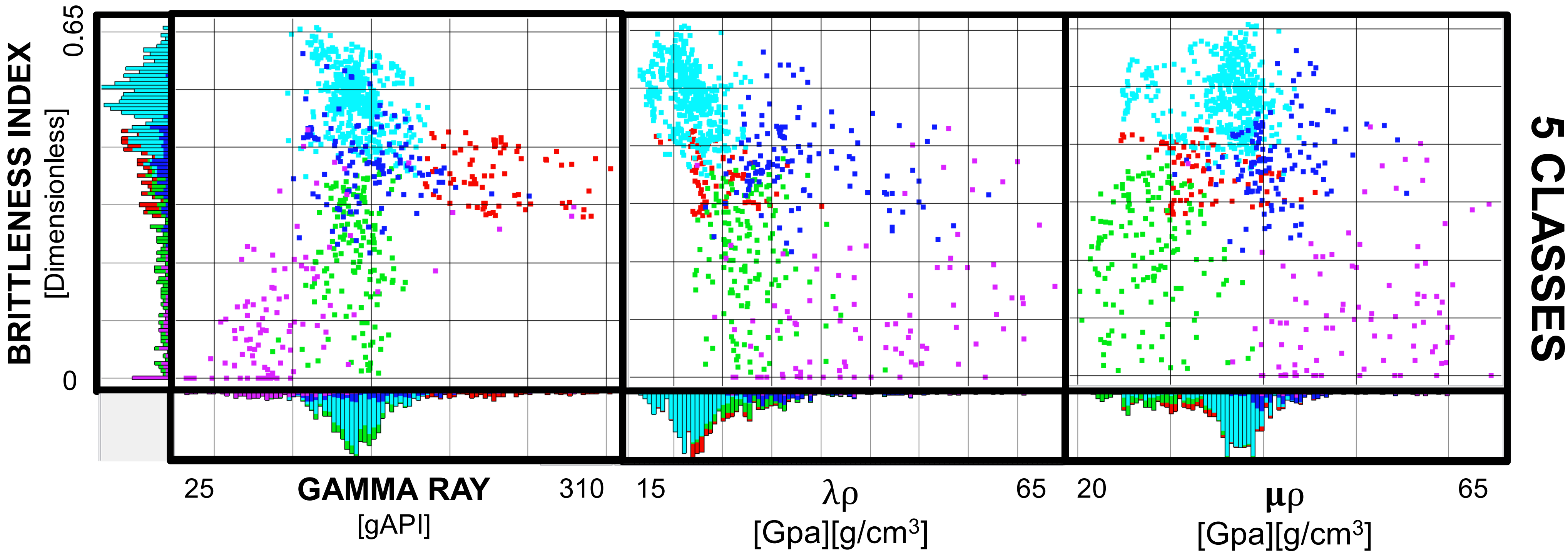
REFINING NON-LINEAR REGRESSION RESULTS

Facies Dependent Brittleness



INTRODUCTION

After removing possible outliers using a non-parametric approach based upon distribution smoothing and degree of rejection (alpha).

Variable	Sensitivity
GR	0.02
λρ	0.83
μρ	0.14
Total	100%

Retained	Sensitivity
1	0.402
2	0.427
3	0.682

Eigenvalue solution

	Eigenvalue	Variance	Cumulative
PCA1	1.836238	0.612079	0.612079
PCA2	0.78276	0.26092	0.873
PCA3	0.381001	0.127	1

Component Loading solution

Variable	PCA1	PCA2	PCA3
GR (Gam...	0.4682	0.864121	0.184616
Lambda_...	-0.604558	0.46564	-0.646289
Mu_Rho (...	-0.644437	0.190981	0.740424

Correlation matrix

Variable	PCA1	PCA2	PCA3
GR (Gamma R...	0.634447	0.76452	0.113955
Lambda_Rho (...	-0.819229	0.411972	-0.398927
Mu_Rho (Pres...	-0.873257	0.168967	0.457026

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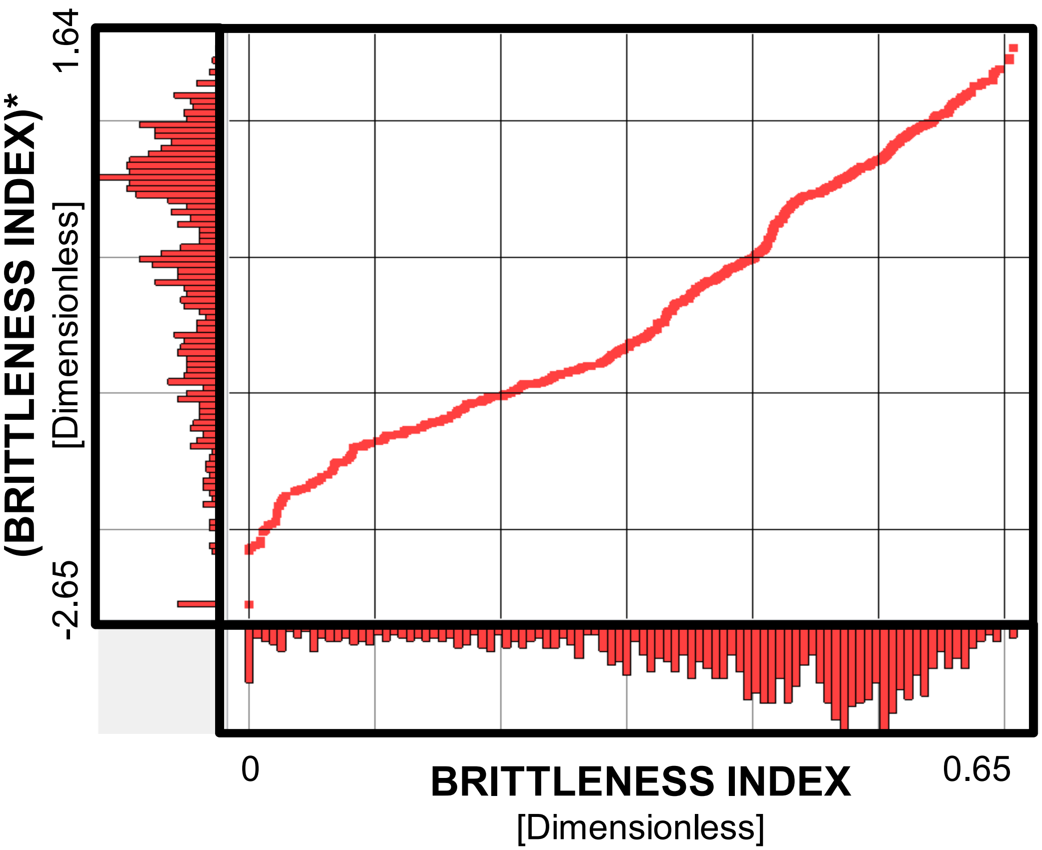
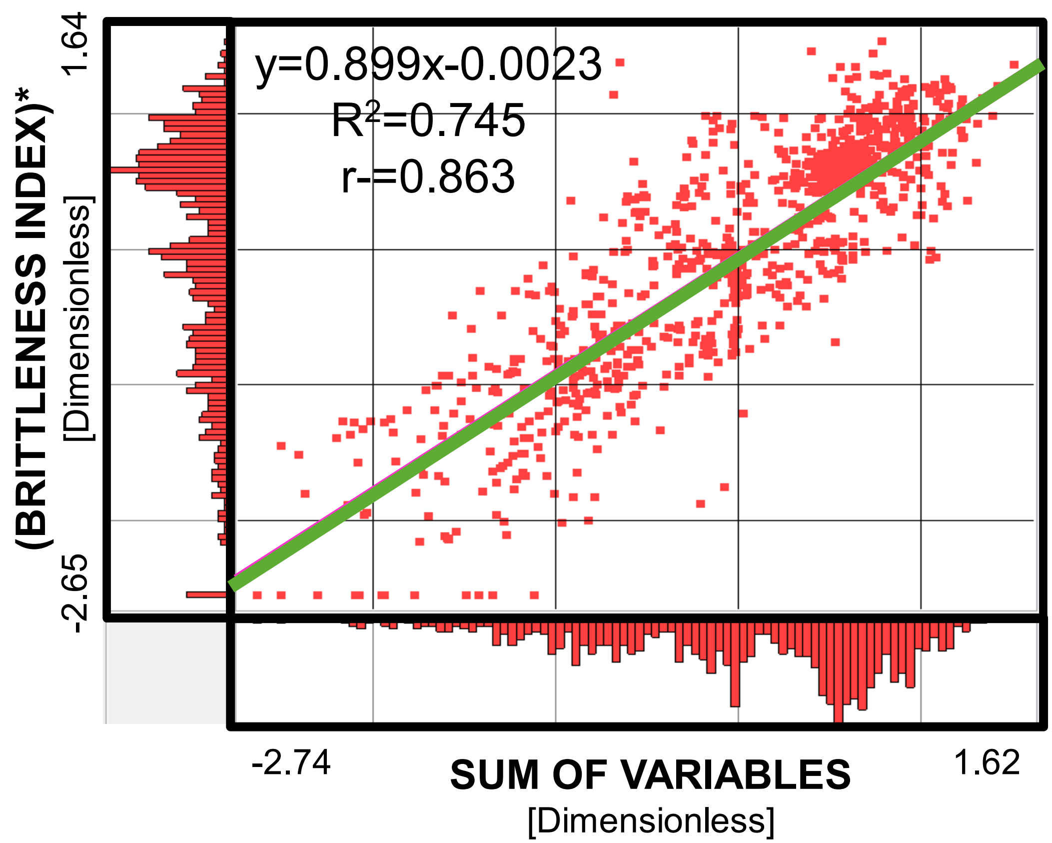
NON-LINEAR REGRESSION RESULTS





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CONCLUSIONS

- In order to generate a brittleness index seismic volume was necessary select a combination of geological and geomechanical seismic attributes
- Non-linear relationships shows better results than the linear methods to calibrate results with seismic data
- Refining BI results by facies definitions is necessary to correlated to geological results from core descriptions

ACKNOWLEDGEMENTS

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