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

Roderick Perez

Search and Discovery Article #80381 (2014)**

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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


SEISMIC BRITTLENESS INDEX VOLUME ESTIMATION FROM WELL LOGS IN UNCONVENTIONAL RESERVOIRS

Roderick Perez A., Ph.D.
Houston, TX / 2014
INTRODUCTION

CONVENTIONAL*

Source

Reservoir

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.

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.

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

*Average values corresponding to the Barnett Shale

*Geological

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OBJECTIVE

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.

Due to the low permeability, it is necessary to 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.

WOODFORD SHALE

Location: Ardmore, OK

Fracture set A — Speed limit 74
Fracture set B — Speed limit 66
Fracture set C — Speed limit 35

0 1 2 3 4 inches

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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

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.

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

$\sigma_c = \text{Compressive strength}$

$\sigma_t = \text{Tensile strength}$

Higher the magnitude of the BI, the more brittle the rock is.
BRITTLENESS INDEX FROM LOGS

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

- \( Qz \) = Quartz
- \( Ca \) = Calcite
- \( Cly \) = Clay
- \( Dol \) = Dolomite
- \( TOC \) = Total Organic Carbon

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BRITTLENESS INDEX FROM LOGS

<table>
<thead>
<tr>
<th>GAMMA RAY [gAPI]</th>
<th>$\lambda \rho$ [GPa][g/cm$^3$]</th>
<th>$\mu \rho$ [GPa][g/cm$^3$]</th>
<th>BRITTLENESS INDEX [Dimensionless]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15</td>
<td>20</td>
<td>0</td>
</tr>
<tr>
<td>300</td>
<td>65</td>
<td>65</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Brittleness Index:

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

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

\[ BI_{Jarvie(2007)} = \frac{Q_z}{Q_z + Ca + Cly} \]

\[ BI_{Wang(2009)} = \frac{Q_z + Dol}{Q_z + Dol + Ca + Cly + TOC} \]

- \( Q_z = \) Quartz
- \( Ca = \) Calcite
- \( Cly = \) Clay
- \( Dol = \) Dolomite
- \( TOC = \) Total Organic Carbon
# BRITTLENESS INDEX (Mineralogy)

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Increase in organic richness</th>
<th>Decrease in bottom water oxygen</th>
<th>Singh (2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ phosphatic deposit</td>
<td></td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Siliceous, non calcareous mudstone</td>
<td></td>
<td>4.5</td>
<td>10 - 15</td>
</tr>
<tr>
<td>Siliceous, calcareous mudstone</td>
<td></td>
<td>3.5</td>
<td>-</td>
</tr>
<tr>
<td>Calcareous laminae</td>
<td></td>
<td>3.5</td>
<td>-</td>
</tr>
<tr>
<td>Micritic / limy mudstone</td>
<td></td>
<td>1.2</td>
<td>10</td>
</tr>
<tr>
<td>Reworked shelly deposit</td>
<td></td>
<td>2.6</td>
<td>2 - 10</td>
</tr>
<tr>
<td>Silty shelly (wavy) interlaminated deposit</td>
<td></td>
<td>-</td>
<td>20</td>
</tr>
</tbody>
</table>
BRITTLENESS AVERAGE (Elastic parameters)

| Well A | GAMMA RAY | BRITTLENESS | DENSITY | P-WAVE Vel | S-WAVE Vel | LAMDA-RHO | MU-RHO | POISSON’S RATIO | YOUNG’S MODULUS | YOUNG’S Britteness | POISSON Britteness | BRITTLENESS AVERAGE | Cluster |
|--------|-----------|-------------|---------|------------|------------|------------|--------|----------------|------------------|------------------|-------------------|-------------------|---------------------|---------|
| 73XX   | 50        | 0.7         | 2.35     | 2.0        | 0           | 6.1        | 1.5    | 0.5            | 0.5              | 0.5              | 0.5               | 0.5               | Cluster             |         |
| 75XX   | 50        | 0.7         | 2.35     | 2.0        | 0           | 6.1        | 1.5    | 0.5            | 0.5              | 0.5              | 0.5               | 0.5               | Cluster             |         |
| 76XX   | 50        | 0.7         | 2.35     | 2.0        | 0           | 6.1        | 1.5    | 0.5            | 0.5              | 0.5              | 0.5               | 0.5               | Cluster             |         |
| 79XX   | 50        | 0.7         | 2.35     | 2.0        | 0           | 6.1        | 1.5    | 0.5            | 0.5              | 0.5              | 0.5               | 0.5               | Cluster             |         |
| 90XX   | 50        | 0.7         | 2.35     | 2.0        | 0           | 6.1        | 1.5    | 0.5            | 0.5              | 0.5              | 0.5               | 0.5               | Cluster             |         |
| 94XX   | 50        | 0.7         | 2.35     | 2.0        | 0           | 6.1        | 1.5    | 0.5            | 0.5              | 0.5              | 0.5               | 0.5               | Cluster             |         |

BRITTLENESS INDEX

\[ E_{brittleness} = \frac{E - E_{min}}{E_{max} - E_{min}}, \quad \nu_{brittleness} = \frac{\nu - \nu_{max}}{\nu_{min} - \nu_{max}}, \quad Brittness_{average} = \frac{(E_{brittleness} + \nu_{brittleness})}{2} \]
ROCK PHYSICS REVIEW

Young’s Modulus

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

S-wave Velocity

\[ V_s = \sqrt{\frac{\mu}{\rho}} \]

P-wave Velocity

\[ M = \lambda + 2\mu \]

P-wave Modulus

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

Young – Poisson Relation

\[ \frac{E}{1 + \nu} = 2\mu \]

\[ \nu = \frac{\lambda}{(2\lambda + 2\mu)} \]
CALIBRATION GEOLOGIC AND GEOMECHANICAL PARAMETERS

LINEAR vs. NON-LINEAR CORRELATION

**LINEAR**

- Variable: Wellbore horizontal distance
- Response: Production

**NON-LINEAR**

- Variable: Wellbore horizontal distance
- Response: Production

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LINEAR CORRELATION

**GEOLOGICAL**

- **Brittleness Index vs. Gamma Ray (gAPI)**
  - Equation: $y = 0.0008389x + 0.2557$
  - $R^2 = 0.0481$
  - $r = 0.208$

- **Brittleness Index vs. $\lambda \rho$ (GPa g/cm$^3$)**
  - Equation: $y = -0.006087x + 0.5744$
  - $R^2 = 0.365$
  - $r = -0.604$

- **Brittleness Index vs. $\mu \rho$ (GPa g/cm$^3$)**
  - Equation: $y = -0.002712x + 0.478$
  - $R^2 = 0.0182$
  - $r = -0.135$

**GEOMECHANICAL**

- **Brittleness vs. GR (Gamma Ray gAPI)**
  - Correlation coefficient:
    - Brittleness vs. GR: 1.0
    - GR vs. Brittleness: 0.208
    - Brittleness vs. Lambda_Rho: -0.604
    - Lambda_Rho vs. Brittleness: -0.343
    - Brittleness vs. Mu_Rho: -0.135
    - Mu_Rho vs. Brittleness: 1.0
    - GR vs. Lambda_Rho: 1.0
    - Lambda_Rho vs. GR: -0.259
    - GR vs. Mu_Rho: -0.015
    - Mu_Rho vs. GR: 1.0
    - Lambda_Rho vs. Mu_Rho: 1.0

- **Lambda_Rho (GPa) vs. Mu_Rho (g/cm$^3$)**
  - Correlation coefficient:
    - Lambda_Rho vs. Mu_Rho: 1.0
    - Mu_Rho vs. Lambda_Rho: -0.732
    - Lambda_Rho vs. GR: -0.142
    - GR vs. Lambda_Rho: 1.0
    - Lambda_Rho vs. Brittleness: -0.732
    - Brittleness vs. Lambda_Rho: -0.343
    - Mu_Rho vs. Brittleness: -0.036
    - Brittleness vs. Mu_Rho: 1.0

**Rank**

- Brittleness vs. GR (Gamma Ray gAPI)
- Lambda_Rho (GPa) vs. Mu_Rho (g/cm$^3$)
- Lambda_Rho (GPa) vs. GR (Gamma Ray gAPI)
- Mu_Rho (g/cm$^3$) vs. Brittleness
- Mu_Rho (g/cm$^3$) vs. Lambda_Rho (GPa)
- GR (Gamma Ray gAPI) vs. Brittleness
- GR (Gamma Ray gAPI) vs. Lambda_Rho (GPa)
- Brittleness vs. Mu_Rho (g/cm$^3$)
PRINCIPAL COMPONENT ANALYSIS

GAMMA RAY [gAPI]

R²=0.403
r=0.634

R²=0.584
r=0.735

R²=0.013
r=0.114

R²=0.671
r=-0.819

R²=1.070
r=-0.412

R²=0.159
r=-0.319

R²=0.763
r=-0.873

R²=0.029
r=0.169

R²=0.209
r=0.457
LINEAR REGRESSION RESULTS

**BRITTLENESS INDEX**

- Predicted: $0.69$, $-0.44$
- Measured: $0.69$, $-0.44$

**Equation:**

$y = x - 7.5^{-7}$  

**Statistics:**

- $R^2 = 0.465$
- $r = 0.682$
- Mean: $-7.03^{-8}$
- Median: $0.002$
- Standard Dev.: $0.0148$
NON-LINEAR REGRESSION RESULTS

- Plateaus at the end of transformations indicate no contributions.
- Plateaus in the middle of transformations indicate an incomplete model – additional variables needed.

NON-LINEAR REGRESSION RESULTS

**Brittleness Index**

- **Predicted (Dimensionless)**: 0.65

**Measured (Dimensionless)**: 0.65

**Equation**: $y = 0.831x + 0.067$

**$R^2$**: 0.747

**$r^2$**: 0.864

**Mean**: 0.00027

**Median**: 0.00038

**Standard Deviation**: 0.0071
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

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

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

Goodway (2007)
$\lambda \rho$ SLICE

Well A

5,XXX

Depth [ft]

7,XXX

GR

A

A'

SHALE

LIMESTONE

$\lambda \rho$

($(\text{GPa})^\ast (\text{g/cm}^3))$

111

Marble Falls Lm

Upper Barnett Sh

Forestburg Lm

Lower Barnett Sh

drillinginfo

better, faster decisions
μρ SEISMIC SLICE
GR SEISMIC VOLUME

![Graph showing GR (API) with correlation and error details]

BRITTLNESS INDEX SEISMIC VOLUME

The image shows a 3D visualization of a seismic volume with color coding representing the brittleness index. The index ranges from 0 to 0.65, with different colors indicating varying levels of brittleness. The probability distribution of the brittleness index is also shown in a histogram, indicating the frequency of occurrence at different index values.

Key statistical measures of the brittleness index include:
- 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

LINEAR RELATIONSHIP

Non-linear Relationship

\[
y = 0.831x + 0.067 \\
R^2 = 0.747 \\
r = 0.864
\]

\[
y = x - 7.5 \times 10^{-7} \\
R^2 = 0.465 \\
r = 0.682
\]

Mean = 7.03 x 10^{-8} 
Median = 0.002 
Stand. Dev. = 0.0148

Mean = -7.03 
Median = 0.002 
Stand. Dev. = 0.0071
SUMMARY

\[ f_{BI}(\lambda \rho, \mu \rho, GR) \]
CORRELATION TO PRODUCTION

**RESPONSE:** Relative EUR

**VARIABLES:**
- Horizontal length
- Azimuth
- Number of stages
- Total stage length

Engineering variables:

\[
y = 0.4728X + 15.81 \\
R^2 = 0.298 \\
r = 0.546
\]

- **Mean** = -0.351
- **Median** = 0.298
- **Stand. Dev.** = 53.1
CORRELATION TO PRODUCTION

RESPONSE: Relative EUR

VARIABLES:
- Horizontal length
- Azimuth
- Number of stages
- Total stage length
- GR
- LambdaRho
- MuRho

PRODUCTION PREDICTED

10

PRODUCTION MEASURED

[Dimensionless]

y = 0.5872x + 12.29

R^2 = 0.465

r = 0.682

Mean = -0.351

Median = 0.298

Stand. Dev. = 53.1

Error

[Dimensionless]

BIN PROBABILITY

0.065

Geological variables

Engineering variables
Correlation results are lower since this is a multivariable problem.

$r = 0.484$
REFINING NON-LINEAR REGRESSION RESULTS

Facies Dependent Brittleness

- No contribution

\[
\text{GAMMA RAY} = (\lambda \rho)^{0.25 - 3}
\]

\[
\text{GAMMA RAY} = [\text{gAPI}]
\]

\[
(\lambda \rho) = 1.68 - 1.74
\]

\[
(\lambda \rho) = [\text{Gpa}][\text{g/cm}^3]
\]

\[
(\mu \rho) = 1.53 - 1.52
\]

\[
(\mu \rho) = [\text{Gpa}][\text{g/cm}^3]
\]
# Refining Non-Linear Regression Results

## Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Values 1</th>
<th>Values 2</th>
<th>Values 3</th>
<th>Values 4</th>
<th>Values 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma Ray</td>
<td>gAPI</td>
<td>0</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>g/cm³</td>
<td>15</td>
<td>65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Viscosity</td>
<td>gPa g/cm³</td>
<td>20</td>
<td>65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Britteness Index</td>
<td>Dimensionless</td>
<td>0</td>
<td>0.65</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Depth

- 8.0XX
- 8.5XX

## Classification

<table>
<thead>
<tr>
<th>Proportion</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
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</tr>
<tr>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

![Graph showing data visualization](image-url)
REFINING NON-LINEAR REGRESSION RESULTS
Facies Dependent Brittleness

Brittleness Index

2 CLASSES
3 CLASSES
4 CLASSES
5 CLASSES

GAMMA RAY [gAPI]

\( \lambda \rho \) [Gpa][g/cm\(^3\)]

\( \mu \rho \) [Gpa][g/cm\(^3\)]
INTRODUCTION

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

<table>
<thead>
<tr>
<th>Variable</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR</td>
<td>0.02</td>
</tr>
<tr>
<td>$\lambda\rho$</td>
<td>0.83</td>
</tr>
<tr>
<td>$\mu\rho$</td>
<td>0.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Retained</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.402</td>
</tr>
<tr>
<td>2</td>
<td>0.427</td>
</tr>
<tr>
<td>3</td>
<td>0.682</td>
</tr>
</tbody>
</table>

Total 100%

**Eigenvalue solution**

<table>
<thead>
<tr>
<th>Eigenvalue</th>
<th>Variance</th>
<th>Cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCA1</td>
<td>1.836238</td>
<td>0.612079</td>
</tr>
<tr>
<td>PCA2</td>
<td>0.78276</td>
<td>0.26092</td>
</tr>
<tr>
<td>PCA3</td>
<td>0.381001</td>
<td>0.127</td>
</tr>
</tbody>
</table>

**Component Loading solution**

<table>
<thead>
<tr>
<th>Variable</th>
<th>PCA1</th>
<th>PCA2</th>
<th>PCA3</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR (Gamma Rho)</td>
<td>0.4682</td>
<td>0.864121</td>
<td>0.184616</td>
</tr>
<tr>
<td>Lambda_Rho</td>
<td>-0.604558</td>
<td>0.46564</td>
<td>-0.646289</td>
</tr>
<tr>
<td>Mu_Rho (Pres)</td>
<td>-0.644437</td>
<td>0.190981</td>
<td>0.740424</td>
</tr>
</tbody>
</table>

**Correlation matrix**

<table>
<thead>
<tr>
<th>Variable</th>
<th>PCA1</th>
<th>PCA2</th>
<th>PCA3</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR (Gamma Rho)</td>
<td>0.634447</td>
<td>0.76452</td>
<td>0.113955</td>
</tr>
<tr>
<td>Lambda_Rho</td>
<td>-0.819229</td>
<td>0.411972</td>
<td>-0.398927</td>
</tr>
<tr>
<td>Mu_Rho (Pres)</td>
<td>-0.873257</td>
<td>0.168967</td>
<td>0.457026</td>
</tr>
</tbody>
</table>
NON-LINEAR REGRESSION RESULTS

(NON-LINEAR REGRESSION RESULTS)

(BRITTLENESS INDEX)*

<table>
<thead>
<tr>
<th>BRITTLENESS INDEX</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Dimensionless]</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>0.65</td>
</tr>
</tbody>
</table>

(SUM OF VARIABLES)

<table>
<thead>
<tr>
<th>SUM OF VARIABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Dimensionless]</td>
</tr>
<tr>
<td>-2.74</td>
</tr>
<tr>
<td>1.62</td>
</tr>
</tbody>
</table>

y = 0.899x - 0.0023

R^2 = 0.745

r = 0.863
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

I would like to thank Devon Energy for providing the seismic and well data, and financial support to complete this project, along with DrillingInfo for providing software licenses of Transform Essential™, and production data. Additionally, we thank the industry sponsors of the Attribute Assisted Seismic Processing and Interpretation (AASPI) Consortium at the University of Oklahoma for their ongoing financial support.