Unconventional Multi-Variate Analysis: A Non-Linear Review of the Most Relevant Unconventional Plays in the U.S.*

Roderick Perez¹

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Abstract

Data is a powerful tool. It can be both overwhelming to the point of being ignored, and addictive, creating tendencies to overanalyze. In the fast-paced business world, successful leaders know the ability to make quick adjustments to workflows can make a huge difference to bottom lines. Data analysis is what identifies trends that seem to be working and that need to be changed.

It is no different in the oil and gas business, and many different industry specific software packages have been developed to try to handle the huge amounts of data that come in from daily operations. However, the key to success is in full scope integration of data from different fields of study. The use of the use multidisciplinary analytical methodologies has become a necessity in order to provide descriptive and predictive models to complement conventional geological, geophysical, and engineering analysis in unconventional resources plays.

The challenge is to unveil relationships and opportunities buried in mountains of geological, geophysical, and engineering data, collated at various scales: in depth as well as in time. This presentation will cover methodologies that can be used to integrate data collected in these various aspects, and review lessons learned from some of the most important unconventional shale plays in the U.S. such as: the Barnett Shale, Eagle Ford Shale, Haynesville Shale, and Utica Shale, in order to discover connections between the available input variables without explicit knowledge of the physical behaviors of the system.

References Cited


UNCONVENTIONAL MULTI-VARIATE ANALYSIS:

A non-linear review of the most relevant unconventional plays in the U.S.

Roderick Perez Altamar, Ph.D.

November, 5th, 2014
ANALYTICS
Analytics is the discovery of meaningful patterns in data.

“The amount of data gathered from production activity has also increased due to placement of downhome sensors that relay information to the operator on a real-time basis.”

The Big Challenges of Big Data for Oil, Gas by Karen Boman

From Murray Roth - An Analytic Approach to Sweetspot Mapping in the Eagle Ford Unconventional Play

(Unconventional) APPLICATION OF ANALYTICS

The data suggests that proximity to a natural gas well is correlated with lower housing prices.

Table 1: Distance to Well and Property Price per Square Foot

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 km threshold</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance to Well</td>
<td>0.014*</td>
<td>0.014*</td>
<td>0.014*</td>
<td>0.012</td>
</tr>
<tr>
<td></td>
<td>(0.008)</td>
<td>(0.008)</td>
<td>(0.008)</td>
<td>(0.009)</td>
</tr>
<tr>
<td>bedrooms</td>
<td>−0.092***</td>
<td>−0.091***</td>
<td>−0.091***</td>
<td>−0.108***</td>
</tr>
<tr>
<td></td>
<td>(0.014)</td>
<td>(0.015)</td>
<td>(0.013)</td>
<td>(0.012)</td>
</tr>
<tr>
<td>baths</td>
<td>0.185***</td>
<td>0.181***</td>
<td>0.180***</td>
<td>0.086***</td>
</tr>
<tr>
<td></td>
<td>(0.021)</td>
<td>(0.020)</td>
<td>(0.020)</td>
<td>(0.020)</td>
</tr>
<tr>
<td>age</td>
<td>−0.012***</td>
<td>−0.012***</td>
<td>−0.012***</td>
<td>−0.010***</td>
</tr>
<tr>
<td></td>
<td>(0.001)</td>
<td>(0.001)</td>
<td>(0.001)</td>
<td>(0.001)</td>
</tr>
<tr>
<td>Observations</td>
<td>29,207</td>
<td>29,207</td>
<td>29,207</td>
<td>29,207</td>
</tr>
<tr>
<td>Adjusted R²</td>
<td>0.230</td>
<td>0.231</td>
<td>0.257</td>
<td>0.357</td>
</tr>
</tbody>
</table>

|                  |       |       |       |       |
| 20 km threshold  |       |       |       |       |
| Distance to Well | 0.009**| 0.009**| 0.009**| 0.010**|
|                  | (0.004)| (0.004)| (0.004)| (0.005)|
| bedrooms         | −0.107***| −0.106***| −0.106***| −0.116***|
|                  | (0.015)| (0.015)| (0.015)| (0.013)|
| baths            | 0.146***| 0.143***| 0.142***| 0.085***|
|                  | (0.034)| (0.033)| (0.033)| (0.021)|
| age              | −0.012***| −0.012***| −0.012***| −0.009***|
|                  | (0.001)| (0.001)| (0.001)| (0.001)|
| Observations     | 44,423 | 44,423 | 44,423 | 44,423 |
| Adjusted R²      | 0.258  | 0.259  | 0.253  | 0.363  |

Fixed Effects: County, County x Year, County Tract & Year

Note: The dependent variable is the log of average price per square foot. Standard errors are clustered at the county level with stars indicating *** 0.01, ** 0.05, * 0.1.

http://freigeist.devmag.net/economics/808-fracking-and-house-prices-on-the-marcellus-shale.html
CLUSTERING ANALYSIS ALGORITHMS & TECHNIQUES

• Classification
  • Fuzzy Logic
  • Supervised
  • Unsupervised
    • K-means
    • SOM
  • Hierarchical
• Regression
  • Linear
    • Principal Component Analysis
  • Non-Linear
  • Neural Networks
LINEAR vs. NON-LINEAR CORRELATION

**LINEAR**

- Variable: Wellbore horizontal distance
- Response: Production

**NON-LINEAR**

- Variable: Wellbore horizontal distance
- Response: Production
ANN vs. Non-Linear Regressions

**ANN**

**Non-Linear Regression Modeling**

From Murray Roth - An Analytic Approach to Sweetspot Mapping in the Eagle Ford Unconventional Play

BRITTLENESS
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.
WHAT IS BRITTLENESS?

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.

\[
BI = \frac{\sigma_c}{\sigma_t}
\]

\(\sigma_c\) = Compressive strength
\(\sigma_t\) = Tensile strength

Higher the magnitude of the BI, the more brittle the rock is.
HOW DO TO QUANTIFY BRITTLENESS???

MINERALOGY

\[ B_{Jarvis}(2007) = \frac{Q_z}{Q_z + Ca + Cly} \]

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

BRITTLENESS

GEOLOGY

Geological properties

GEOMECHANICAL

Young's modulus & Poisson's ratio

ELASTIC PARAMETERS

Brittleness average

\[ E_{brittleness} = \frac{E - E_{min}}{E_{max} - E_{min}} \]

\[ \nu_{brittleness} = \frac{\nu - \nu_{max}}{\nu_{min} - \nu_{max}} \]

\[ Brittleness_{average} = \frac{(E_{brittleness} + \nu_{brittleness})}{2} \]
BARNETT SHALE
### BRITTLENESS INDEX (Mineralogy)

<table>
<thead>
<tr>
<th>LITHOFACIES</th>
<th>Average TOC (wt%)</th>
<th>Average silica (SiO$_2$) %</th>
</tr>
</thead>
<tbody>
<tr>
<td>In situ phosphatic deposit</td>
<td>6</td>
<td>10 - 15</td>
</tr>
<tr>
<td>Siliceous, non calcareous mudstone</td>
<td>4.5</td>
<td>30</td>
</tr>
<tr>
<td>Siliceous, calcareous mudstone</td>
<td>3.5</td>
<td>-</td>
</tr>
<tr>
<td>Calcareous laminae</td>
<td>3.5</td>
<td>-</td>
</tr>
<tr>
<td>Micritic / limy mudstone</td>
<td>1.2</td>
<td>10</td>
</tr>
<tr>
<td>Reworked shelly deposit</td>
<td>2.6</td>
<td>2 - 10</td>
</tr>
<tr>
<td>Silty shelly (wavy) interlaminated deposit</td>
<td>-</td>
<td>20</td>
</tr>
</tbody>
</table>

**Increase in organic richness**

**Decrease in bottom water oxygen**

**Singh (2008)**

![Graph](https://via.placeholder.com/150)

**Legend:**
- **High TOC**
- **Ductile**
- **Less ductile**
- **Less brittle**
- **High Brittle**
BRITTLENESS AVERAGE (Elastic parameters)

\[ E_{\text{brittleness}} = \frac{E - E_{\text{min}}}{E_{\text{max}} - E_{\text{min}}}, \quad \nu_{\text{brittleness}} = \frac{\nu - \nu_{\text{max}}}{\nu_{\text{min}} - \nu_{\text{max}}}, \quad \text{Brittleness}_{\text{average}} = \frac{E_{\text{brittleness}} + \nu_{\text{brittleness}}}{2} \]
CALIBRATION GEOLOGIC AND GEOMECHANICAL PARAMETERS

• Perez, R. and K. Marfurt, 2014, Mineralogy-Based Brittleness Prediction from Surface Seismic Data: Application to the Barnett Shale (Manuscript ID: INT-2013-0161)
CALIBRATION OF BRITTLENESS TO ELASTIC ROCK PROPERTIES VIA MINERALOGY LOGS
CALIBRATION GEOLOGIC AND GEOMECHANICAL PARAMETERS

Microseismic

BRITTleness INDEX

Upper and Lower Barnett Shale
UNCONVENTIONAL MULTI-VARIATE ANALYSIS – Roderick Perez A., Ph.D.

CALIBRATION GEOLOGIC AND GEOMECHANICAL PARAMETERS

STAGE 1

STAGE 2

BOTH STAGES

Well C

Depth (ft)

Ductile Zone

Frequency

0 100

BI classification

Upper Barnett Sh

Forestburg Lm

Lower Barnett Sh

(a)

(b)

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STATISTICAL ANALYSIS
Brittleness Index:

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

Brittleness Index:

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

GEOLOGICAL

\[ y = 0.0008389x + 0.2557 \]
\[ R^2 = 0.0481 \]
\[ r = 0.208 \]

GEOMECHANICAL

\[ y = -0.006087x + 0.5744 \]
\[ R^2 = 0.365 \]
\[ r = -0.604 \]

\[ y = -0.002712x + 0.478 \]
\[ R^2 = 0.0182 \]
\[ r = -0.135 \]

<table>
<thead>
<tr>
<th>Britteness</th>
<th>GR (Gamma Ray)</th>
<th>Lambda</th>
<th>Mu_Rho</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brittleness</td>
<td>1.0</td>
<td>-0.604</td>
<td>-0.135</td>
</tr>
<tr>
<td>GR (Gamma Ray)</td>
<td>0.208</td>
<td>1.0</td>
<td>-0.259</td>
</tr>
<tr>
<td>Lambda_Rho</td>
<td>-0.604</td>
<td>-0.259</td>
<td>1.0</td>
</tr>
<tr>
<td>Mu_Rho (P)</td>
<td>-0.135</td>
<td>-0.343</td>
<td>0.603</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Britteness</th>
<th>GR (Gamma Ray)</th>
<th>Lambda</th>
<th>Mu_Rho</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brittleness</td>
<td>1.0</td>
<td>0.015</td>
<td>-0.732</td>
</tr>
<tr>
<td>GR (Gamma Ray)</td>
<td>0.015</td>
<td>1.0</td>
<td>-0.142</td>
</tr>
<tr>
<td>Lambda_Rho</td>
<td>-0.732</td>
<td>-0.142</td>
<td>1.0</td>
</tr>
<tr>
<td>Mu_Rho (P)</td>
<td>-0.036</td>
<td>-0.34</td>
<td>0.419</td>
</tr>
</tbody>
</table>
PRINCIPAL COMPONENT ANALYSIS

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=0.159
r=-0.319

R2=0.763
r=-0.873

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LINEAR REGRESSION RESULTS

- BRITTLENESS INDEX PREDICTED
  - Dimensionless
  - y = x - 7.5^-7
  - R^2 = 0.465
  - r = 0.682

- BRITTLENESS INDEX MEASURED
  - Dimensionless
  - Error
  - Mean = -7.03^-8
  - Median = 0.002
  - Stand. 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]

MEASURED
[Dimensionless]

y = 0.831x + 0.067
R² = 0.747
r = 0.864

Mean = 0.00027
Median = 0.00038
Stand. Dev. = 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)
SEISMIC ATTRIBUTES

Well A

A

A'

GR

5,XXX

7,XXX

Depth [ft]

SHALE

LIMESTONE

λρ

((GPa)∗(g/cm³))

111

13

Marble Falls Lm

Upper Barnett Sh

Forestburg Lm

Lower Barnett Sh
SEISMIC ATTRIBUTES

Well A

A

A'

5,XXX

7,XXX

Depth [ft]

GR

μρ

((GPa)*(g/cm³))

0 145

0 3.25

SHALE

LIMESTONE

Marble Falls Lm

Upper Barnett Sh

Forestburg Lm

Lower Barnett Sh

μρ

((GPa)*(g/cm³))

100 15

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SEISMIC ATTRIBUTES – 2D colorbar visualization

(a) Well B

(b) Well B

(c) Well B

(d) 2D colorbar and 2D histogram

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UNCONVENTIONAL MULTI-VARIATE ANALYSIS – Roderick Perez A., Ph.D.

SEISMIC ATTRIBUTES – 2D colorbar visualization
Microseismic events trend towards quartz rich areas, avoiding clay rich zones (green).
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).
NON-LINEAR REGRESSION ANALYSIS
WORKFLOW SUMMARY

\[ f_{BI}(\lambda \rho, \mu \rho, GR) \]
GR SEISMIC VOLUME

BRITTleness INDEX VOLUME

BRITTleness INDEX

[Dimensionless]

LOW

HIGH

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
BRITTLENESS INDEX VOLUME + ENGINEERING VARIABLES

Plot 2: Data Correlations (44)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.297</td>
<td>-0.7</td>
<td>-0.001</td>
<td>-0.02</td>
</tr>
<tr>
<td>0.297</td>
<td>1.0</td>
<td>0.394</td>
<td>0.281</td>
<td>-0.389</td>
</tr>
<tr>
<td>-0.7</td>
<td>0.394</td>
<td>1.0</td>
<td>0.145</td>
<td>-0.207</td>
</tr>
<tr>
<td>-0.001</td>
<td>0.281</td>
<td>0.145</td>
<td>1.0</td>
<td>0.06</td>
</tr>
<tr>
<td>-0.02</td>
<td>-0.389</td>
<td>-0.207</td>
<td>0.06</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Plot 3: Samples in plot: 105

Brittleness Index

Plot 4: Samples in plot: 105

Stage number

Plot 5: Samples in plot: 105

Stage length

Plot 6: Samples in plot: 105

EUR
BRITTLENESS INDEX VOLUME + ENGINEERING VARIABLES

Engineering variables

Engineering variables + BI
BRITTLENESS INDEX VOLUME + ENGINEERING VARIABLES

UNCONVENTIONAL MULTI-VARIATE ANALYSIS – Roderick Perez A., Ph.D.
AZIMUTHAL VOLUMES
ANISOTROPY DIRECTION & INTENSITY + BI
EAGLEFORD
EF OIL/GAS/CONDENSATE PRODUCTION

From Murray Roth
EF DRILLING AND COMPLETION DATA

From Murray Roth
EF DRILLING AND COMPLETION DATA

From Murray Roth

Engineering variables

G&G variables
SWEEPSPOT MAP
SUMMARY
WORKFLOW SUMMARY

\[ f_{BI}(\lambda \rho, \mu \rho, GR) \]
ANALYTIC WORKFLOW

1) Multi-Variate Statistical Analysis
   - Assign Properties To Wellbore Zones
   - Correlation of Engineering Parameters with Production, Correcting for Spatial Geo Data Effects

2) Engineering “Best Practices”

3) Prospectivity Maps
   - Correlation of Geo Data with Production, Correcting for Variability in Engineering Parameters

From Murray Roth - An Analytic Approach to Sweetspot Mapping in the Eagle Ford Unconventional Play
THANK YOU

Questions & Open Discussion
PRODUCTION HISTORY
Barnett Shale
PRODUCTION HISTORY

EagleFord
PRODUCTION HISTORY
Marcellus

(Color by:
operator
- ABARTA OIL & GAS, I
- ALLIANCE PETROLEUM
- ALPHA SHALE RES L
- AMER OIL & GAS LL
- AMERICAN ENERGY
- ANADARKO
- ANTERO RESOURCES
- BAKER GAS INC
- BARRA A & FRED
- BASE PETROLEUM, I
- BECK ENERGY COR
- BLACKROCK ENTER
- BLX INC
- BRAXTON OIL & GAS
- BUCKEYE OIL PROD
- BURNETT OIL COMP
- CABOT OIL & GAS C
- CAD ENERGY CORP
- CARL FRANCIS E
- CAMPBELL OIL & GA
- CARRIZO
- CHESAPEAKE
- CHEVRON
- CHEIF OIL & GAS LL
- CHRISS GLADE OIL &
- CITRUS ENERGY CO...
PRODUCTION HISTORY

Woodford
PRODUCTION SCENARIO ANALYSIS
PRODUCTION SCENARIO ANALYSIS

Workflow

1. Type Curve Inputs
2. Production Scenario
3. Well Economics Scenario
4. Publish & Analyze Cases
PRODUCTION SCENARIO ANALYSIS

Barnett Shale

Peak Monthly Rate Gas (Mcf)

Type Curve Variable | Average | Median | Well Count
--- | --- | --- | ---
Peak Rate Oil (Bbl/day) | 18 | 0 | 19,534
Peak Rate Gas (Mcf/day) | 1,551 | 1,256 | 10,534
b-Factor | 1.28 | 1.21 | 6,294
Effective Annual Secant Decline (Desi) (%) | 60% | 61% | 6,294
PRODUCTION SCENARIO ANALYSIS
Barnett Shale

<table>
<thead>
<tr>
<th>Type Curve Variable</th>
<th>Average</th>
<th>Median</th>
<th>Well Count</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Rate Oil (Bbl / Day)</td>
<td>18</td>
<td>0</td>
<td>19,534</td>
<td>0</td>
</tr>
<tr>
<td>Peak Rate Gas (Mcf / Day)</td>
<td>1,551</td>
<td>1,256</td>
<td>19,534</td>
<td>1,256</td>
</tr>
<tr>
<td>β-Factor</td>
<td>1.28</td>
<td>1.21</td>
<td>6,294</td>
<td>1.21</td>
</tr>
<tr>
<td>Effective Annual Secant Decline (Desi) (%)</td>
<td>60 %</td>
<td>61 %</td>
<td>6,294</td>
<td>60 %</td>
</tr>
</tbody>
</table>