From Reservoir Characterization, 3D Seismic multi-attribute analysis and machine learning classification to Well Performance Simulation: A Woodford Shale Case Study in North of Oklahoma, USA

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Collaboration

Institute of Reservoir Characterization, OU

Attribute Assisted Seismic Processing and Interpretation (AASPI), OU
Presentation Outline

1. Introduction
2. Integration Workflow
3. Geo-cellular model
4. 3D seismic classification (SOM, GTM, K-means)
5. 3D unconventional reservoir properties modeling
6. Type Curve classification
7. Simulation
8. Conclusions
The value of integration

Stratigraphy: Outcrop to Subsurface

Rock Mechanics (fractures)

Organic Matter Content

Geophysics

Sweet Spot Detection

Landing Zones

Fluid Flow

(Institute of Reservoir Characterization, 2018)
STUDY AREA

- Location Map of the principal geologic and production provinces in Oklahoma (Northcutt et al., 2001).
What do why mean by top Woodford shale sweet spots?

- Stratigraphic chart for the Arkoma Basin, southeastern Oklahoma (Perry, 1995 in Portas, 2009).
IRC Depositional Models from North to South through Woodford shale sea level cycles

- The early stage of falling sea level may result in water mass isolation and restricted water circulation over topographic depressions left by karst/incised valley development on the underlying carbonate platform.

Modified from Slatt, 2016
The areas where the Woodford thickens correspond to the areas where the Hunton thins = Cana Field

There is an inverse relation between thickness of the Hunton unconformity and the overlying Woodford Shale.

Craig D. Caldwell, 2013. Cana Woodford Shale Play, Anadarko Basin: The Effects of Mudrock Lithologies and Mechanical Stratigraphy on Completion and Production. OGS Oklahoma shale gas and oil workshop 2013
Important of Woodford shale Depositional Fairways
For rock mechanics

**Biogenic sediments**

- Reservoir rock (radiolaria)
- Clays, detrital quartz, TOC
- Turbidity flow surges into the sea from a river mouth

**Detrital sediments**

- Brittle layer
- Higher Brittleness layer

Galvis, 2017
Becerra, 2017
Ghosh, 2017

Slatt and Torres, OCGS April 2018 luncheon
Woodford shale rock mechanics

Brittle (reservoir)-Ductile (organic rich source rock) couplets seen in outcrops ('Brittle-ductile couplets' after Slatt and Abousleiman, 2011)
Proposed Geo-cellular Modeling Workflow

- Post-stack seismic and velocity volumes
- Core and Log data for stratigraphic and reservoir properties characterization: DT, RHOB, GR, Res, Vp and Vs. UCS, E and v
- Well Tops and stratigraphic maps
- TOC, rock Eval pyrolysis and biomarkers
- Density, porosity and saturation measurements

Extract seismic statistical wavelet
- Create synthetics seismograms
- Seismic phase rotation and Well Ties

- Interpret main horizons and faults
- Seismic attributes
- Seismic Analysis
- Coherence K1 and K2 principal curvatures
- Model based post-stack inversion
- Identification of possible fracture zones as geohazards
- Build low frequency background model
- Inversion analysis
- Generate post-stack inversion

Unsupervised machine learning
- P-Impedance Volume
- Self Organizing Maps (SOM)
- Zp, seismic trace dip azm, RMS amp., Curvature
- Vertical upscaling and lateral property propagation

Collocated co-kriging for guiding reservoir modeling sequential gaussian simulation

- 3D structural framework
- Time – depth conversion
- 3D structural framework

Identify possible fracture zones as geohazards

Generate structural maps

Model based post-stack inversion

Build low frequency background model

Inversion analysis

Generate post-stack inversion

Unsupervised machine learning
Seismic Interpretation and Well Control

Total 21 wells available with sonic and density logs
WDFD Time structure map (ms)
Pre-WDFD Time thickness

S-A'
S-A
S-B
S-C
S-D
S-E
S-F
Low frequency Background model using multilinear regression of single well models and instantaneous frequency and phase attributes.
Machine learning Classification Methods

Let’s get some seismic facies in my shale reservoir!

➢ K-means
➢ Self Organizing Maps (SOM)
➢ Generative Topographic Mapping (GTM)
➢ Support Vector Machine (SVM)
➢ Gaussian Mixture Models (GMM)
➢ Artificial Neural Networks (ANN)

(Meldahl et al., 2011; Roy and Marfurt, 2013; Snyder, 2016; Zhao et al., 2016; Qi et al., 2016; Infante-Paez, 2018)
Let’s get some seismic facies in my shale reservoir!

When is a coffee mug a donut? Topology explains it

- K-means
- Self Organizing Maps (SOM)
- Generative Topographic Mapping (GTM)
- Support Vector Machine (SVM)
- Gaussian Mixture Models (GMM)
- Artificial Neural Networks (ANN)


(Meldahl et al., 2011; Roy and Marfurt, 2013; Snyder, 2016; Zhao et al., 2016; Qi et al., 2016; Infante-Paez, 2018)
Petrophysical properties upscaling and variogram distribution for lateral interpolations based on collocated co-kriging

Inverted P-impedance: interpolated

Self Organizing Map (SOM)
Geomechanical Properties from Well Logs

**Young’s Modulus**
\[ E = \frac{\rho V_s^2 (3V_p^2 - 4V_s^2)}{(V_p^2 - V_s^2)} \]

**Poisson’s Ratio**
\[ v = \frac{(V_p^2 - 2V_s^2)}{2(V_p^2 - V_s^2)} \]

**Bulk Modulus**
\[ K = \rho V_p^2 - \frac{4}{3} \rho V_s^2 \]

**Shear Modulus**
\[ G = \rho V_s^2 \]

**Fracture Toughness**
\[ K_{ic} = 0.05E \]

**Horizontal Stress**
\[ S_h = \left( \frac{v}{1-v} \right) S_v + \left( \frac{1-2v}{1-v} \right) \alpha \rho \]

**Fracture Gradient**
\[ FG = \frac{S_h + T_o}{Depth(m)} \]
Geomechanical Properties from Well Logs
Reservoir modeling guided with seismic rock properties

Fracture Toughness

Shear Modulus

Young’s Modulus

Poisson’s Ratio
Calculation of TOC

- Passey’s Vs. Schmocker ???

*Passey’s (1990)*

\[
\Delta \log R = \log_{10} \left( \frac{R}{R_{\text{baseline}}} \right) + 0.02 \times (\Delta t - \Delta t_{\text{baseline}})
\]

\[
\text{TOC} = (\Delta \log R) \times 10^{(2.97 - 0.1688 \times \text{LOM})}
\]

*Applied Schmocker's – calibrated with core and cuttings TOC%*

\[
\text{TOC [wt\%]} = \left[ (-56.547 \times \text{RHOB}) + 154.867 \right] / 2
\]
Calculation of TOC with well logs
TOC Calculation – Average in zone of interest
Reservoir model

Vertical Exaggeration: 10
Reservoir simulation – area selection

Inverted P-impedance: interpolated

Self Organizing Map (SOM)
The value of integration

- Stratigraphy: Outcrop to Subsurface
- Organic Matter Content
- Geomechanics (fractures)
- Sweet Spot Detection
- Landing Zones
- Fluid Flow
- Geophysics
Identify areas with:

- High Thickness
- Low FG (brittle)
- High TOC
- High impedance

GRP-5 mainly hard beds.
GRP-4 Mainly Soft beds.
**Coupled Simulation**

*Geomechanical Coupling (Fully coupled, two way)*

- **Fluid Model**
  - Rich Condensate
  - Seven Lumped components
  - Same for all TC areas
  - Primary aim is to see geology variations

Conceptual implementation of Barton – Bandis model (after Tran et al., 2009).
Coupled Simulation: Geomechanical properties + fluid flow

Well bottom-hole pressure for the injection.

Gas rate, BHP and cumulative gas for Area 1 well

Gas oil ratio for area 1 well

- 5,200 ft lateral length
- Fracture stage every 220 ft.
- 250,000 gallons slick water
- Dew point 4,200 PSI
- 0.65 specific gravity
- 55 API Gravity
### EUR Summary

#### Simulation Results

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<tr>
<th>Area</th>
<th>TC Well EUR (MBOE)</th>
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<tbody>
<tr>
<td>1</td>
<td>1802</td>
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<tr>
<td>4</td>
<td>729</td>
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#### Operator xxx Results

<table>
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<th>TC Well EUR (MBOE)</th>
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<tbody>
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<tr>
<td>3</td>
<td>1385</td>
</tr>
<tr>
<td>4</td>
<td>509</td>
</tr>
</tbody>
</table>

**Inverted P-impedance: interpolated**

**Self Organizing Map (SOM)**
Conclusions

➢ Our study identifies geological sweet spots and type curves in the Woodford shale (TOC, geomechanical parameters)

➢ Study shows using best of all available dataset can enormously increase the resolution and confidence on static model

➢ Results show multi-attribute analysis provide a promising alternative way of deriving the type curves

➢ Geomechanical simulation provides a robust way to model gradual closing of fractures and hence a time variant “shrinking” simulated rock volume instead of conventional history matching with multiple permeability zones
A HUGE THANK YOU!!!

• Henry Galvis
• Daniela Becerra
• Dr. Sayantan Ghosh
• Dr. R. Paul Philp
• Rafael Pires da Lima
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