Seismic Analysis of Paleotopography and Stratigraphic Controls on Total Organic Carbon (TOC) Distribution in the Woodford Shale, Oklahoma (U.S.A.)*

Lennon Infante1, Felipe Cardona1, Brenton McCallough1, and Roger Slatt1

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Abstract

The Devonian Woodford Shale is a prolific unconventional resource shale for both oil and gas. Like many such shales, the Woodford sits atop an unconformity on the surface of underlying carbonate rocks (mainly the Hunton Limestone in this case). There is variable topographic relief on the unconformity surface due to incised valley, cave collapse and/or karst formation during periods of subaerial exposure resulting from eustatic sea level fluctuations. Anomalously high thicknesses of the shale, with relatively high TOC, can form within these topographic depressions, giving rise to potential ‘sweet spots’ as drilling targets. It is likely that the topographic relief that formed during subaerial exposure created areas of restricted marine circulation (or possibly hypersaline lakes) during early fall in sea level, and thus, localized anoxic depositional environments conducive to preservation of organic matter (TOC). Seismic analysis, calibrated with well logs and cuttings, of two areas on the Cherokee Platform of Oklahoma were completed in order to test the discontinuous and isolated distribution, both vertically and horizontally, of the TOC. In one area, the TOC ranged up to 10% and in the other area, up to 13%. Seismic inversion and attribute analysis demonstrated the patchy distribution of the TOC both vertically and laterally in both areas. This patchy, discontinuous distribution spotlights areas where TOC was preserved (in the mini-basins), and point to potential sweet spot locations. The delineation of organic-rich sweet spots was accomplished by integrating geological, geochemical and geophysical data in probabilistic neural networks obtaining seismic impedance-derived TOC that was mapped across different locations in the Cherokee Platform.

Selected References


Comer, J.B., 2008, Woodford Shale in the southern Midcontinent, USA-transgressive systems tract marine source rocks in an arid passive continental margin with persistent ocean upwelling: AAPG Annual Convention, San Antonio, Texas.


Presenter’s notes: There is a common feature on many of the US shale plays, and that is they all sit atop of an unconformity (which is a carbonate in most cases) thus making this study applicable not only to the Woodford Shale but to different plays.
Presenter’s notes: Study comprises four areas in Central Oklahoma.
Geologic Model

TOC

Passey (A3-A4)

Seismic Inversion

Study Area 1

Study Area 2

Study Area 3

Study Area 4

Seismic Inversion

Location-Background

Modern Analog

Woodford Correlation

Study Area 1

Study Area 2

Study Area 3

Study Area 4

After Bauernfeind, 1980

Highstand of sea level

Falling stage of sea level

Early stage of sea level rise

Continued sea level rise

Improved water circulation

Less preserved TOC

Geologic time

Valley / karst carved

Valley / karst filled

One Sea Level Cycle


Hunton Unconformity

HIGH

LOW

FALLING LIMB

RISING LIMB

After Bauernfeind, 1980

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- **Modern Analogs**
- **Woodford Correlation**
- **Study Area 1**
- **Study Area 2**
- **Study Area 3**
- **Study Area 4**
- **TOC Passey (A3-A4)**
- **Seismic Inversion**
- **TOC Prediction**

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*Image of a geological diagram showing sinkholes, springs, and groundwater flow.*

*After Grotzinger and Jordan, 2010*
Institute of Reservoir Characterization

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After Grotzinger and Jordan, 2010
### Institute of Reservoir Characterization

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<tbody>
<tr>
<td>Debris (soil, rock, etc.)</td>
<td>Sinkholes</td>
<td>River</td>
<td>Sinkholes</td>
<td>Stream disappears underground</td>
<td>Cave mouth</td>
<td>Groundwater table</td>
<td>Cave</td>
<td>Stream appears from underground</td>
<td></td>
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*After Grotzinger and Jordan, 2010*
Institute of Reservoir Characterization

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- **Debris (soil, rock, etc.)**
- **Sinkholes**
- **Stream disappears underground**
- **Stream appears from underground**
- **Groundwater table**
- **Cave mouth**
- **Cave**
- **Limestone**

*After Grotzinger and Jordan, 2010*
The image appears to be a geological cross-section diagram, likely related to the Woodford Formation, showing various parasequences and thin sections. Here is a breakdown of the key components:

**Parasequences**
- Flooding surfaces
- Transgression
- Progradation

**Thin Sections**
- Top Woodford
- Top Hunton
- Flatten on MFS

**Geological Model**
- Study Area 1
- Study Area 2
- Study Area 3
- Study Area 4

**Geologic Model**
- Location-Background
- Modern Analogs
- Woodford Correlation

**Modern Analogs**
- Payne
- Payne
- Chain
- McCollough
- Amorcho
- Cardona
- Molinares
- Trenton et al.

**Geologic Location**
- TST
- HST
- MFS

**Geologic Model Study**
- Area 1
- Area 2
- Area 3
- Area 4

**Modern Analogs**
- Modern Analogs

**Geologic Model**
- Geologic Model

**Geologic Background**
- Background

**Geologic Study**
- Study

**Geologic Area**
- Area

**Geologic TOC**
- TOC

**Geologic Passey (A3-A4)**
- Passey (A3-A4)

**Geologic Inversion**
- Inversion

**Geologic Prediction**
- Prediction

**Geologic Woodford Correlation**
- Woodford Correlation

**Geologic Woodford Correlation**
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**Geologic Woodford Correlation**
- Woodford Correlation

**Geologic Woodford Correlation**
- Woodford Correlation
Institute of Reservoir Characterization

At the bottom right of the image, there is a map of Oklahoma labeled "Carbonate Platform." The map is divided into different areas: Area 1, Area 2, Area 3, and Area 4. Each area is marked with a different color:

- Area 1: Purple
- Area 2: Red
- Area 3: Yellow
- Area 4: Green

The map also shows additional geological locations such as Anadarko Basin, Arbuckle Uplift, and others. The map indicates that the areas of study are located within this geological framework.

At the bottom of the image, it states "After OGS mapping 2012."
### Institute of Reservoir Characterization

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#### Study Area 1

- **Area 1**
- **Area 2**
- **Area 3**
- **Area 4**

**Carbonate Platform**

Modern Analogs:

- Woodford Correlation

Geologic Model:

- Study Area 1
- Study Area 2
- Study Area 3
- Study Area 4

TOC Passey (A3-A4): 

- Seismic Inversion
- TOC Prediction

---

**Area 1**

- Area 2
- Area 3
- Area 4
After Althoff 2012
Institute of Reservoir Characterization

Location-Background | Geologic Model | Modern Analogs | Woodford Correlation | Study
Area 1 | Study Area 2 | Study Area 3 | Study Area 4 | TOC Passey (A3-A4) | Seismic Inversion | TOC Prediction

After Althoff 2012
Institute of Reservoir Characterization

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<td></td>
<td></td>
<td></td>
<td></td>
<td>Study Area 2</td>
<td></td>
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- Carbonate Platform
- Area 1
- Area 2
- Area 3
- Area 4

Modern Analogs

Geologic Model

Woodford Correlation

Study Area 1

Study Area 2

Study Area 3

Study Area 4

TOC Passey (A3-A4)

Seismic Inversion

TOC Prediction

Institute of Reservoir Characterization

Modern Analogs

Woodford Correlation

Study Area 1

Study Area 2

Study Area 3

Study Area 4

TOC Passey (A3-A4)

Seismic Inversion

TOC Prediction

Carbonate Platform

Area 1

Area 2

Area 3

Area 4
Institute of Reservoir Characterization

Location-Background | Geologic Model | Modern Analogs | Woodford Correlation | Study Area 1 | Study Area 2 | Study Area 3 | Study Area 4 | TOC Passey (A3-A4) | Seismic Inversion | TOC Prediction

- Woodford Correlation
- Study Area 1
- Study Area 2
- Study Area 3
- Study Area 4
- TOC Passey (A3-A4)
- Seismic Inversion
- TOC Prediction
Hunton Unconformity

Woodford Correlation

Geologic Model

Modern Analogs

Woodford Correlation Study Area 1

Study Area 2

Study Area 3

Study Area 4

TOC Passey (A3-A4)

Seismic Inversion

TOC Prediction

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10 MI

Hunton Unconformity
## Woodford Correlation

### Geologic Model Study

**Location-Background**

- **Study Area 1**: Passey (Area 3-A4)
- **Study Area 2**: Seismic Inversion Prediction

### Modern Analogs

- **Institute of Reservoir Characterization**

### Study Area 3

#### 10 MI

- **Woodford Shale**
  - **Location**: Hunton Group
  - **Thick**: 0 ft. to 500 ft.
  - **B**: Red line
  - **B’**: Red line

#### 10 MI

- **Location**: Woodford Shale
  - **Thick**: 0 ft. to 500 ft.
  - **B**: Red line
  - **W3**: Red line
  - **A’**: Red line
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Location-Background | Geologic Model | Modern Analog | Woodford Correlation | Study Area 1 | Study Area 2 | Study Area 3 | Study Area 4 | TOC | Seismic Inversion | TOC Prediction

- Woodford Correlation
- Geologic Model
- Location-Background
- Modern Analog
- Seismic Inversion
- TOC
- TOC Prediction

**Study Area 2**

- Study Area 2
- Study Area 3
- Study Area 4
- TOC Passey (A3-A4)

**Prediction**

- Prediction
- Prediction
- Prediction

**Modern Analogs**

- Modern Analogs
- Modern Analogs
- Modern Analogs

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### Figure

- **Top Woodford**
- **Base Woodford**
- **Top Hunton Unconformity**
- **Onlap**

**Thickness (ft.)**

- Thickness (ft.)
- Thickness (ft.)
- Thickness (ft.)
- Thickness (ft.)

**Map**

- Hunton Group
- OKLAHOMA
- Thickness (ft.)
- 0
- 100
- 200
- 300
- 400

**A**

- A
- A
- A
- A

**A’**

- A’
- A’
- A’
- A’
Institute of Reservoir Characterization

Woodford Correlation

Geologic Model
Modern Analog
Woodford Correlation
Study Area 1
Study Area 2
Study Area 3
Study Area 4
TOC Passey (A3-A4)
Seismic Inversion
TOC Prediction

Location-Background

100 ft.
Top Woodford

<2 MI> GR <3 MI> GR <1 MI> GR <3 MI> GR <1 MI> GR <4 MI> GR <2 MI> GR <1 MI> GR <4 MI> GR

Top Hunton Unconformity
Onlap

Base Woodford

Mayes
Woodford
Hunton
Sylvan

Woodford Shale

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Institute of Reservoir Characterization

Location Background | Geologic Model | Modern Analogs | Woodford Correlation | Study Area 1 | Study Area 2 | Study Area 3 | Study Area 4 | TOC Prediction
---|---|---|---|---|---|---|---|---
Passey (A3-A4)

After Passey et al., 1990
### Institute of Reservoir Characterization

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- **Area 1**
- **Area 2**
- **Area 3**
- **Area 4**

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**Carbonate Platform**

- Area 4
- Area 1
- Area 3
- Area 2
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![Map with coherency and geological features](image-url)
P-impedance from Model based Seismic Inversion
Presenter’s notes: Now that we have continuous TOC logs in every well, the idea is to see this distribution in 3D, so we use seismic data.
Institute of Reservoir Characterization

Location-Background  Geologic Model  Modern Analogs  Woodford Correlation  Study Area 1  Study Area 2  Study Area 3  Study Area 4  TOC Passey (A3-A4)  Seismic Inversion  TOC Prediction

Area 1
Area 2
Area 3
Area 4

Woodford Correlation

Geologic Model Study

Study Area 1
Study Area 2
Study Area 3
Study Area 4

TOC Passey (A3-A4)

Seismic Inversion

Carbonate Platform

TOC

Passey (A3-A4)

Seismic Inversion

TOC Prediction

3D view

P-impedance from Model based Seismic Inversion
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Multi Attribute Stepwise Linear Regression
Decide Convolution Operator Length and number of attributes

Train Neural Network (PNN)

Apply Trained Neural Network

Validation
Compare the prediction at wells not used in the training

After Verma 2015
Institute of Reservoir Characterization

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TOC from Sequential Gaussian Simulations

- **Top Woodford**
- **Top Hunton**
- **Normal fault**

**Area 1**
**Area 2**
**Area 3**
**Area 4**

**Carbonate Platform**
- Area 4
- Area 1
- Area 3
- Area 2

**Woodford TOC Map**
- Well A

**TOC %**
- 0 to 13

**VE = 9**

1000 ft.
Presenter's notes: Generalized sequence stratigraphic model of unconventional resource shales. SB = Sequence Boundary; TSE = Transgressive Surface of Erosion; TST = Transgressive Systems Tract; CS = Condensed Section; mfs = maximum flooding surface; HST = Highstand Systems Tract. Two conceptual gamma ray logs are shown on the upper figure and on the lower left, to demonstrate the log responses of the different components. The lower middle diagram is a relative sea level curve illustrating the positions or times within a sea level cycle when each component is formed. The lower right diagram (after VanWagoner et al., 1990), shows 2nd and 3rd order cycles and a composite relative sea level curve of these two orders of cyclicity.
One Sea Level Cycle

End of highstand-progradation

Time 5

Gamma log response

Sea Level

TSE

SB

mfs

CS

TST

SL

FSST/LST

Geologic time

HIGH

FALLING LIMB

Sea Level

LOW

RIsing LIMB

Valley/Karst filled

Pause/salt/blanket
Exploration Implications!!!!

Assuming similar maturity
Thank You !!!!

Questions??
References


References


Back slides  UP
(McCullough, 2014)
Well B

Well Z

Resistivity Base Line

Woodford

Hunton

Sylvan

TOC (%)
Acknowledgments

We wish to thank Luis Castillo and Pathfinder Exploration LLC for providing part of the data sets used in these studies as well as to the member companies of the Woodford Stratigraphy Consortium, managed by the IRC at the University of Oklahoma, who generously funded this research: Marathon Oil Co., Ward Petroleum, Vitruvian Expl. Co., BHP Billiton, Conoco-Phillips Co., Chaparral Energy, Haliburton, Payrock Energy, Longfellow Co., Apache Inc., Pathfinder Exploration, and Potts and Stevenson Co. Furthermore, we would like to thank B. Cardott with the Oklahoma Geological Survey form assuring vitrinite reflectance from the cuttings. We would like to thank Schlumberger and CGG for the Petrel and Hampson & Russel software respectively. Similarly we would like to express our gratitude to Dr. K.J. Marfurt and his students for letting us use the AASPI software to compute volumetric coherency and curvature. We also made extensive use of well as laboratories provided by the University of Oklahoma for which we are very grateful.