New Insights and Perspectives on the Effects of Structural Reactivation on the Upper Devonian Antrim Shale, Michigan Basin*

Cameron J. Manche¹, Kyle J. Patterson², and William B. Harrison, III¹

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¹Western Michigan University, Kalamazoo, MI 49008 (cameron.j.manche@wmich.edu)
²Miller Energy Company, Kalamazoo, MI 49007

Abstract

The Upper Devonian Antrim Shale of the Michigan Basin has proven significant economic viability with a total cumulative gas production of >3.43 TCF. Over 11,000 Antrim wells have been completed with 9181 of those wells being online as of January, 2016. Spatially, production volumes and the chemical composition of both natural gas and formation waters vary throughout the Antrim Shale. Previous studies have attributed variable natural-gas compositions to mixing, bacterial alteration and migration, whereas formation waters indicate the mixing of brines from deeper formations with freshwater recharge. Recent studies of noble gas signatures suggest that the source of natural gas in the Antrim Shale has migrated vertically from deeper formations. Variability in the natural gas and formation-water composition were attributed to microbial methanogenesis of thermogenic gas due to the influx of meltwater proximal to the Antrim subcrop following the Wisconsin glaciation. Currently, there is limited knowledge on the mechanism that has induced migration and the controls on the distribution of thermogenically derived hydrocarbons. Evaluation of the spatial distribution of the specific gravity and chloride of formation waters and gas composition suggest the occurrence of localized thermogenic hydrocarbon (e.g., C₂⁺ -ethane) anomalies. The preservation of thermogenic components is attributed to isolation from meltwater invasion or recent migration of hydrocarbons due to neotectonic influences. Localized thermogenic hydrocarbon anomalies were observed spatially proximal to the subcrop, suggesting the occurrence of structural conduits that have enabled the migration of dense saline brines as well as thermogenically derived hydrocarbons. Evaluation of structural-contour and derivative models suggest that these younger structural lineaments extend vertically through the Traverse Limestone as well as the Sunbury Shale, the lower and upper stratigraphic boundaries of the Antrim Shale.
respectively. It is proposed that these structural lineaments overlie deep-seated basement faults enclosed within a regional transtensional pull-apart subbasin. Subsequent reactivation within the Michigan Basin is proposed to have induced movement along the deeper pull-apart system extending vertically through the Sunbury Shale. Overall, this study provides new insights and a conceptual model for the potential structural mechanism that controls the occurrence and distribution of thermogenically derived hydrocarbons.

**Selected References**


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1 Western Michigan University, Kalamazoo, MI 49008
2 Miller Energy Company, Kalamazoo, MI 49007

2016 Eastern Section – AAPG | Lexington, Kentucky
Structure and Tectonic Effects on Reservoirs | Monday, September 26th, 2016
Purpose of Study

- Assess the geological controls on natural gas accumulation
- Determine the origin of Antrim Gas
- Provide a new analog to explain controls on natural gas production

Antrim Production Curve

Mean Mcf/D 3’93

Source: GRI/SPE - Antrim Shale Workshop 1994

Data Source: MPSC
Purpose of Study

- Assess the geological controls on natural gas accumulation
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Antrim Shale
Play Fairway
Purpose of Study

- Assess the geological controls on natural gas accumulation
- Determine the origin of Antrim Gas
- Provide a new analog to explain controls on natural gas production

Antrim Production Curve

Data Source: MPSC

Antrim Thermal Maturity

Source: USGS DDS-69-T
Western Michigan University

Background – Stratigraphy

Latuszek B1-32

St. Loud D3-20

Late Devonian – Michigan Basin

Mean Antrim Thickness

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<thead>
<tr>
<th>Member</th>
<th>Thickness (ft.)</th>
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<tbody>
<tr>
<td>Lachine</td>
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<tr>
<td>Paxton</td>
<td>40</td>
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<td>Norwood</td>
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Source: Ron Blakey
Michigan Basin Stratigraphic Lexicon

<table>
<thead>
<tr>
<th>GEOLOGIC TIME</th>
<th>OUTCROP NOMENCLATURE</th>
<th>DOMINANT LITHOLOGY</th>
<th>SUBSURFACE NOMENCLATURE</th>
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<td>EPOCH</td>
<td>NORTH AMERICAN STAGES</td>
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<td>Senecan</td>
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</tbody>
</table>

Source: Michigan Basin Geological Society
Effects of Chemocline on Black Shale Preservation

*Michigan Basin*

**Aerobic Conditions**
- Lower Chemocline
- TOC Less Preserved

**Anaerobic Conditions**
- Higher Chemocline
- TOC More Preserved

Source: Formolo et al., 2014
St. Chester #18 - Total Organic Content, Quartz, Calcite and Clay Mineral Intensities

Data Source: Dellapenna, 1991
Latuszek B1-32 - Total Organic Content, Fracture Frequency Curve

Data Source: Dellapenna, 1991
Background – Mineralogy

Latuszek B1-32

Antrim TOC Data

Data Source: Dellapenna, 1991

Data Source: MGRRE

0.3 – 18% TOC
Latuszek B1-32

Data Source: Dellapenna, 1991

Latuszek B1-32 (1602.3’) – Silicified *Tasmanites*

Silicification of *Tasmanites* is the proposed origin of authigenic Quartz (Hathan, 1979)

Wt.% Quartz: 20 – 41%
Wt.% TOC: 0.3 – 24%
Source: Ding et al., 2012
Background – Fractures

St. Chester #18 - Fracture Distribution

Fracture Trend of the Antrim Shale

Holst & Foote, 1981

Burial History from Maturation Modeling

Apotria et al., 1994

Data Source: Dellapenna, 1991
Background – Fractures

BWL Fracture/EUR Relationship

Fracture Frequency vs. EUR

R² = 0.7465

Estimated Ultimate Recovery (Bcf) vs. Total Fractured Footage

Data Source: Muskegon Development Company

Extensive Fractures
IP: 500 Mcf/D
BWL B1-24

Poorly Fractured
IP: 50 Mcf/D
BWL A3-23

Data Source: Goodman & Maness, 2008
Basin Margin – Thermogenically Immature

Antrim Shale – Maturation Data

Transition Window

Imature

Source: USGS DDS-69-T

Data Source: MGRRE
Origin of Natural Gas

Topographic Relief of the Antrim Play Fairway

Legend

- **Well Type**
  - ♦ Natural Gas Well
  - ● Oil Well
- **DEM Meters**
  - High: 450
  - Low: 200

- **Antrim Play Fairway**
- **County Boundary**

Glacial Advance and Scouring
Structural Cross Section (Subsea Depth)

Key:
5. Ellsworth Sh., 6A. Antrim Sh.—Lachine Mbr., 6B. Antrim Sh.—Paxton Mbr.,
6C. Antrim Sh.—Norwood Mbr., 7. Squaw Bay—Traverse Group
Origin of Natural Gas

Specific Gravity of Formation Water

Legend
- SWD Samples
- Antrim Play Fairway
- County Boundary

Specific Gravity
- High: 1.21
- Low: 1

Data Source: Muskegon Development Company
Gas Composition – Interpretation of Gas Origin

Source: Martini et al., 2003, Goodman & Maness, 2008
Gas Composition of Antrim Play Fairway

Legend
- Antrim Gas Sample
- Antrim Play Fairway
- County Boundary
- C1/ (C2+C3)
  - <1
  - 1-10
  - 10-20
  - 20-30
  - 30-40
  - 40-50
  - 50-100
  - 100-250
  - 250-1,000
  - 1,000-10,000
  - >10,000

Data Source: MPSC
Origin of Natural Gas

Wt. % Ethane of Antrim Play Fairway

Legend
- Antrim Gas Sample
- Antrim Play Fairway
- County Boundary

Wt.% C2 (Ethane)
High: 13.48
Low: 0

Data Source: MPSC
Origin of Natural Gas

BTU of Antrim Play Fairway

Legend
- Antrim Gas Sample
- Antrim Play Fairway
- County Boundary
- BTU
  - High: 1150
  - Low: 700

Data Source: MPSC
Hill Shade (North Lit) – 3rd Order Structural Derivative

- Sunbury Shale—Hill Shade Relief
  3rd Order Structural Derivative Model

- Traverse Limestone—Hill Shade Relief
  3rd Order Structural Derivative Model

15,286 Wells
Structural Interpretation of Pull-Apart Sub-Basin

Sand Box Model

Dooley & McClay, 1997

Transtensional Pull-Apart Analog

Legend
- Antrim Producing Units
- County Boundary
- Sunbury 3rd Order Derivative
  - High
  - Low

Structural Lineaments
Migration Pathways

EUR/Well in respect to Position on or off Structure

Legend

Well EUR (Mcf)
- 0 - 50,000
- 50,001 - 150,000
- 150,001 - 250,000
- 250,001 - 500,000
- 500,001 - 938,427

Geologic Section (CBIL)

Cross-Section Wells

Bass Lake

Antrim Producing Units

Lineaments

N

0 4 Kilometers

0 4 Miles
Cross Section Across Minor Relief
Structural Interpretation of Pull-Apart Sub-Basin

Subsidence or Collapse?

Sand Box Model

Dooley & McClay, 1997

Transtensional Pull-Apart Analog
Discussion

EUR/Well in respect to Position on or off Structure

Borehole Imaging Log Location
Conceptual Model: Listric Faults, Collapse, Fracture Development, Joint Propagation, Gas Migration

A. Twiss & Moore 2007; B. Hustoft et al., 2010
Relief Model - Bouguer Gravity Anomaly
Line of Sight N 30° W, Inclination of 45°

Source: Hinze, 1971
Antrim Gas is derived from two sources: thermogenic and biogenic.

High organic and quartz content in the Antrim Shale is attributed to the occurrence of *Tasmanites*.

Preservation of the black shales is the result of cyclical times of anoxia.

Quartz is proposed to be the lithological control on fracture development.

Tectonic and neotectonic influences are suggested as the dominant extrinsic control on fracture development.

Structural lineaments penetrate through stratigraphic units overlying and underlying the Antrim Shale.

The development of pull-apart basins is attributed to post-Mississippian (youngest bedrock) reactivation.
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Questions?

Cameron J. Manche
Ph.D. Graduate Student
Western Michigan University
Cameron.J.Manche@wmich.edu