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

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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., C_{2+} -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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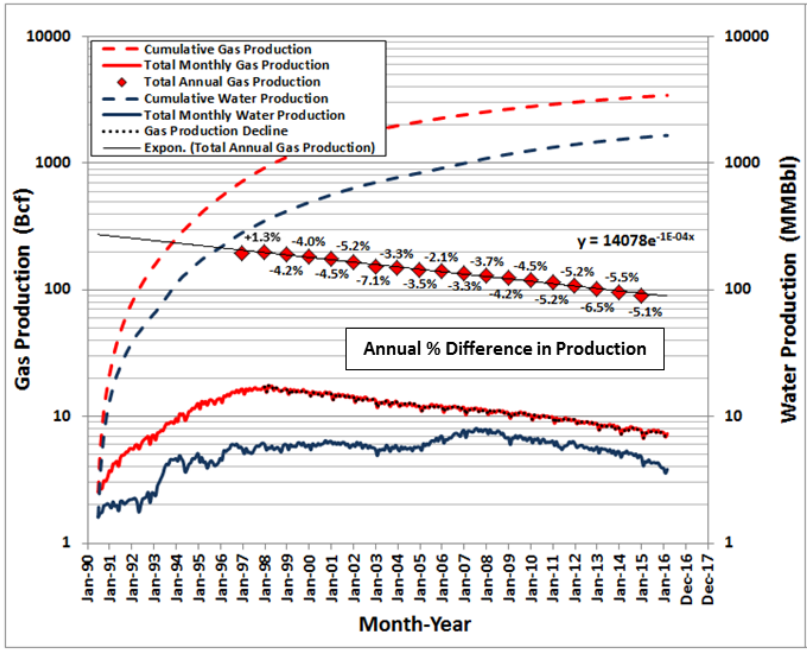
2016 Eastern Section – AAPG | Lexington, Kentucky

Structure and Tectonic Effects on Reservoirs | Monday, September 26th, 2016

Purpose of Study

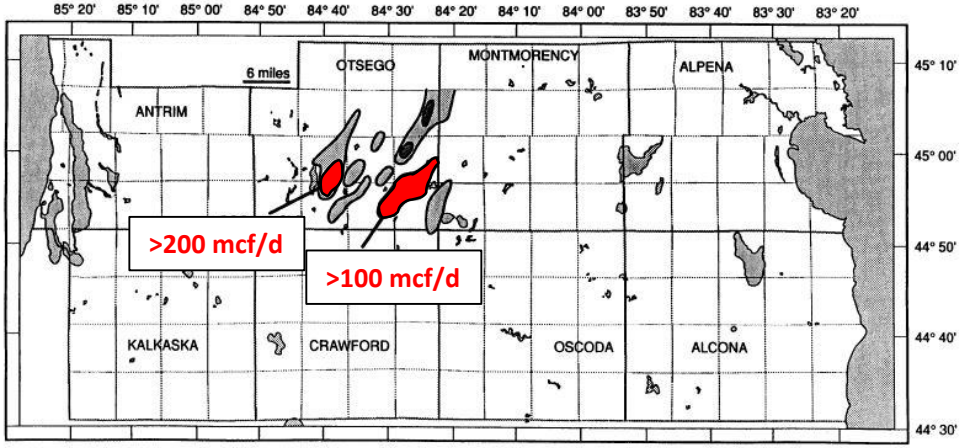
- Assess the geological controls on natural gas accumulation
- Determine the origin of Antrim Gas
- Provide a new analog to explain controls on natural gas production

Antrim Production Curve



Data Source: MPSC

Mean Mcf/D 3/'93



Source: GRI/SPE - Antrim Shale Workshop 1994

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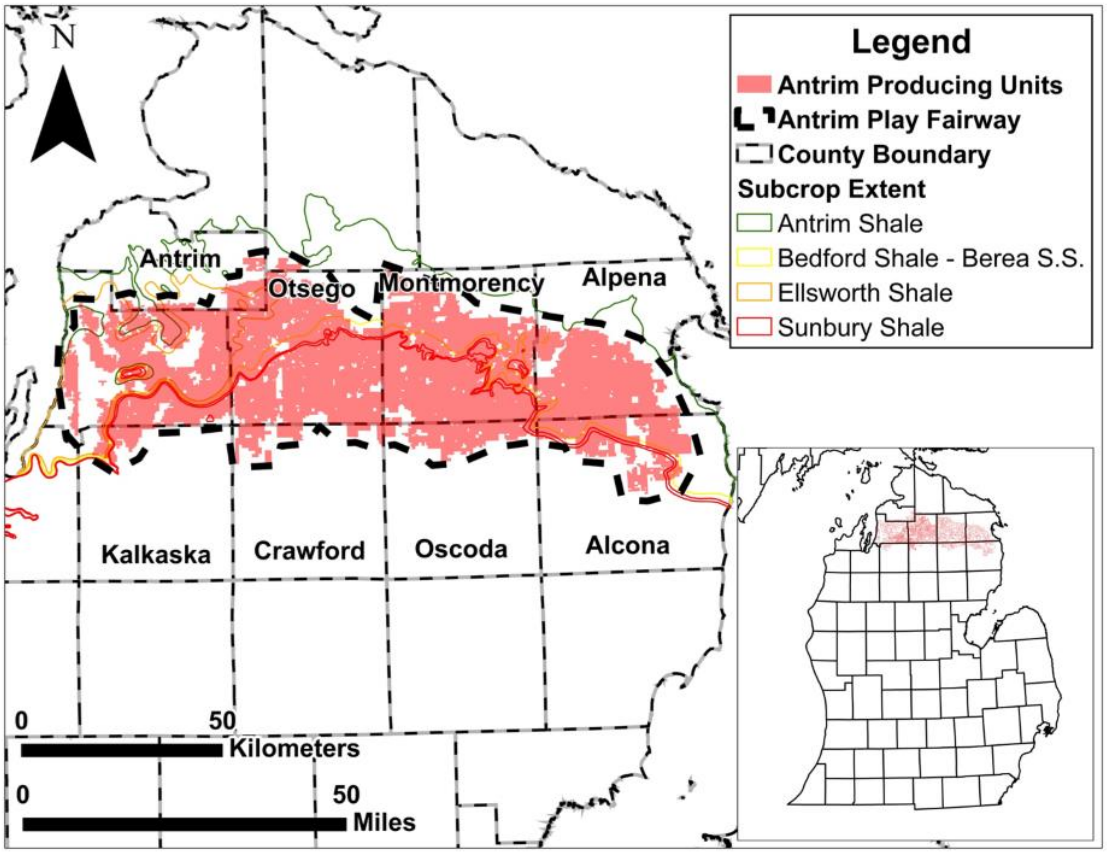
Antrim Shale Play Fairway



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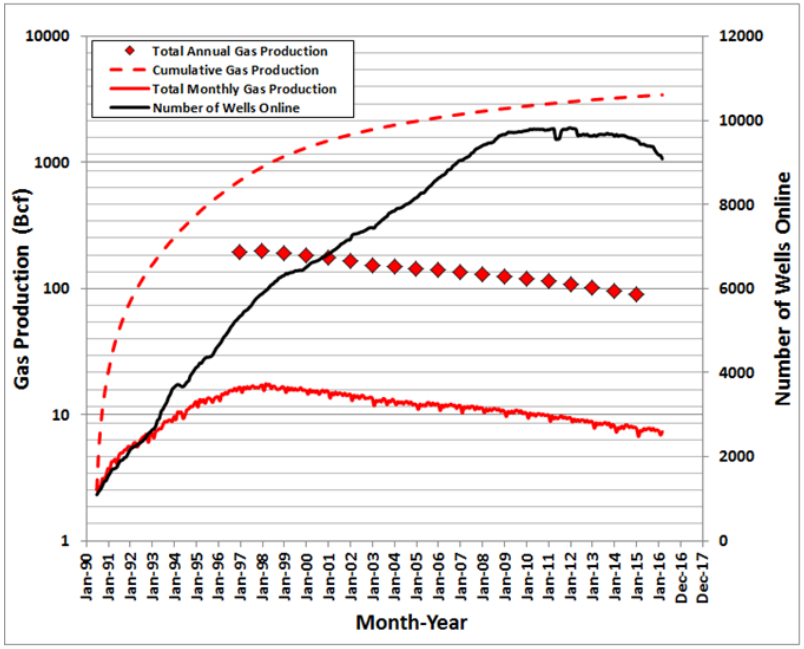
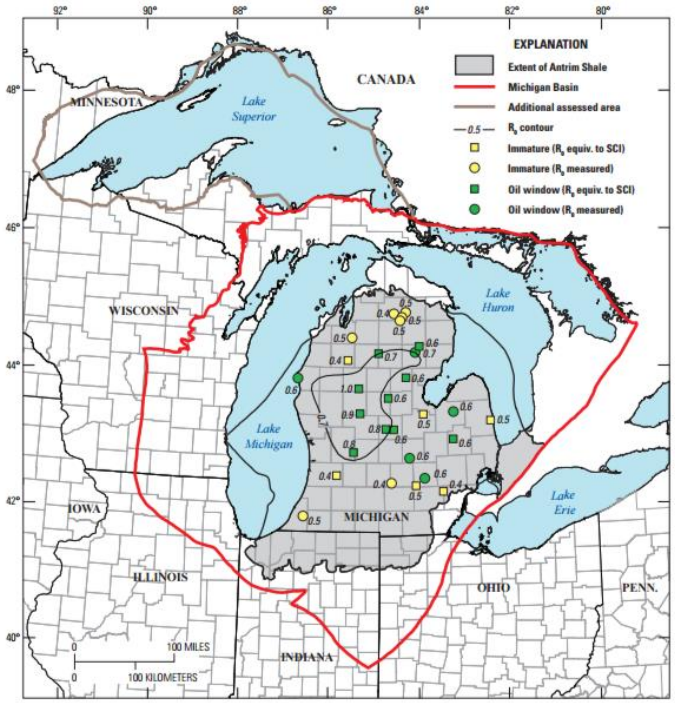


Data Source: MPSC

Antrim Thermal Maturity

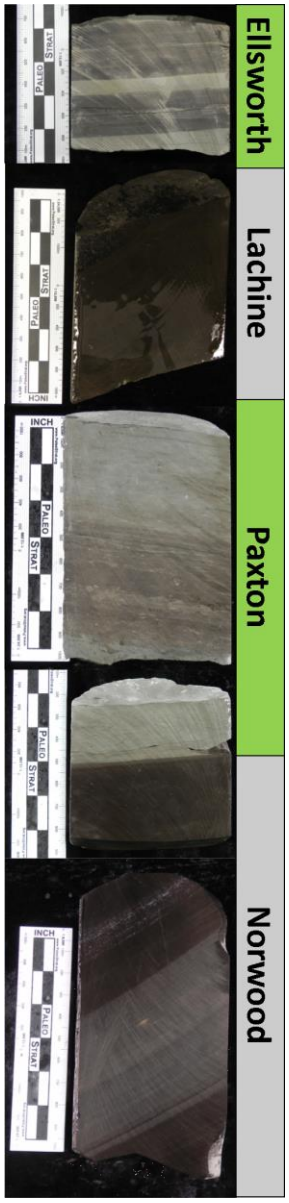


Source: USGS DDS-69-T

Western Michigan University

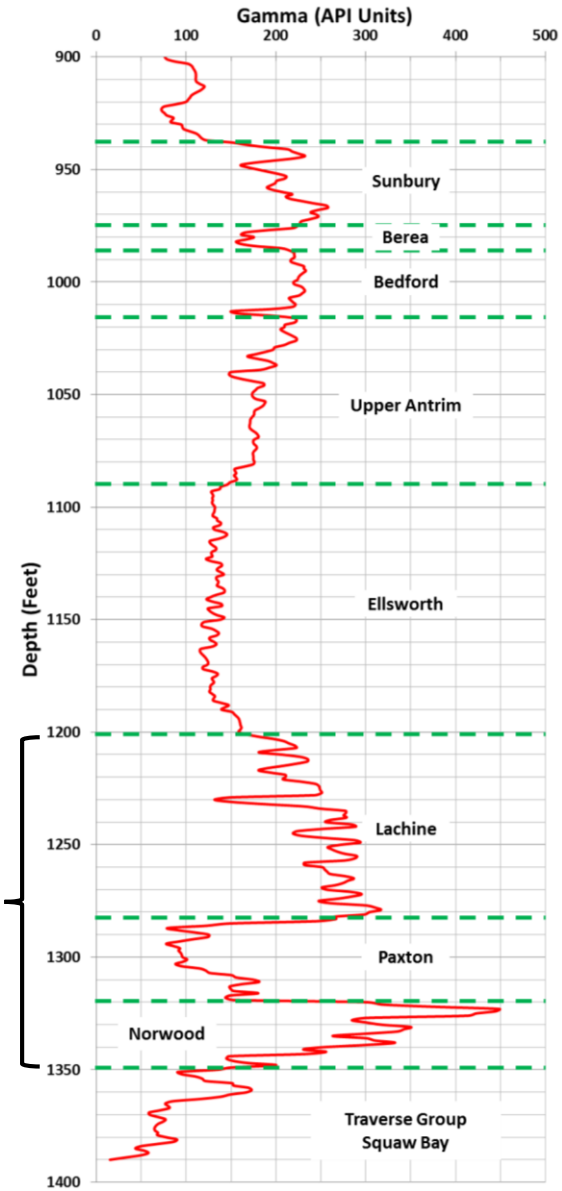
Background – Stratigraphy

Latuszek B1-32

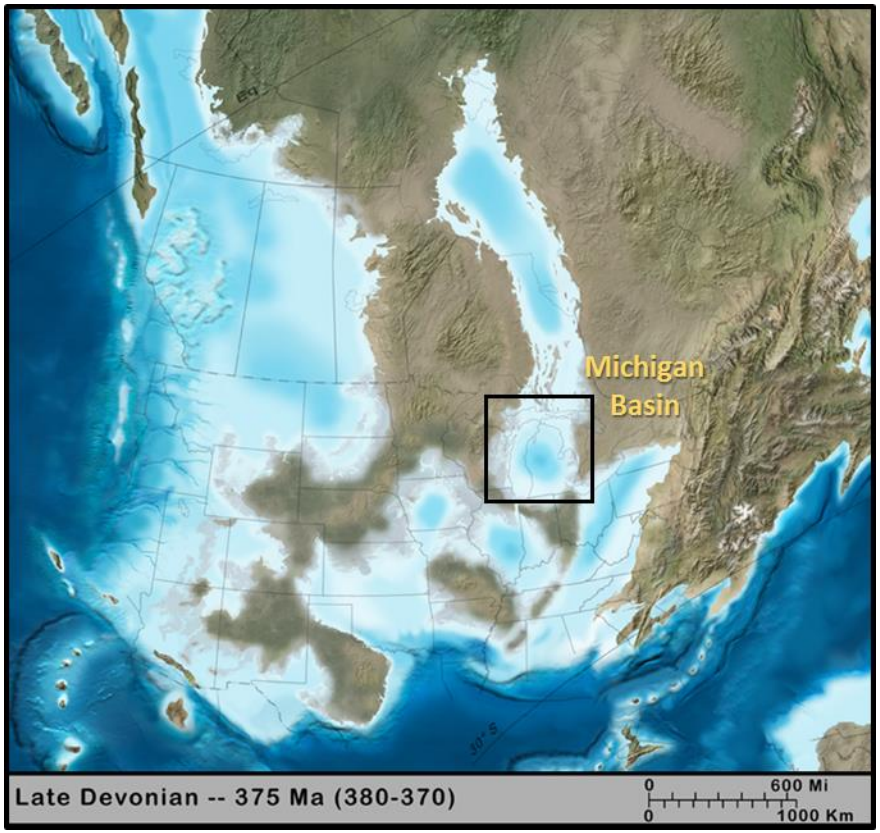


Antrim Shale

St. Loud D3-20



Late Devonian – Michigan Basin

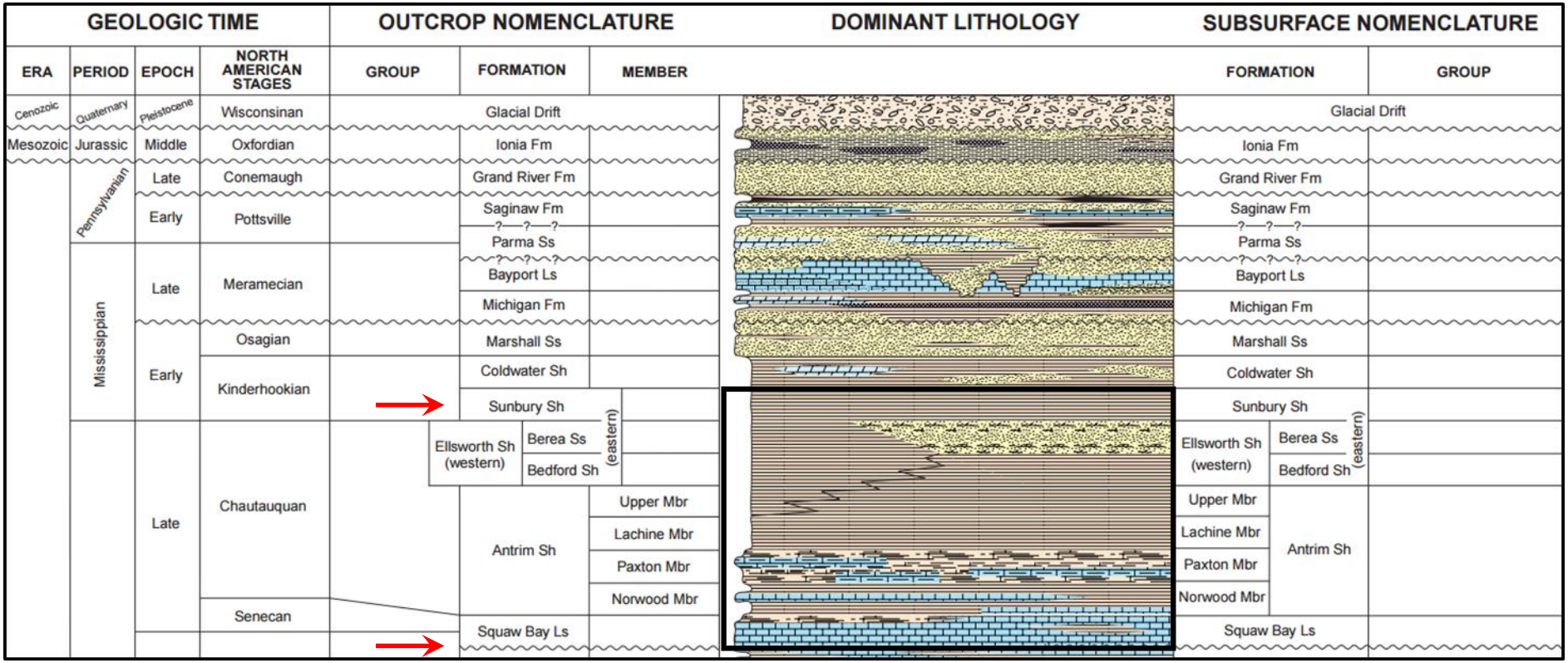


Source: Ron Blakey

Mean Antrim Thickness	
Member	Thickness (ft.)
Lachine	80
Paxton	40
Norwood	20

Background – Stratigraphy

Michigan Basin Stratigraphic Lexicon



Source: Michigan Basin Geological Society

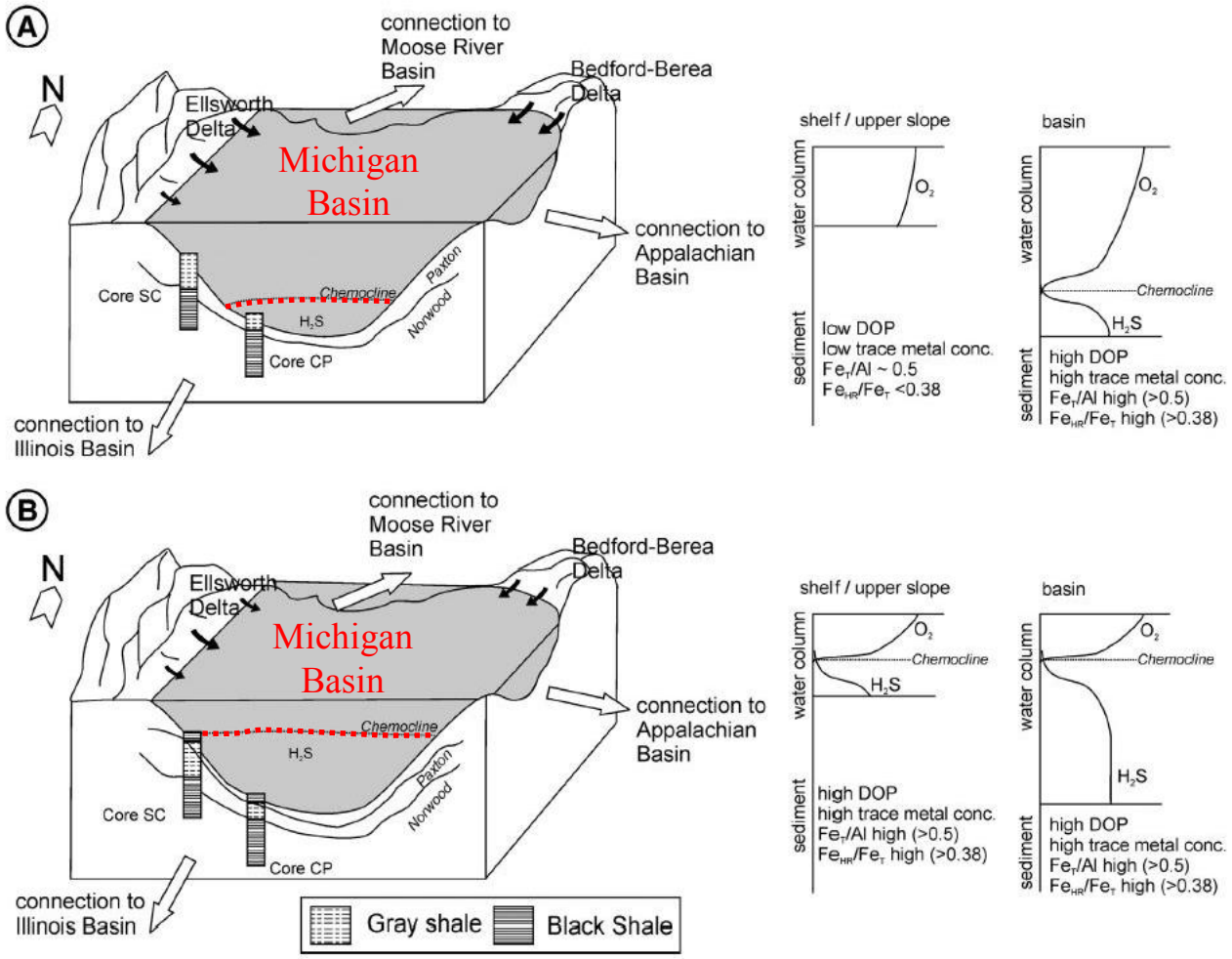
Background – Deposition

Effects of Chemocline on Black Shale Preservation

Aerobic Conditions
Lower Chemocline
TOC Less Preserved

Late Devonian Fluctuation

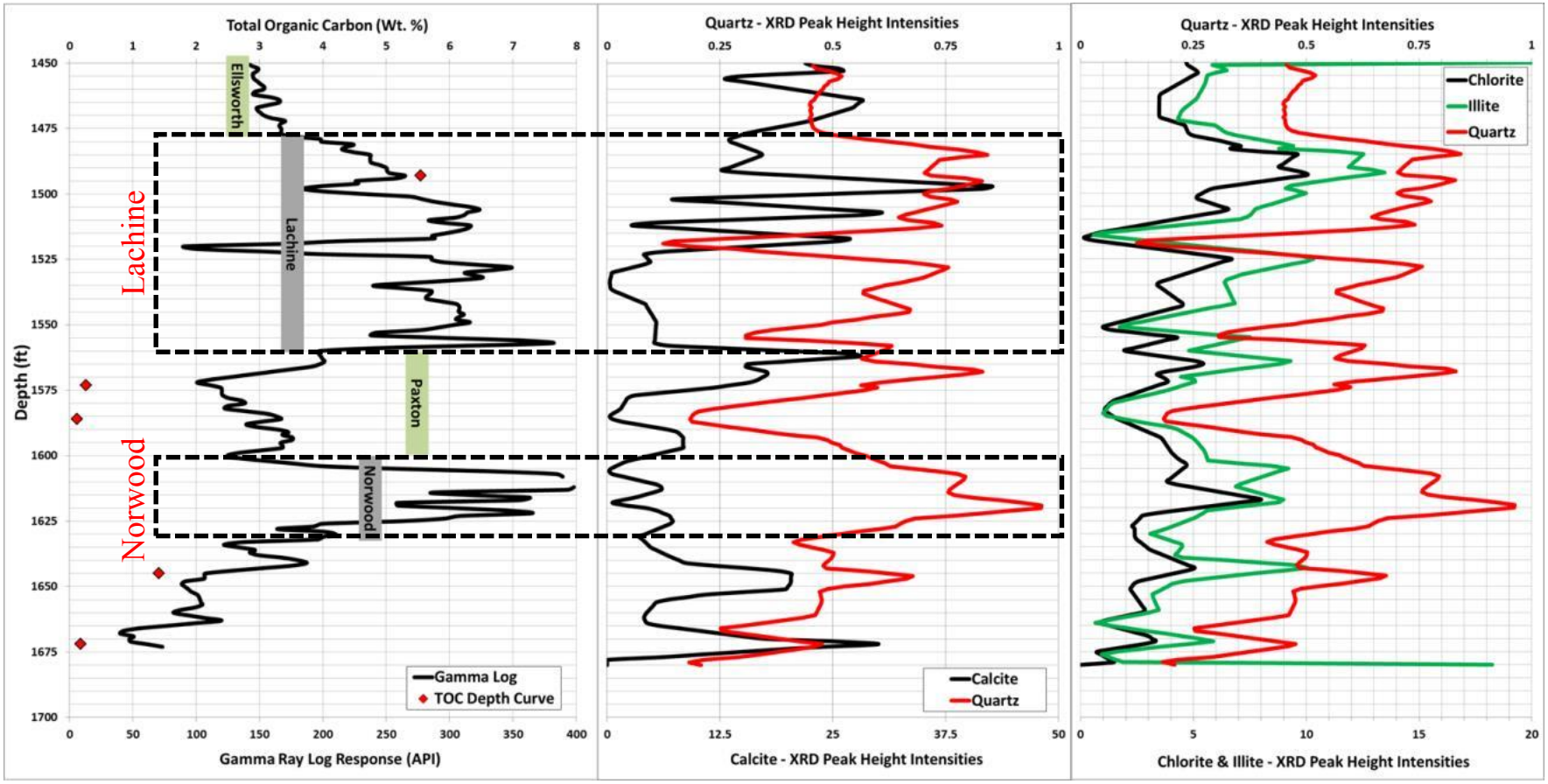
Anaerobic Conditions
Higher Chemocline
TOC More Preserved



Source: Formolo et al., 2014

Background – Mineralogy

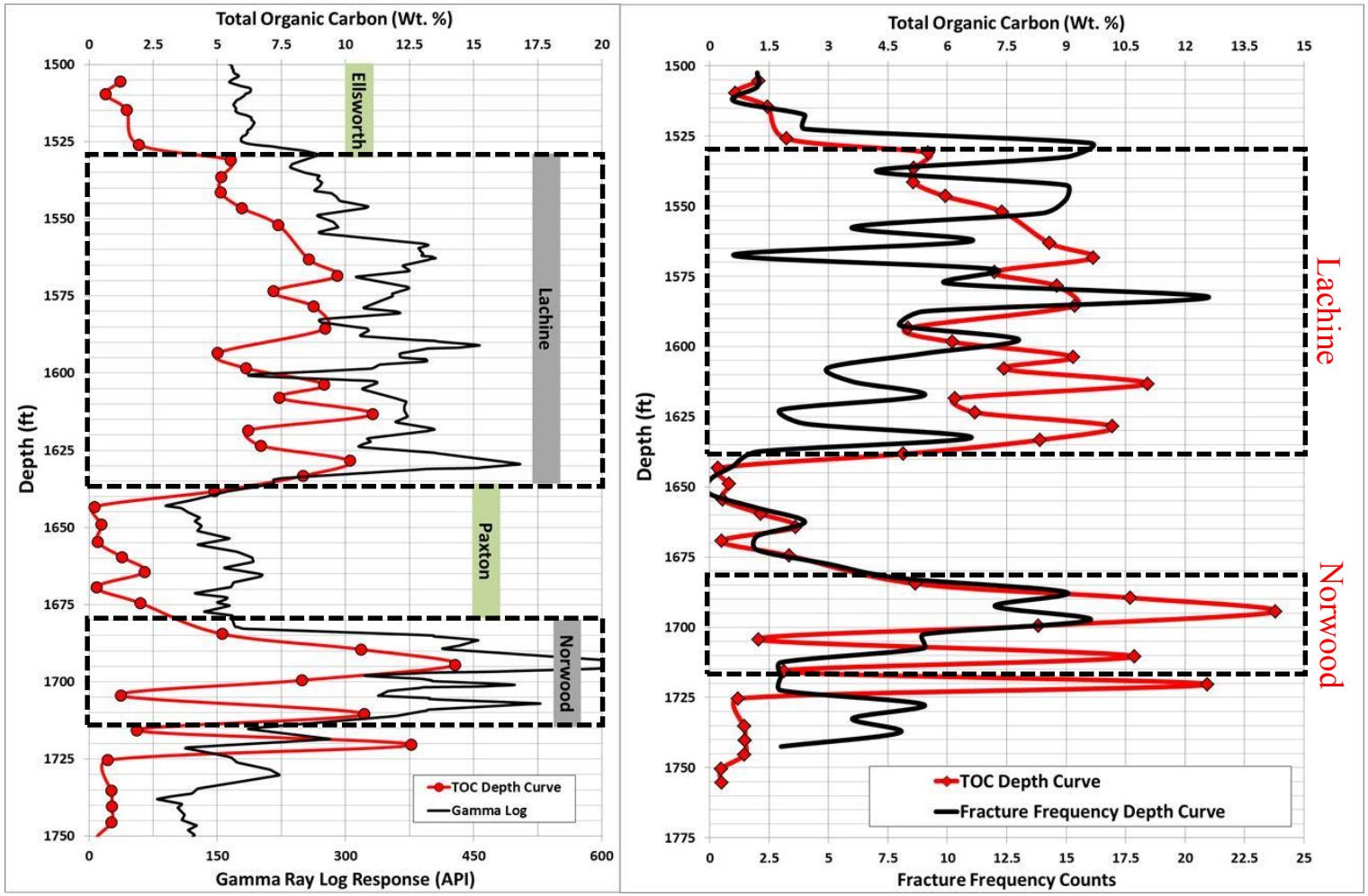
St. Chester #18 - Total Organic Content, Quartz, Calcite and Clay Mineral Intensities



Data Source: Dellapenna, 1991

Background – Mineralogy

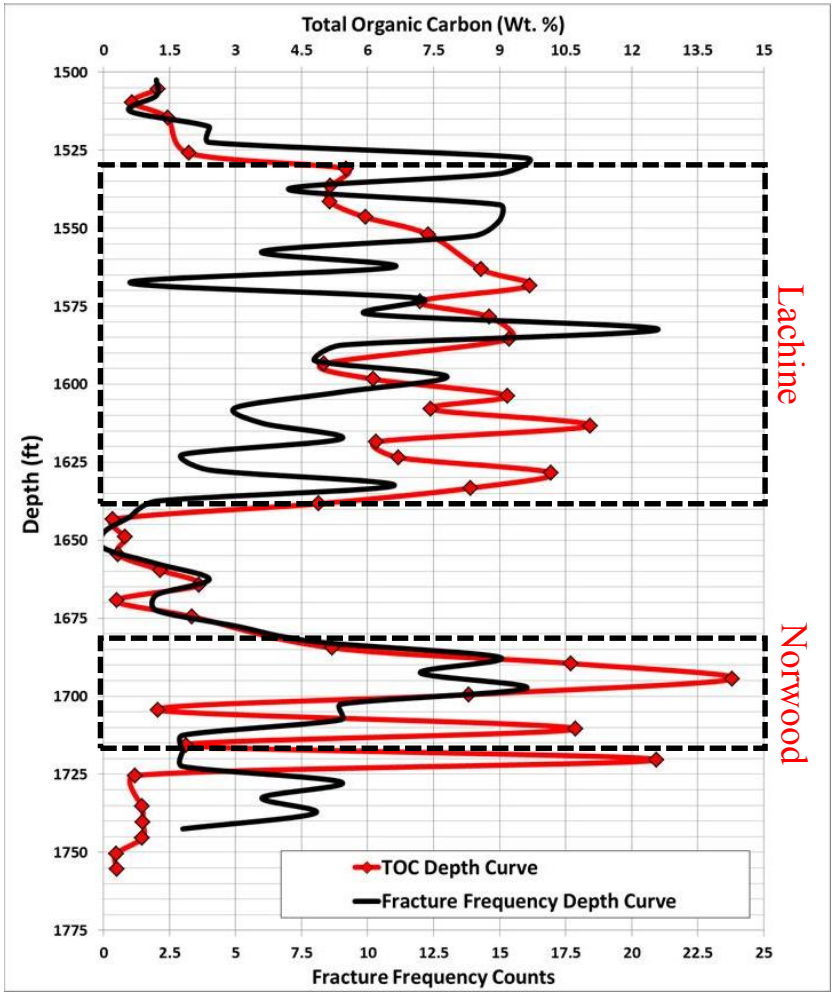
Latuszek B1-32 - Total Organic Content, Fracture Frequency Curve



Data Source: Dellapenna, 1991

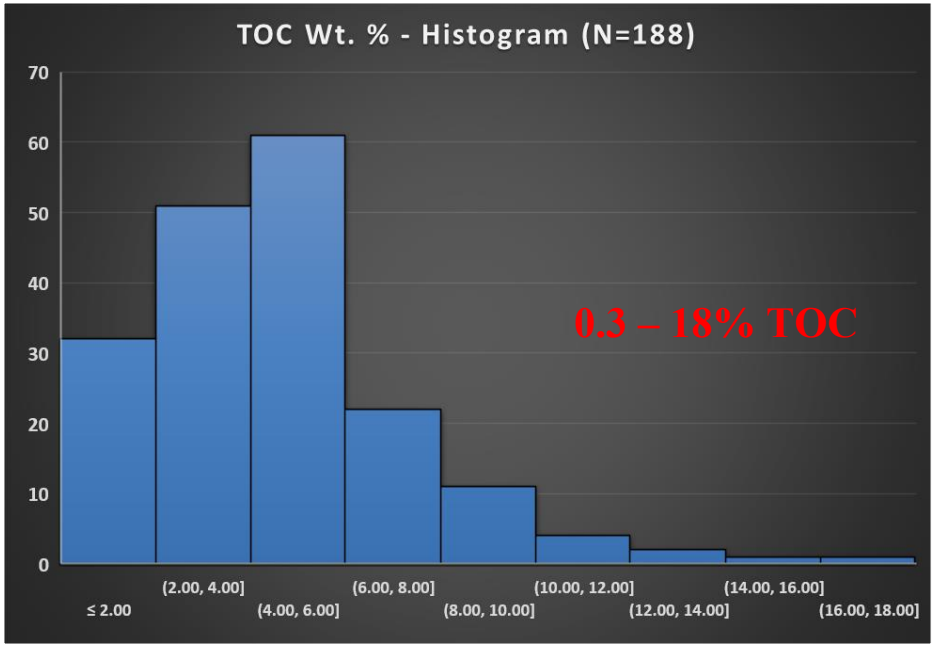
Background – Mineralogy

Latuszek B1-32



Data Source: Dellapenna, 1991

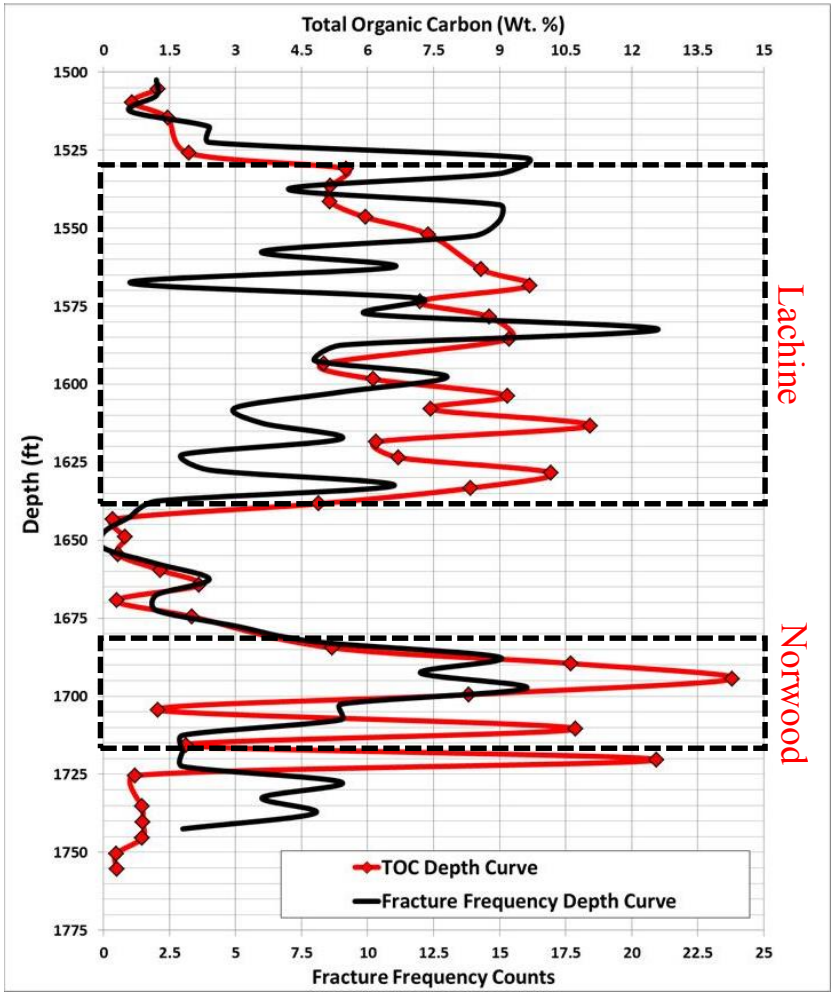
Antrim TOC Data



Data Source: MGRRE

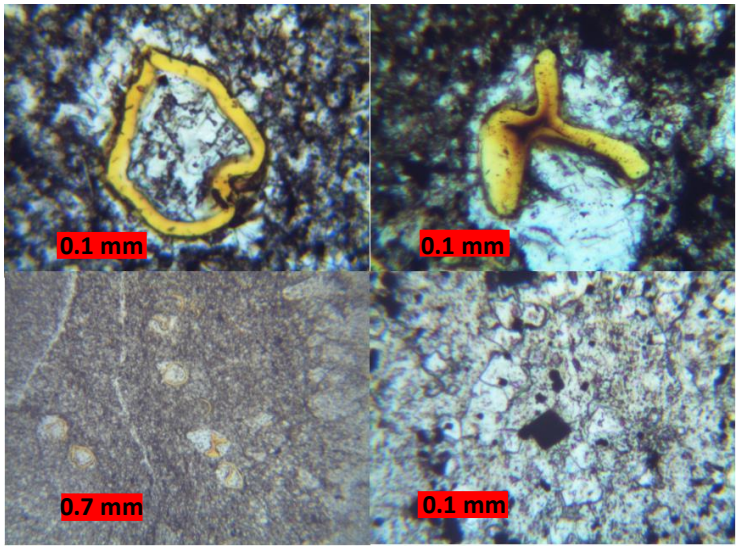
Background – Fractures

Latuszek B1-32



Data Source: Dellapenna, 1991

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

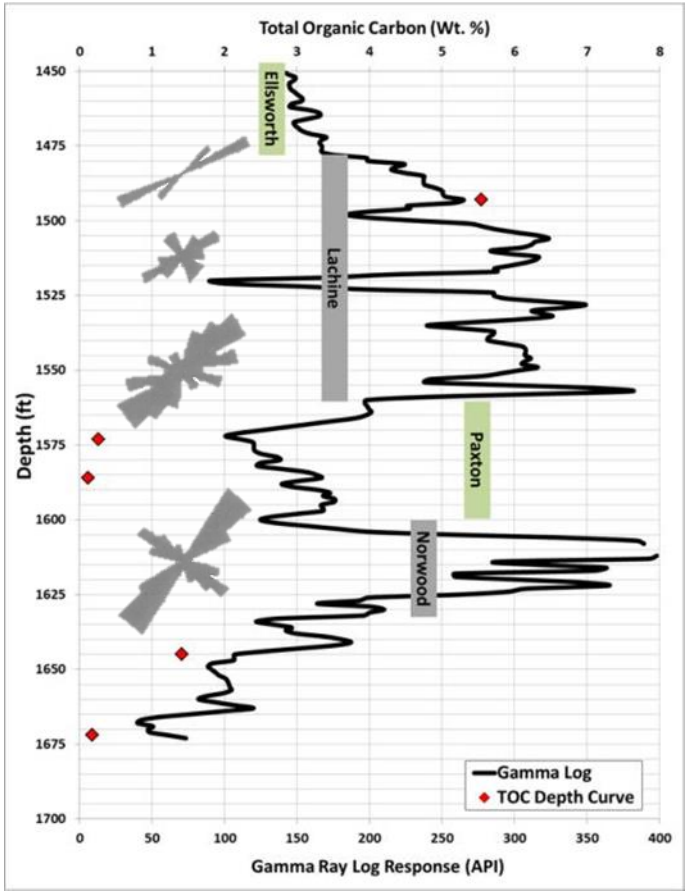


Silicification of *Tasmanites* is the proposed origin of authigenic Quartz (Hathan, 1979)

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

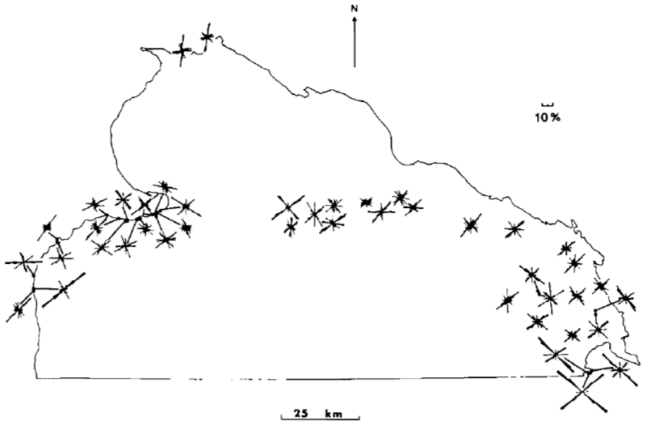
Background – Fractures

St. Chester #18 - Fracture Distribution



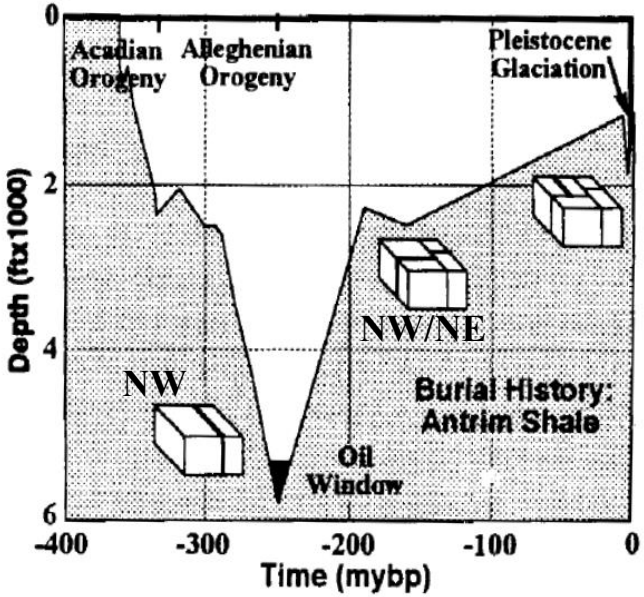
Data Source: Dellapenna, 1991

Fracture Trend of the Antrim Shale



Holst & Foote, 1981

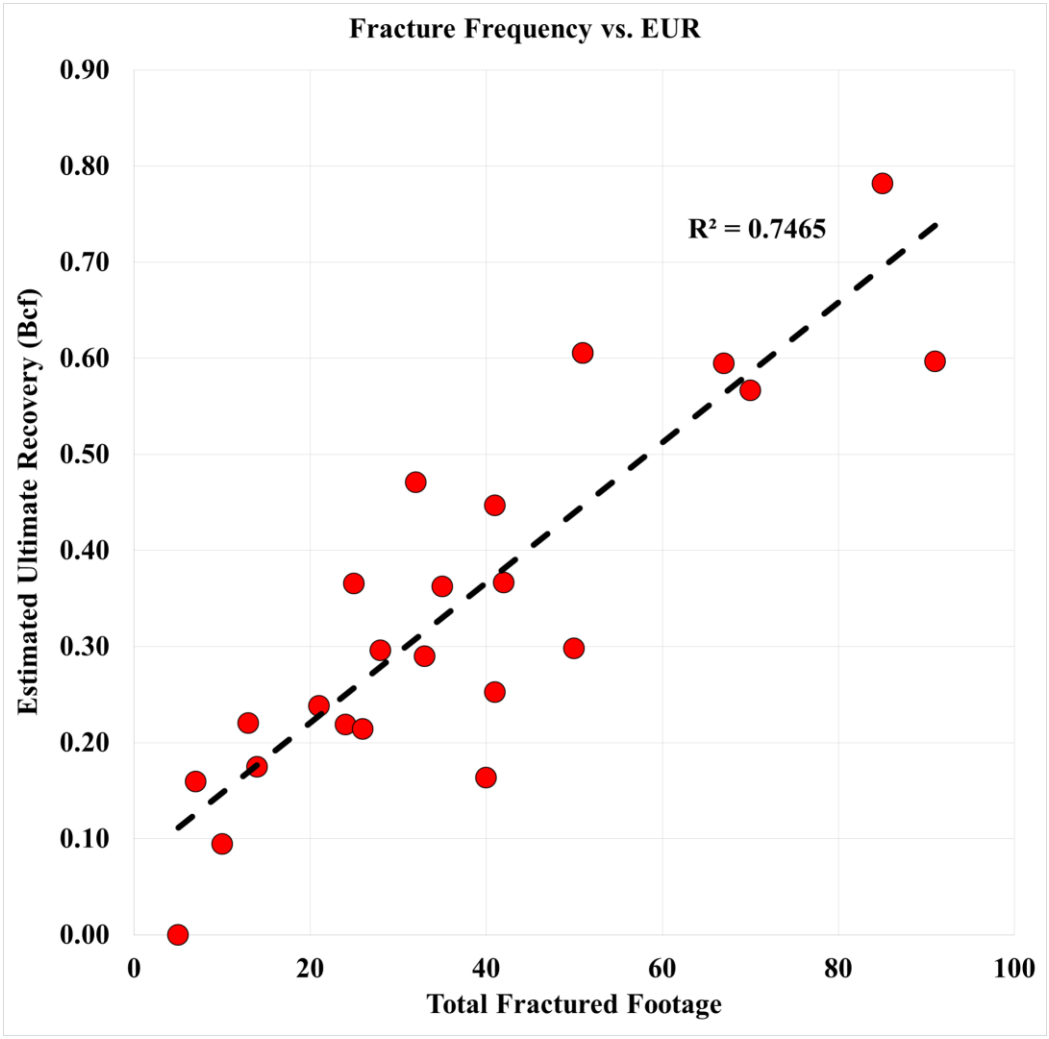
Burial History from Maturation Modeling



Apotria et al., 1994

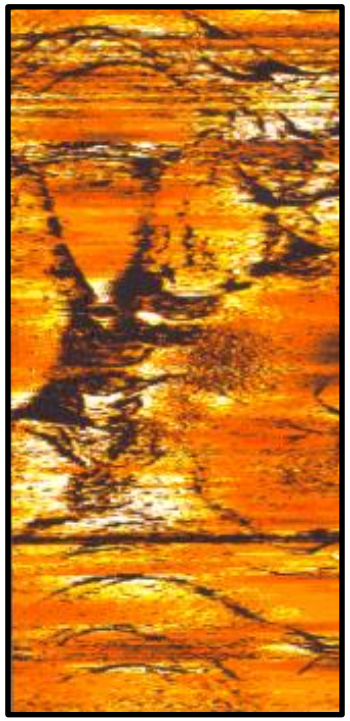
Background – Fractures

BWL Fracture/EUR Relationship



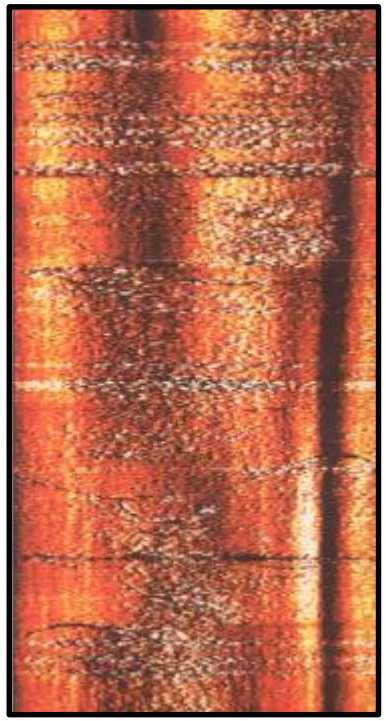
Data Source: Muskegon Development Company

Extensive Fractures



IP: 500 Mcf/D
BWL B1-24

Poorly Fractured

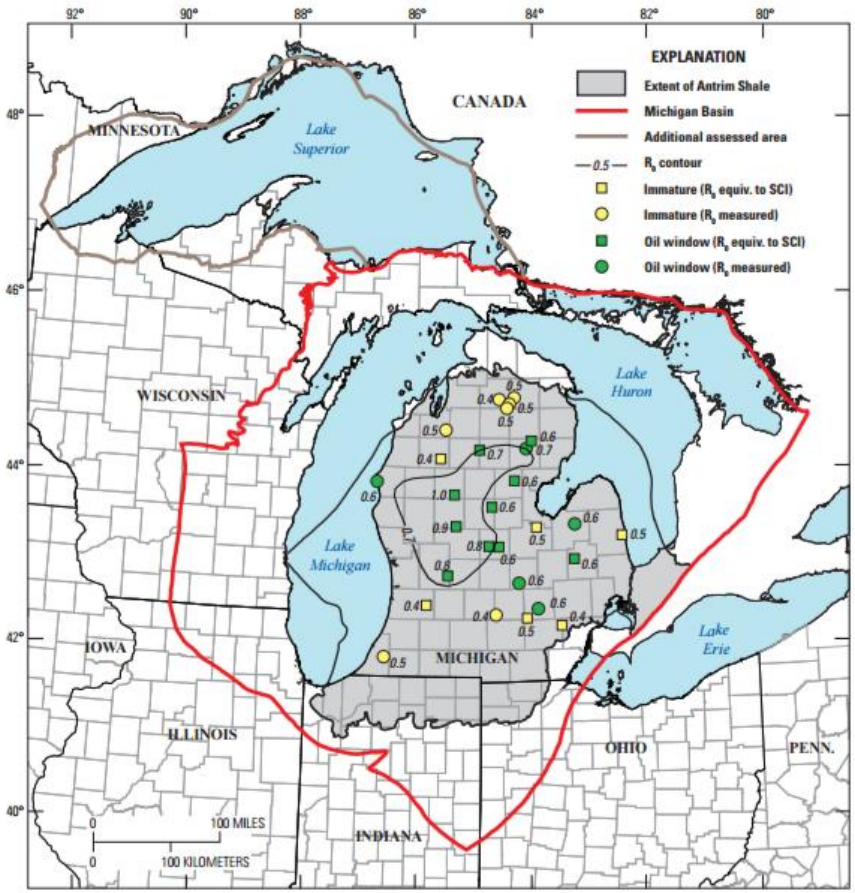


IP: 50 Mcf/D
BWL A3-23

Data Source: Goodman & Maness, 2008

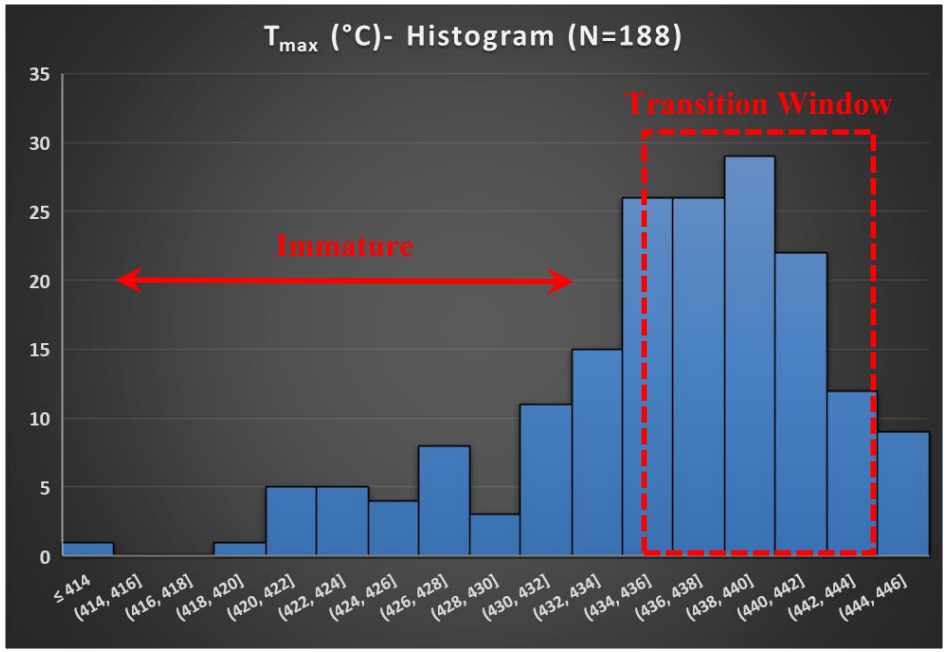
Thermal Maturation

Basin Margin – Thermogenically Immature



Source: USGS DDS-69-T

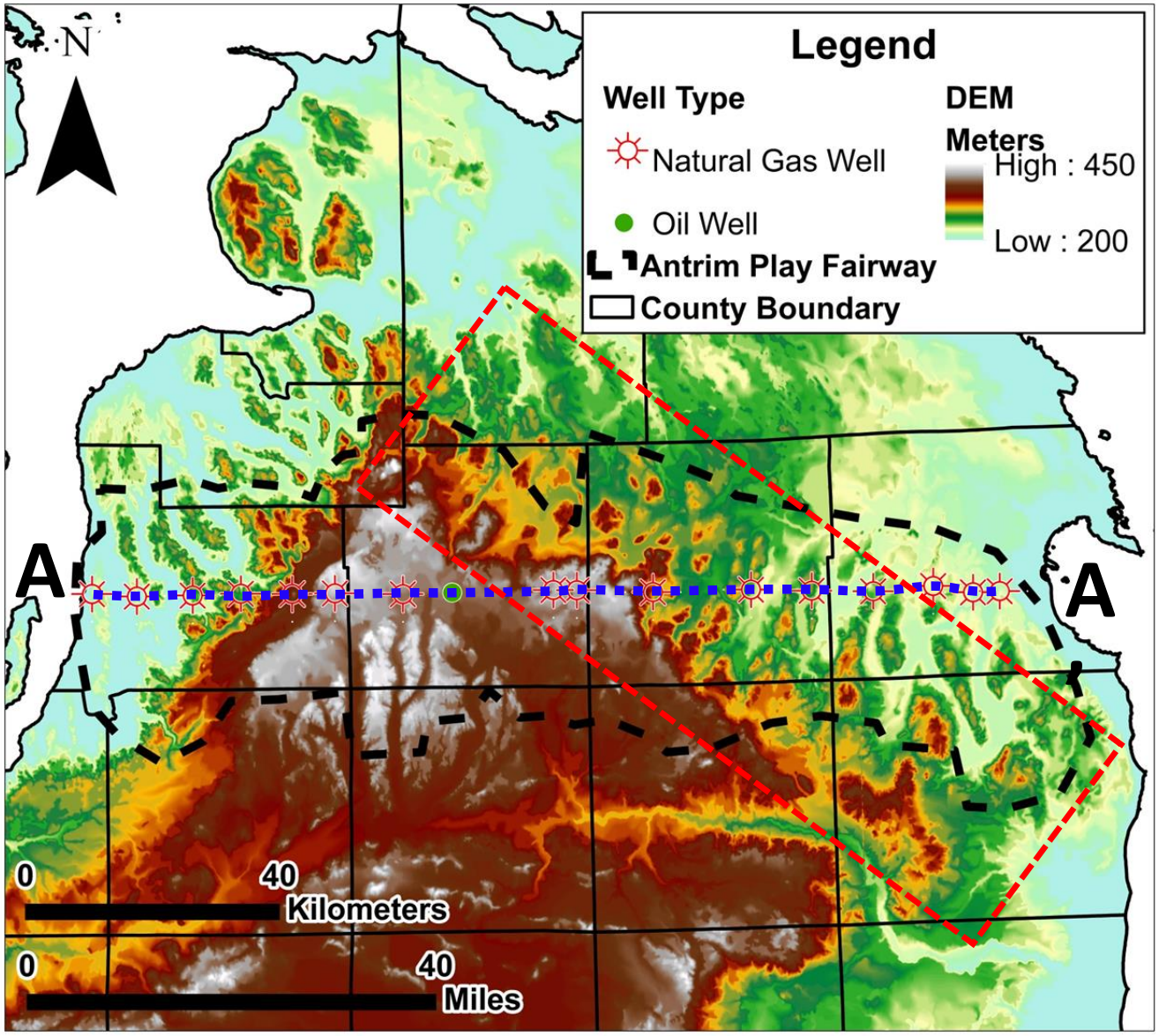
Antrim Shale – Maturation Data



Data Source: MGRRE

Origin of Natural Gas

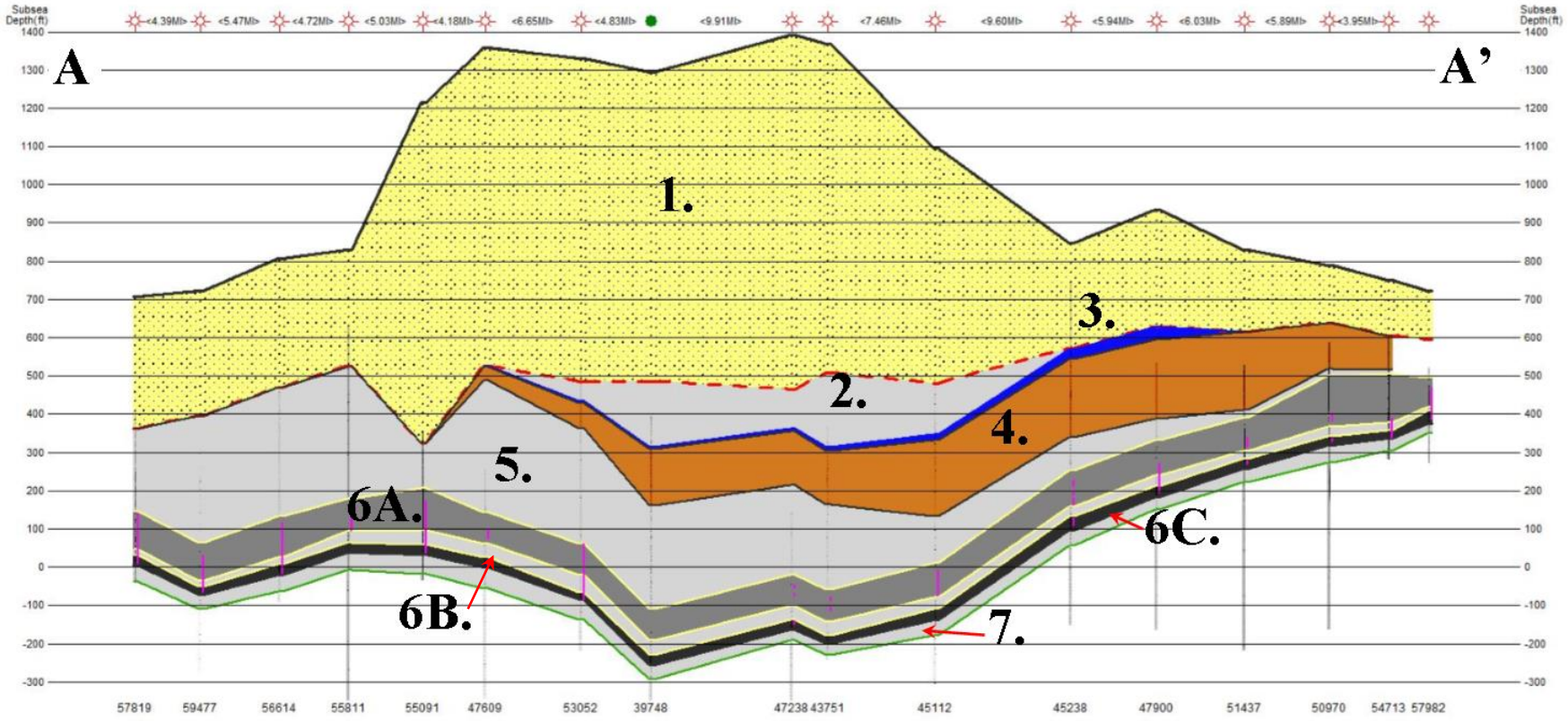
Topographic Relief of the Antrim Play Fairway



Glacial Advance and Scouring

Origin of Natural Gas

Structural Cross Section (Subsea Depth)

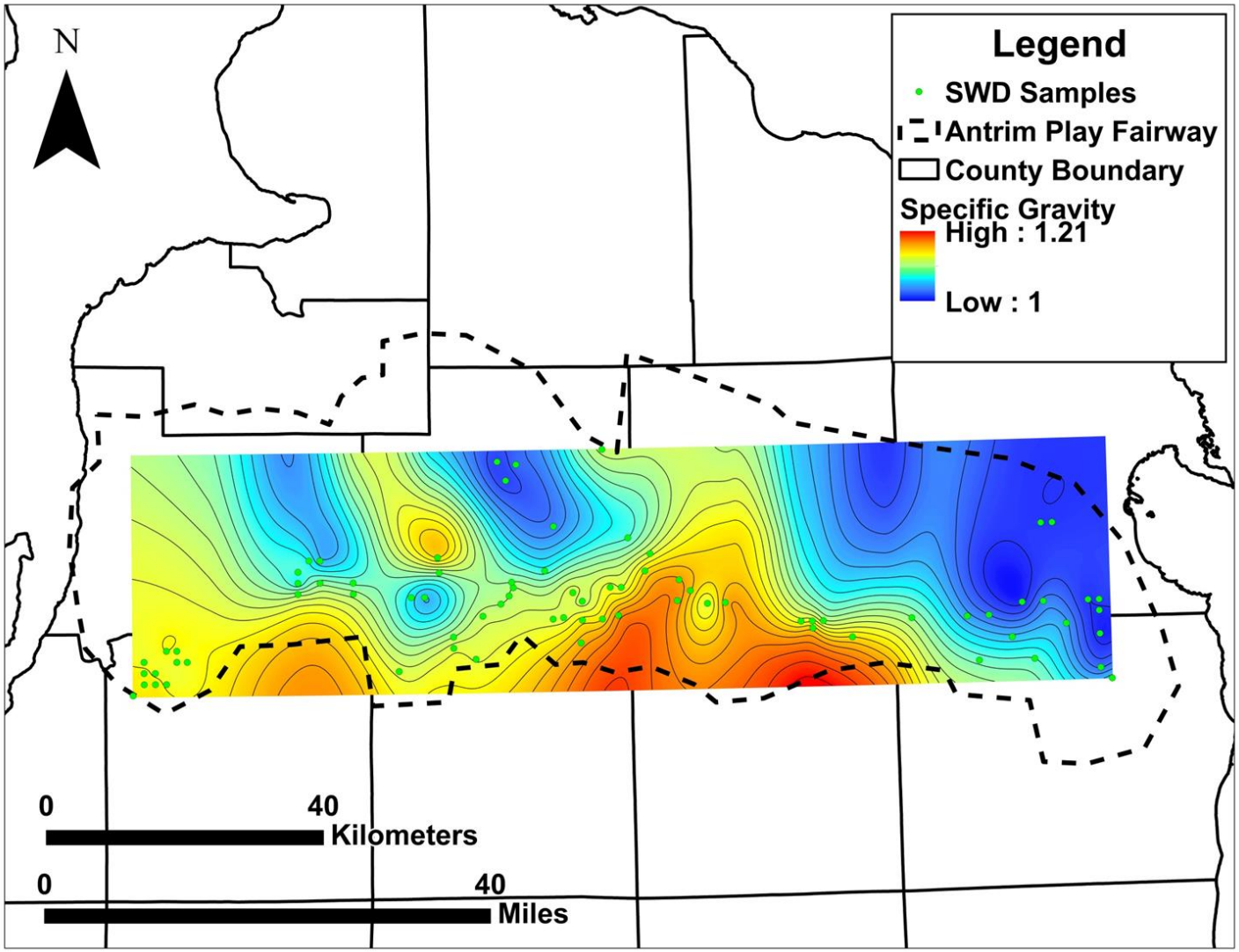


Key:

1. Glacial Drift, **2.** Coldwater Sh., **3.** Sunbury Sh., **4.** Upper Antrim/Bedford Sh./Berea S.S.,
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

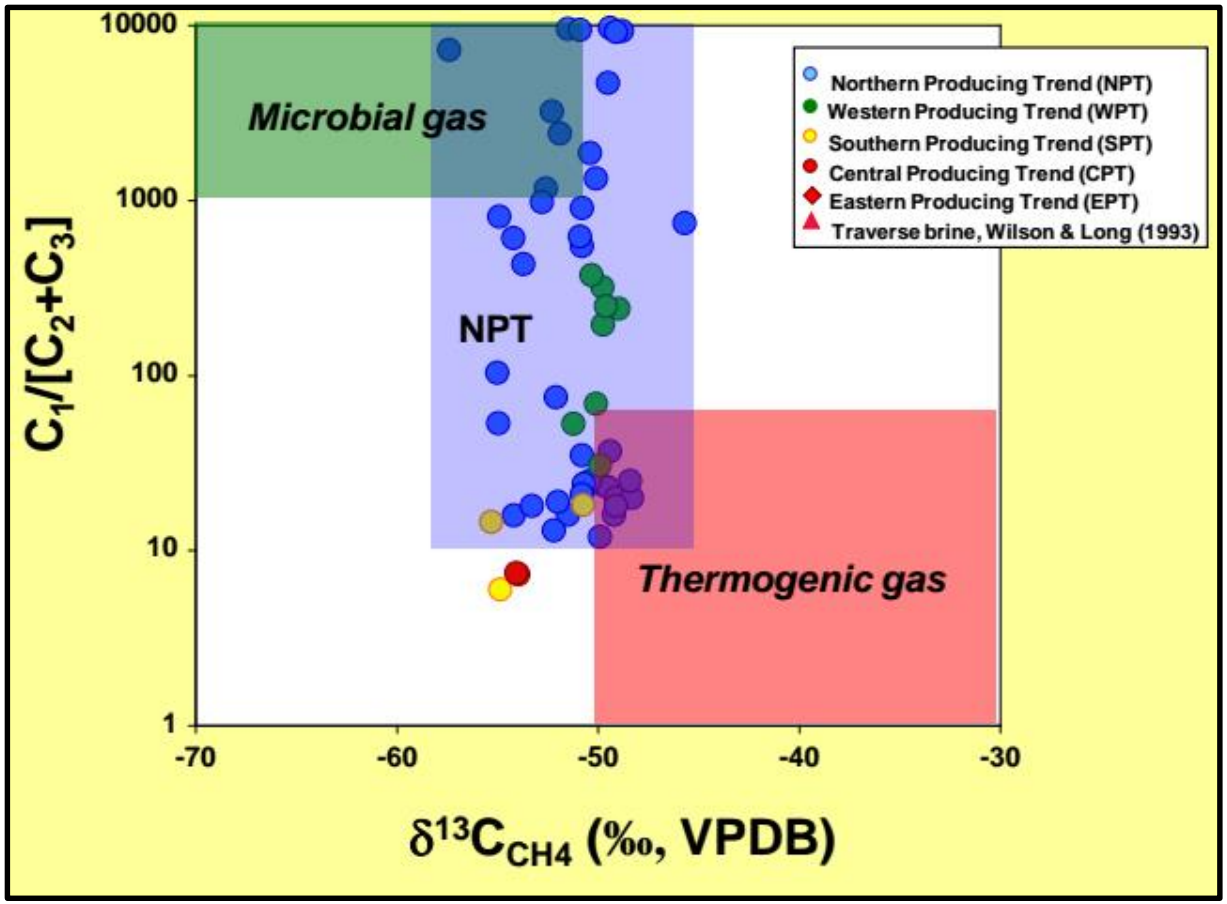
Specific Gravity of Formation Water



Data Source: Muskegon Development Company

Origin of Natural Gas

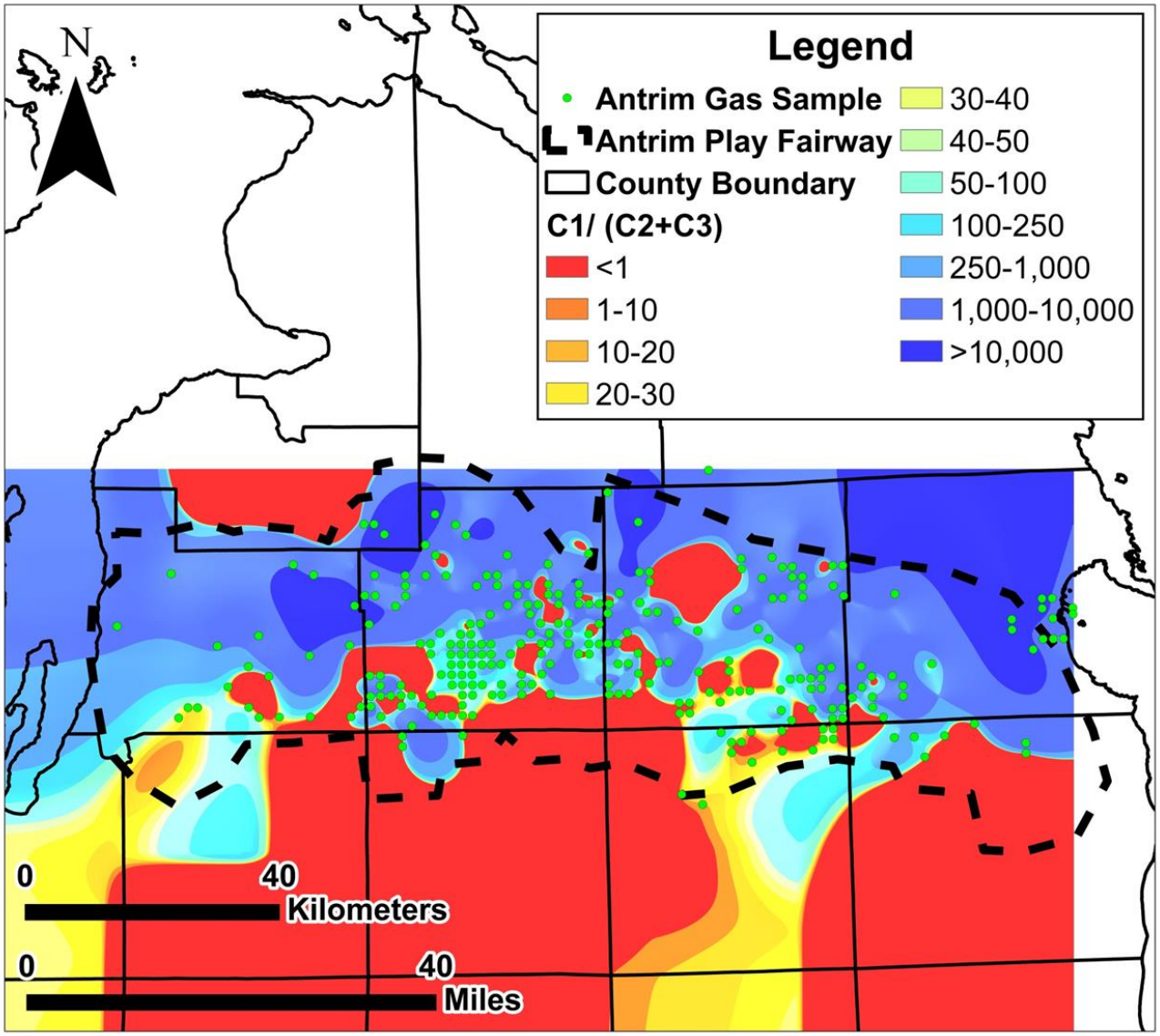
Gas Composition – Interpretation of Gas Origin



Source: Martini et al., 2003, Goodman & Maness, 2008

Origin of Natural Gas

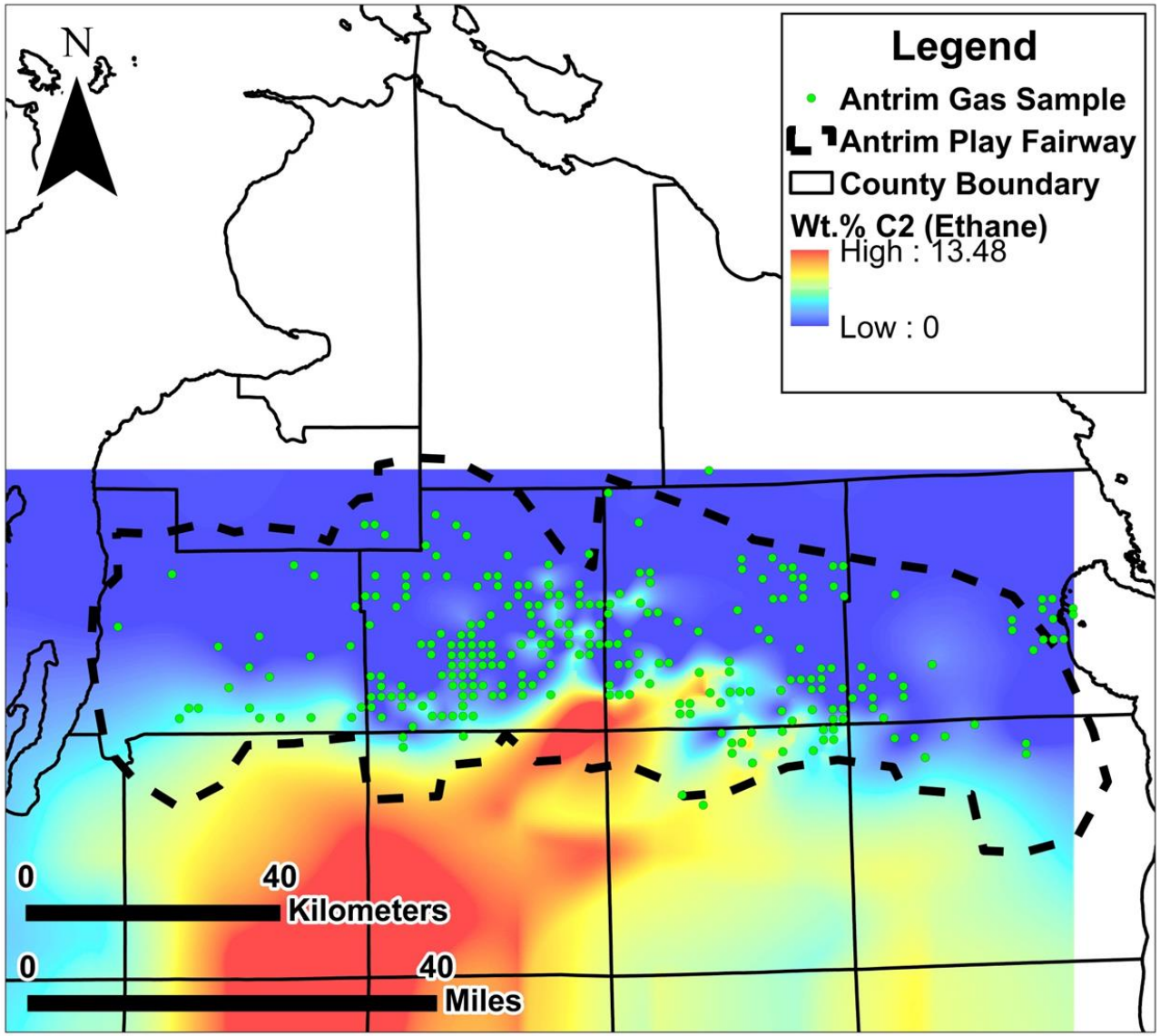
Gas Composition of Antrim Play Fairway



Data Source: MPSC

Origin of Natural Gas

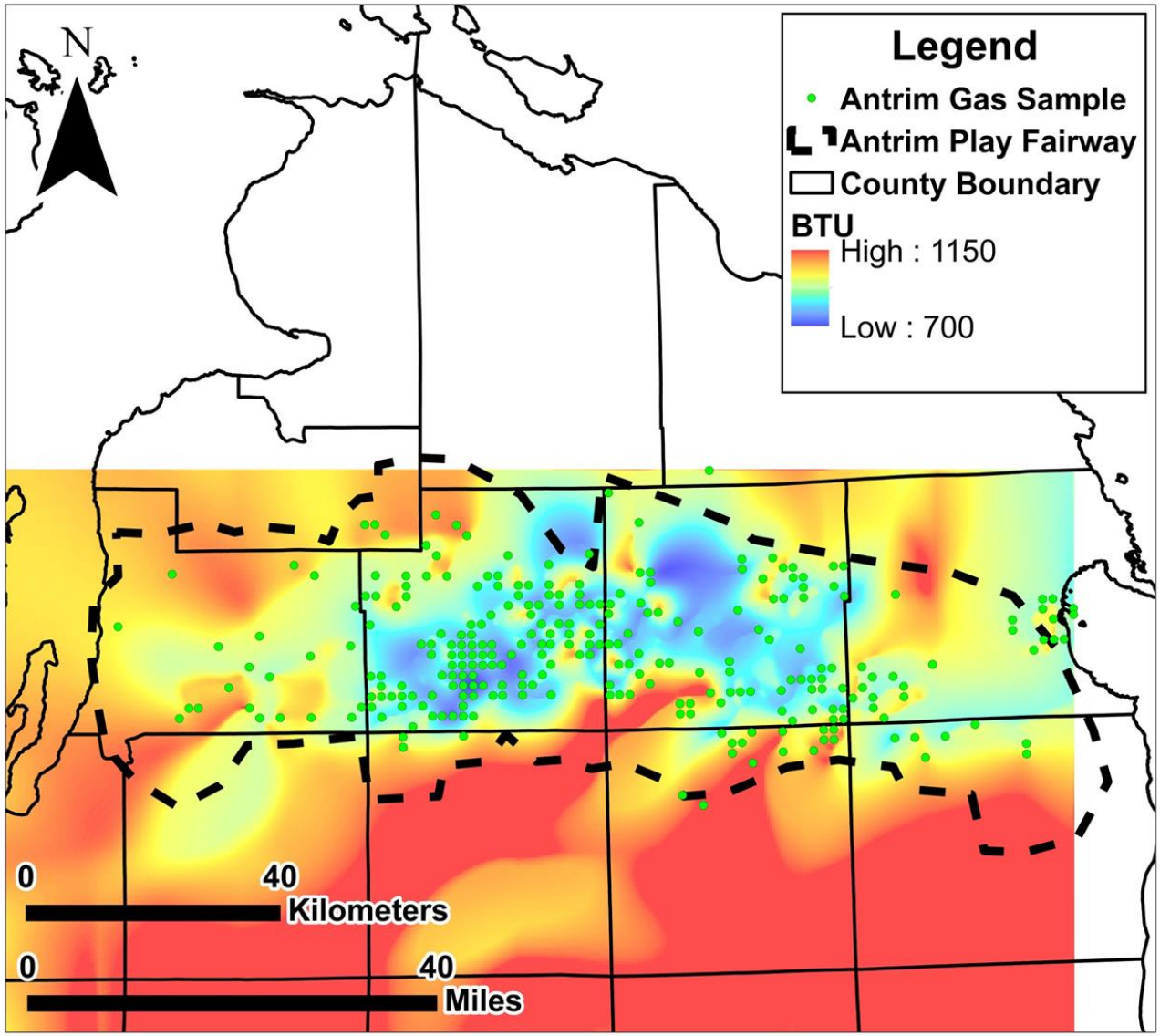
Wt. % Ethane of Antrim Play Fairway



Data Source: MPSC

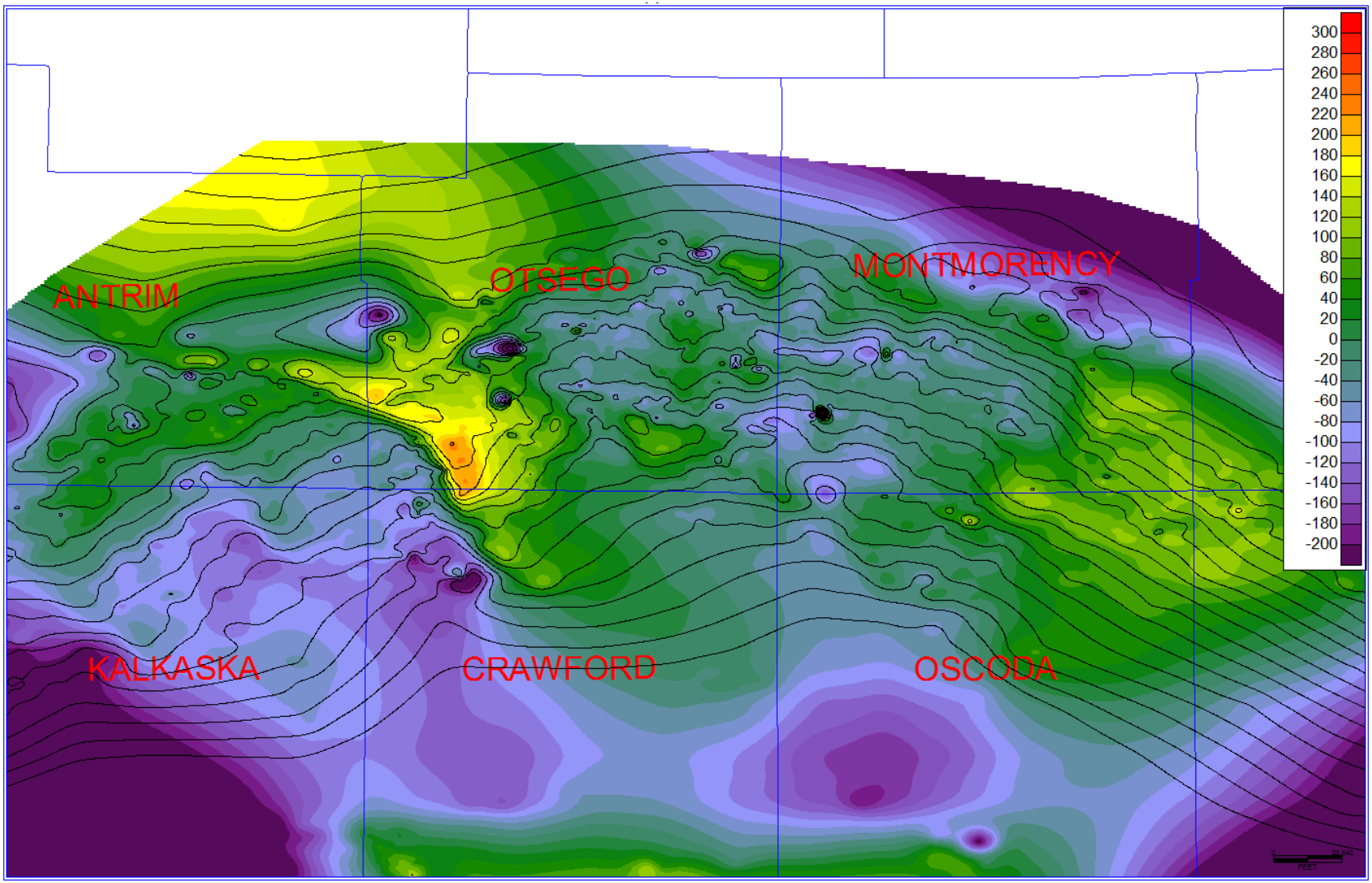
Origin of Natural Gas

BTU of Antrim Play Fairway



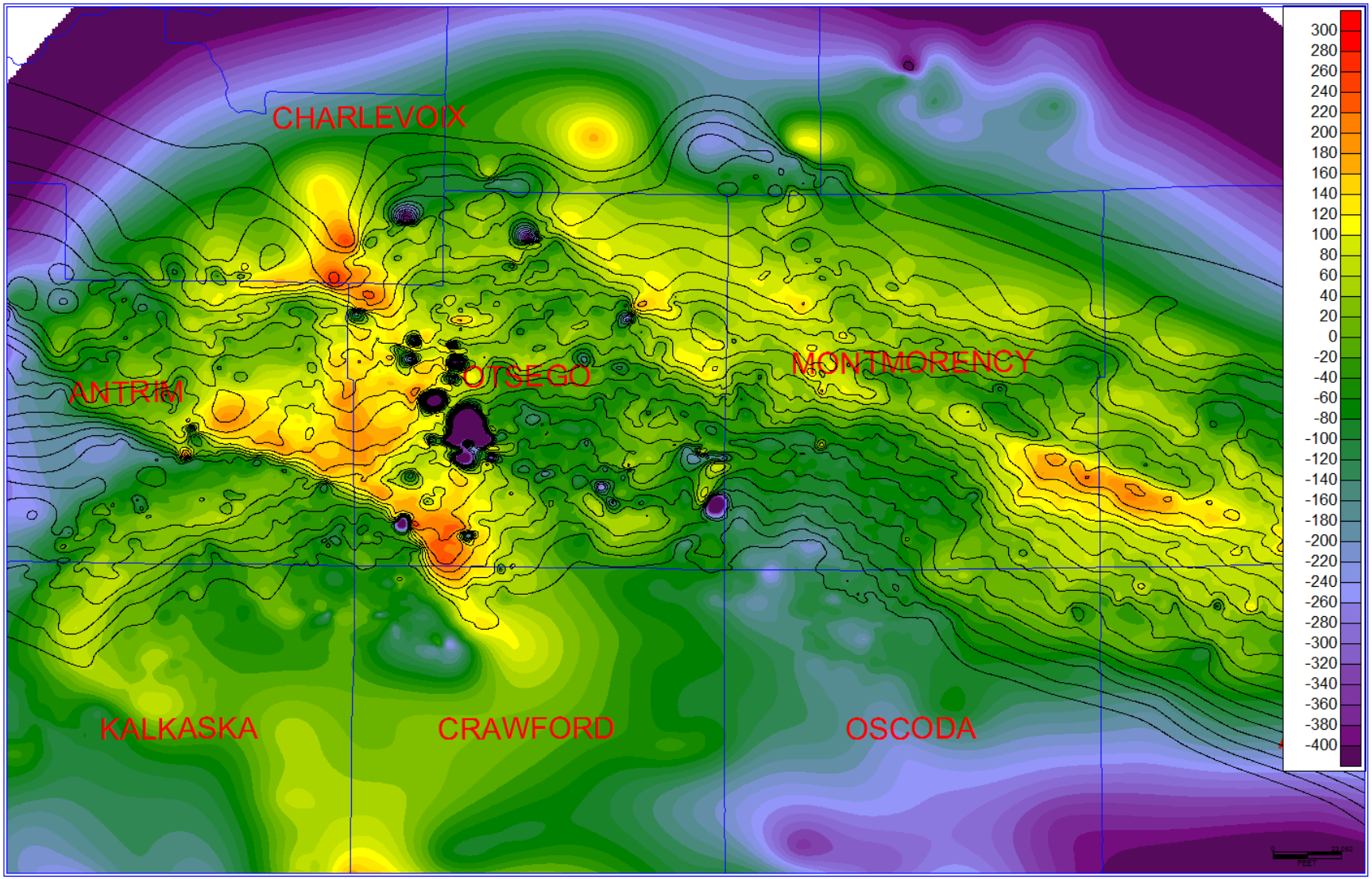
Data Source: MPSC

Migration Pathways



Sunbury Shale—Structure (Contours: 50 ft. Intervals) and 3rd Order Structural Derivative Model (Color Fill: 20 ft. Intervals). Warmer Colors Indicate Positive Relief.

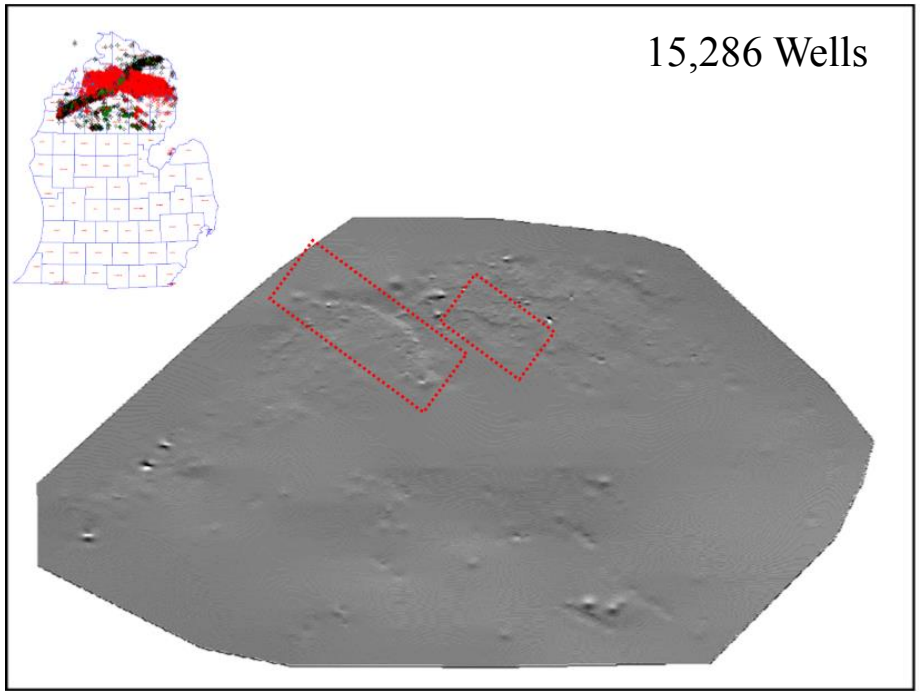
Migration Pathways



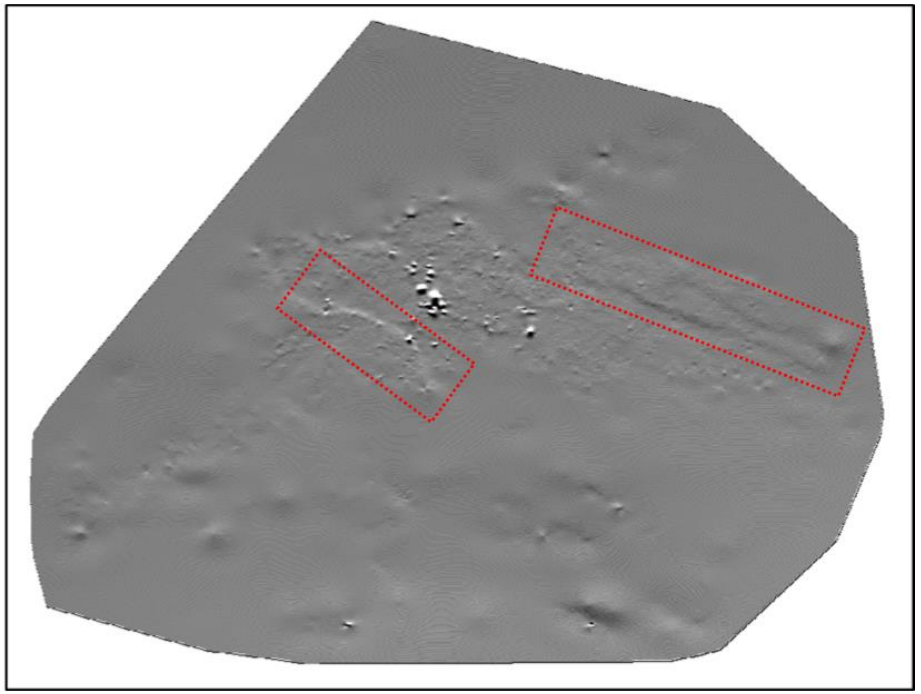
Traverse Limestone—Structure (Contours: 50 ft. Intervals) and 3rd Order Structural Derivative Model (Color Fill: 20 ft. Intervals). Warmer Colors Indicate Positive Relief.

Migration Pathways

Hill Shade (North Lit) – 3rd Order Structural Derivative



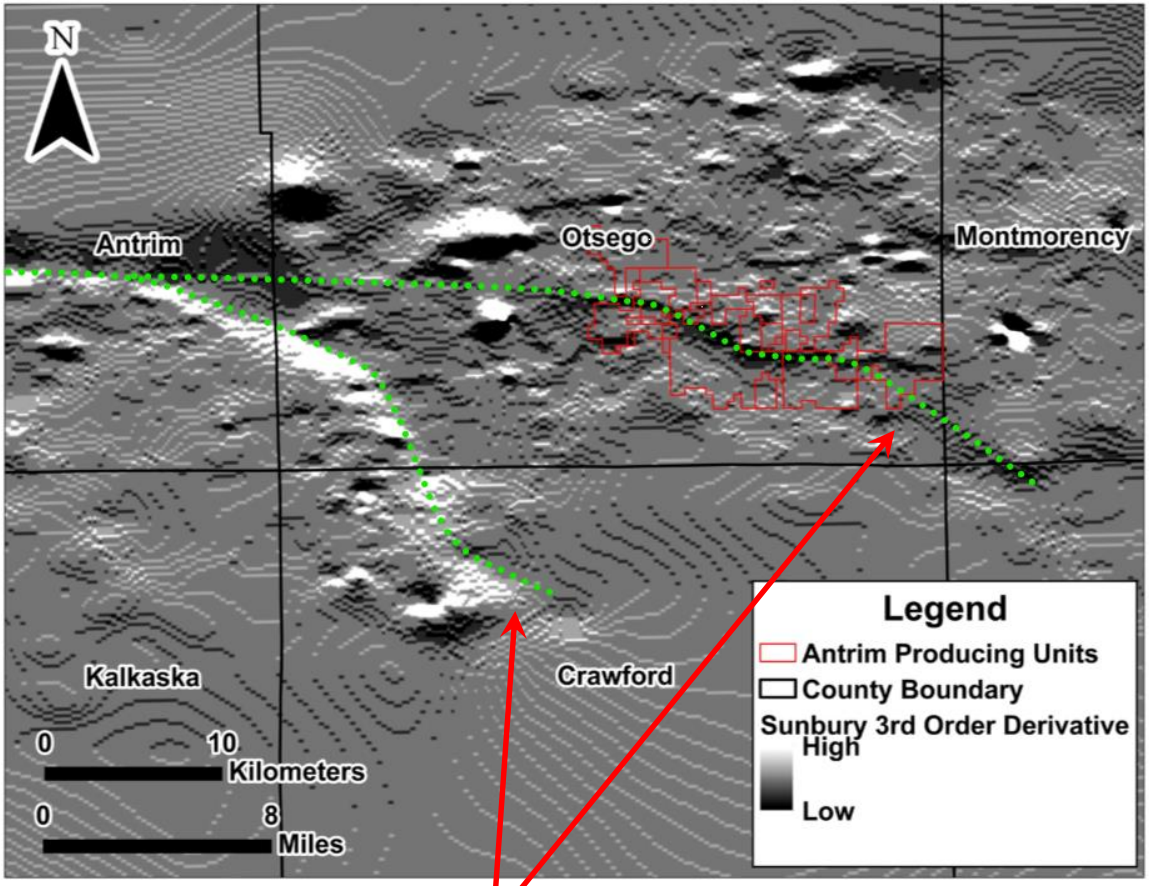
Sunbury Shale—Hill Shade Relief
3rd Order Structural Derivative Model



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

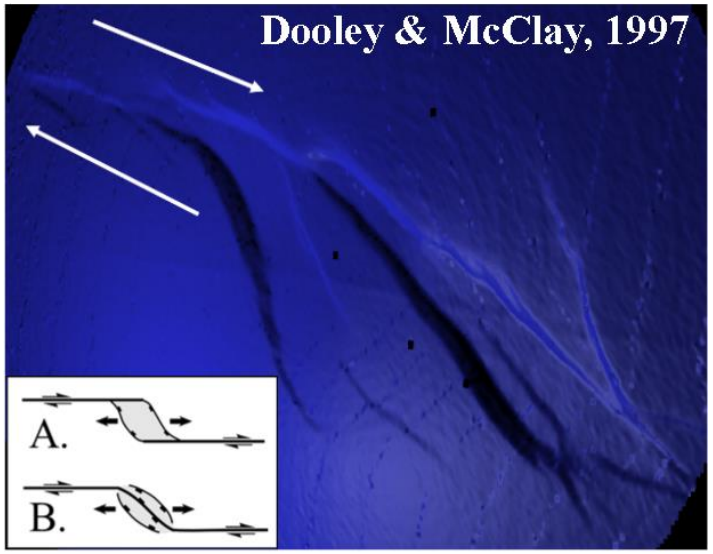
Migration Pathways

Structural Interpretation of Pull-Apart Sub-Basin



Structural Lineaments

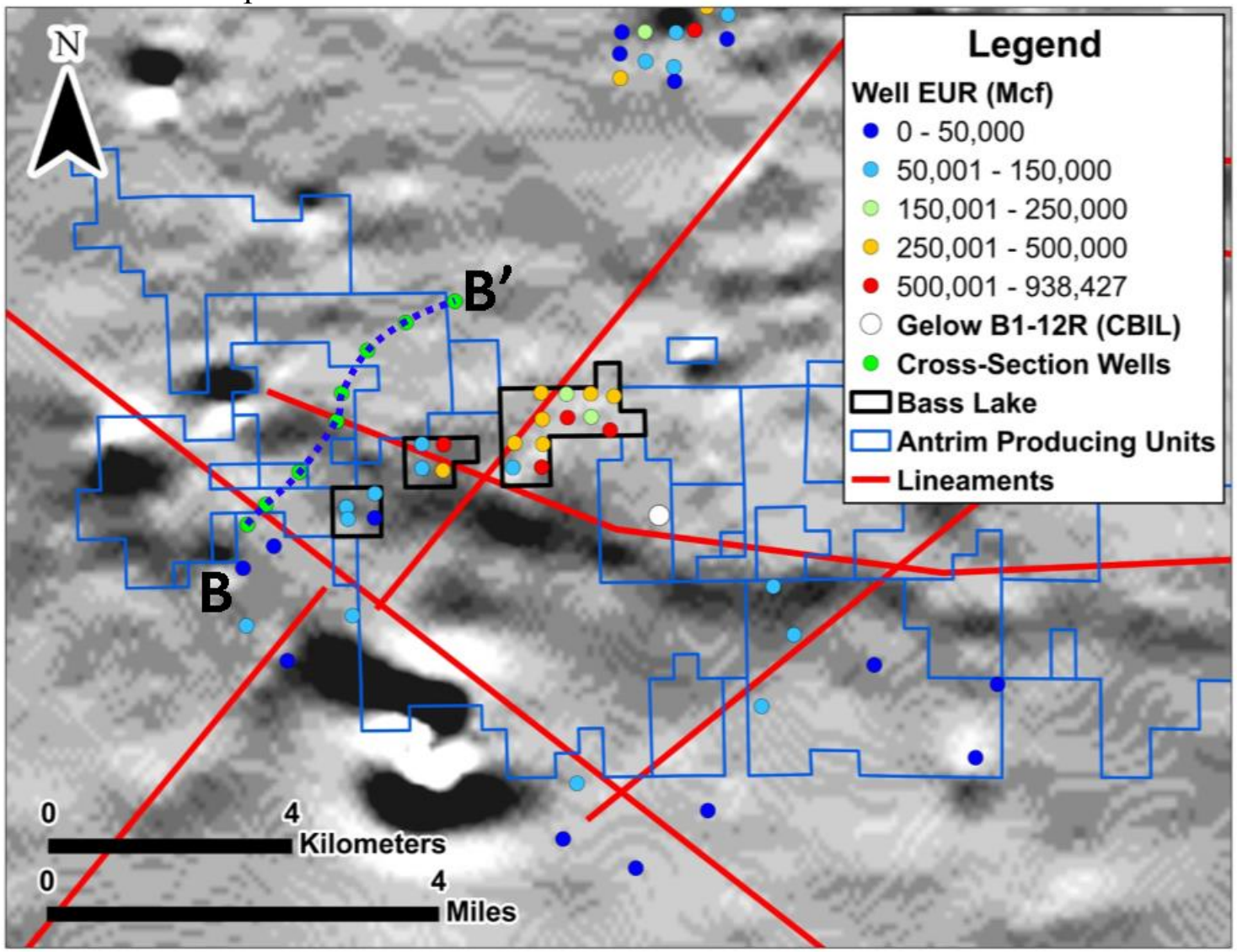
Sand Box Model



Transtensional Pull-Apart Analog

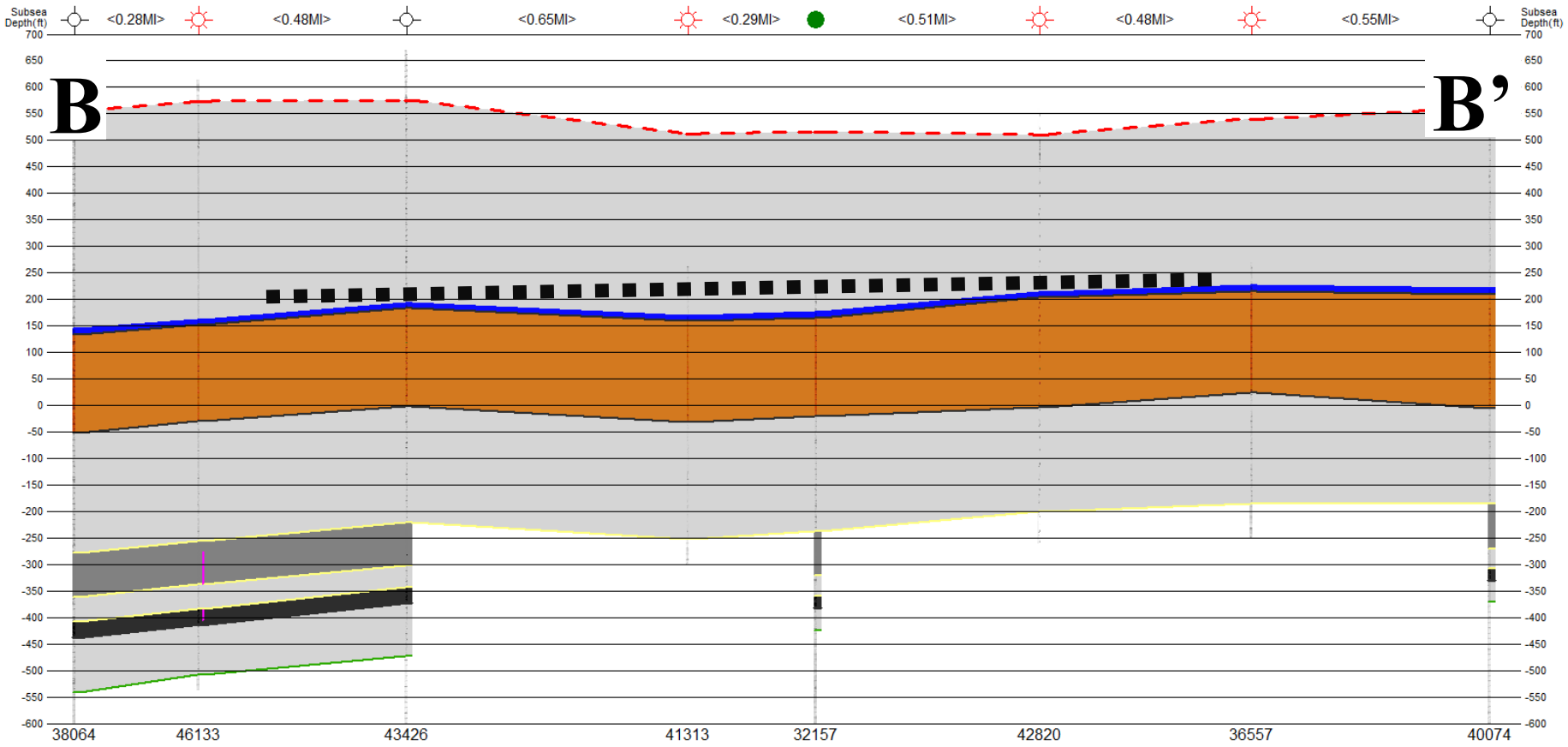
Migration Pathways

EUR/Well in respect to Position on or off Structure



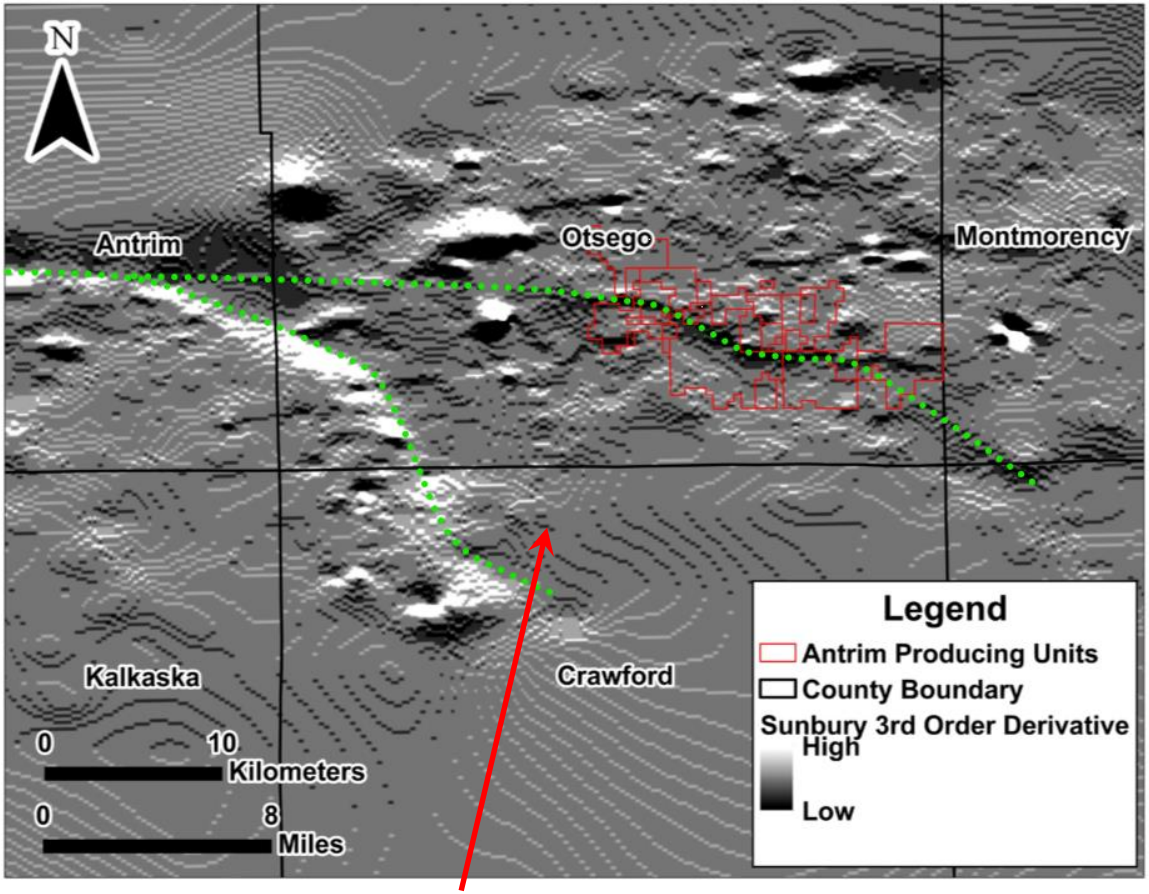
Migration Pathways

Cross Section Across Minor Relief



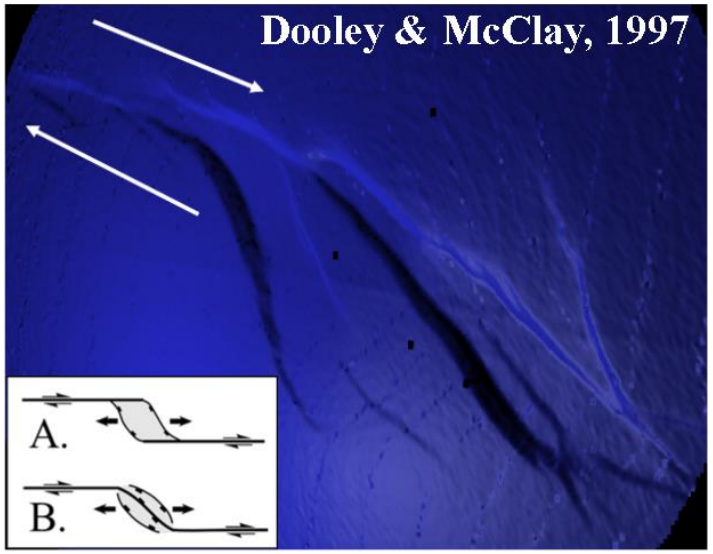
Discussion

Structural Interpretation of Pull-Apart Sub-Basin



Subsidence or Collapse?

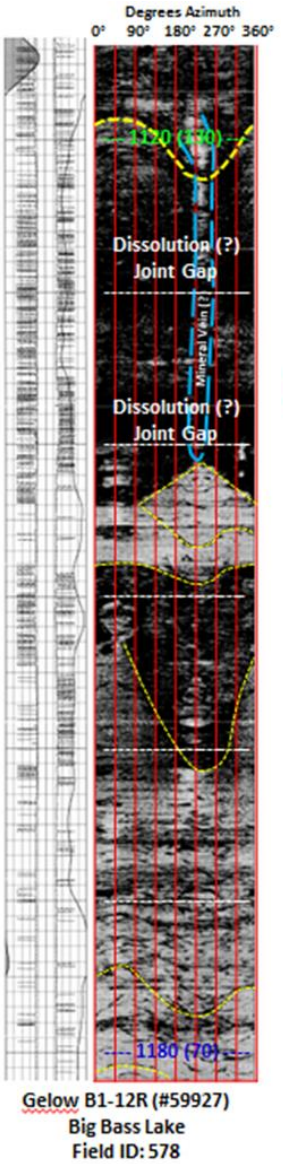
Sand Box Model

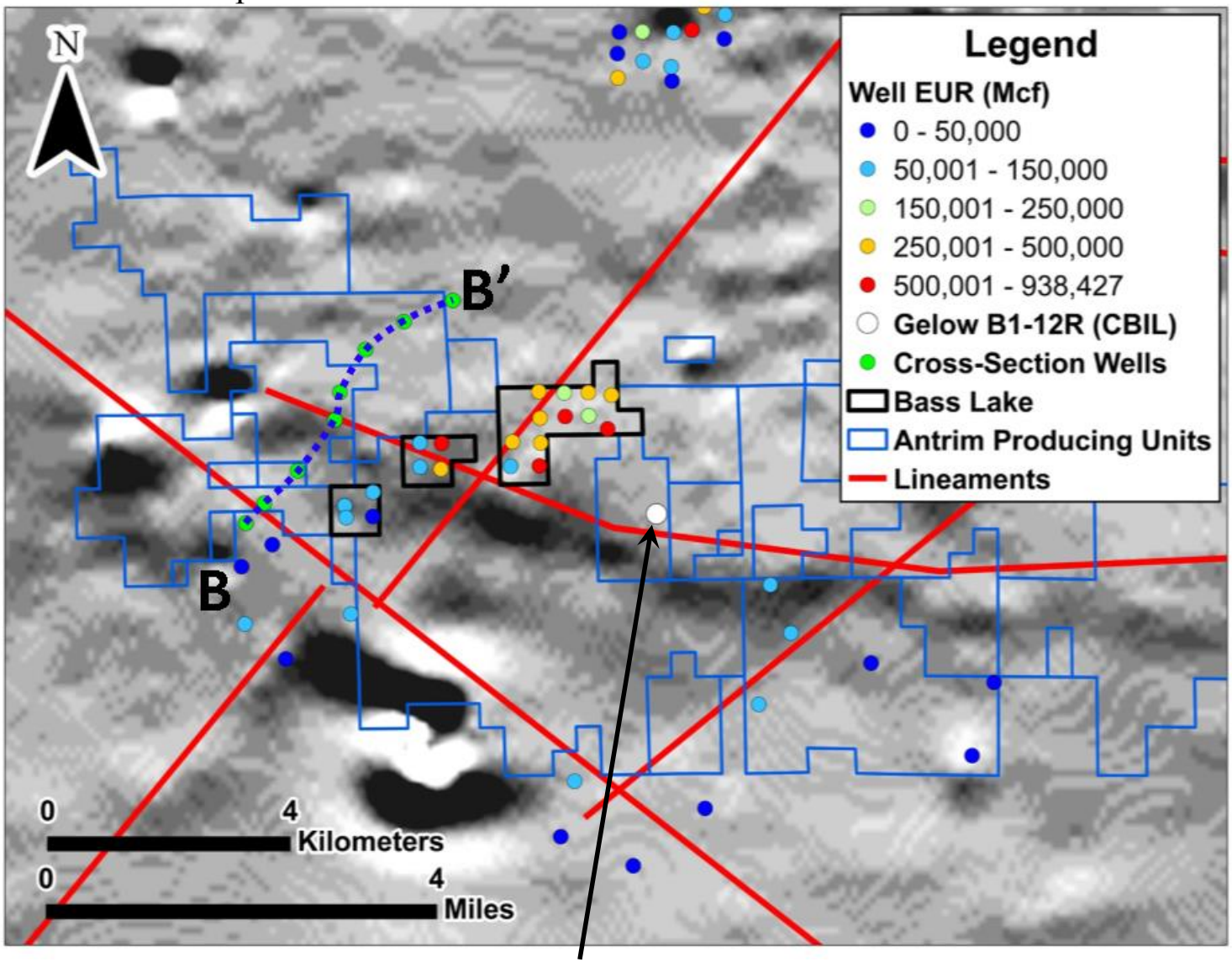


Transtensional Pull-Apart Analog

Discussion

EUR/Well in respect to Position on or off Structure

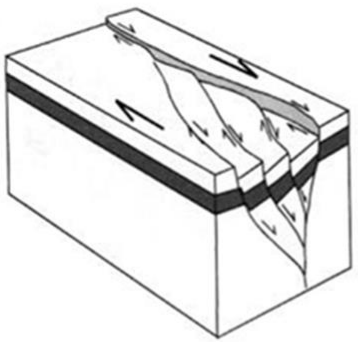


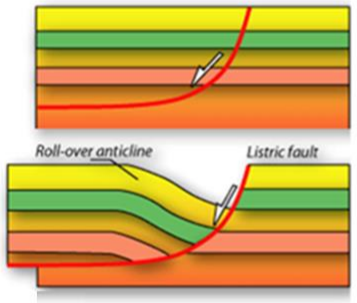


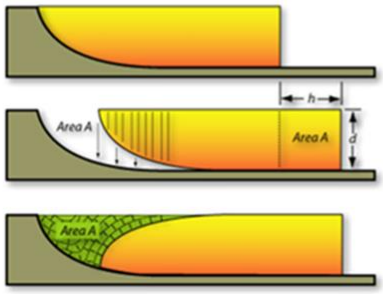
Borehole Imaging Log Location

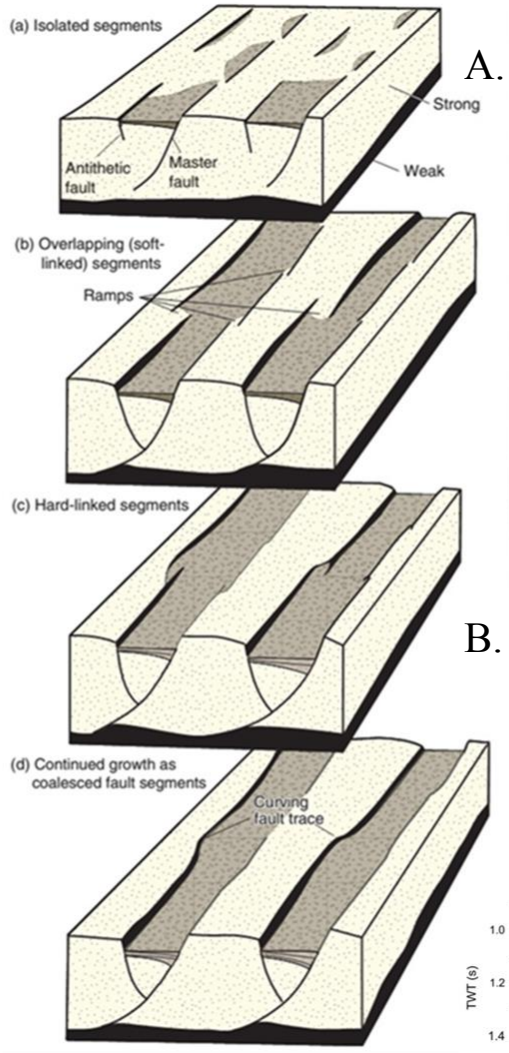
Discussion

Conceptual Model: Listric Faults, Collapse, Fracture Development, Joint Propagation, Gas Migration

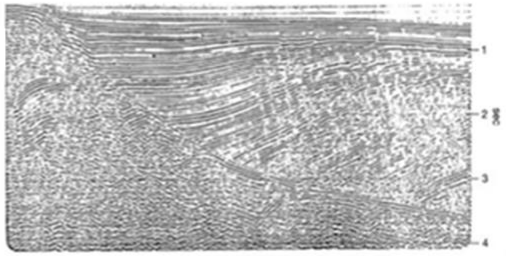


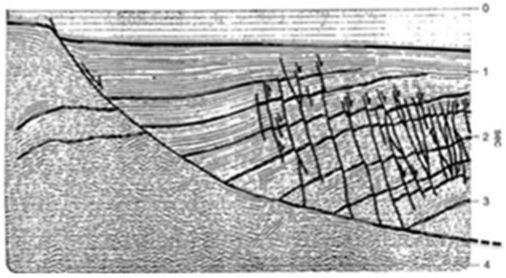






A.





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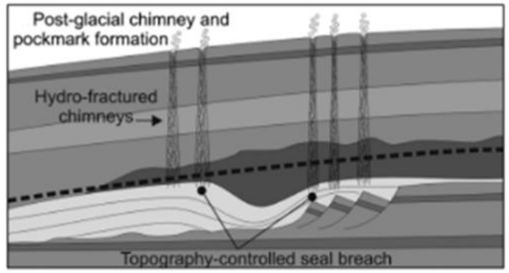
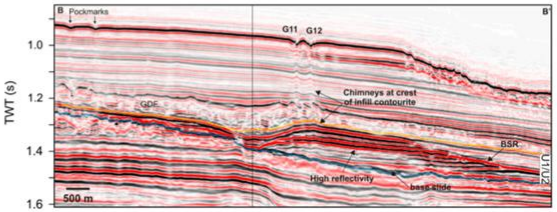
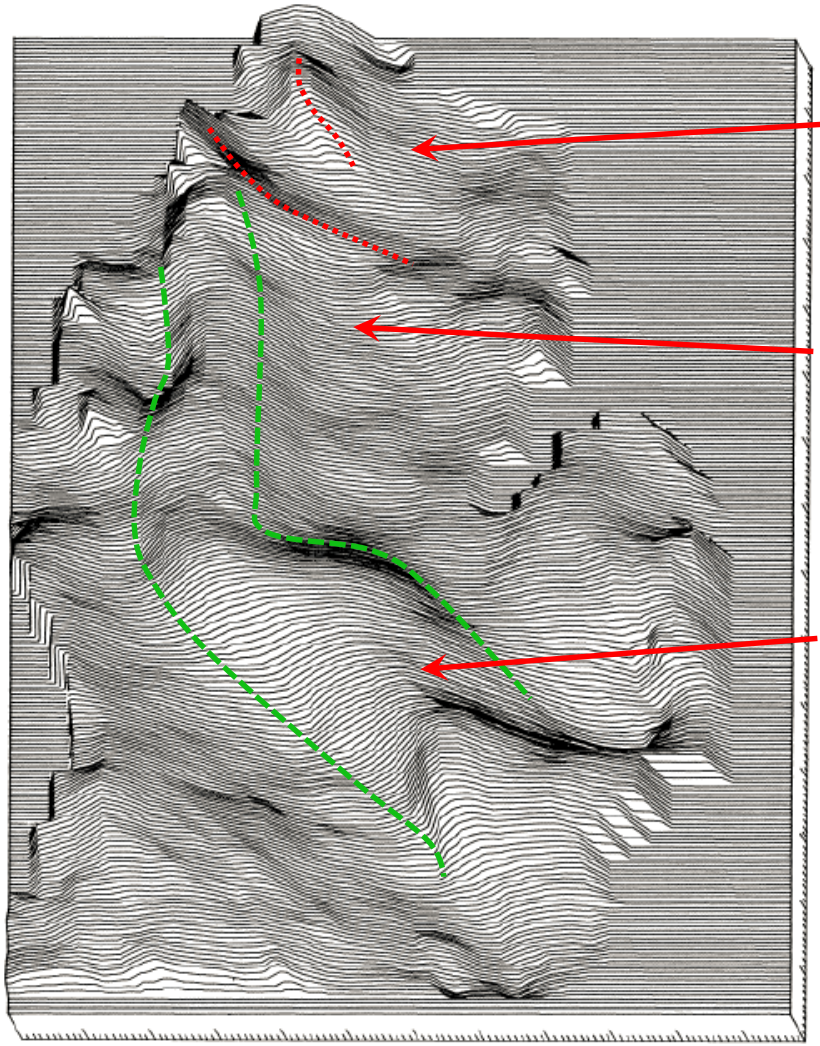




A. Twiss & Moore 2007; B. Hustoft et al., 2010

Discussion



Relief Model - Bouguer Gravity Anomaly
Line of Sight N 30° W, Inclination of 45°

Source: Hinze, 1971

Conclusion

- 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?

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