Unconventional Resource Play Potential of the Pennsylvanian Leo/Minnelusa Formations of the Powder River and Denver Basins: A Perspective via Integrated Petroleum Systems Analysis*

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Abstract

A successful unconventional resource play is often linked to commercial conventional plays; typically an unconventional source/reservoir contains petroleum of variable saturation in a mixed lithology of fine-grained siliciclastics, variable amount of carbonate, and mature organic matter deposited in a marine environment such as the Wolfcamp play in the Permian Basin and the Eagle Ford play in Texas. Based on regional understanding of stratigraphy and structural geology and a review of historical petroleum production data, our basin-scale screening efforts identified the Pennsylvanian Leo/Minnelusa Formations and equivalents of the Powder River and Denver Basins with potential for an unconventional resource play. While our evaluation is multi-disciplinary and integrated; in this presentation we focus on petroleum systems analysis including the evaluation of source potential and maturity, bulk and molecular properties of reservoir fluid and source rock (SR) extracts, 3D burial history model, reservoir pressure/temperature and PVT considerations for the purpose of evaluating reservoir fluid deliverability.

We utilized a large database of historical data, including conventional oil and gas production, formation tops of more than 64,000 wells, core analyses, wireline logs, geochemistry analyses, pressure and temperature data, about 800-mile of 2D seismic interpreted with 20 synthetic ties, and relevant published literature. We analyzed basin-scale variation in SR organofacies and maturity, bulk and molecular properties of SR extracts and reservoir fluids and we built a 3D burial history model which

includes multiple stratigraphic horizons, uplift/erosion and spatially-variant temperature gradients. We then calibrated the model to observed basin-scale trends in hydrogen index (HI) data and the published maturity map (Ro equivalent) for the data-rich shallower Mowry interval of Cretaceous age.

Our integrated evaluation identified high-quality and mature source rock and our calibrated 3D burial history model predicts a large area with desirable maturity for the Leo/Minnelusa Formations in the Powder River and Denver Basins. However, individual source beds in the Leo/Minneulsa Formations are thin and OM-related porosity is volumetrically insignificant. While we interpret the bulk of petroleum fluids in the Leo/Minnelusa Formations likely of the same origin, the observed variability in fluid properties (bulk and molecular) appears to be at "disequilibrium" with predicted maturity. We interpret such dis-equilibrium as the result of effective lateral migration from the basin center to basin margin and we perceive limited basin-wide retention of petroleum of in-situ maturity within the Leo/Minnelusa Formations (which is confirmed by petrophysics interpretations of 20 wells in the Powder River and Denver Basins). The reservoir pressure generally is at or below hydrostatic condition, consistent with observed porosity vs. permeability data and the aforementioned interpretation of effective lateral petroleum migration. We believe the stratigraphic architecture and the Laramide-related uplift and erosion may have contributed to basin-scale dissipation of pressure and/or petroleum distribution; and that such factors collectively may have rendered the Leo/Minnelusa Formations in the Powder River and Denver Basins ineffective for a viable basin-scale unconventional resource play.

References Cited

Higley, D.K., D.O. Cox, and R.J. Weimer, 2003, Petroleum System and Production Characteristics of the Muddy (J) Sandstone (Lower Cretaceous) Wattenberg Continuous Gas Field, Denver Basin: Colorado: American Association of Petroleum Geologists Bulletin, v. 87/1, p. 15-37.

Higley, D.K., R.R. Charpentier, T.A. Cook, T.R. Klett, R.M. Pollastro, J.W. Schmoker, and C.J. Schenk, 2003, 2002 USGS Assessment of Oil and Gas Resource Potential of the Denver Basin Province of Colorado, Kansas, Nebraska, South Dakota, and Wyoming: U.S. Geological Survey Fact Sheet 002-03, 3 p.

Modica, C.J., and S.G. Lapierre, 2012, Estimation of Kerogen Porosity in Source Rocks as a Function of Thermal Transformation: Example from the Mowry Shale in the Powder River Basin of Wyoming: American Association of Petroleum Geologists Bulletin, v. 96/1, p. 87-108.

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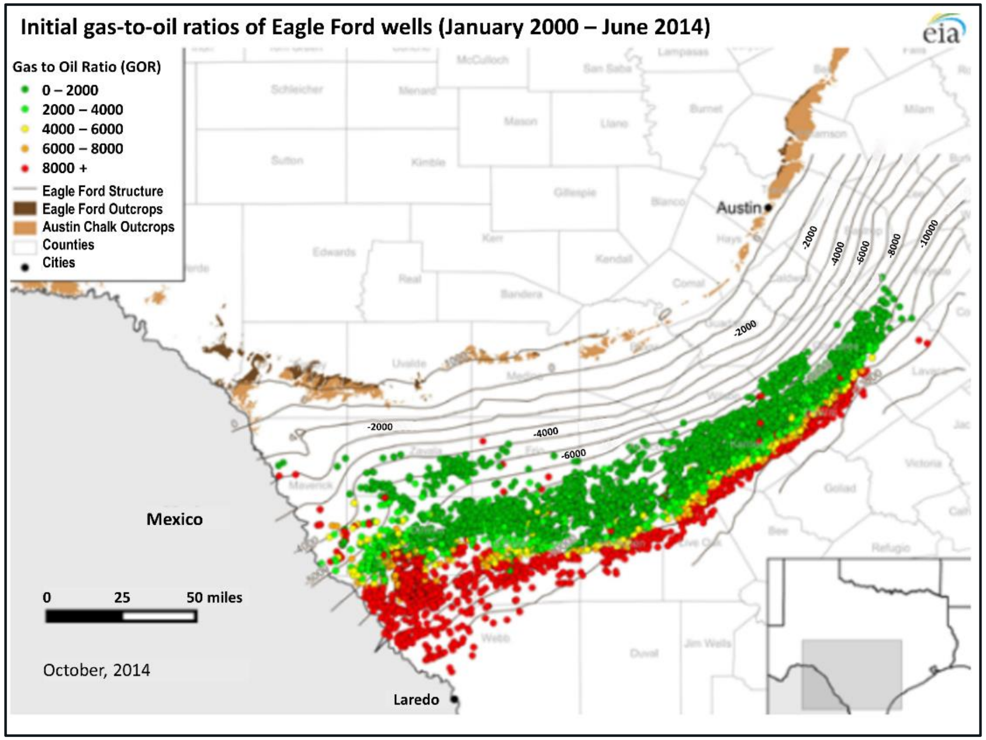
Outline

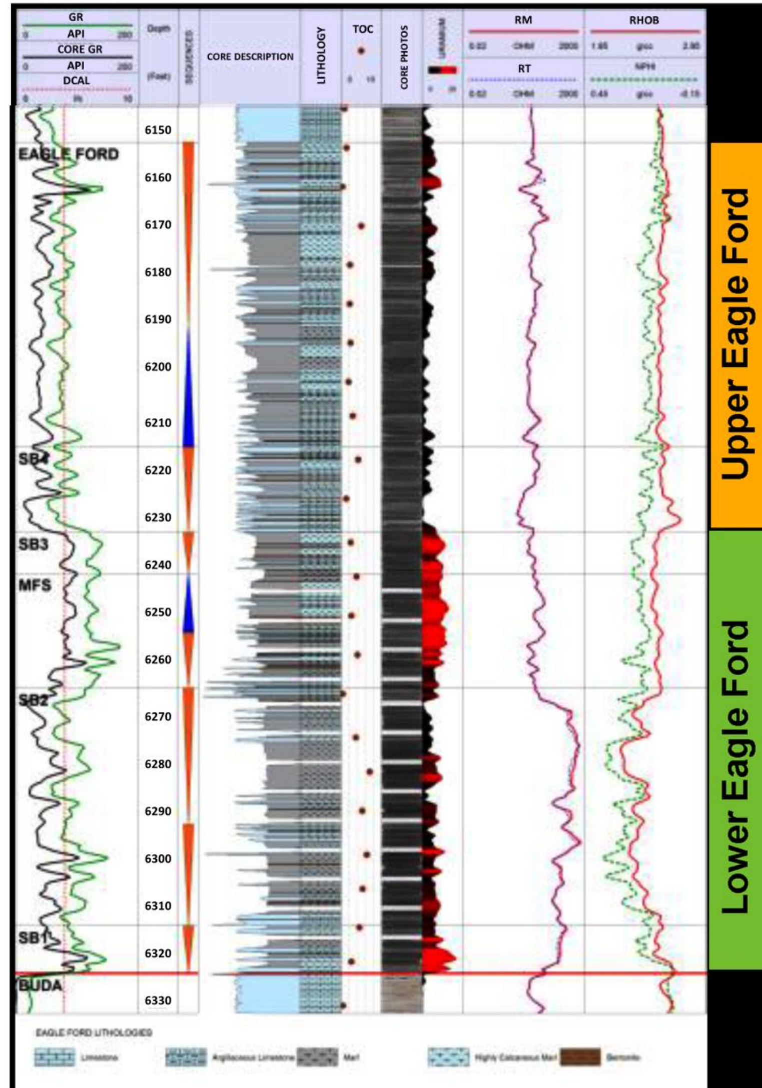
- **Introduction to the Workflow**
- **Unconventional Resource Play Potential of the Minnelusa FM (& equivalents)**
- **Source Potential and Maturity**
- **3D Burial History Model**
  - Model input
  - Model calibrations (HI & Ro equivalents)
  - Predicted maturity & reservoir fluid property
- **Reservoir Pressure (energy) & Reservoir Architecture**
- **Predicted Liquid Producibility**
- **Summary & Conclusion**

Key Attributes of the Eagle Ford Unconventional Resource Play



Source: U.S. Energy Information Administration and Drillinginfo Inc.

Note: EIA calculates the initial gas-to-oil ratio for each well using the 2nd through 4th contiguous months of liquid and/or gas production. GORs are expressed as cubic feet per barrel (cf/bbl). The first month of production may not represent full production and thus is not included in the initial GOR calculation.



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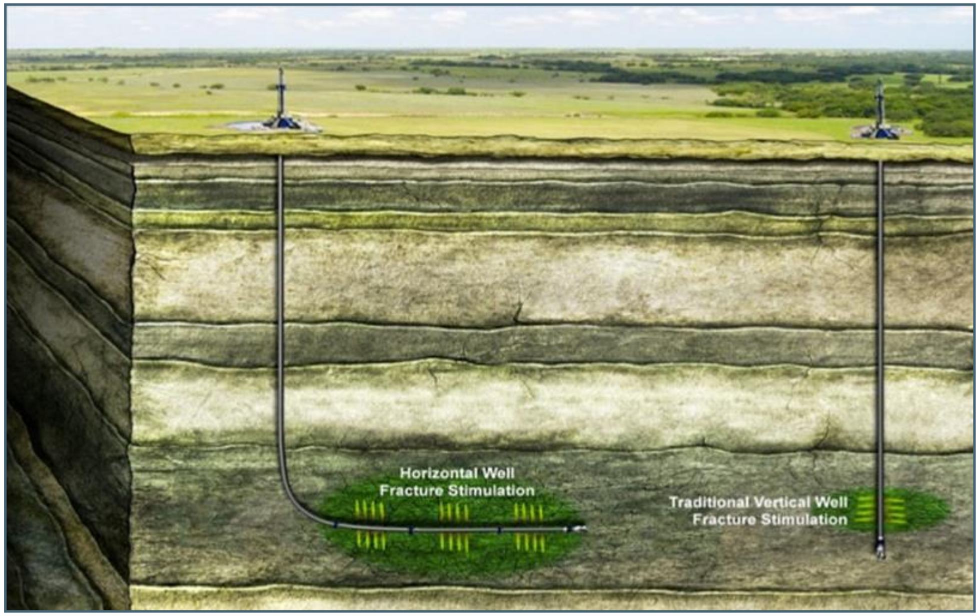
A Workflow for Evaluating Unconventional Resource Plays

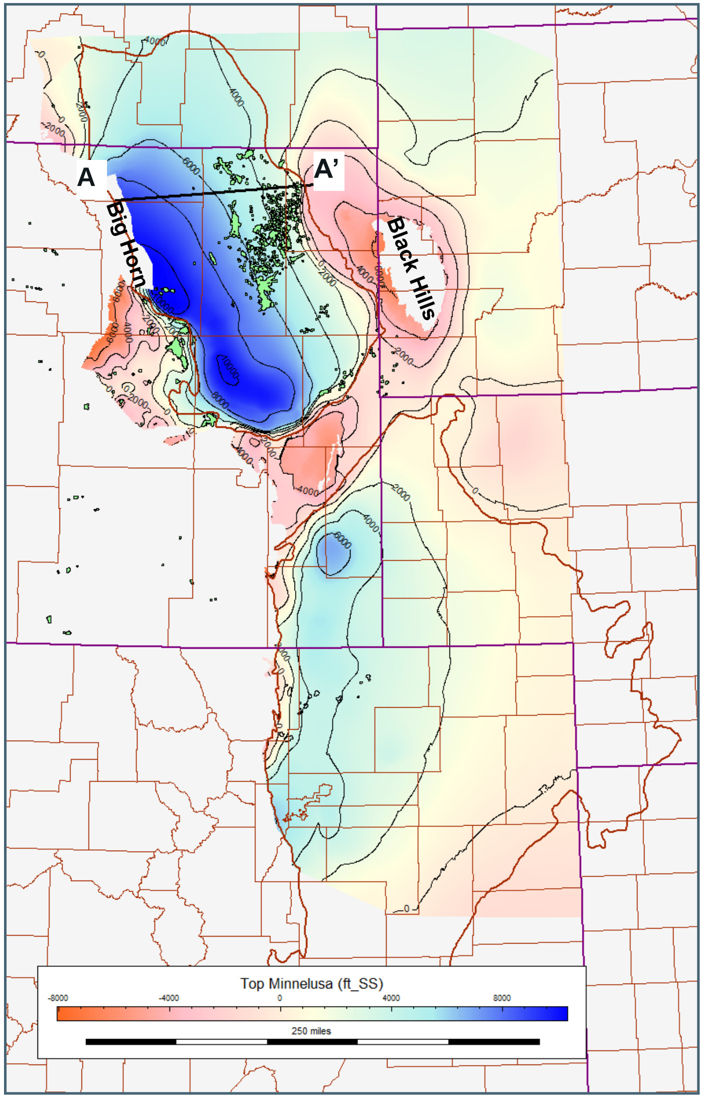
- **Resource in-place (Storage; Rs)**
  - OOIP/OGIP (So * ϕ * h * Area)
  - *Sorbed* vs. *fluid* phase storage
- **Reservoir deliverability (Rd)**
  - Reservoir & fluid properties: thickness & permeability (k); GOR & viscosity
  - Reservoir energy: pressure and/or overpressure; PVT considerations
- **Optimizing completion design (Rf)**
  - Maximize exposure to reservoir via long laterals
  - Enhance connectivity & k (effective drainage area) via hydraulic fracturing

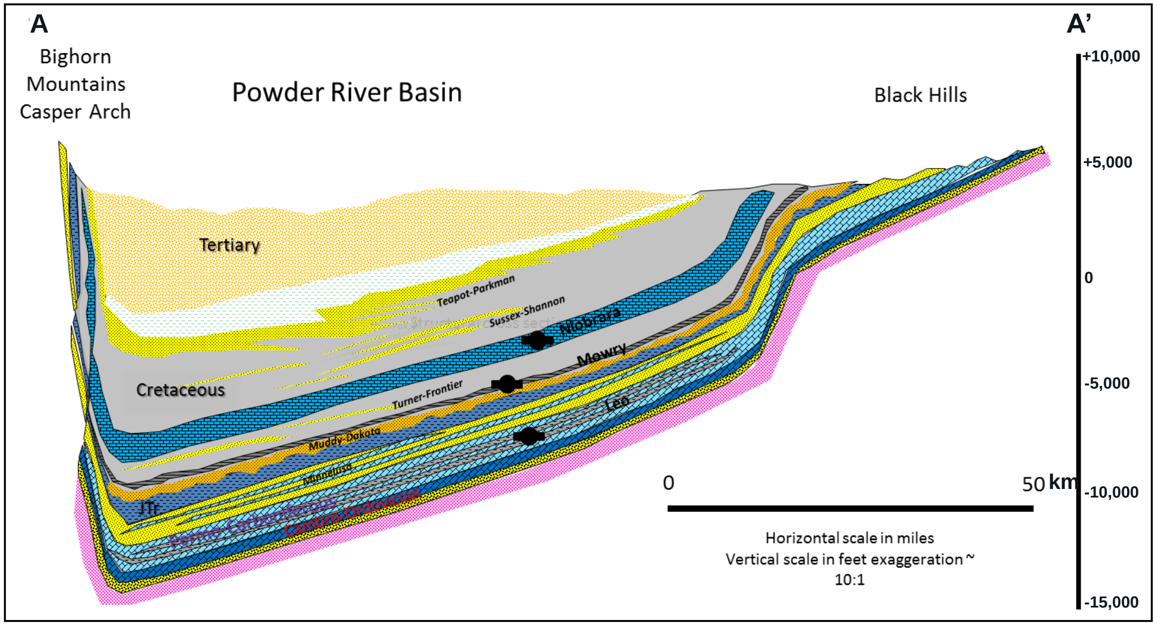


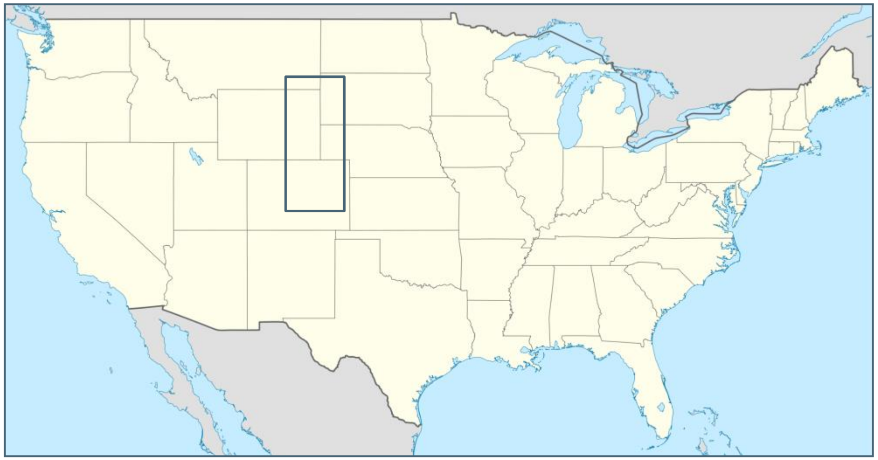
$$\text{Storage} = \frac{\text{phi} * h * (1 - S_w)}{\text{FVF}}$$

$$\text{Liquid Producibility} = \frac{k * h * \Delta P * \text{OMF}}{\mu}$$

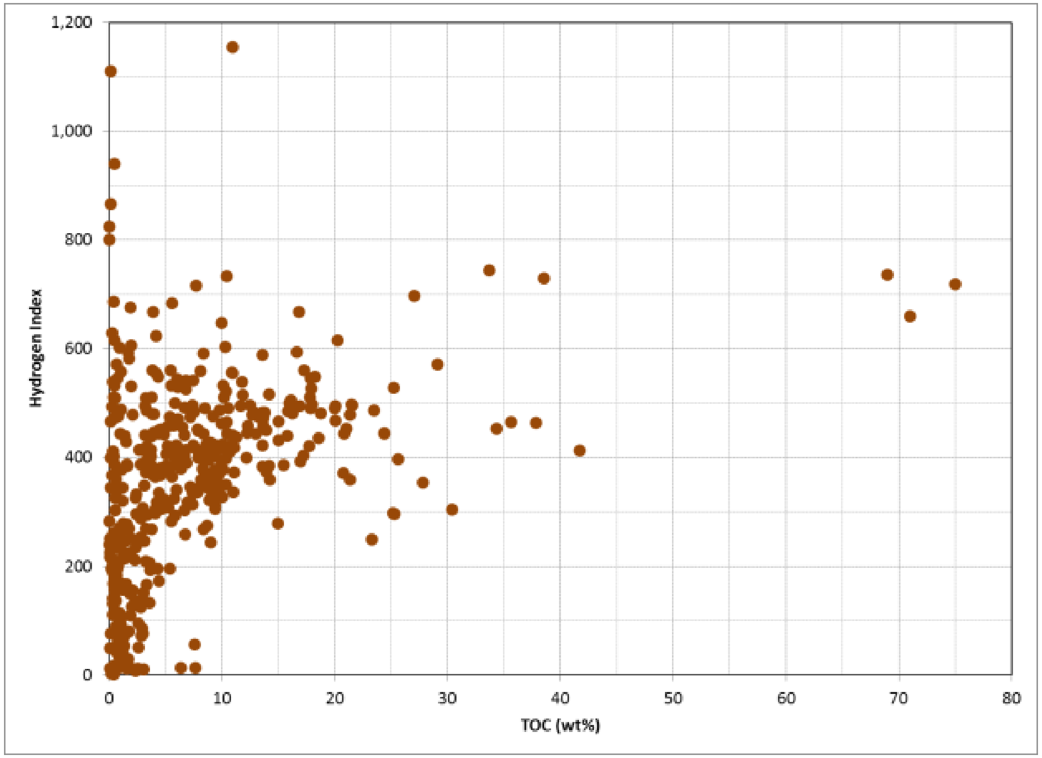
Introduction to the Powder River Basin and the Minnelusa FM

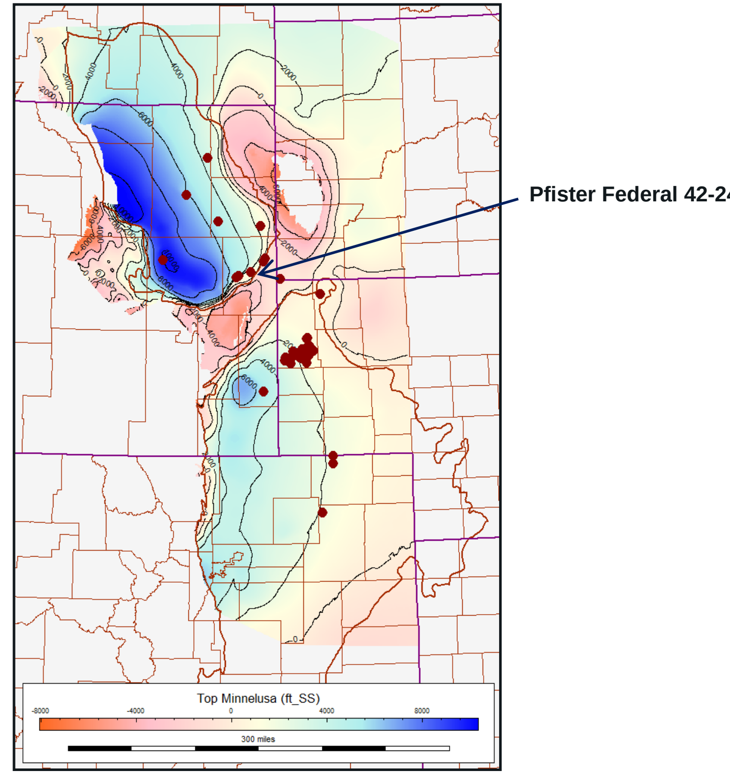




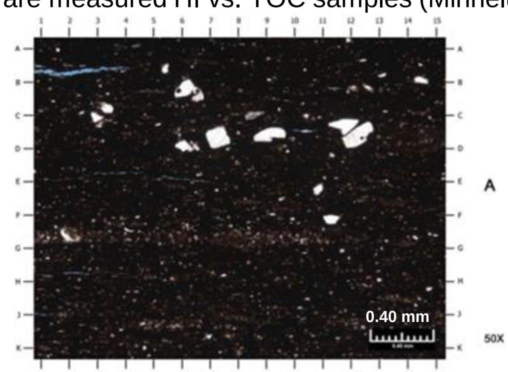


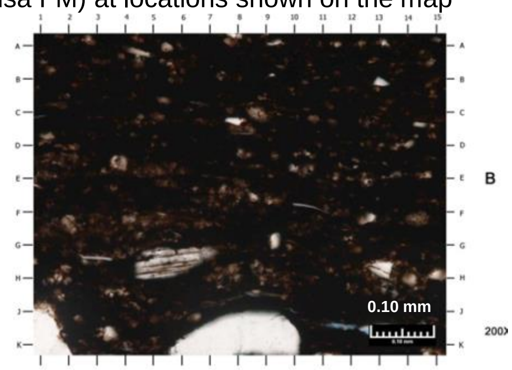
Source Potential & Maturity (Minnelusa FM)

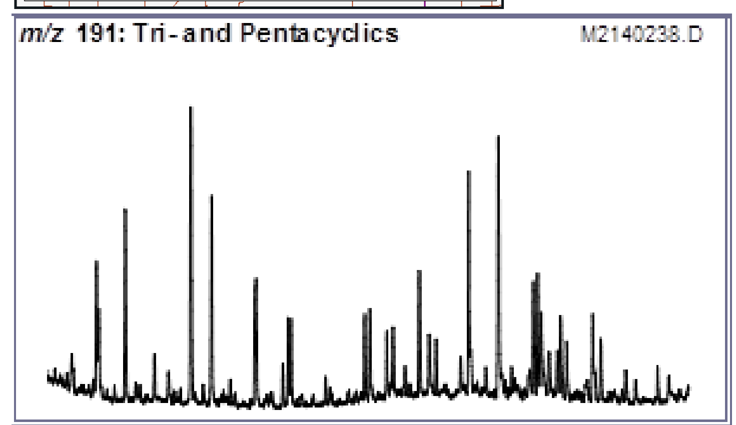




BHPB SR/Fluid Database: Brown color filled circles, on the cross-plot and the map, are measured HI vs. TOC samples (Minnelusa FM) at locations shown on the map

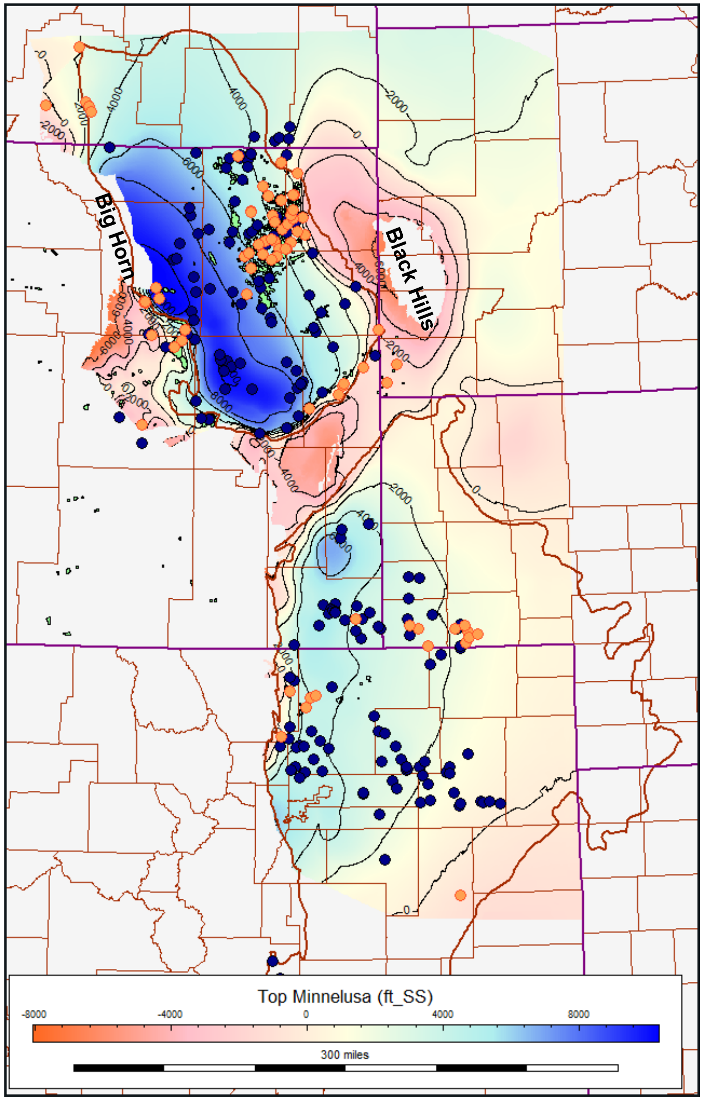


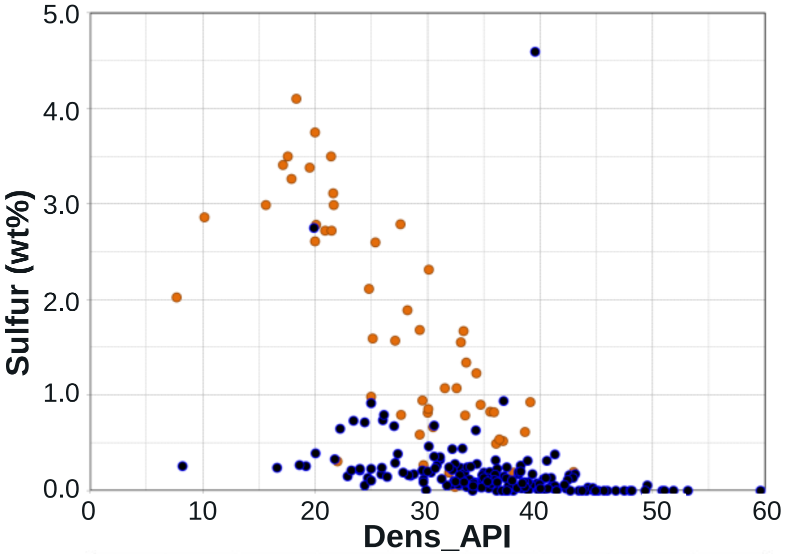


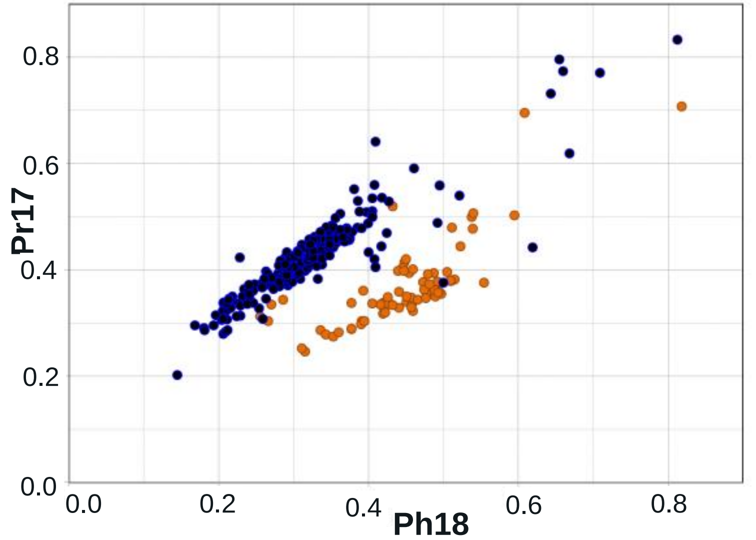


Pfister Federal 42-24; 3,407.40
Image Source: USGS

Genetic Correlation of Oils



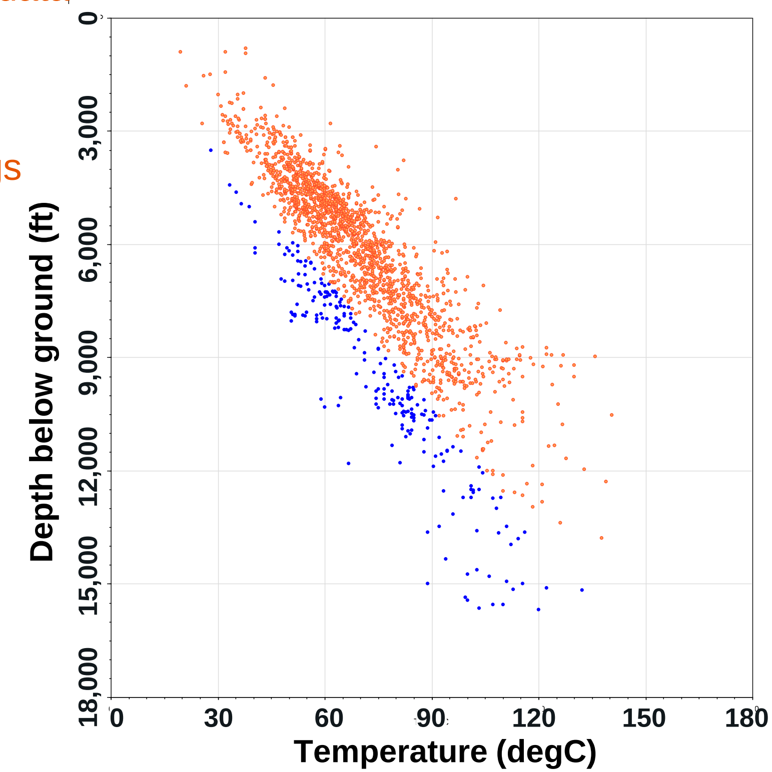


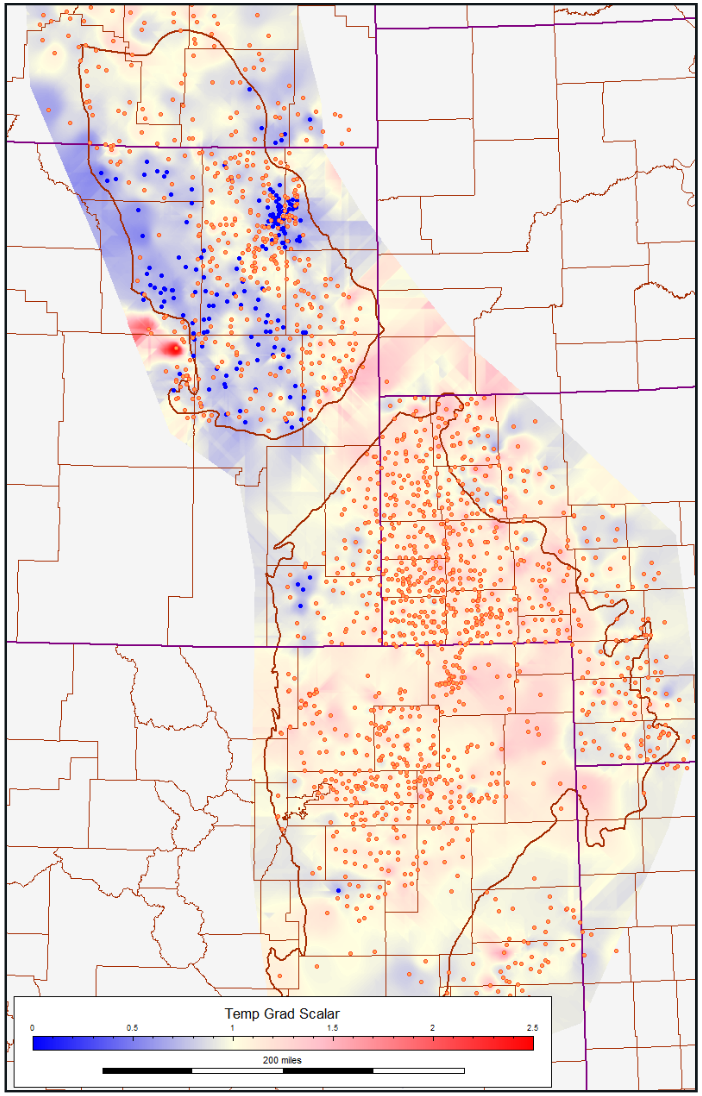


Blue & orange color filled circles are Sulfur (wt%) vs. API gravity of oils (upper chart) and Pr17 vs. Ph18 (lower chart) on cross-plots & map

An Integrated 3D Burial History Model

- 15 structure maps (64,000+ FM tops)
- Subsurface pressure & temperature data (Nehring Associates)
- SR & fluid geochemistry data
- Production data
- 2D seismic
- Wireline logs

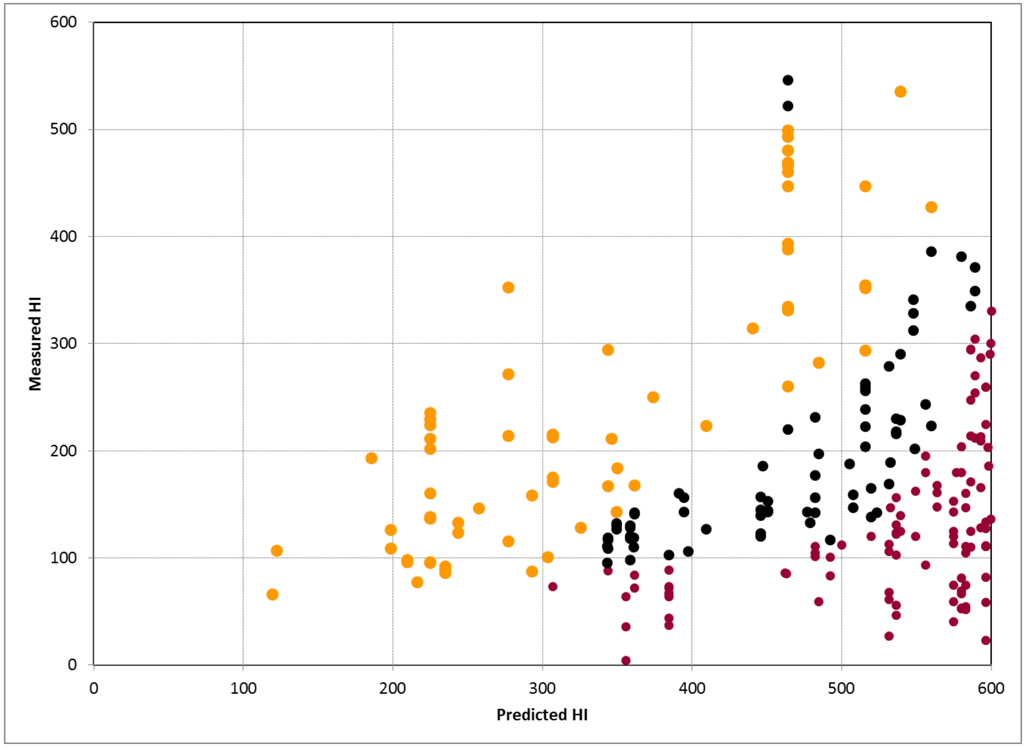


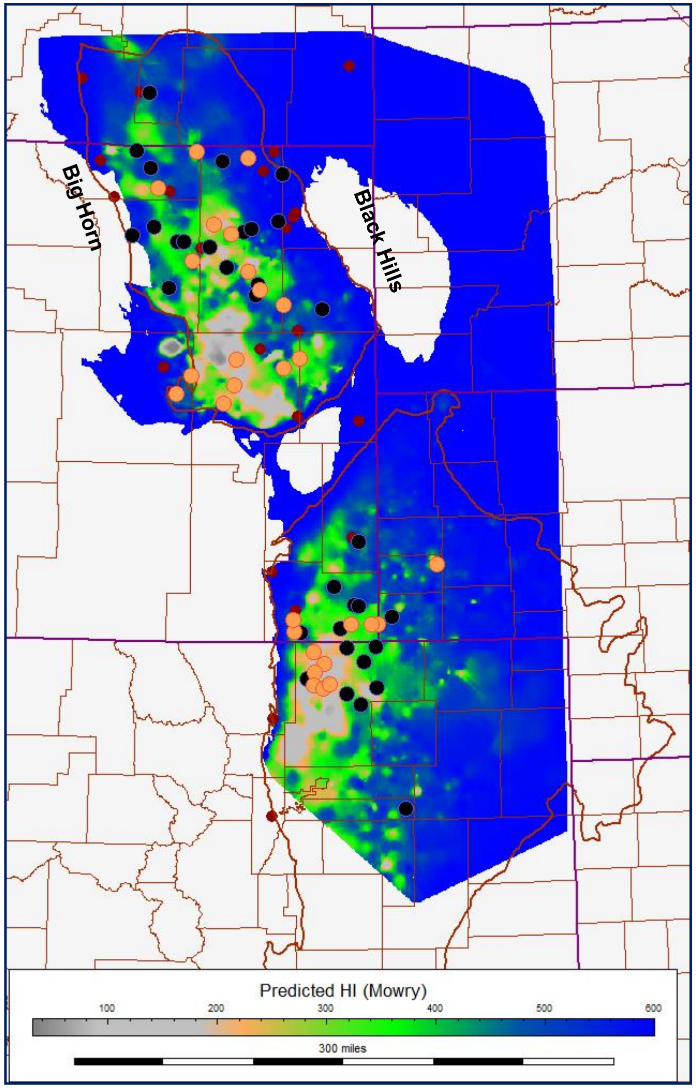


Well location data permission to use granted by Nehring Associates

Model Calibration

A Reasonable Match between Measured and Predicted HI





Model Calibration

A Reasonable Match between Predicted and Published Ro

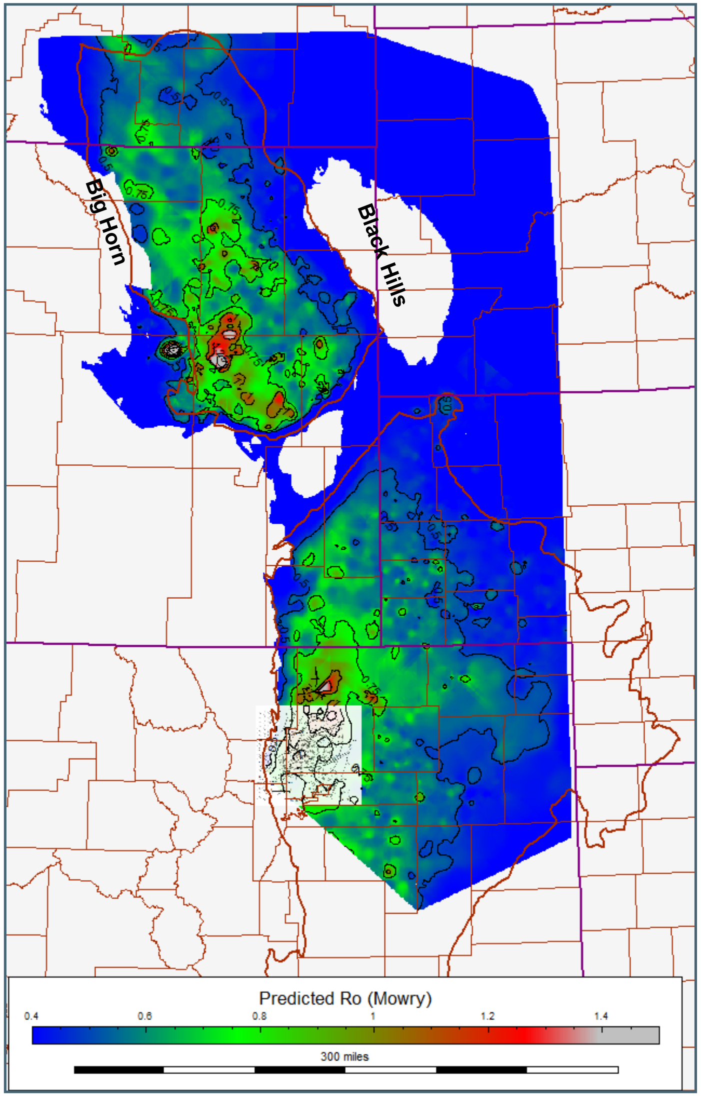


Image of Ro contours: Higley, 2003

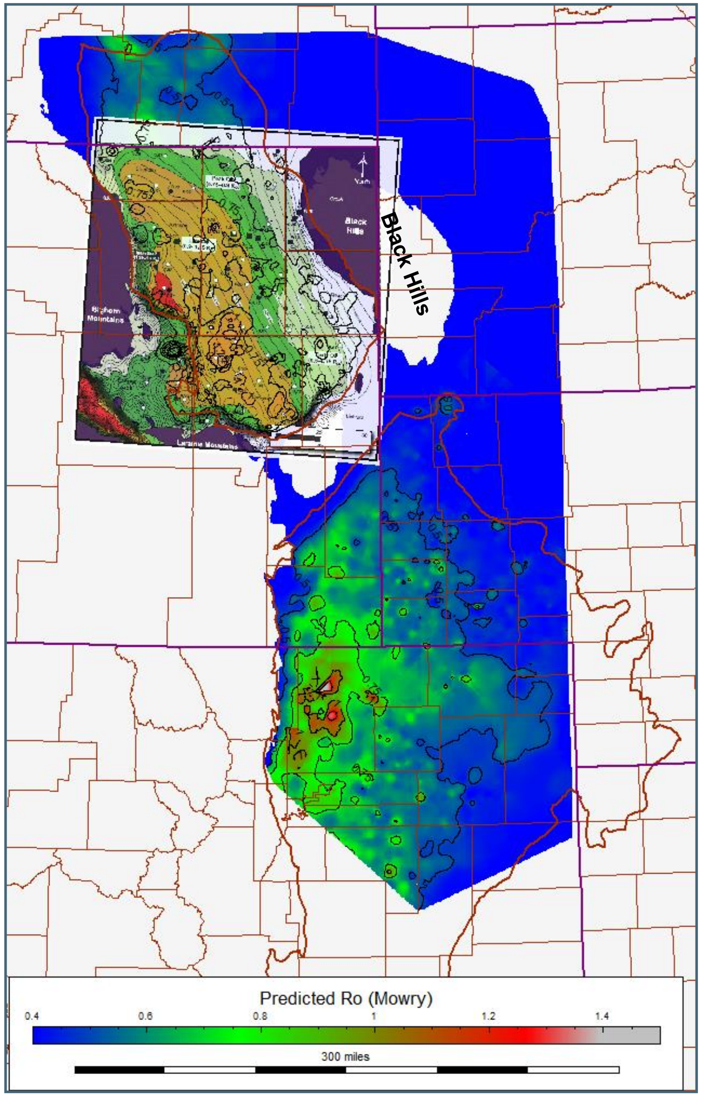
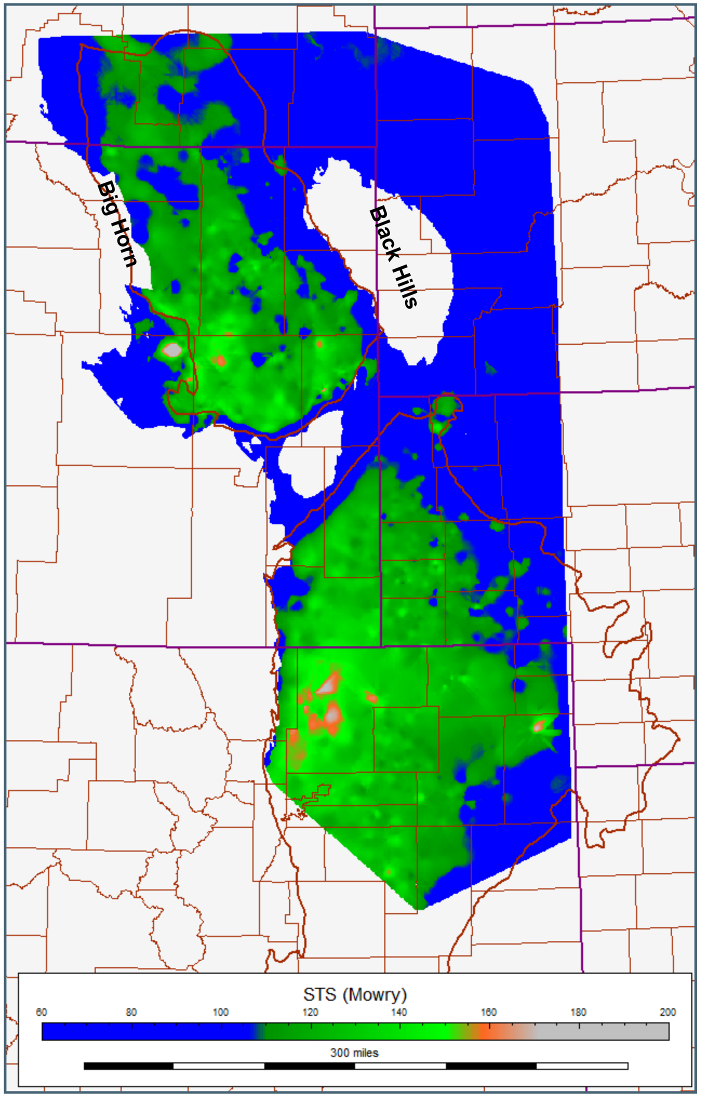
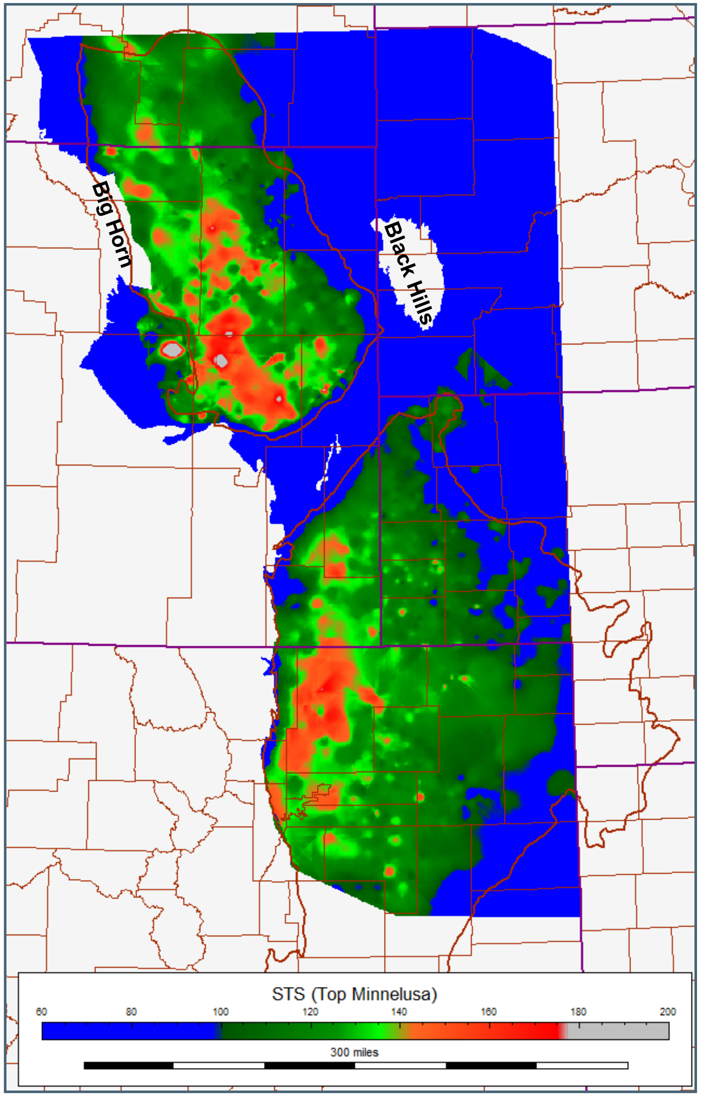


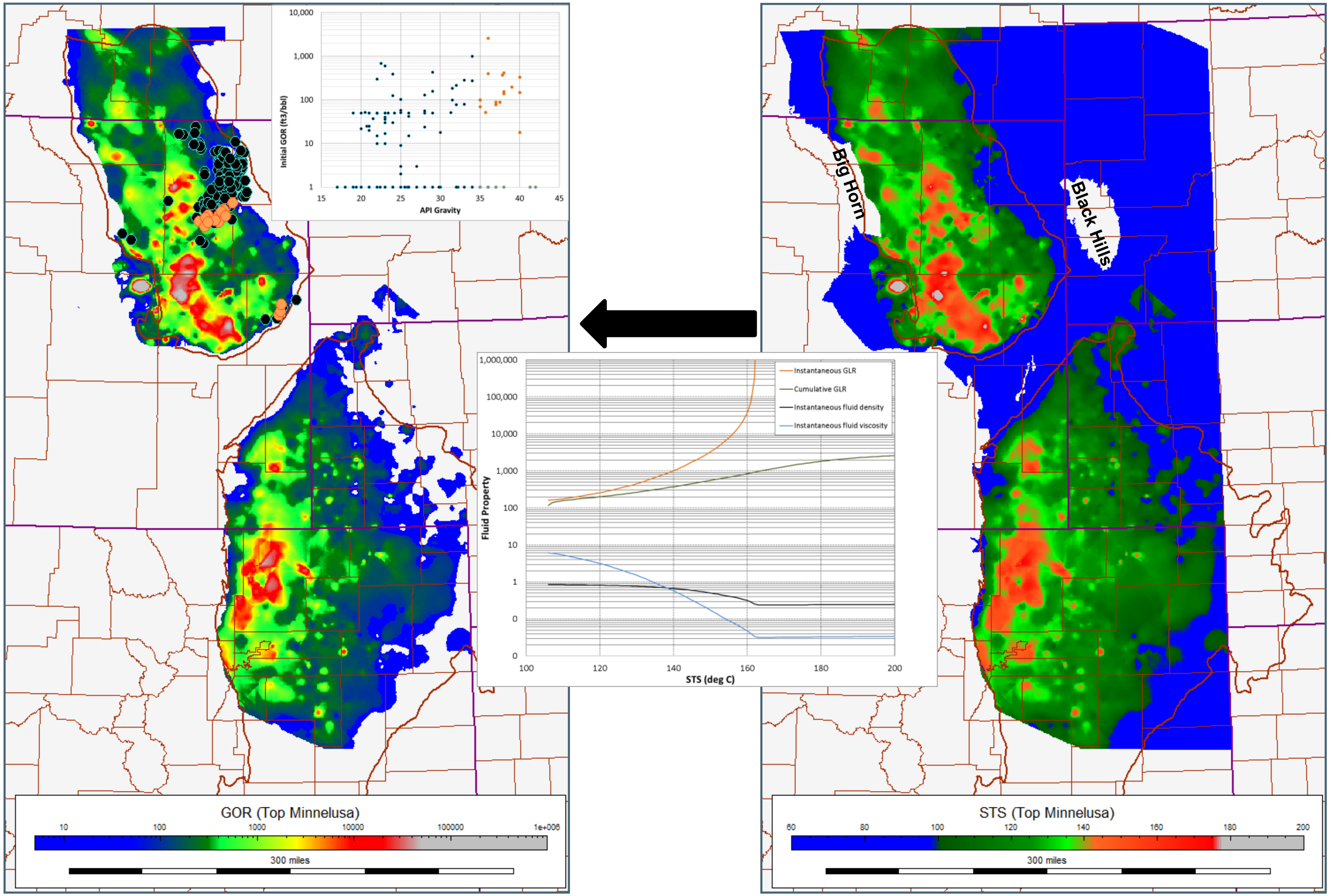
Image of Ro contours: Modica, 2012

Predicted STS (Maturity) Maps

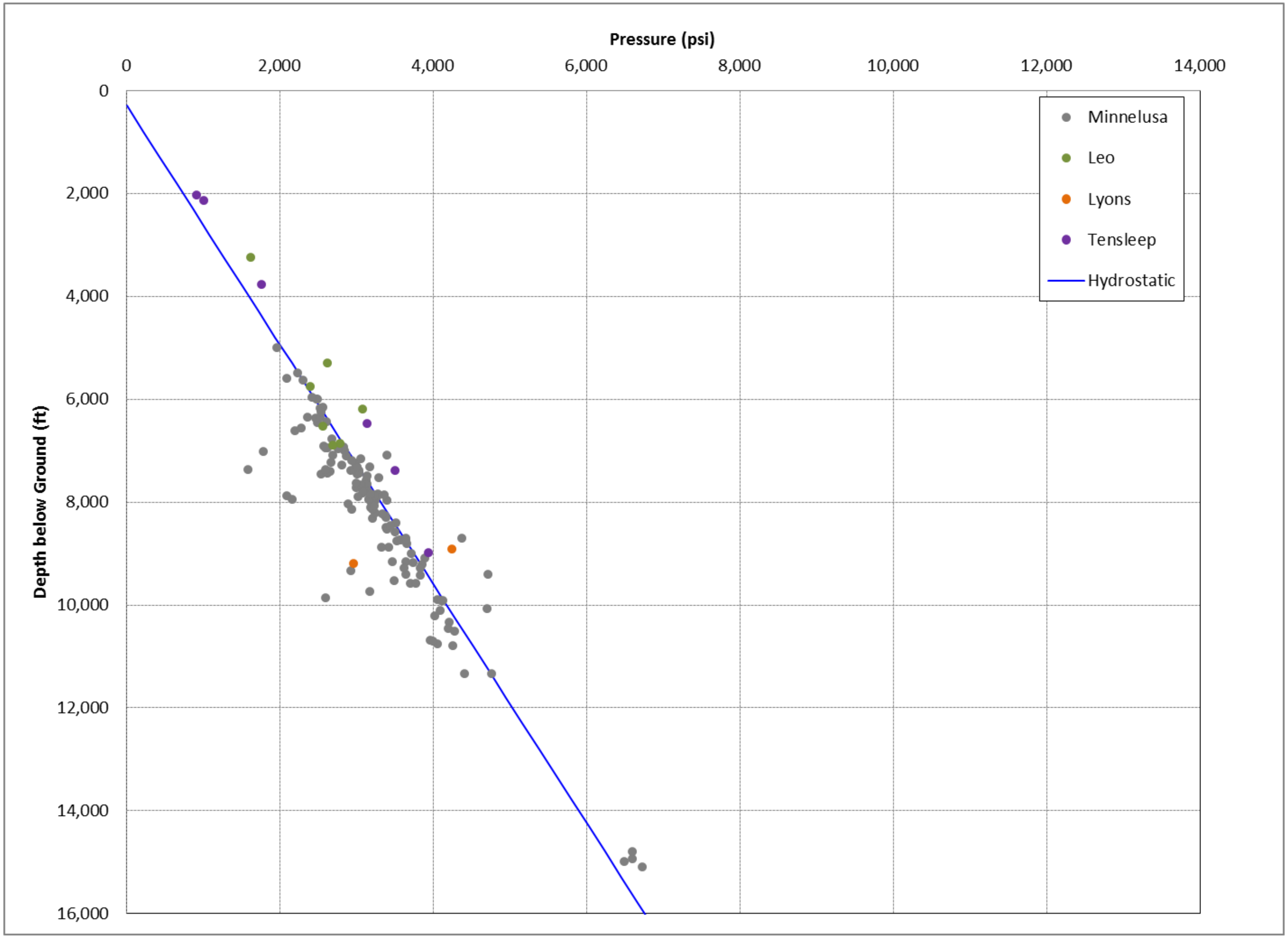




Predicted GOR via Maturity

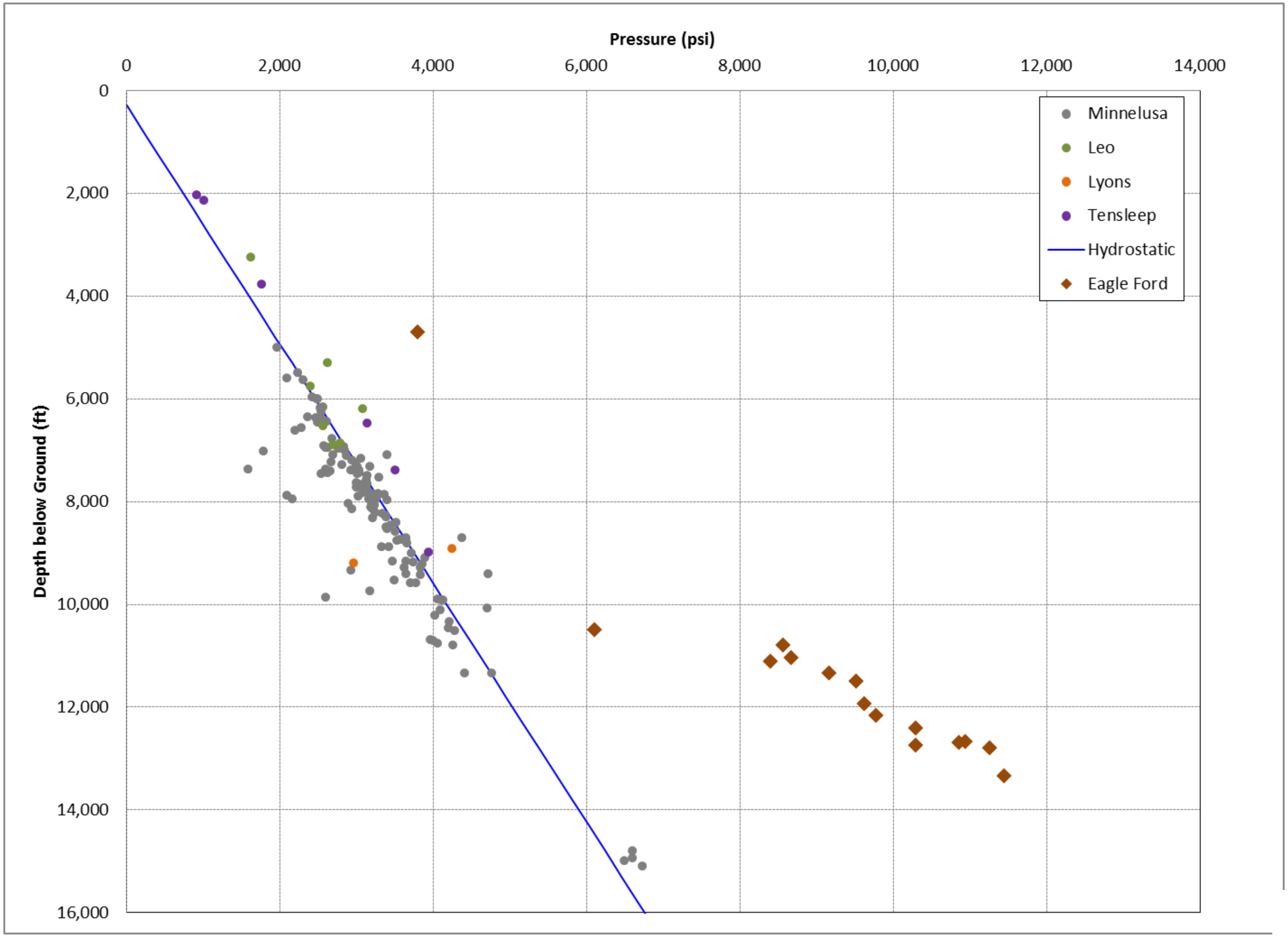


Reservoir Pressure vs. Depth

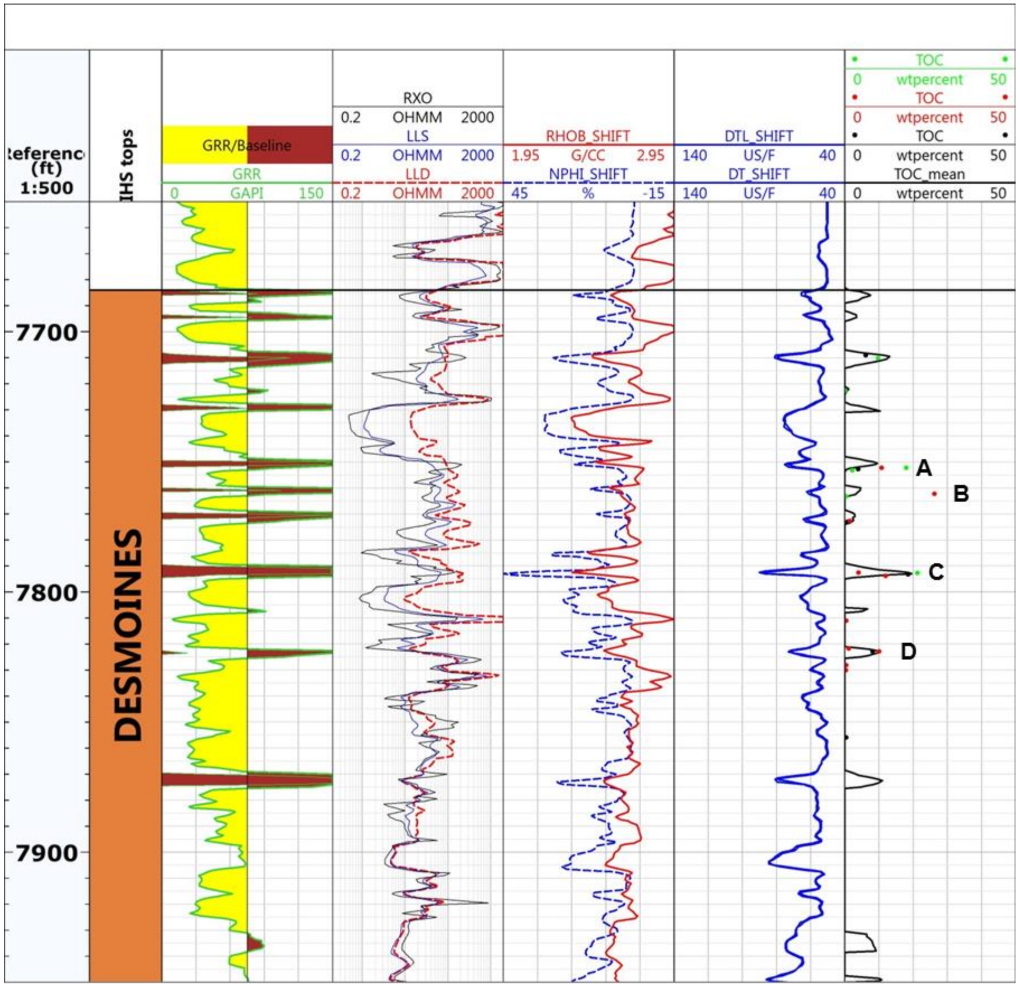


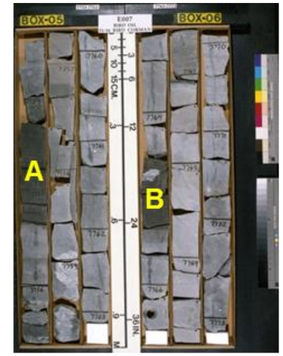
Reservoir Pressure vs. Depth

Lower reservoir pressure in contrast to the Eagle Ford

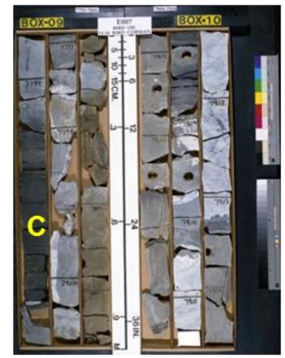


Reservoir Architecture





Zone A: 1' thick, detected by logs but not resolved
Zone B: 9" thick, barely detected by logs



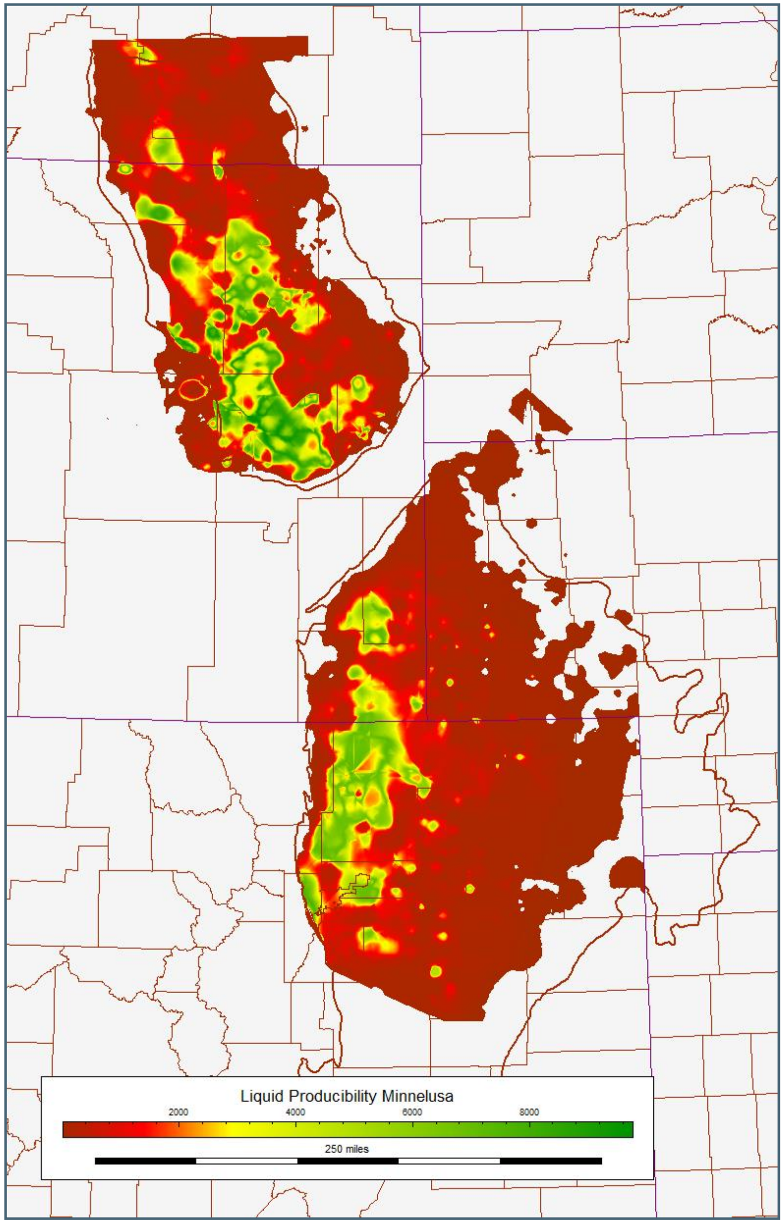
Zone C: 1.5' thick, logs probably reach the correct value in the centre of the bed

Zone D: 2' thick, logs probably reach the correct value in the centre of the bed

Source of images: USGS

Predicted Liquid Producibility

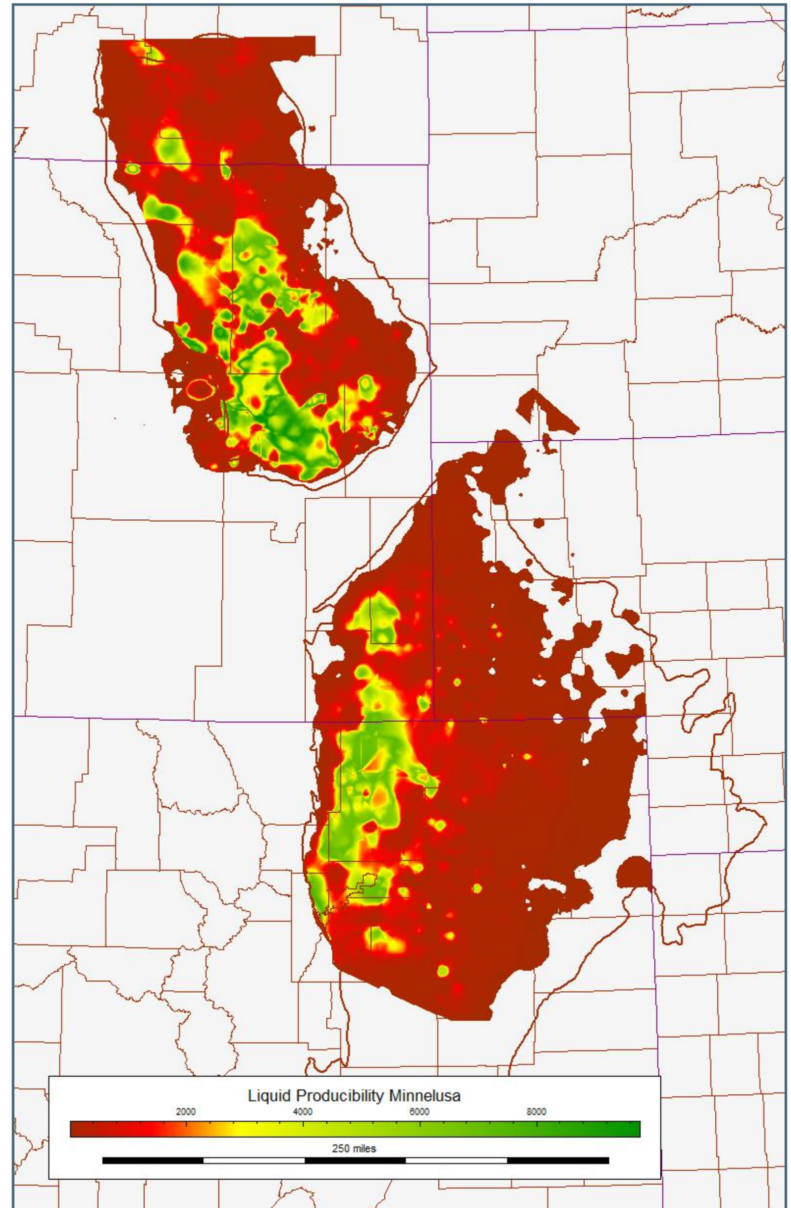
$$\text{Liquid Producibility} = \frac{k * h * \Delta P * OMF}{\mu}$$



Summary & Conclusion

- Demonstrated a case study of applying an integrated workflow for evaluating unconventional reservoir deliverability

- The Minnelusa FM (& equivalents) is not a viable unconventional resource play due to:
  - Effective lateral migration of hydrocarbons away from the source/reservoir intervals
  - Low reservoir pressure/energy
  - Thin-bed nature of the source/reservoir intervals



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