The Woodford Shale of the Greater Permian Basin: Thermal Maturity, Total Hydrocarbon Generation, and Oil Migration Pathways

William R. Drake[1]

Search and Discovery Article #51723 (2026)**
Posted October 23, 2026

*Adapted from extended abstract based on oral presentation given at WTGS/AAPG SWS, 12-16 Sep 2026, Midland, TX.
**Datapages © 2026. Serial rights given by author. For all other rights contact author directly. DOI:10.1306/51723Drake2026

[1]Kimmeridge Energy

Abstract

The Upper Devonian Woodford Shale has long been recognized as a major source rock across the greater Permian Basin region. However, variability in Woodford hydrocarbon generation and its relationship to oil migration are not well understood. The objectives of this study are to characterize the spatial distribution of Woodford source-rock properties, quantify total hydrocarbon generation, and compare these results with oils produced from Woodford-sourced reservoirs. Basin-scale maps of thermal maturity, original total organic carbon (TOC), generative potential, and transformation ratio were integrated to determine hydrocarbon generation and evaluate regional differences. Woodford thermal maturity is guided largely, but not entirely, by burial depth. Areas with highest original TOC coincide well with the thickest Woodford intervals in the distal Tobosa Basin depocenter. Consequently, variability in hydrocarbon generation is controlled primarily by original depositional conditions and highly heterogeneous thermal maturity. Mean hydrocarbon generation across the approximately 40,000-square-mile study area is ~41 MMRBO/Sec, with a basin-wide total exceeding 1.6 trillion RBO (HCPV). Differences between source-rock thermal maturities and the maturities of produced Woodford oils reveal evidence for both intraformational and interformational migration. Oils that are more mature than the local Woodford source rock indicate migration from deeper, higher-maturity areas. Interformational migration into reservoirs deeper than the Woodford is recognized in the northernmost Permian Basin, the northern Midland Basin, and along the Central Basin Platform. Elsewhere, migration of Woodford-derived hydrocarbons is predominantly into shallower reservoirs.

References

Afanasieva, M.S., 2020, Devonian Radiolarian Ecozones of Northern Eurasia: Paleontological Journal, vol. 54, no. 9, p. 947-1093, https://doi.org/10.1134/s0031030120090014

Algeo, T. J. and Lyons, T. W ., 2006, Mo total organic carbon covariation in modern anoxic marine environments: Implications for analysis of paleoredox and paleohydrographic conditions, Paleoceanography, vol. 21 , PA1016, https://doi.org/10.1029/2004pa001112

Algeo, T. J., Lyons , T. W ., Blakey , R. C ., and Over , D. J ., 2007, Hydrographic conditions of the Devono-Carboniferous North American seaway inferred from sedimentary Mo-TOC relationships: Palaeogeography, Palaeoclimatology, Palaeoecology , vol. 256, p. 204-230, https://doi.org/10.1016/j.palaeo.2007.02.035

Comer, J.B., 1991, Stratigraphic analysis of the Upper Devonian Woodford Formation, Permian Basin, West Texas and southeastern New Mexico: Report of Investigations No. 201, Bureau of Economic Geology, University of Texas at Austin, 63 p., https://doi.org/10.23867/ri0201d

Daly, A.R. and Edman, J.D., 1987. Loss of organic carbon from source rocks during thermal maturation: AAPG Bulletin, vol. 71, p. 546.

Drake, W. R., Longman, M.W., and Kostelnik, J., 2017, The role of silica nanospheres in porosity preservation in the Upper Devonian Woodford Shale on the Central Basin Platform, West Texas: RMAG and DWLS Fall Symposium, Geology and Petrophysics of Unconventional Mudrocks, Golden, CO, September 27, 2017, 10 p.

Drake, W.R., Longman, M.W., and Moses, A., 2018, Assessment of the Woodford Shale Petroleum System within a Deep Subbasin on the Central Basin Platform, Permian Basin: AAPG ACE, Salt Lake City, UT, May 20-23, 2018, extended abstract,13 p., AAPG Search and Discovery Article #11105: http://www.searchanddiscovery.com/documents/2018/11105drake/ndx_drake.pdf

Haq, B. U. and Schutter, S. R., 2009, A chronology of Paleozoic sea-level changes: Science, vol. 322, p. 64-68, https://doi.org/10.1126/science.1161648

Hemmesch, N.T., Harris, N.B., Mnich, C.A., and Selby, D., 2014, A sequence stratigraphic framework for the Upper Devonian Woodford Shale, Permian Basin, west Texas: AAPG Bulletin, vol. 98, p. 23-47, https://doi.org 10.1306/05221312077

Jarvie, D., 2008, Geochemical Characteristics of the Devonian Woodford Shale: Oklahoma Geological Survey, Oklahoma Gas Shales Workshop, Oct 22, 2008, Oklahoma City, Oklahoma

Jarvie, D.M., 2017, Geochemical Assessment and Characterization of Petroleum Source Rocks and Oils, and Petroleum Systems, Permian Basin, U.S.: The Houston Geological Society Bulletin, vol. 60, no. 4, p. 14-18.

Longman, M.W., Drake, W.R., Milliken, K.L., Olson, T.M., 2019, A comparison of silica diagenesis in the Devonian Woodford shale (central basin platform, west Texas) and Cretaceous Mowry shale (Powder river basin, Wyoming), In: Camp, W., Milliken, K., Taylor, K., Fishman, N., Hackley, P., Macquaker, J. (Eds.), Mudstone Diagenesis: Research Perspectives for Shale Hydrocarbon Reservoirs, Seals, and Source Rocks, AAPG Memoir 120, p. 49–68, https://doi.org/10.1306/13672210M12163

Matchus, E.J., and Jones, T.S ., 1984, East west cross section through Permian Basin of West Texas: West Texas Geological Society Publication, p. 78-84.

Rudnicki, M.D., 2016, Variation of organic matter density with thermal maturity: AAPG Bulletin, vol. 100, p. 17–22, http://dx.doi.org/10.1306/08181515024

Ruppel, S. C., Rowe, H., Reed, R. M., Barrick, J. E., James, E. W., and Loucks, R. G., 2020, The Woodford Formation of the Permian Basin: Regional, Middle to Late Devonian Transgression of the Southern Midcontinent and Accompanying Global Anoxia, in Ruppel, S. C., ed., Anatomy of a Paleozoic Basin: The Permian Basin, USA, Volume 2: The University of Texas at Austin, Bureau of Economic Geology, Report of Investigations No. 285; AAPG Memoir 118, p. 75–124.

Sinninghe Damsté, J. S., Wakeham, S. G., Kohnen, M. E. L., Hayes, J. M., and de Leeuw, J. W., 1993, A 6,000-year sedimentary molecular record of chemocline excursions in the Black Sea: Nature, vol. 362, p. 827-829, http://dx.doi.org/ 10.1038/362827a0

Sluijs, A., Van Roij, L., Harrington, G.J., Schouten, S., Sessa, J.A., LeVay, L.J., Reichart, G.J. and Slomp, C.P., 2014, Warming, euxinia and sea level rise during the Paleocene Eocene Thermal Maximum on the Gulf Coastal Plain: Implications for ocean oxygenation and nutrient cycling: Climate of the Past, vol. 10, p. 1421-1439, https://doi.org/10.5194/cp-10-1421-2014

Waples, D.W. and Marzi, R.W., 1998, The universality of the relationship between vitrinite reflectance and transformation ratio: Organic Geochemistry, vol. 28, no. 6, p. 383-388, https://doi.org/10.1016/s0146-6380(97)00122-8

Zambito, J.J., IV, Haas, L.D., and Batten W.G., 2017, Industrial sand resources of west-central Wisconsin, Wisconsin Geological and Natural History Survey Open-File Report 2017-06, 18 p.

The Woodford Shale of the Greater Permian Basin: Thermal Maturity, Total Hydrocarbon Generation, and Oil Migration Pathways

William R. Drake

16 September 2026

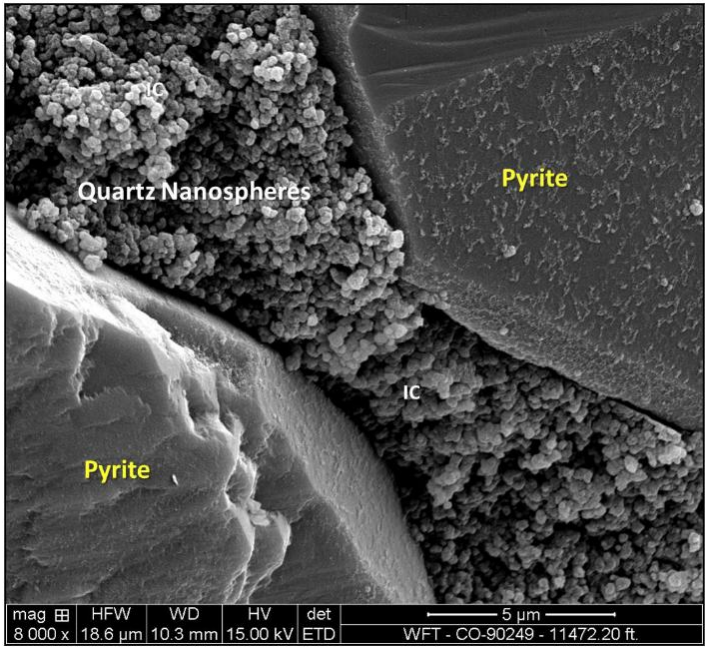
william.drake@kimmeridge.com

The Woodford Shale of the Permian Basin

The Upper Devonian Woodford Shale (~385-360 Ma) has long been recognized as a prolific source rock in Oklahoma and in the Permian Basin. Composition, original depositional conditions in the Tabosa Basin, and thermal maturity in the Permian contribute to highly variable source rock characteristics.

- The Woodford Shale in the Permian Basin consists predominantly of black, organic-rich siliceous mudstone with chert, siltstone, and dolomite (e.g., Comer, 1991; Hemmesch et al., 2014) and was deposited at the peak of a 2nd-order, marine eustatic high reached in the Frasnian Stage of the Upper Devonian (Haq and Schutter, 2008).
- The Woodford Shale was deposited in the ancestral Tobosa Basin, the precursor to the modern Permian Basin, where the thickest section accumulated along the axial depocenter of the basin.
- Ranges in thickness up to ~750 feet, with the thickest section preserved in the deepest part of the Delaware Basin and along the northern Central Basin Platform.

FE-SEM Image of Woodford (8000X)

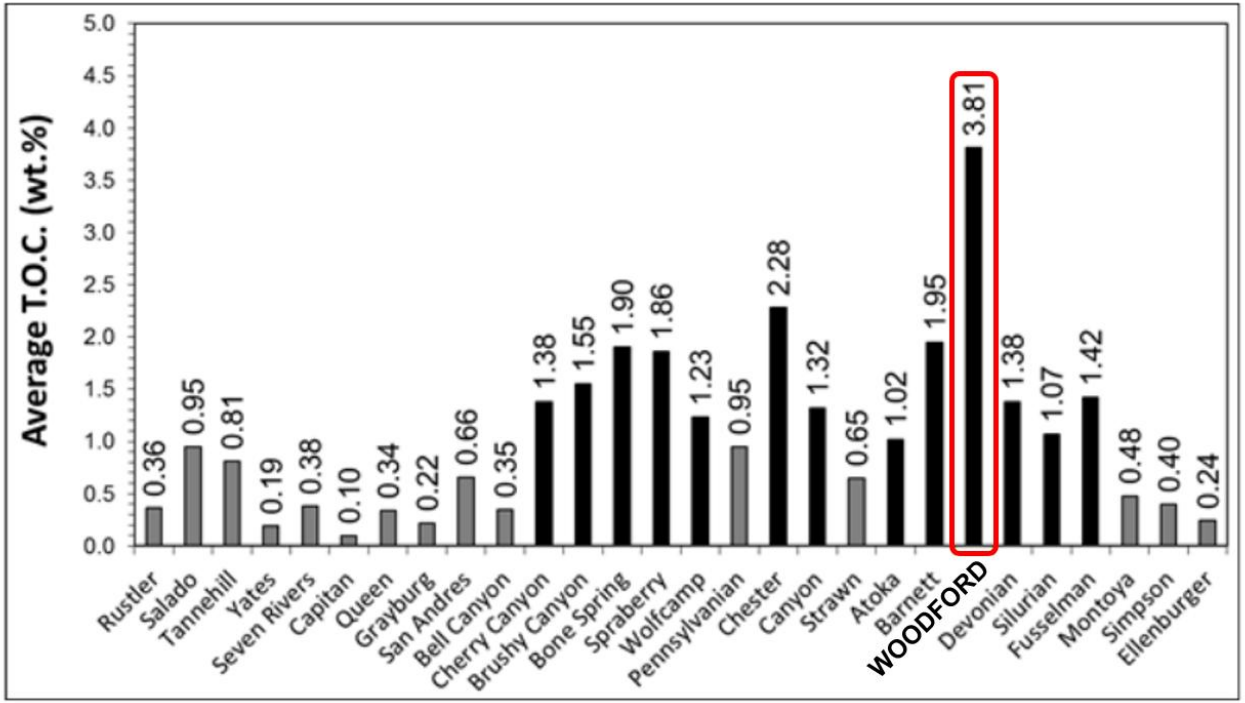


Source: Drake et al., 2017

The Importance of the Woodford in the Permian Basin

Kimmeridge

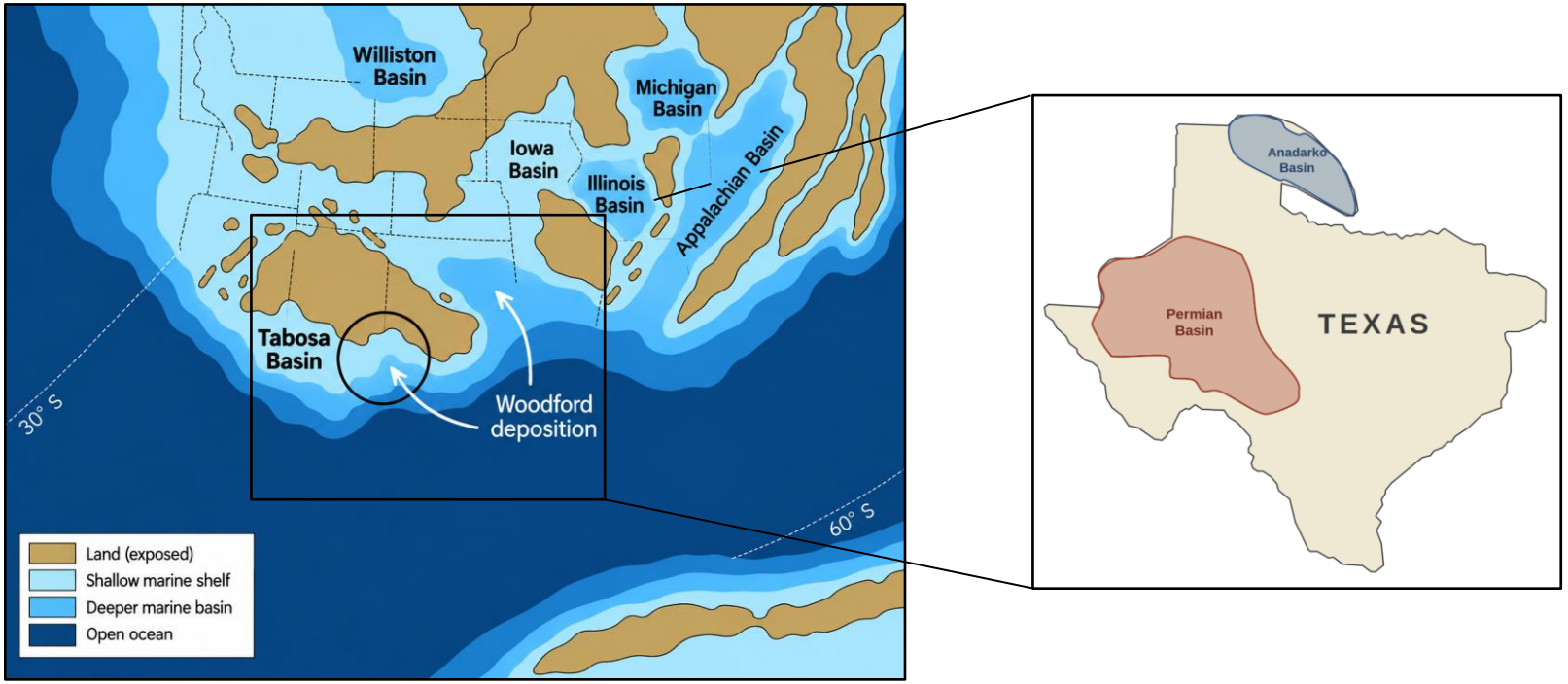
Average present-day TOC values from cuttings from Permian Basin formations highlight the primary source rocks (black) relative to primary reservoir rocks (gray). The Woodford Shale stands out as an excellent source rock within the most prolific oil producing basin in North America.



Source: Jarvie, 2017

Late Devonian Paleogeography

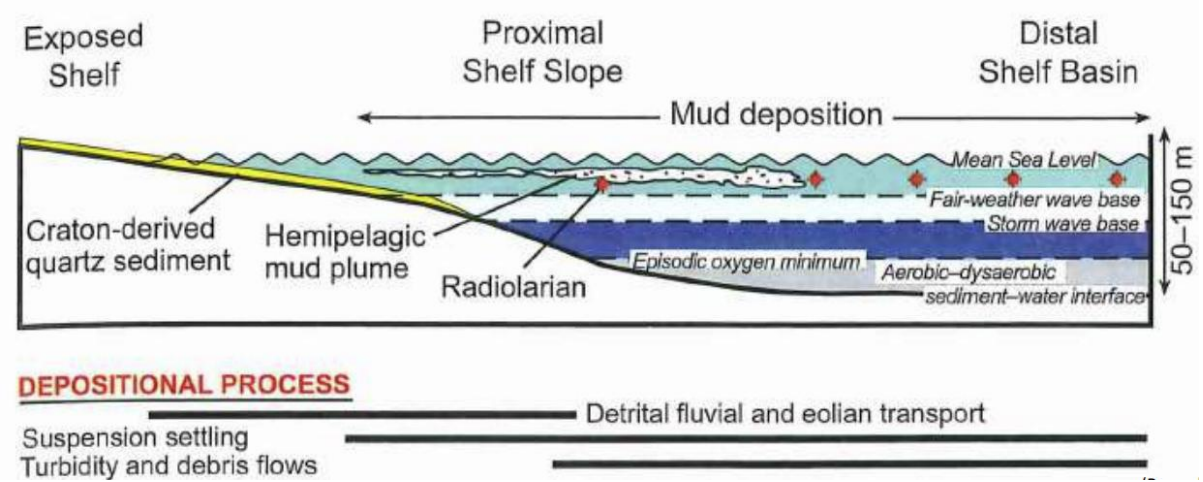
The North American craton was characterized by widespread flooding and deposition of organic-rich shales in epeiric seaways. Major source rocks of this age: Woodford (Permian, Anadarko), Bakken (Williston), Illinois (New Albany Shale), Antrim Shale (Michigan), Chattanooga (Appalachian), and Duverney (WCSB).



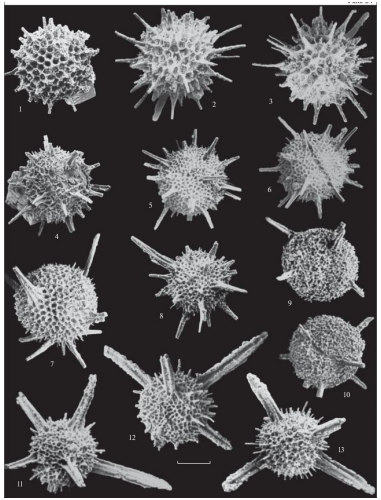
Sources: modified from Zambito et al. 2017, after Blakey, 2014

Depositional Model for the Woodford Shale

Deposition consisted of a combination of pelagic and mud-rich deep-water gravity flows into stratified water column which ranged from fully oxygenated (surface) to anoxic (basin floor). The Woodford is rich in silica due to biogenic deposition (mainly radiolarians) and later authigenic cement.



Devonian Radiolaria



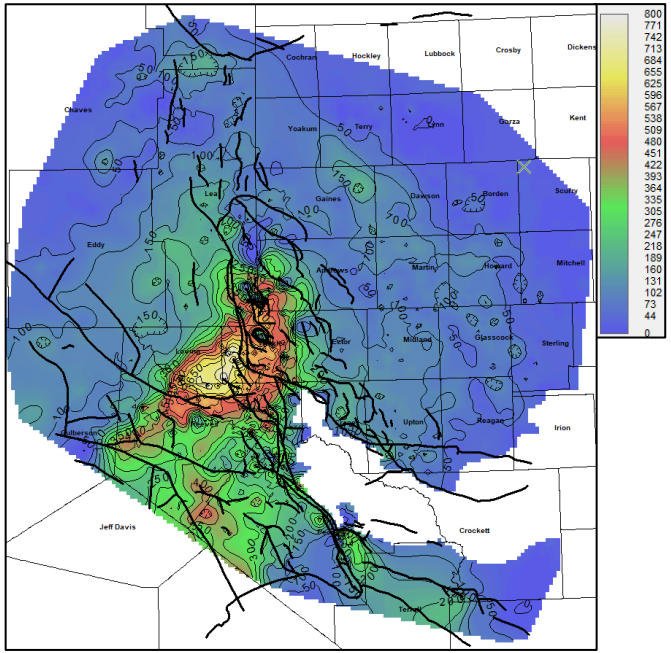
Sources: Ruppel et al., 2020; Afanasieva, 2020

Woodford Thickness and Depth Structure

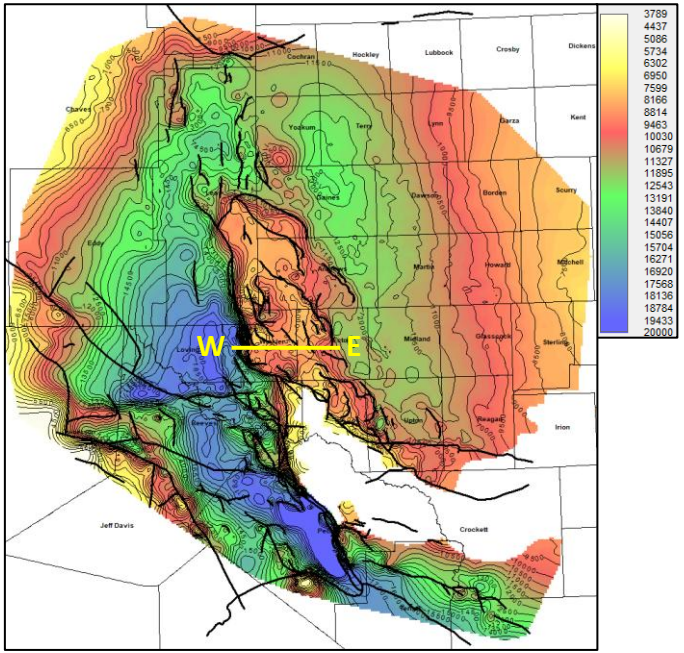
Kimmeridge

Woodford thickness is calculated against all unconformable underlying surfaces (Devonian, Silurian, Fusselman, Sylvan, Montoya, Simpson, and Ellenburger). Where not eroded along the eastern Central Basin Platform (CBP), the formation thick represents the depocenter of the former Tobosa Basin. The Woodford is deepest in the Delaware Basin, less deep in the Midland Basin, and shallowest along the uplifted CBP and along the Permian Basin edges.

Woodford Thickness (ft)

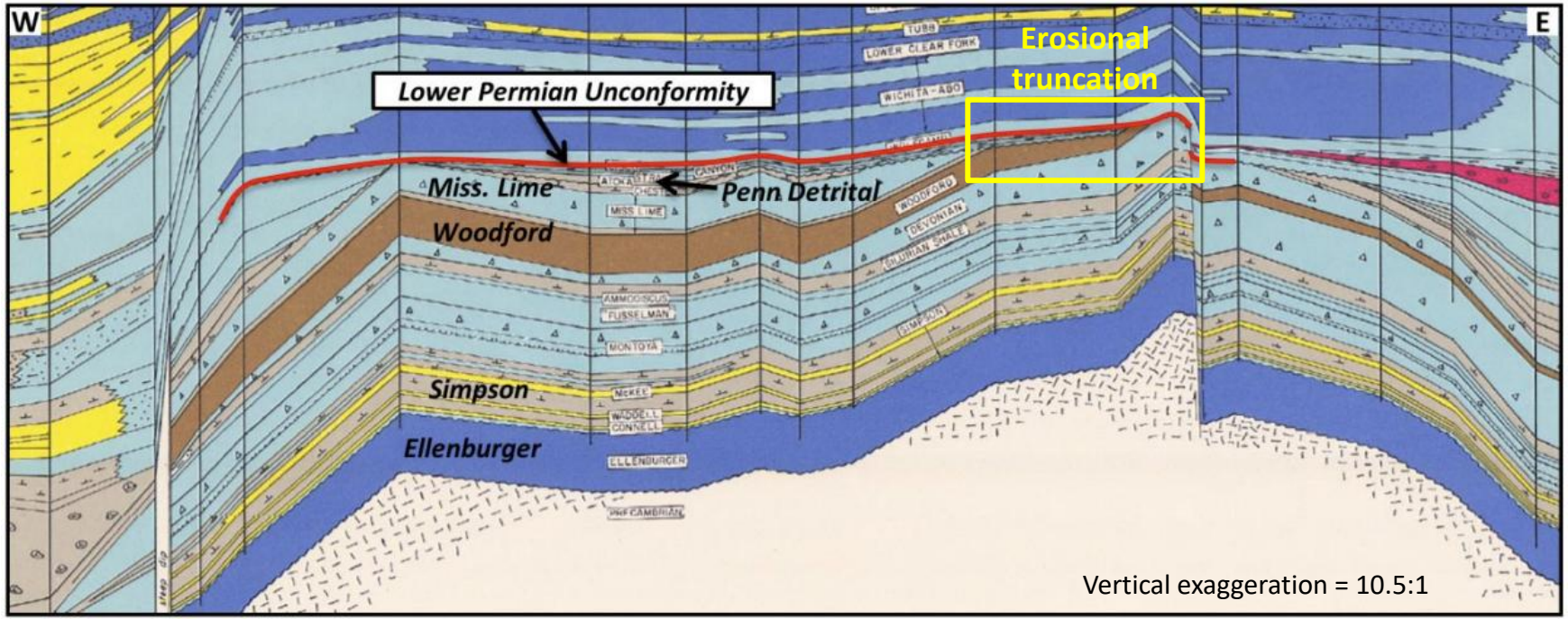


Woodford Depth Structure (ft)



Cross Section over the Central Basin Platform

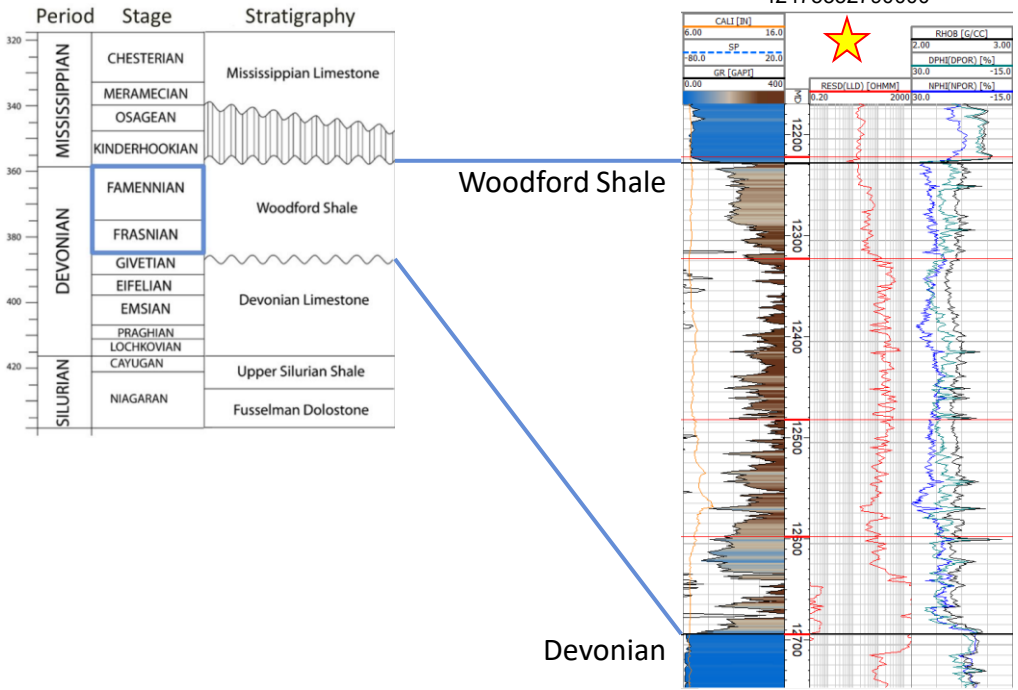
West-East structural cross section from the eastern Delaware Basin across the CBP to the western Midland Basin. Note the effects of major faults, erosional thinning, and stratigraphic thinning.

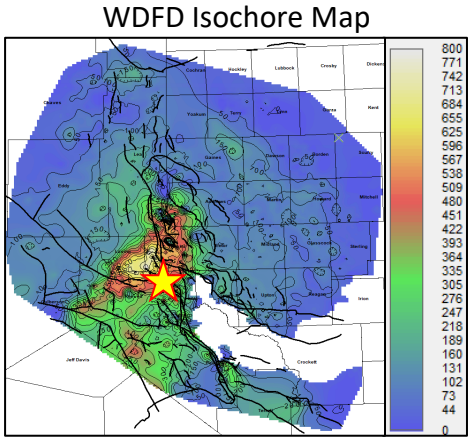


Source: modified from Matchus and Jones, 1984

Woodford Section

In the subsurface, the Woodford is characterized by a very high gamma ray response due to high uranium associated with elevated organic carbon. The Woodford is framed by sequence boundaries.

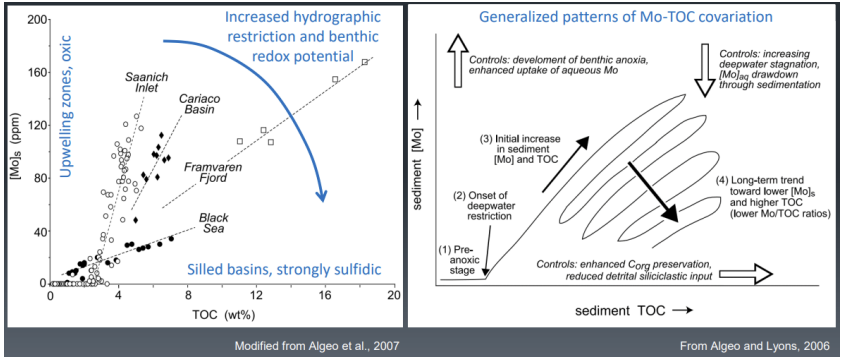


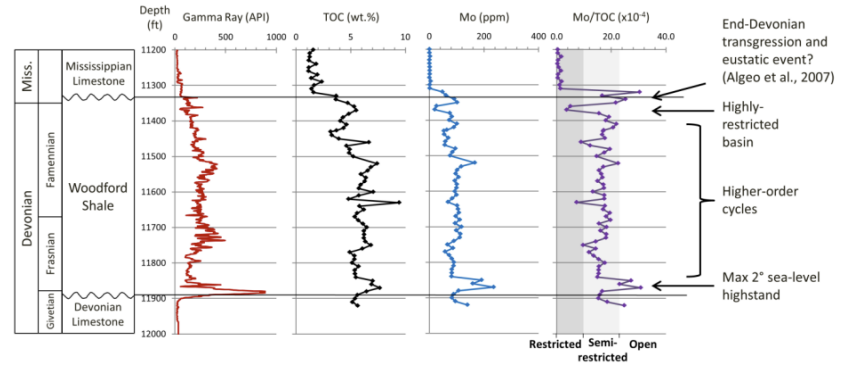


Source: modified from Hemmesch et al., 2014, after Comer, 1991

Molybdenum/TOC as an Indicator of Basin Restriction

Restricted or silled basins: lower sea-level stands, limited deepwater resupply of Mo. Weakly restricted basins: higher sea-level stands, open-marine conditions, enhanced deepwater renewal of Mo (increased connectedness to undepleted ocean). Note TOC loss and enrichment of Mo can be influenced by later thermal maturation.





<u>Oil biomarkers from the distal Tobosa Basin:</u>

- Further evidence of basin shallowing comes from oil biomarkers such as carotenoids, which can be useful in predicting water depths (i.e., light penetration) during source-rock deposition.

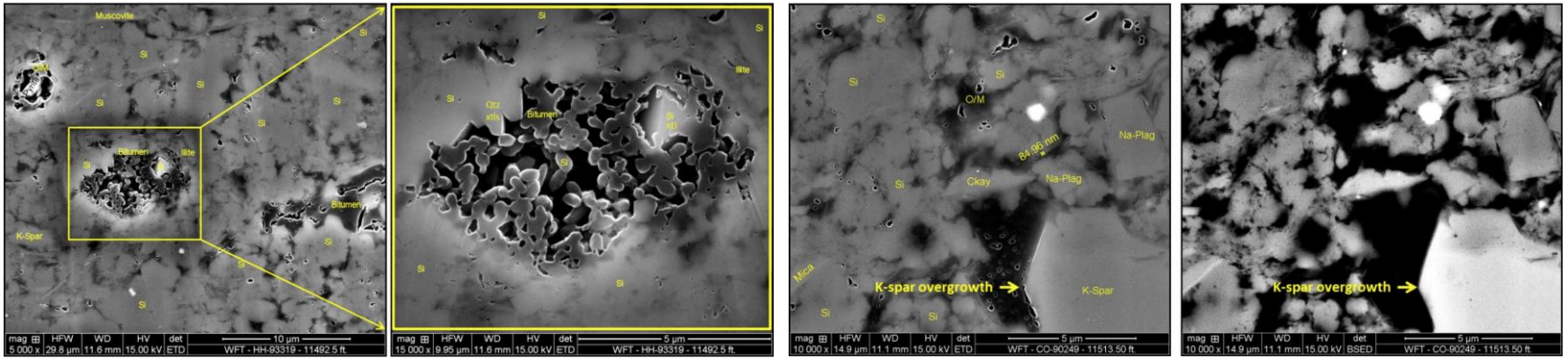
- The presence of the biomarker paleoisorieneratane in Winkler Co. suggests highly anoxic shallow waters during source-rock deposition (aka photic zone euxinia) (Sinninghe Damsté et al. 1993) in a restricted, semi-enclosed basin (e.g., Sluijs et al., 2014), despite the distalmost and presumably deepest portion of the former Tobosa Basin.

Source: Drake et al., 2018

FE-SEM Imaging | Interparticle and Organic Porosity

Kimmeridge

Listed in order of decreasing abundance, silica components of the Woodford are: 1) newly-identified silica nanospheres (200-500 nm in diameter); 2) radiolarians; 3) detrital quartz silt; 4) unidentified micron-sized microfossils; and 5) sponge spicules.



- Argon ion milled surface at 5000X (left) and 15000X (right) showing silica nanospheres (~200-500 nm in diameter).
- Black areas: open pore space and bitumen. Quartz overgrowths formed at expense of nanospheres.
- *Very early diagenetic silica helped prevent compaction of the rock matrix, while authigenic reprecipitation of quartz (overgrowths) degrade porosity.*

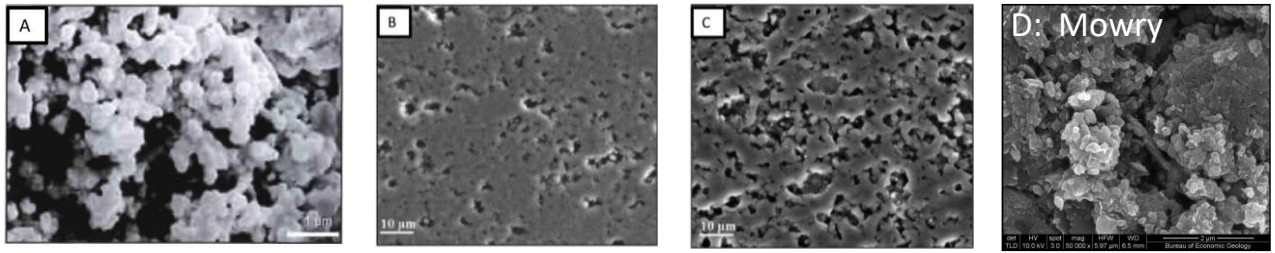
- Argon ion milled surfaces at 10000X, secondary electron (left), backscatter electron (right).
- Micron-size quartz crystals, including silica nanospheres (cloudy texture), detrital silt grains, and organic matter.
- Organic porosity, bitumen-filled interparticle porosity.

Source: Drake et al., 2017

Possible Origin of Silica Nanospheres

Kimmeridge

Silica nanospheres observed in early Cambrian Athel Silicilyte of South Oman Salt Basin (A-C), and in Cretaceous Mowry Shale (D), suggesting the work of sulfate-reducing microbes over >440 million years.



- Dissolution of radiolarians and reprecipitation has been evoked for silica in Woodford and Mowry, but Athel Silicilyte predates the evolution of radiolarians.
- Silica nanospheres occur in relatively sediment-starved, marine deposits that are enriched in pyrite, organic matter, uranium, and molybdenum indicates that dysoxic to anoxic conditions existed during the early burial history.
- Formed early in the diagenetic process, probably penecontemporaneously with deposition, preventing any significant compaction. As the silica precipitated, oxygen was removed from the adjacent water column. This may have created anoxic bottom-water conditions that promoted the preservation of the organic matter.

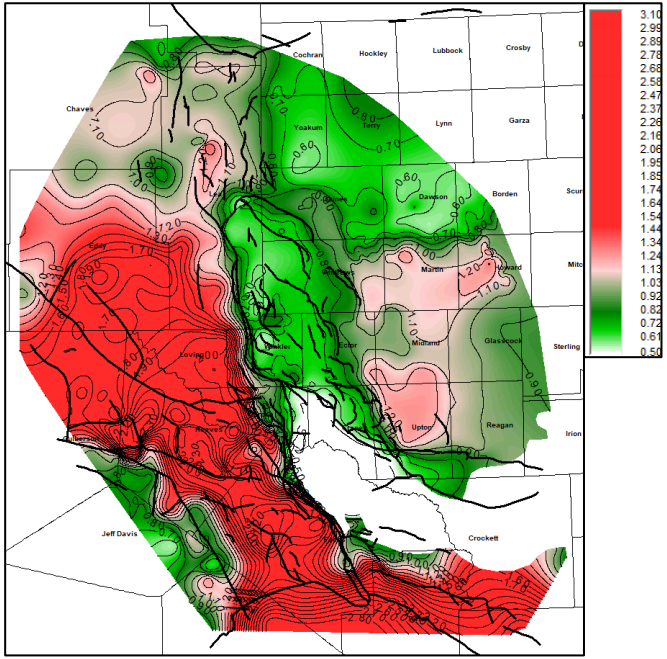
Source: Longman et al., 2019

Woodford Thermal Maturity

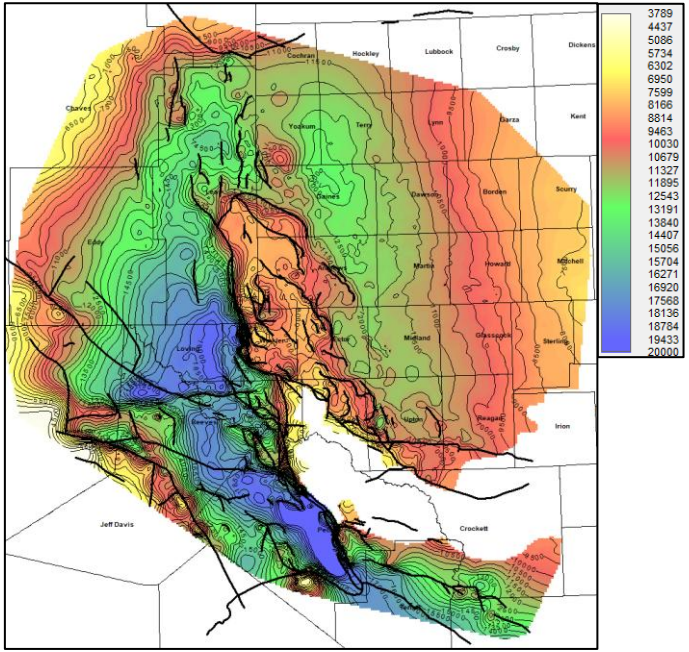
Kimmeridge

Thermal maturity determined using screened and validated rock pyrolysis and vitrinite reflectance data (n=466). Depth-maturity relationship used for CBP and two counties, maps combined, and hand contoured. Deep Delaware is less conditioned but is all in the dry gas window. Data sources: GeoMark, USGS, and publications.

Woodford Thermal Maturity (%Ro)



Woodford Depth Structure (ft)

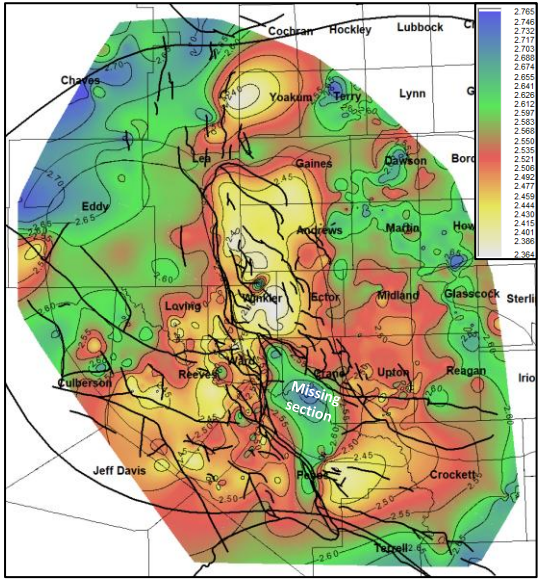


Calculating Present Day TOC

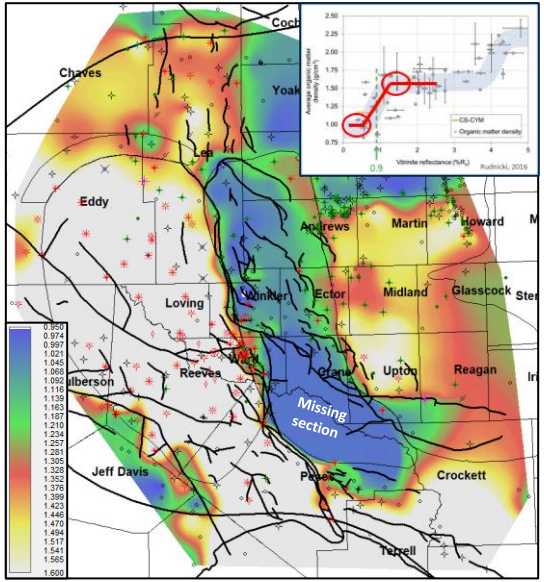
Kimmeridge

Average TOC_{pd} calculated by transform from bulk density (RhoB) and organic matter density (RhoK), which varies with thermal maturity. RhoK below 0.60 Ro is considered 1.00 g/cm^3; RhoK above 1.6 Ro is considered 1.59 g/cm^3 (100% transformation). Highest TOC_{pd} is located along the central Tobosa basin depocenter and along the CBP where thermal maturity is lowest.

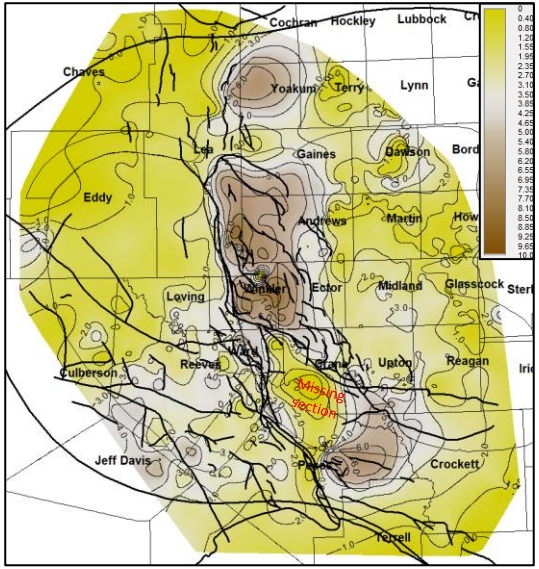
Average RhoB



Average RhoK as a function of Maturity



Average Present Day TOC



Note: gridding over missing section is for the purpose of calculating TOC_o.

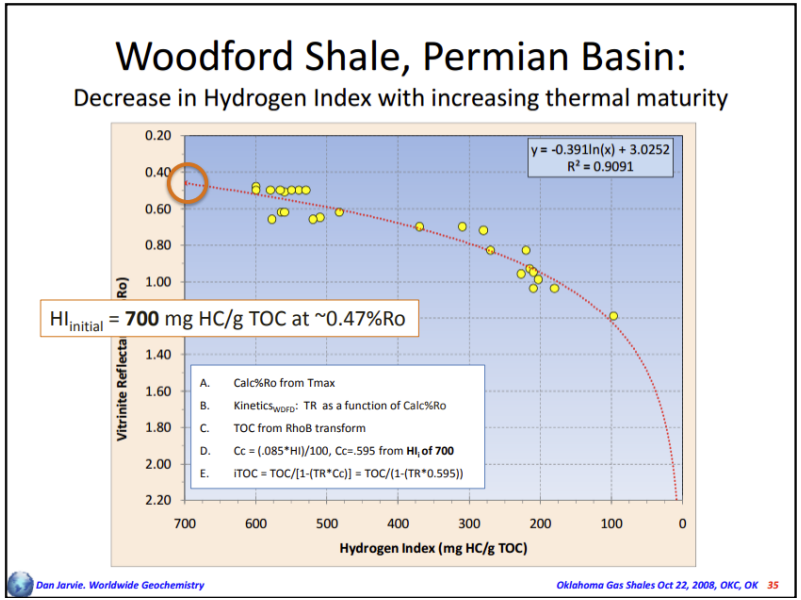
TOC_{pd} = (100*((2.685-RhoB)/RhoK))/(4.655-3.055*(2.685-RhoB)/RhoK); 2.685 is the dry grain density of siliciclastic shale with TOC of ~0% at this density value and higher.

Calculating Original TOC

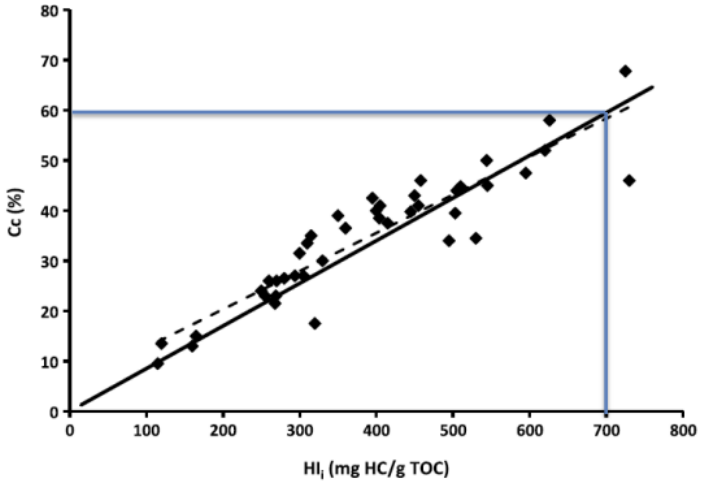
TOC_o is calculated as a function of thermal maturity, transformation ratio, original hydrogen index (HI_o), and convertible carbon:

$TOC_o = TOC_{pd}/(1-(TR*Cc))$, where HI_o=700 and Cc=0.085*700=59.5%.

WDFD Original Hydrogen Index



Convertible Carbon (Cc) from HI_o



Cc (%) = 0.085 × HI_o (Orr, 1981)

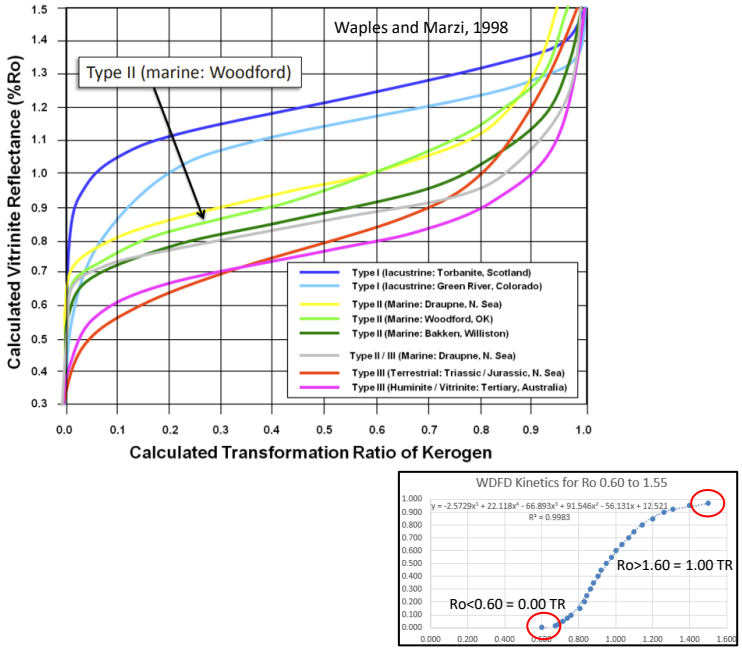
So, Cc = 0.085 x 700 = 59.5%, so 0.595

Source: Drake, 2019 after Jarvie, 2008, and Daly and Edman, 1987

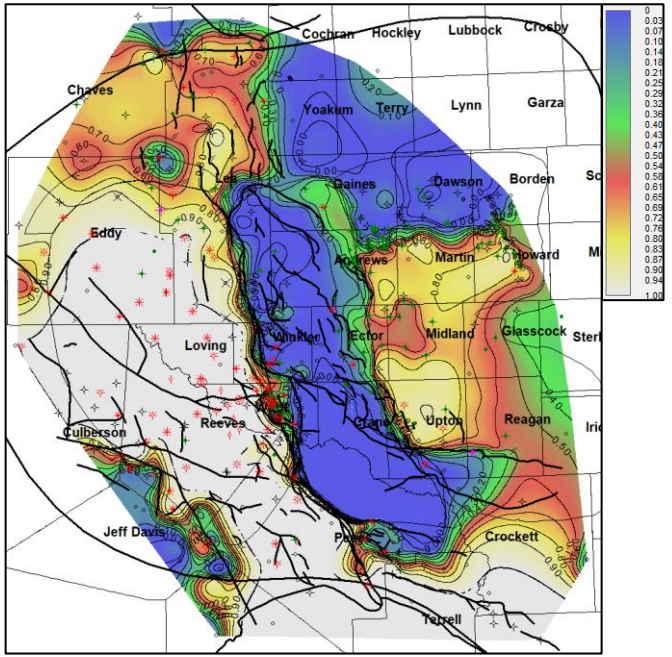
Woodford Kinetics

The ratio of the labile portion of Woodford kerogen transforms to hydrocarbon as a function of thermal maturity. To capture transformation ratio in map form, the WDFD kinetics curve is digitized with flipped axes. TR below 0.60 Ro is considered 0.00; TR above 1.6 Ro is considered 1.00 (100% transformation).

Transformation Ratio Map



Transformation Ratio Map

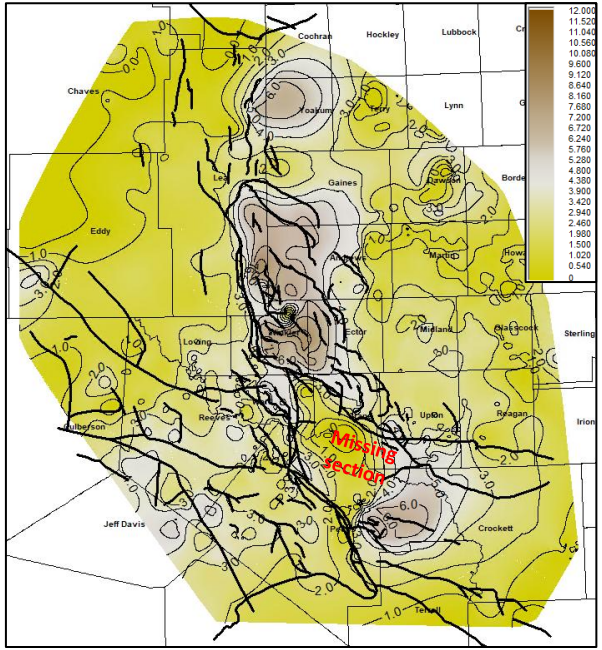


TR = $-2.5729x^5 + 22.118x^4 - 66.893x^3 + 91.546x^2 - 56.131x + 12.521$, where x = thermal maturity map

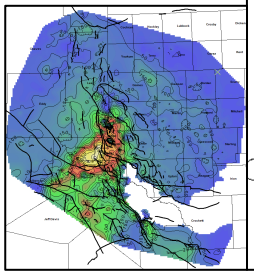
Comparison of Woodford TOC_{pd} and TOC_o

Highest present-day TOC (left) has been affected strongly by the effects of thermal maturity. Restoring original TOC (right) better reveals the organic matter's original deposition and preservation trends before basin subsidence and thermal maturation took place. Note the similarity of Woodford thickness and average TOC_o.

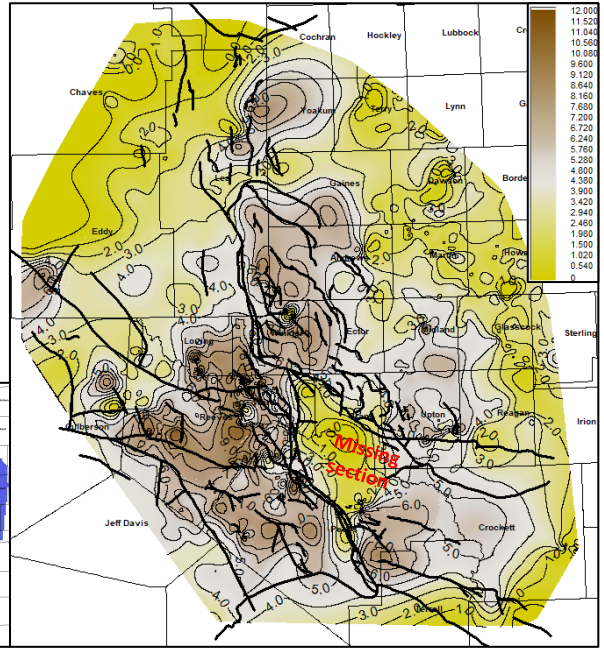
Average Present Day TOC



WDFD Thickness



Average Original TOC



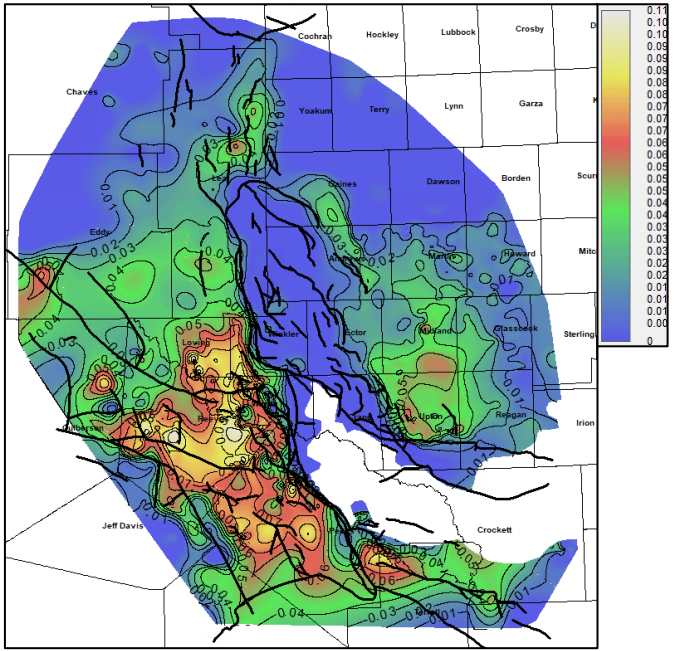
$TOC_o = TOC_{pd}/(1-(TR*Cc))$, where Cc=0.595

Quantifying Organic Matter Porosity

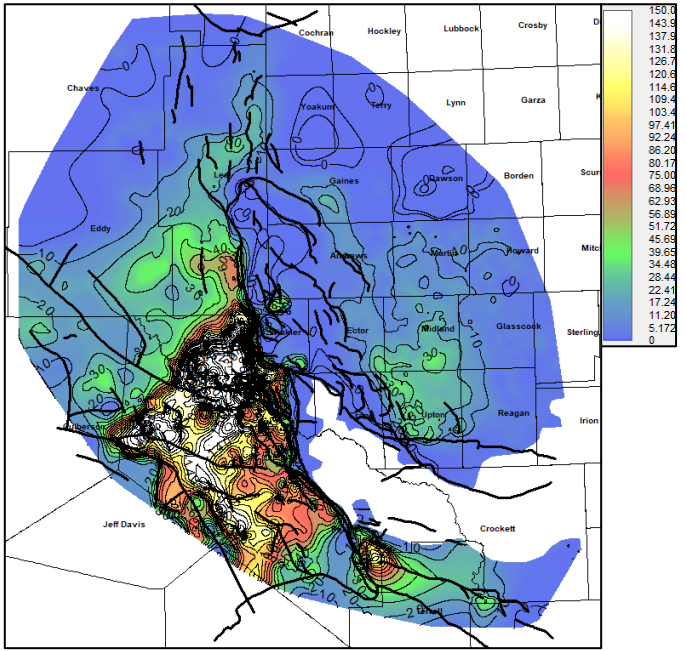
Kimmeridge

Avg OM Porosity is controlled by TOC_o, convertible carbon, transformation ratio (which is a function of thermal maturity) and the relationship of bulk density to organic matter density (which is also a function of thermal maturity). OOIP is strongly driven by variability in thermal maturity, TOC_o, and WDFD thickness.

Average OM Porosity



OOIP HCPV (MMRBO/sec)

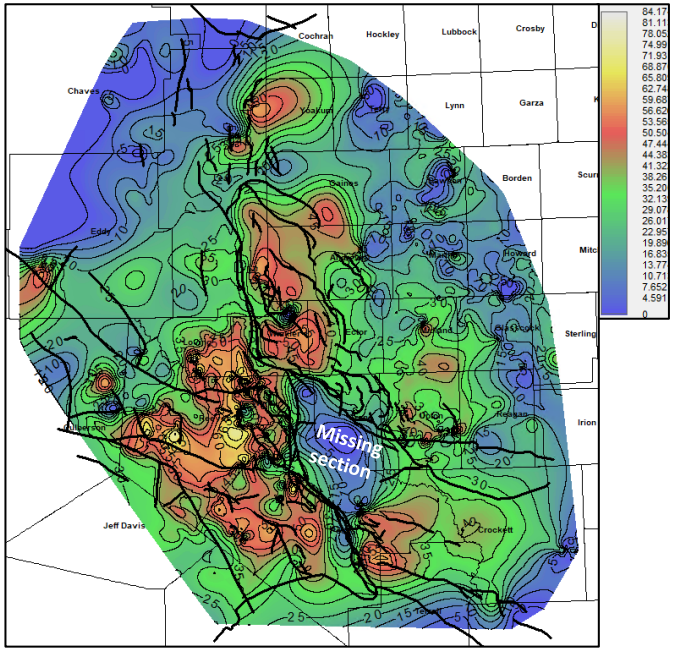


Avg OM Porosity = ((TOC$_o$/100)*Cc*TR)*k*(RHOB/RHOK), k = 0.95/0.85 = 1.118; assumes ~95% TOC$_o$ is from kerogen, Cc mass is ~85% of convertible kerogen mass.

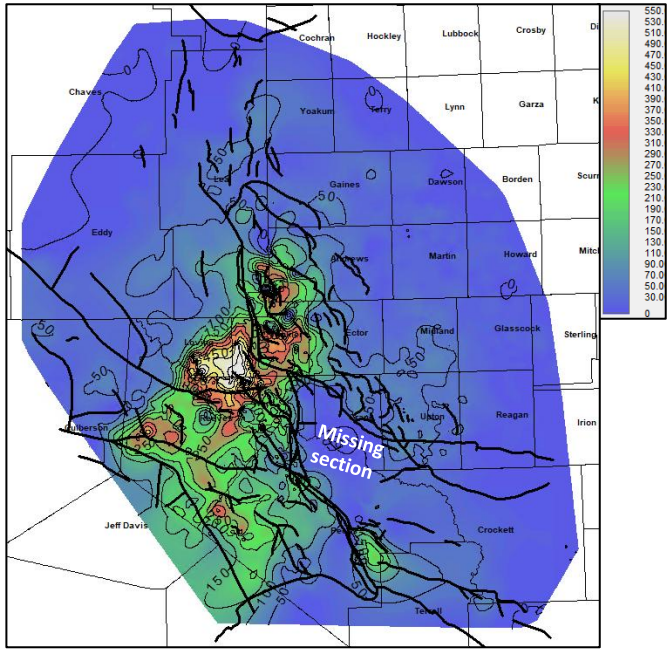
Maximum Generative Potential of the Woodford

Full generative potential is determined by: $S2_o=(HI_o*TOC_o)/100$ mg HC/g rock. This is converted to MMRBO/Sec by scaling and using WDFD thickness for H. The maximum generation potential of the Woodford, however, was only reached where thermal maturity (transformation) reached 100%.

Generative Potential (mg HC/g rock)



Generative Potential (MMRBO/Sec)



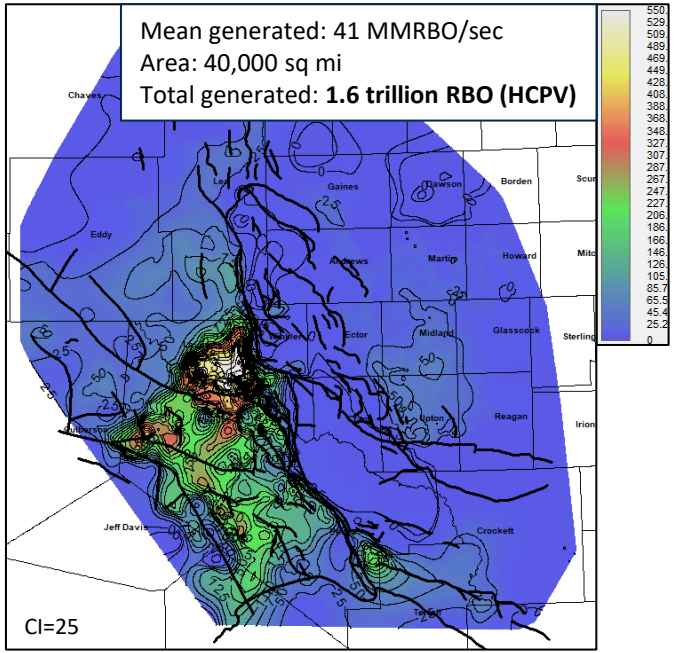
$S2_o$ OOIP HCPV (MMRBO/Sec) = ($S2_o$ mg HC/g rock map*20.082*640*WDFD thickness map)/1,000,000

Woodford Generated Hydrocarbons (HCPV)

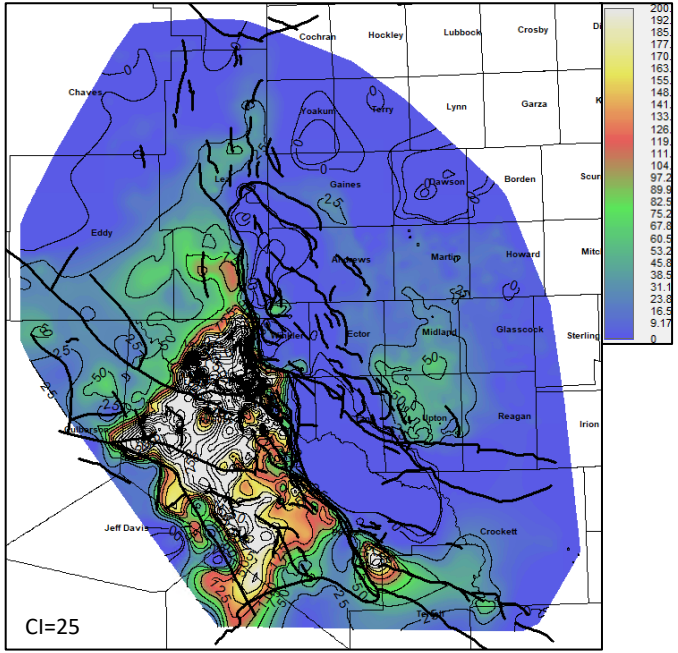
Kimmeridge

Multiplying the full generative potential of the Woodford by the transformation ratio map yields the volume of hydrocarbons actually generated by the Woodford. Hydrocarbons generated by the Woodford across the Permian Basin total ~1.6 trillion BOE (HCPV). Rescaled color bar helps highlight areas for comparison to organic porosity OOIP (HCPV).

Generated Hydrocarbons (MMRBO/Sec)



Generated HCs Rescaled Color Bar

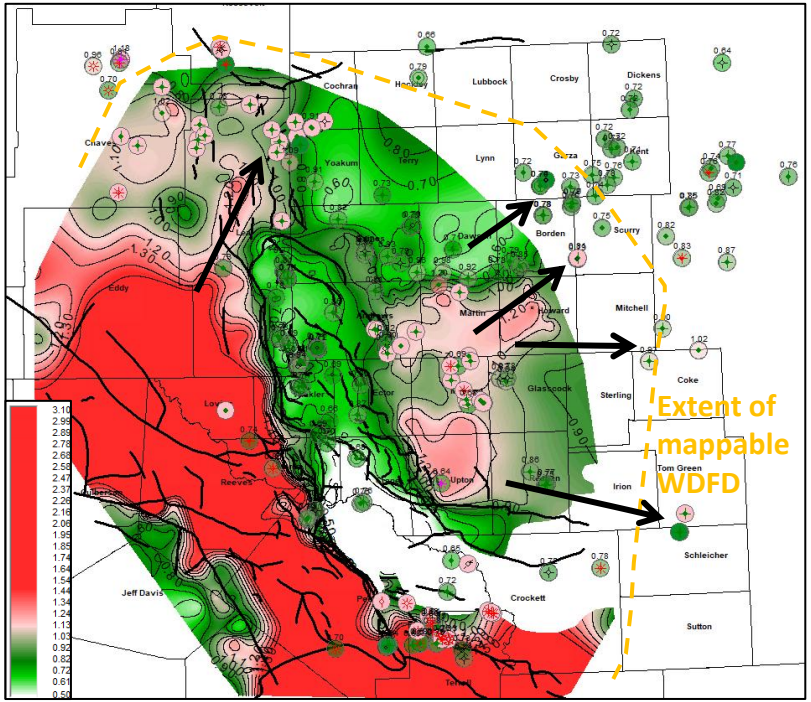


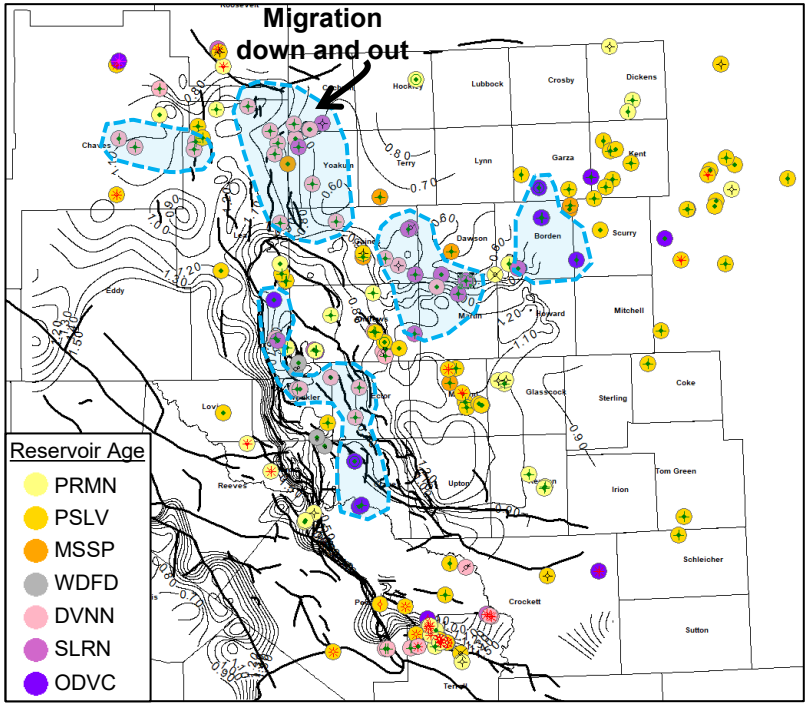
Hydrocarbons generated = Max Generative Potential map*Transformation Ratio map

Woodford Oils | Variability in Migration

Kimmeridge

Produced WDFD oils from a variety of reservoirs are plotted with estimated source rock maturity (from GeoMark) using the same color bar as the WDFD thermal maturity map. Source rock maturity can only be estimated for moderate (oil window) to higher (condensate) maturities. Mismatches between source rock maturity and oil maturity suggest migration.





Conclusions

- The Woodford Shale is a prolific source rock across nearly the entire greater Permian Basin
- High silica content plays an important role in sedimentation, diagenesis and reprecipitation, and destruction/preservation of interparticle porosity and microporosity
- Highest average TOC coincides well with the thickest WDFD of the distal Tobosa Basin depocenter
- Variability in hydrocarbon generation is controlled primarily by:
    1) Original WDFD depositional conditions – note thickest, most distal section and highest TOC_o
    2) Highly heterogeneous thermal maturity – note where high transformation ratio occurs with thickest WDFD
- Total WDFD hydrocarbon generation exceeds 1.6 trillion RBO (HCPV)
- TOC with variable thermal maturity across the basin control organic porosity, a major (if not dominant) contributor to total hydrocarbon storage in the Woodford
- WDFD system shows strong evidence for both interformational and intraformational migration