Pennsylvanian Source Rocks in the Anadarko Basin: An Example from the Missourian Series Hogshooter Formation in Mills Ranch Field, Texas and Oklahoma*

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Abstract

The Anadarko Basin is one of the most petroliferous basins in the world, and has a poly-basin history that can be subdivided into Ordovician, Devonian-Mississippian, and Pennsylvanian petroleum systems. Several previous studies within the Anadarko Basin highlight the potential of Pennsylvanian mudstones/shales as viable hydrocarbon sources. However, unlike source rocks in the Ordovician and Devonian-Mississippian petroleum systems, where clear geochemically validated examples of sourcing contributions in the basin exist, those of the Pennsylvanian system lack any clear geochemical ties. This study highlights the hydrocarbon-source relationship within Mills Ranch Field (Hogshooter Formation, Missourian Series) along the Texas and Oklahoma border by clearly demonstrating the genetic relationship between produced oils/condensates and Missourian shales.

Bitumen extracts from two mudstone-shale cores in the Hogshooter portion of the field were used to link the produced fluids to Missourian source beds. To validate key geochemical correlation characteristics, low maturity extracts from other representative source facies within the Anadarko Basin were also used for comparison. Additionally, data from Woodford Shale produced oils were used as a Devonian source control. Based on gas chromatography, coupled gas chromatography/mass spectrometry, and stable carbon isotope-ratio-mass-spectrometry analyses, light oils and condensates produced from Mills Ranch Field are genetically related to local Missourian mudstones/shales. Key geochemical attributes that set the Pennsylvanian oils apart from the Ordovician and Devonian-Mississippian systems are Mango K1 and K2 ratios, C27/C29 14α and 14β-sterane ratios > 1,

abundant diahopane relative to 17α-hopane and high saturate/aromatic fraction δ13C canonical variables. At least three organic-facies are identified within the Missourian section from integration of sedimentology, petrography and geochemistry. However, there is just one primary type-II organic-facies that is geochemically tied to the petroleum liquids. Models for the distribution of the primary type-II liquids-generating organic-facies have led to an improved assessment of the Mills Ranch Field Missourian section, and a better understanding of the economic potential of Pennsylvanian shales in the Anadarko Basin.

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PENNSYLVANIAN SOURCE ROCKS IN THE ANADARKO BASIN: AN EXAMPLE FROM THE MISSOURIAN SERIES HOGSHOOTER FORMATION IN MILLS RANCH FIELD (TX & OK)

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June 3, 2015

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Chesapeake ENERGY

PROBLEM

- What is the provenance of the produced petroleum from the Hogshooter Formation sands in Mills Ranch Field?

- Are these derived from deeper, middle and/or lower Paleozoic source rocks?

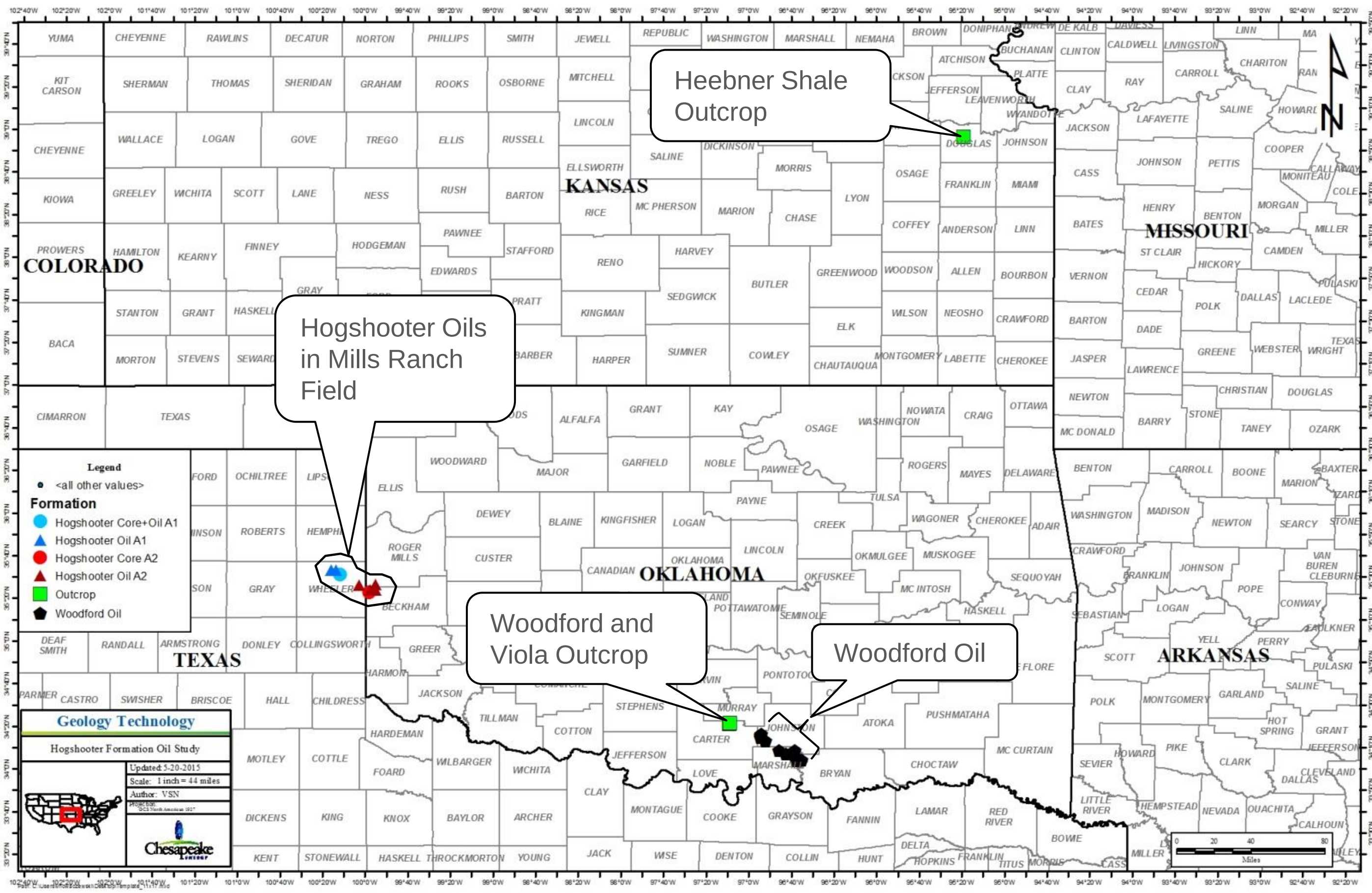
- Alternatively, is the petroleum from the Pennsylvanian system itself? Presence of organic-rich mudstones in the Missourian interval offer this potential.

- Using bulk and molecular geochemistry techniques we will determine the most likely provenance of the produced petroleum.

SOURCES OF DATA

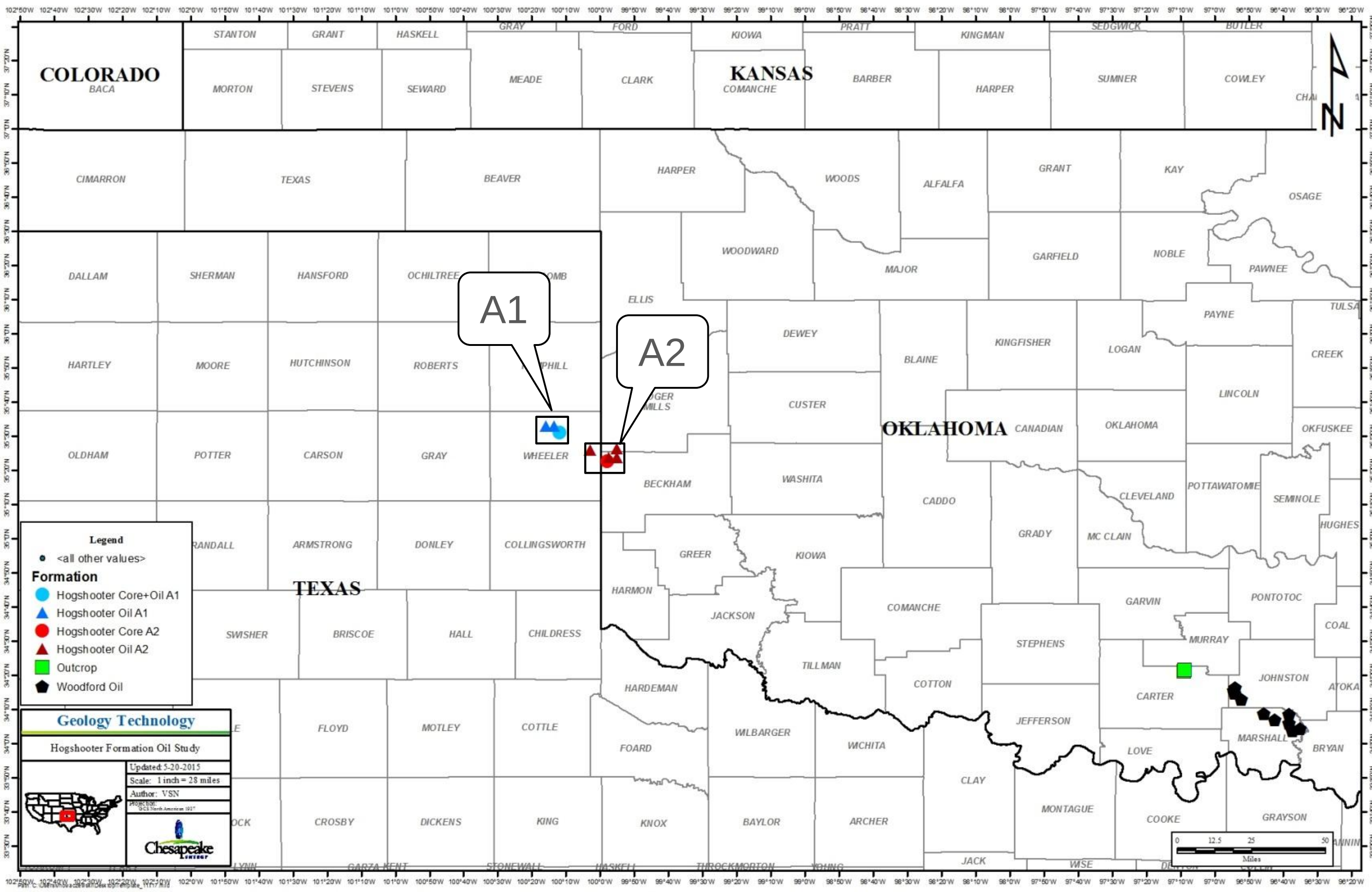
- Chesapeake Reservoir Technology Center (CRTC) and Weatherford Laboratories (WTFD) for Gas Chromatography(GC) and coupled Gas Chromatography-Mass Spectrometry (GCMS) data.
- WTFD for Isotope Ratio Mass Spectrometry (IRMS) data.
- CRTC for core photos, spectral gamma ray, TOC/SRA, XRD and TRA data.
- Chesapeake Energy Mid-Continent business unit for logs and specialty geologic maps.
- Literature for comparison to previous work.

SAMPLE LOCATIONS



- Samples from Mills Ranch field are distributed in Wheeler Co, TX and Beckham Co, OK.
- Woodford and Viola Formation outcrop samples are from the Arbuckle Mountains and the Heebner Shale outcrop sample from Lawrence, KS.
- On-strike with the Hogshooter production are Woodford Shale produced oils in the western Arkoma Basin.

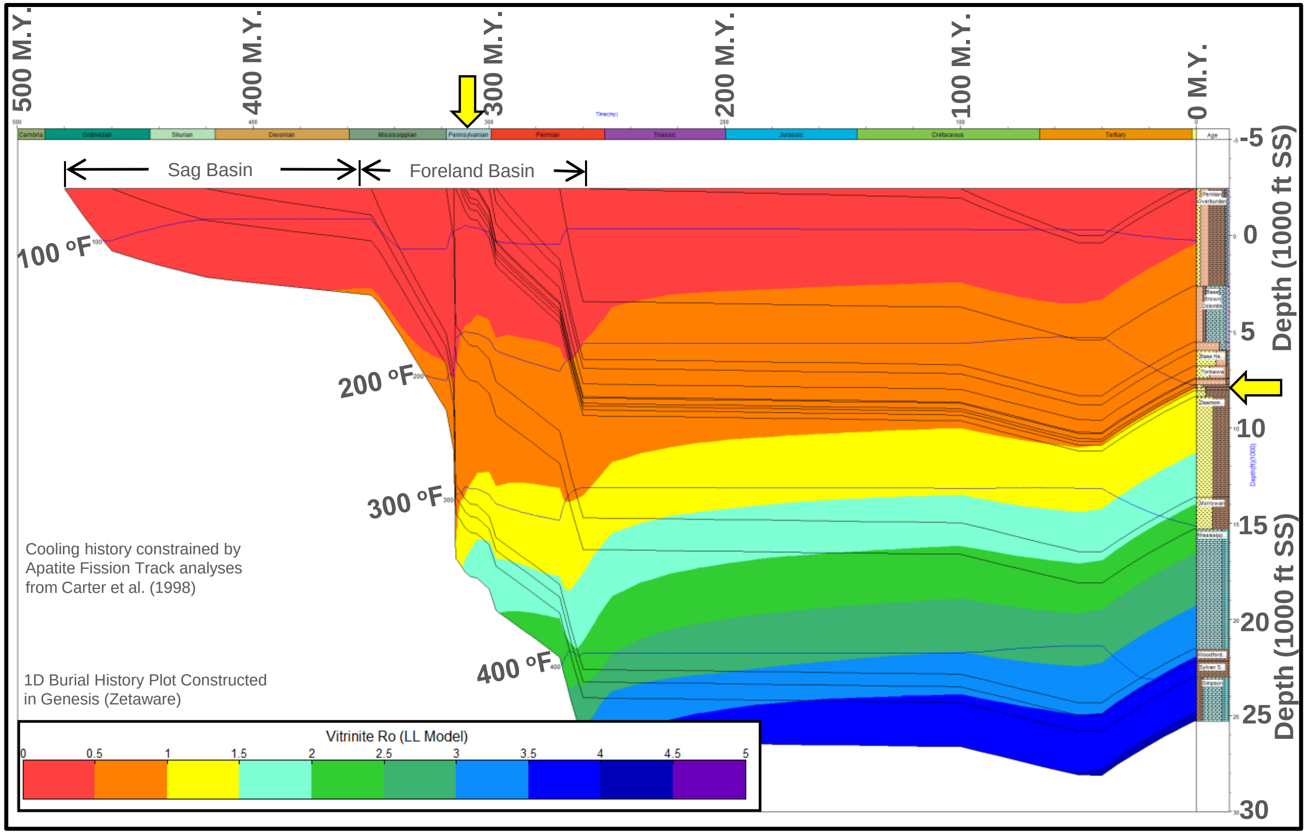
TWO SETS OF HOGSHOOTER SAMPLES



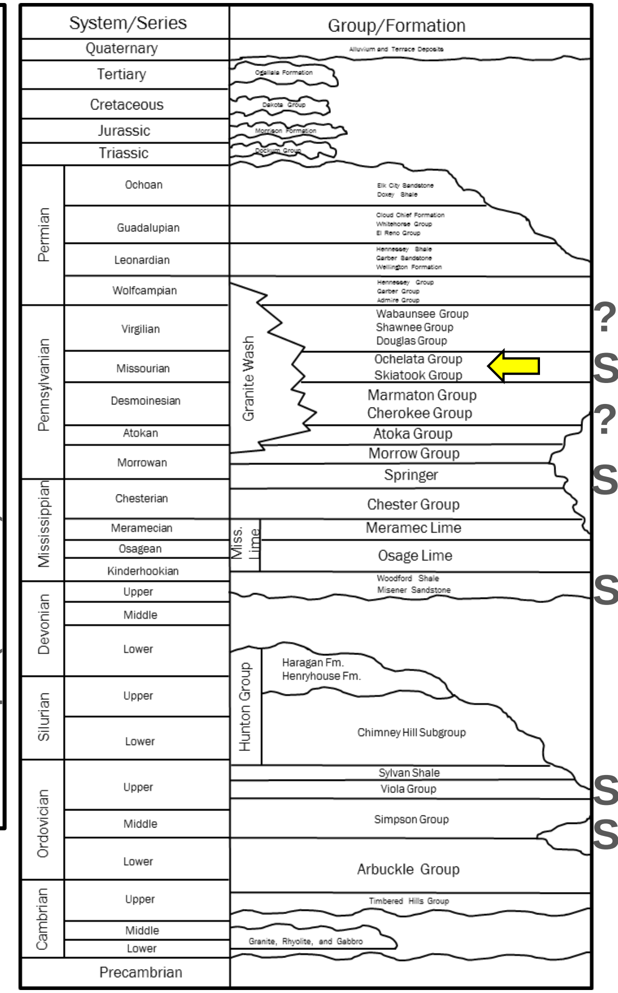
- Two different areas in Mills Ranch Field where the Hogshooter was sampled (A1 and A2).
- These two areas differ in Hogshooter thermal maturity with A1 being less mature than A2.

BURIAL HISTORY AND STRATIGRAPHIC POSITION

Burial History Plot for the Meek 41 10H (A1)



Anadarko Basin Stratigraphic Chart

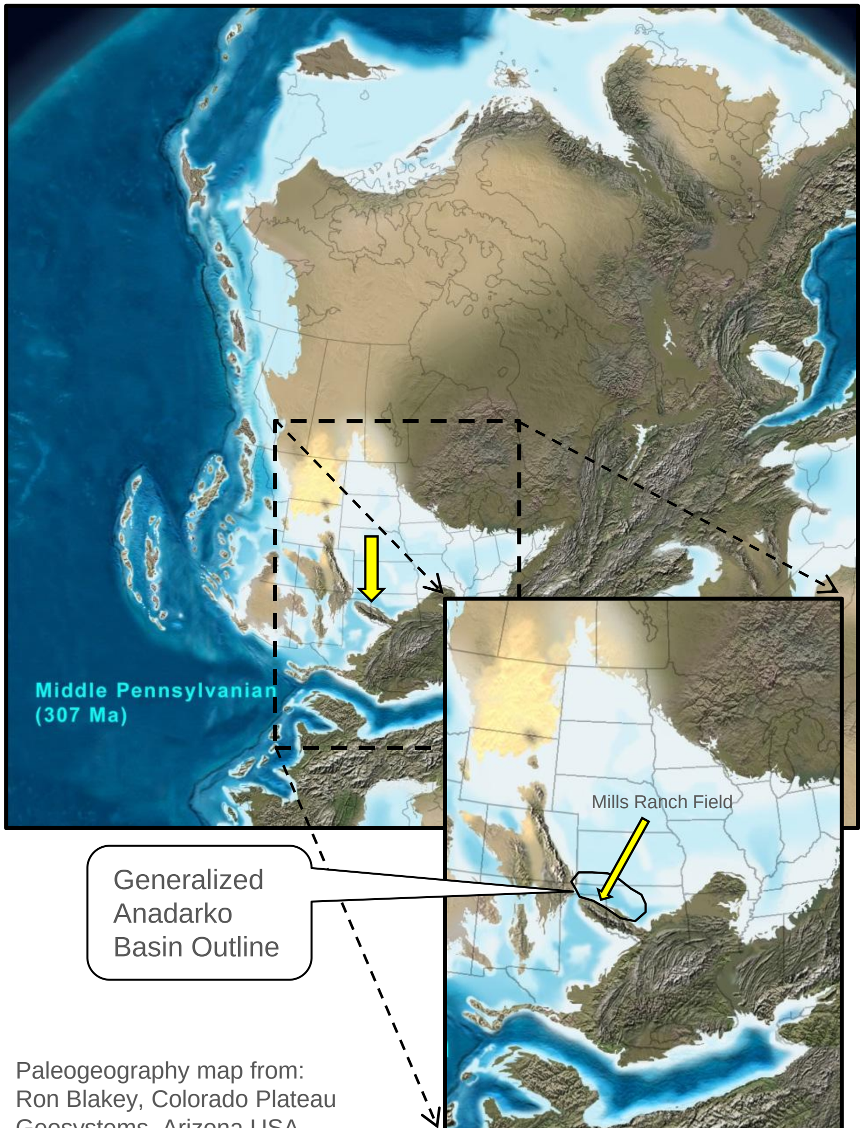


Modified from Johnson and Cardott (1992)

- In the Anadarko Basin, late Paleozoic formations including the Hogshooter formation (yellow arrow), were deposited within a quickly subsiding foreland basin.

- Lower and middle Paleozoic formations were deposited during a sag basin phase that followed a failed Cambrian rift system (e.g., Feinstein, 1981).

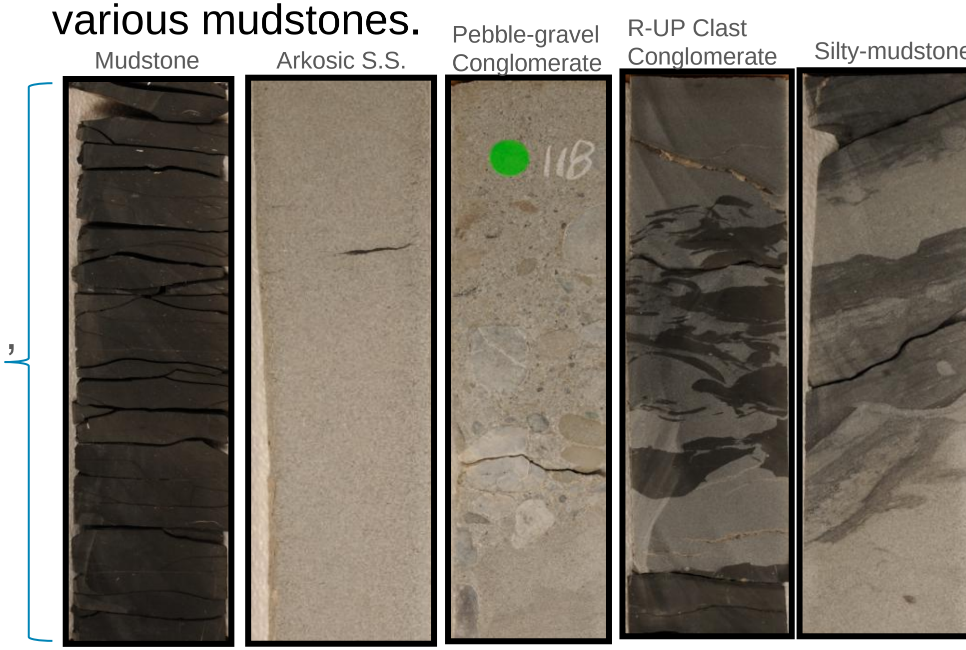
PALEOGEOGRAPHY AND MAJOR FACIES PRESENT



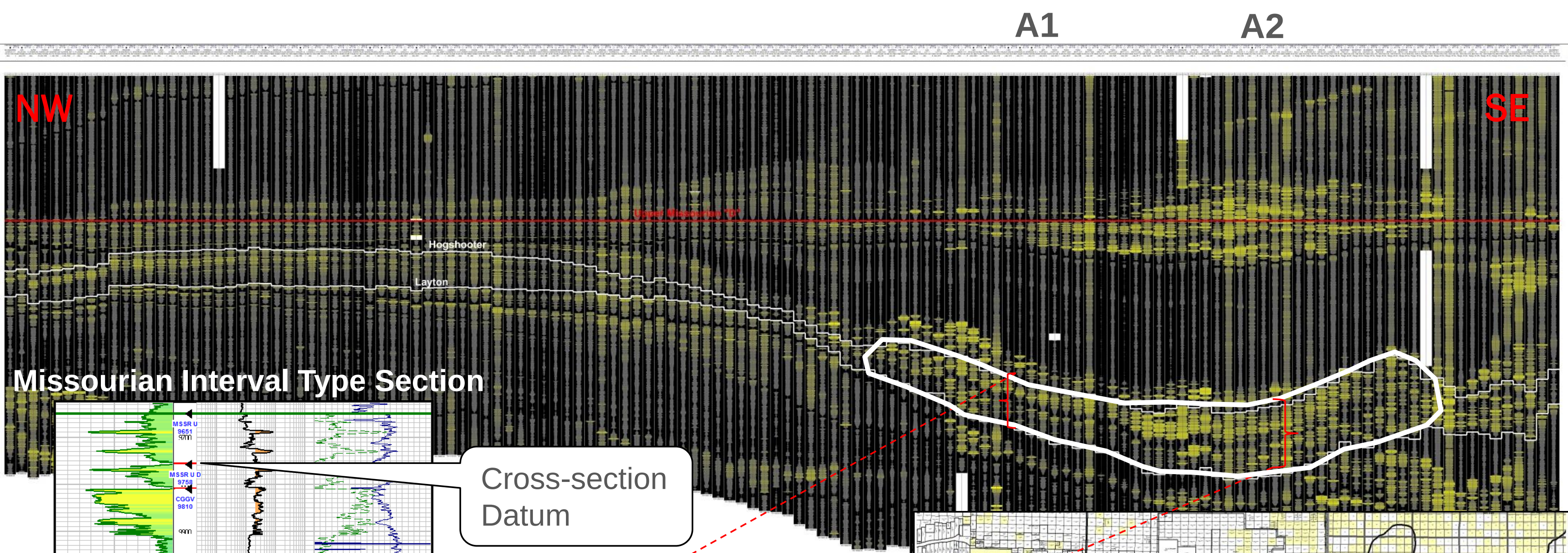
Paleogeography map from: Ron Blakey, Colorado Plateau Geosystems, Arizona USA

- There are a wide variety of lithologies present within the Hogshooter, representing deposition along a steep-marine-shelf in a fore-deep environment during active mountain building and erosion (Wichita Mountain Front).

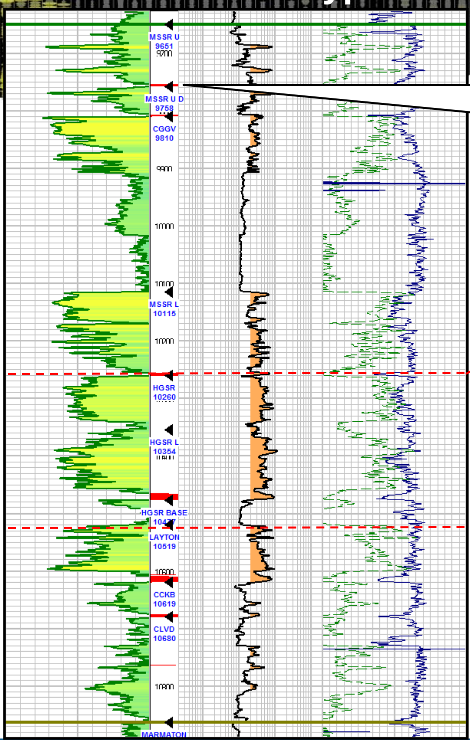
- These lithofacies are a mixture between arkosic sandstones-conglomerates and various mudstones.



CROSS-SECTION OF MISSOURIAN INTERVAL

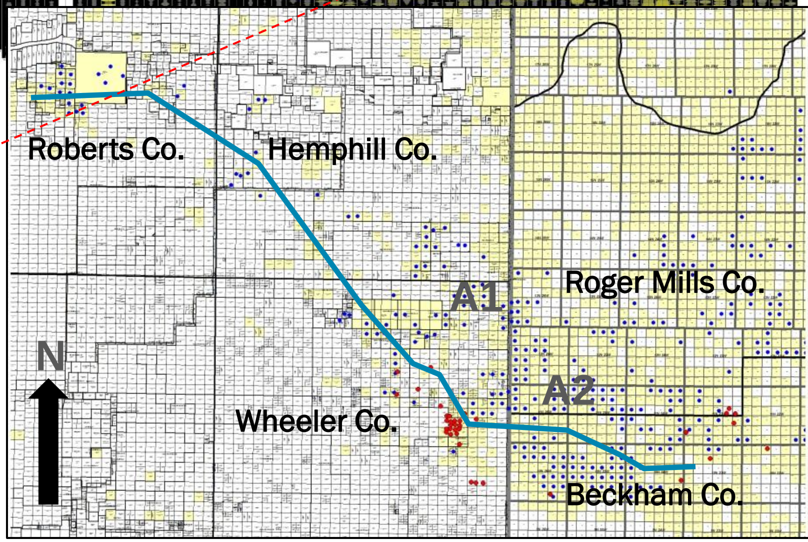


Missourian Interval Type Section



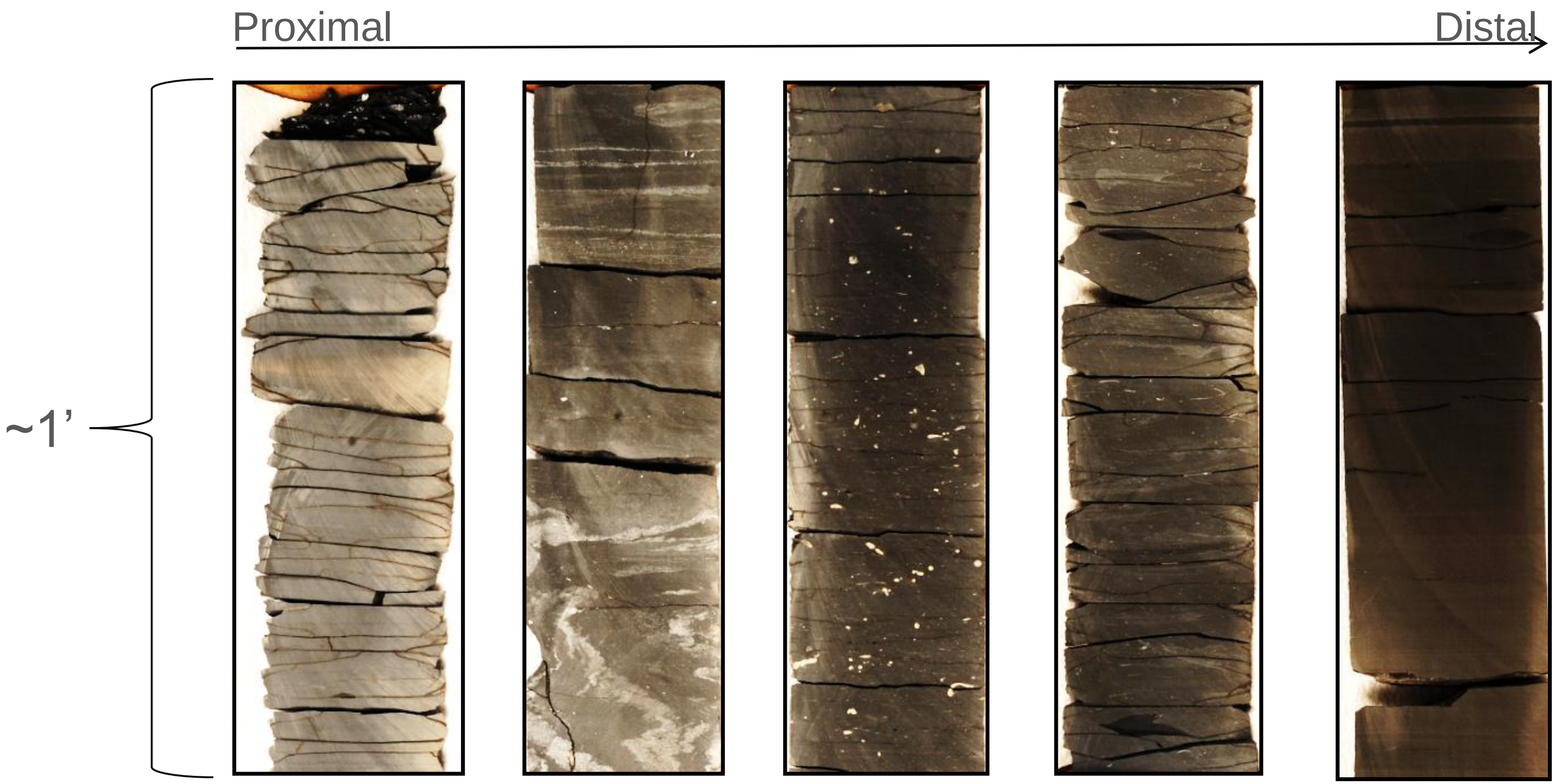
Cross-section Datum

This roughly strike-parallel stratigraphic cross-section shows the main Hogshooter portion of the field delineated by strong sandstone development



Hoaglund (2014)

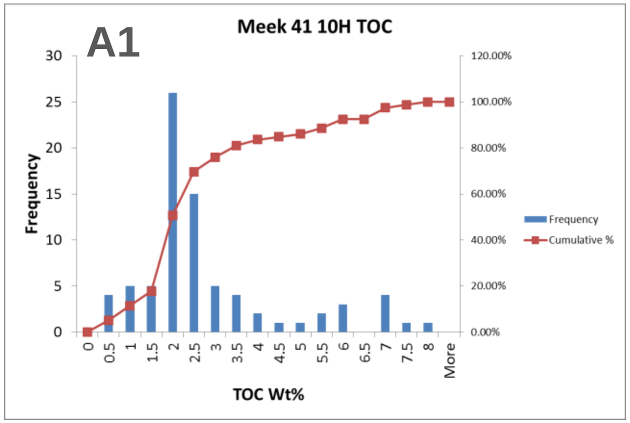
CLOSER LOOK AT MUDSTONE LITHOFACIES

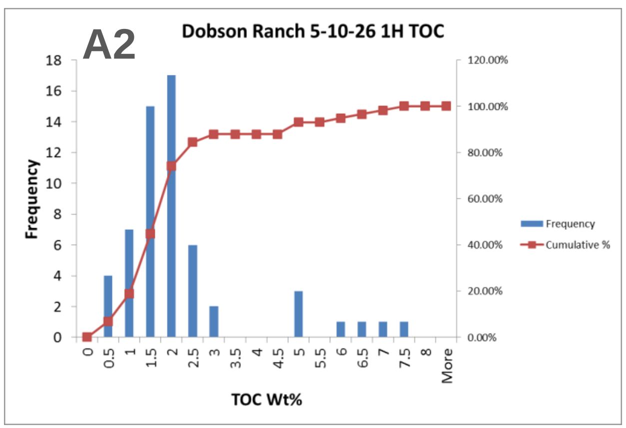


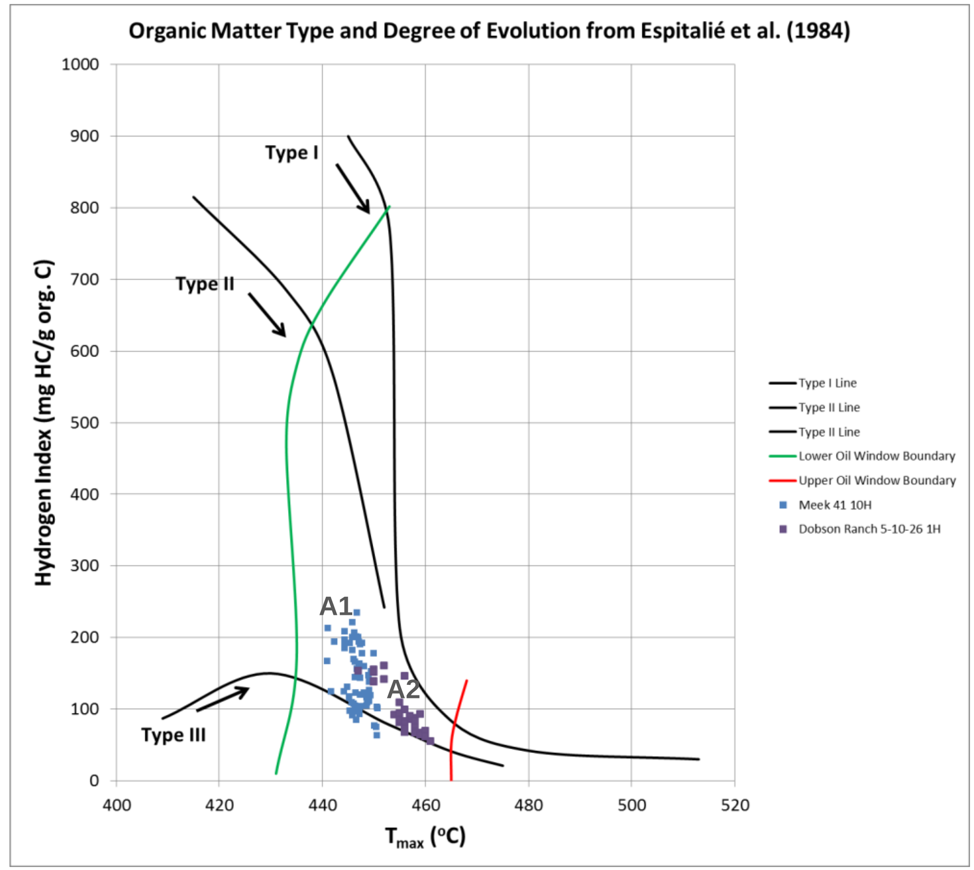
Brightness and contrast maximized for these images

- Broadly, mudstone lithofacies can be divided into black-brown shales, silty mudstones and thickly-bedded green mudstones and coaly mudstones.
- Example core images are given above.
- Black-brown shales are very organic-rich and oil-prone while the silty and/or thickly-bedded grey and green mudstones are of poor to moderate organic-richness and more (theoretically) gas-prone.

HOGSHOOTER MUDSTONE ORGANIC RICHNESS AND THERMAL MATURITY





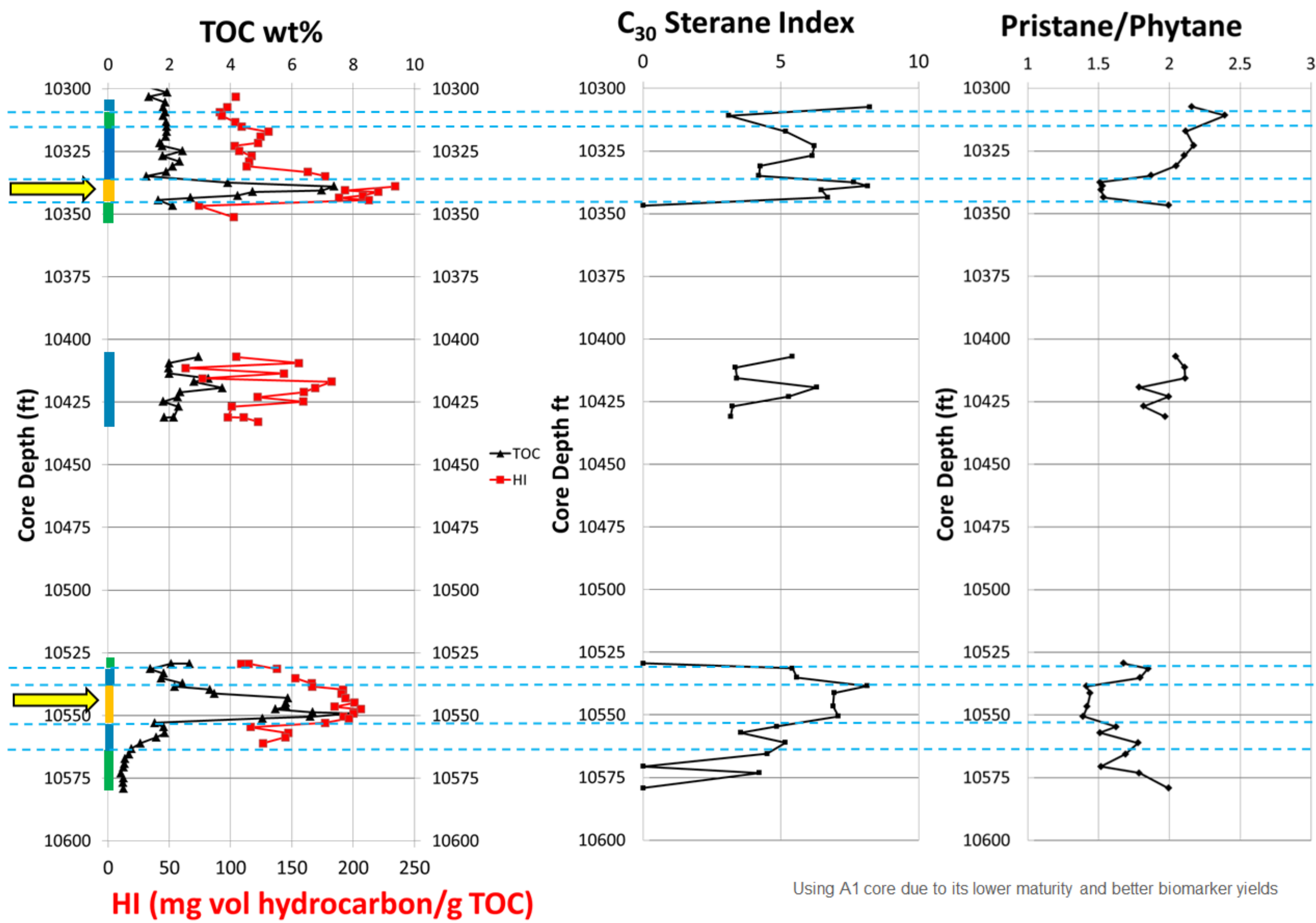


- Bimodal distribution of TOC. Average of mode#1 between 1.5 and 2.5 wt% TOC, and mode#2 centers between 6.0 to 7.0 Wt%.
- Apparent kerogen-types vary from type II to type II-III to type III.
- T_{max} values for type II plotting samples center around 445 ºC (~0.9 $\%R_o$) in the Meek 41 10H and 452 ºC (~1.0 $\%R_o$) in the Dobson Ranch 5-10-26H.
- These systems are in the late stage of the oil window.

EXAMPLE OF ASSIGNING MUDSTONE FACIES BASED ON BIOMARKERS—MEEK 41 10H (A1-REP)

- Using profiles of key biomarker parameters we can gain insight into the nature of the mudstone depositional environments complementary to sedimentological observations.

- <u>Three major groups of mudstone environments are recognized here, and these are given below.</u>



Paralic Depositional Conditions

Open-Shallow-Neritic Depositional Conditions

Restricted-Deep-Neritic to Restricted-Shallow-Pelagic Depositional Conditions

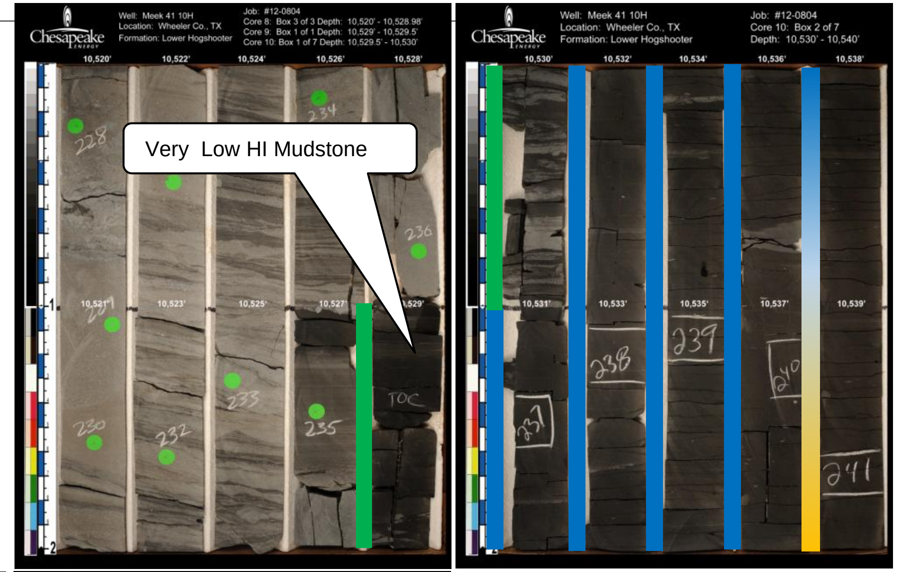
CORE PHOTOS FOR BASAL SHALE

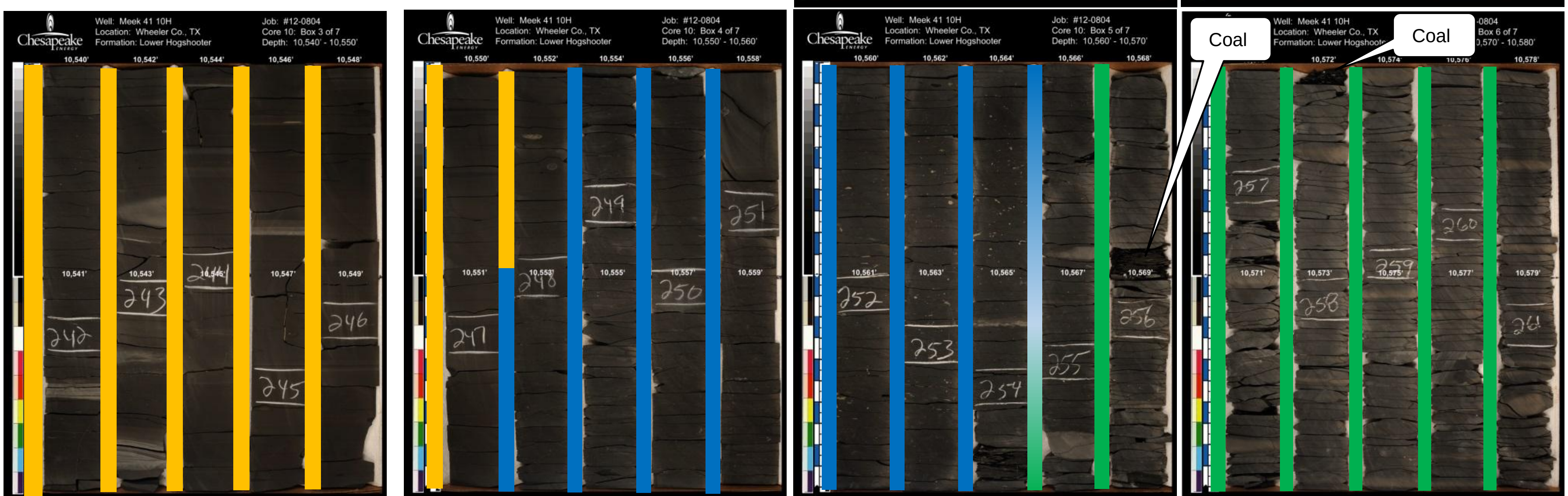
- When plotting biomarker-facies assignments on the core photos the segregation of associated lithofacies becomes apparent.
- Paralic deposition occurs at the beginning and end of these mudstone sequences.
- <u>The pattern of facies captures the cyclical, but asymmetric nature of these mudstone units and the transition out of and into higher energy deposition.</u>

Paralic Depositional Conditions

Open-Shallow-Neritic Depositional Conditions

Restricted-Deep-Neritic to Restricted-Shallow-Pelagic Depositional Conditions





OIL APPARENT THERMAL MATURITY: CTEMP COMPARISON TO MEEK 41 10H EXTRACTS AND ASSOCIATED OILS

	Oil Sample	C_{temp} (ºC)
A1	Thurman Horn 406H (A1)	128.15
A1	Meek 41 10H (A1)	126.35
A1	Zybach 6010H (A1)	129.20
A2	Bulldog 14-11-26 (A2)	140.75
A2	Davis 65-25-4 (A2)	141.92
A2	Nabors 35-11-26 (A2)	140.88
A2	KRY 33-11-26 2H (A2)	142.57

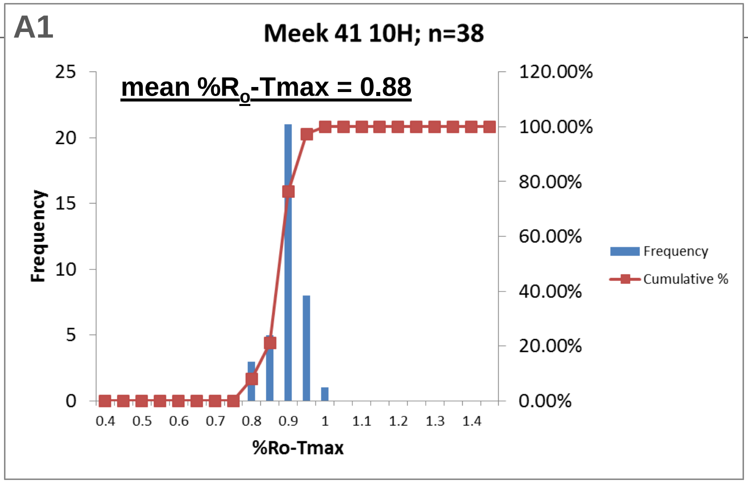
- Inspection of select gasoline range hydrocarbons detected in the A1 and A2 Hogshooter oils suggests that the A2 Hogshooter oils were generated at significantly higher temperatures than the A1 Hogshooter oils.
- By C_{temp} analysis the low molecular weight component of the A1 Hogshooter oils was generated at an approximate average $\%R_o$ of 0.85.
- By C_{temp} analysis the low molecular weight component of the A2 Hogshooter oils was generated at an approximate average $\%R_o$ of 1.0.

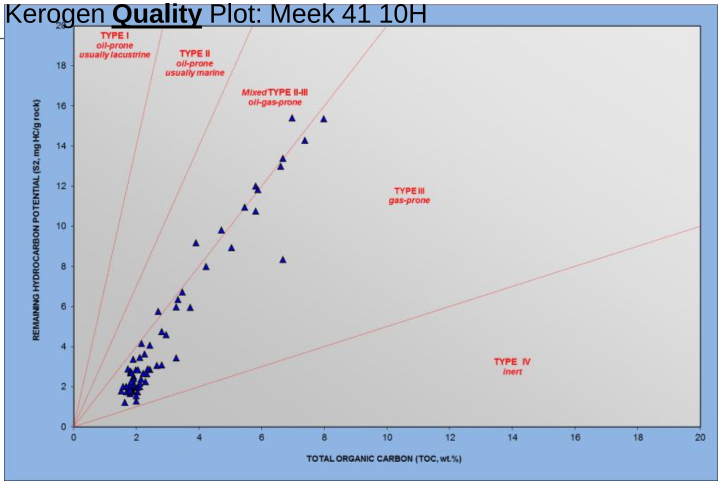
C_{temp}: 140 + 15 ln(2,4-DMP/2,3-DMP)

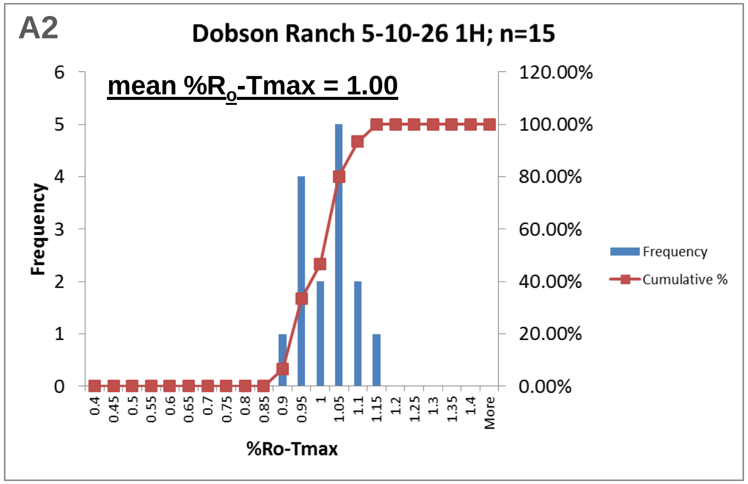
Mango (1997)

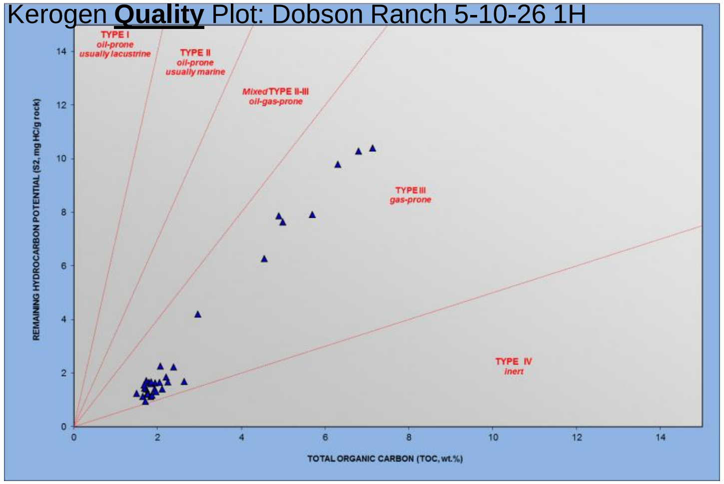
Conversion of Ctemp to %Ro using Burnham and Sweeny (1989)

MATURITY: ROCK EVAL COMPARISON BETWEEN MEEK 41-10H AND DOBSON RANCH 5-10-26 1H



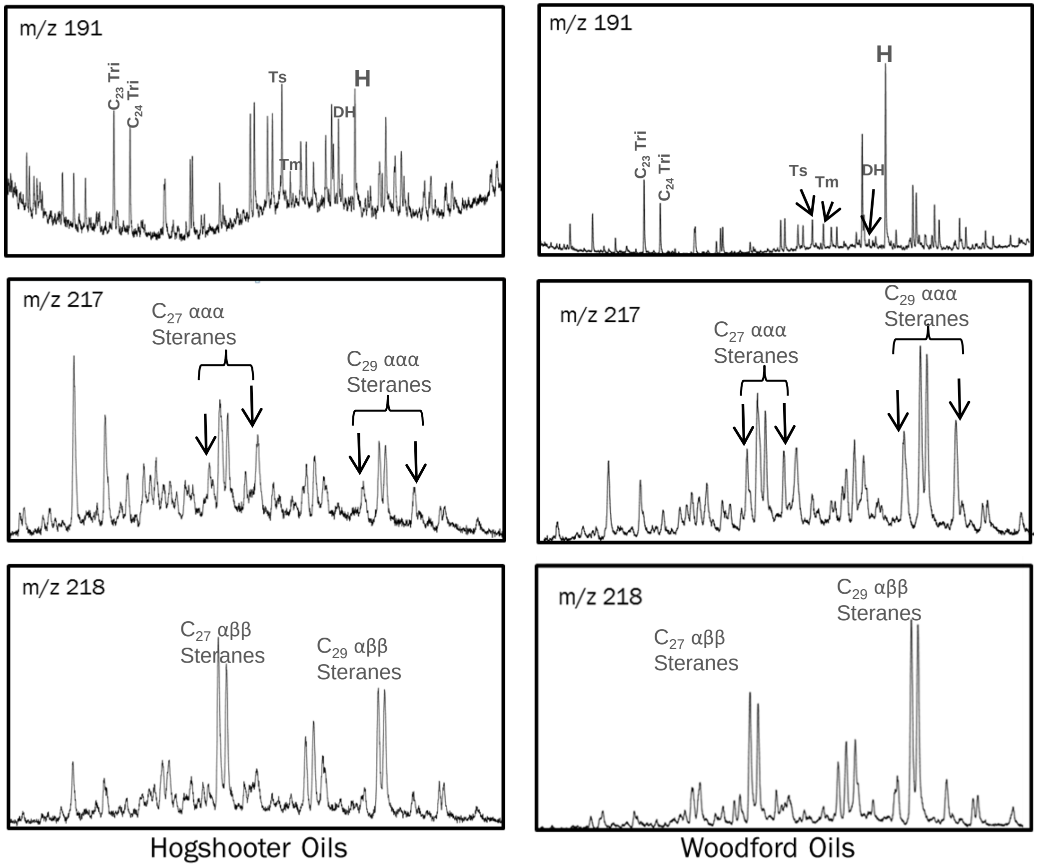






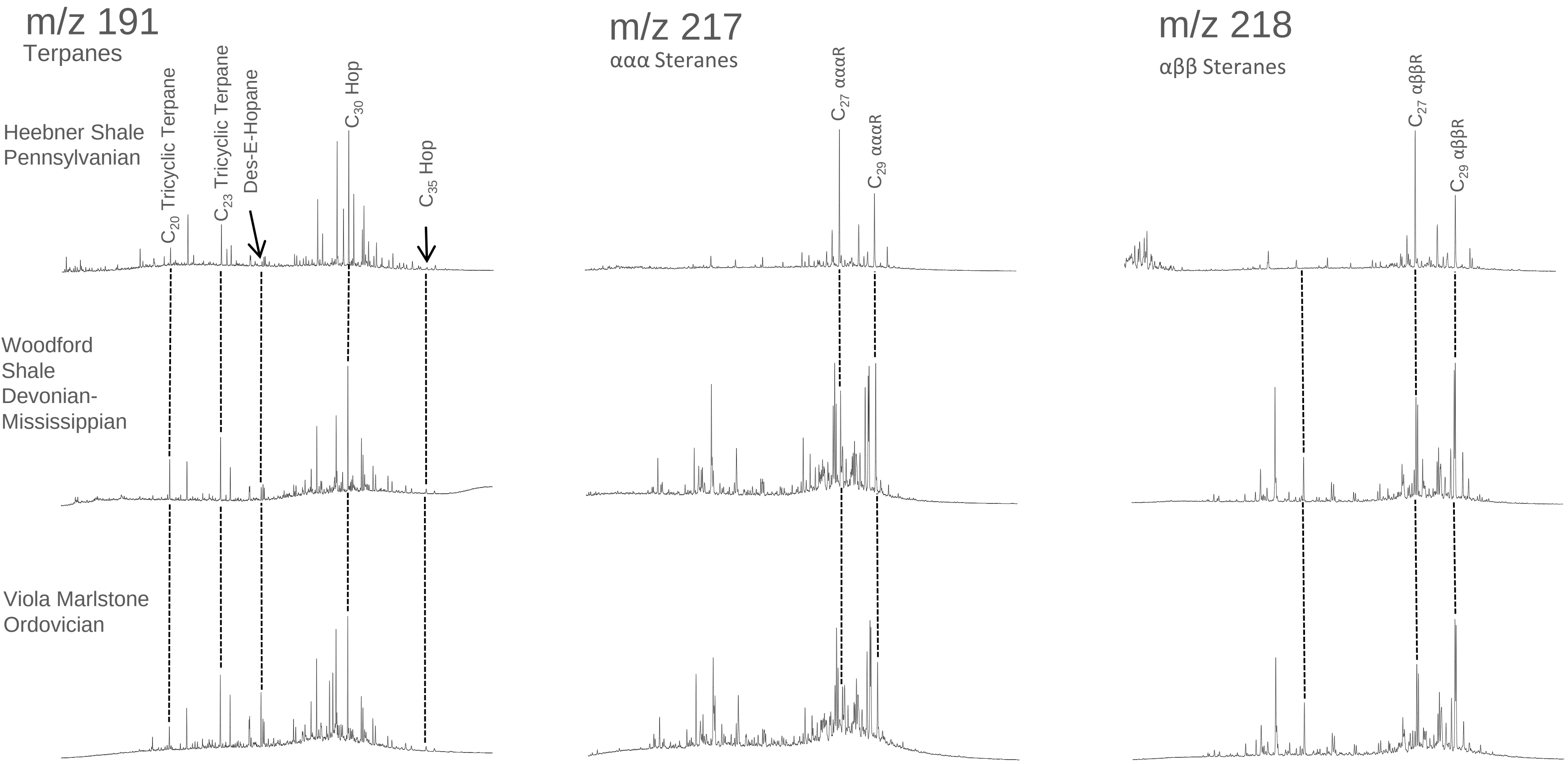
- The pyrolysis data on organic-rich shales > 2% TOC in both the Meek and Dobson Ranch cores reflect the thermal maturity difference between the A1 and A2 areas.
- The mean calculated $\%R_o$ values in both cores are congruent with the C_{temp} measurements made on the produced oils.
- At a gradient of 8.3 ^{o}C/1000’ (estimated from Carter et al., 1998) there should be a 1500’ max TVD differential between these locations. This is very close to the present day differential of ~1100’ leaving 300-400’ of estimated overburden removed between the two areas.
- **The correspondence of fluid thermal maturities to source rock thermal maturities suggests *in situ* generation and limited migration.**

COMPARISON OF WOODFORD PRODUCED OILS TO HOGSHOOTER OILS



- The Hogshooter produced oils differ markedly from the Woodford oils in major sterane and hopane biomarker classes.
- Proportions of regular steranes, tricyclic terpanes and hopanes are the most obvious sources of these differences.

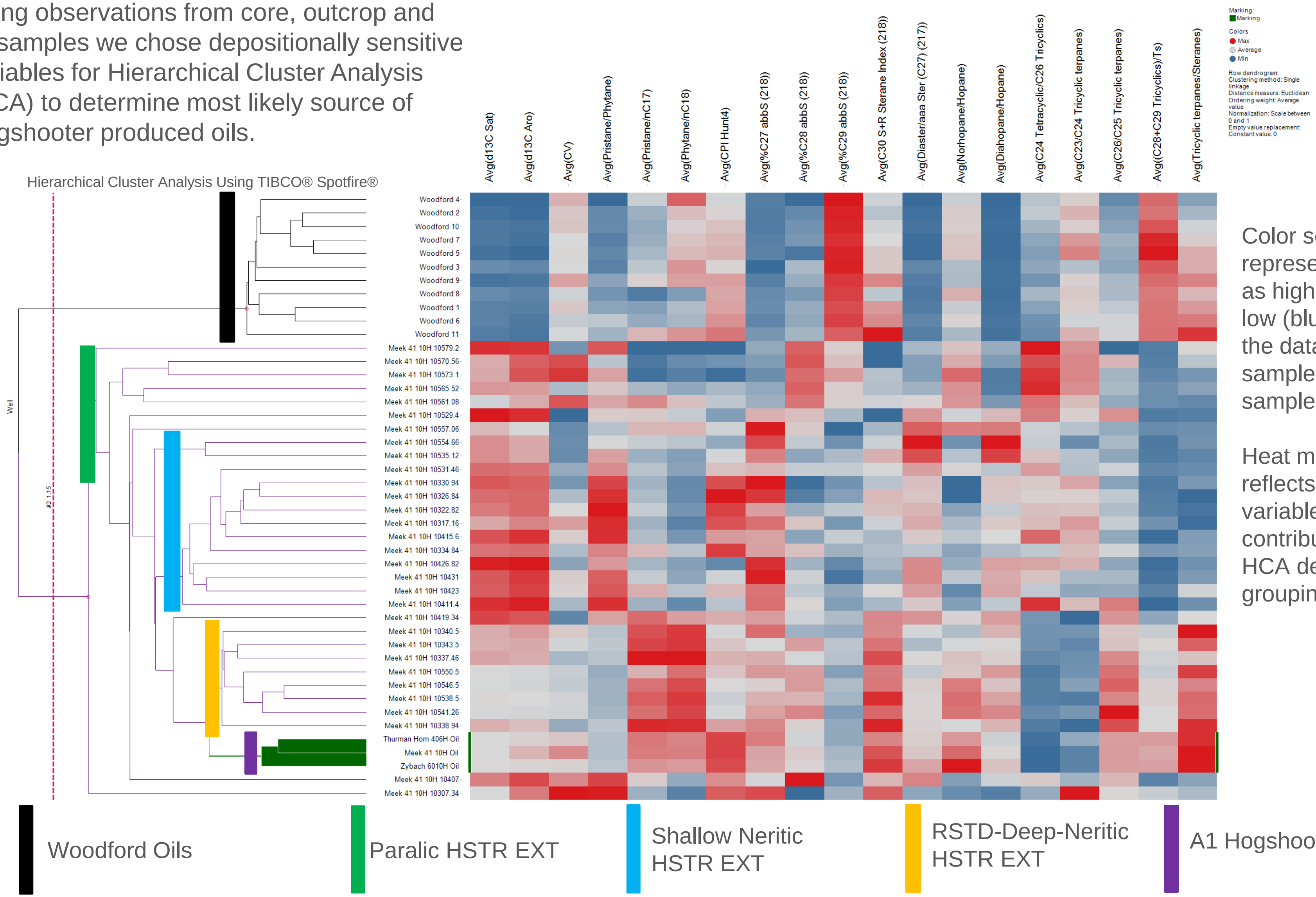
EXAMPLES OF THERMALLY IMMATURE ORDOVICIAN, DEVONIAN AND PENNSYLVANIAN SOURCE FACIES



- Comparison of immature examples of the Ordovician, Devonian and Pennsylvanian source rocks highlights features common to each system.
- Lower Paleozoic petroleum systems will have a pronounced C_{29} dominance in steranes and less complex tricyclic terpane distributions.
- These broad-system-scale insights can help us differentiate oils at a high level.

MULTIVARIATE COMPARISON OF GEOCHEMISTRY

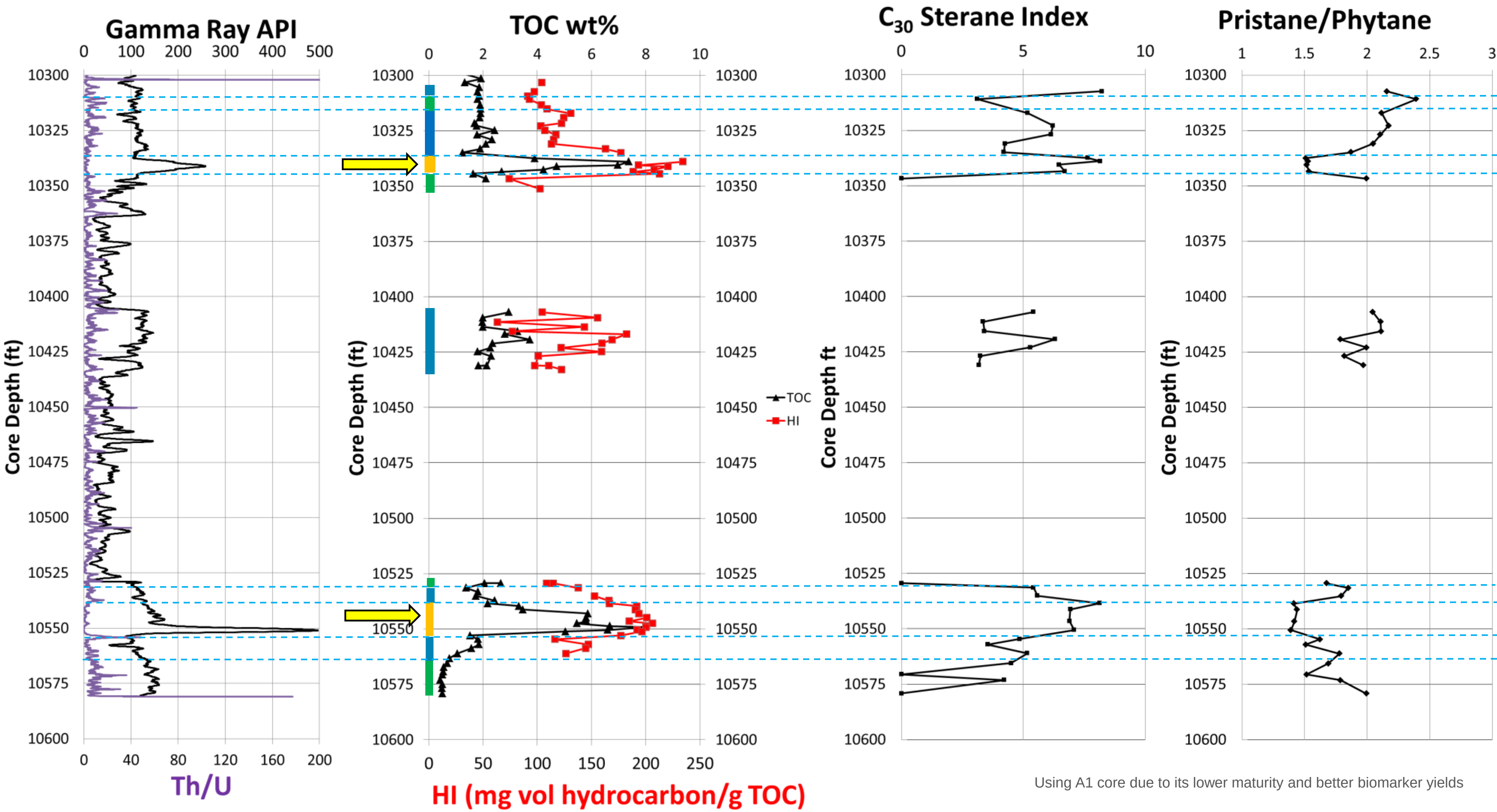
Using observations from core, outcrop and oil samples we chose depositionally sensitive variables for Hierarchical Cluster Analysis (HCA) to determine most likely source of Hogshooter produced oils.



Color scale represents values as high (red) or low (blue) within the dataset on a sample-by-sample basis.

Heat map pattern reflects which variables contribute to the HCA dendrogram groupings.

EXAMPLE OF ASSIGNING PRIMARY SOURCE FACIES BASED ON BIOMARKERS—MEEK 41 10H (A1-REP)



Using A1 core due to its lower maturity and better biomarker yields

Restricted-Deep-Neritic to Restricted-Shallow-Pelagic Depositional Conditions

Paralic Depositional Conditions

Open-Shallow-Neritic Depositional Conditions

INSIGHTS FROM MULTIVARIATE COMPARISON

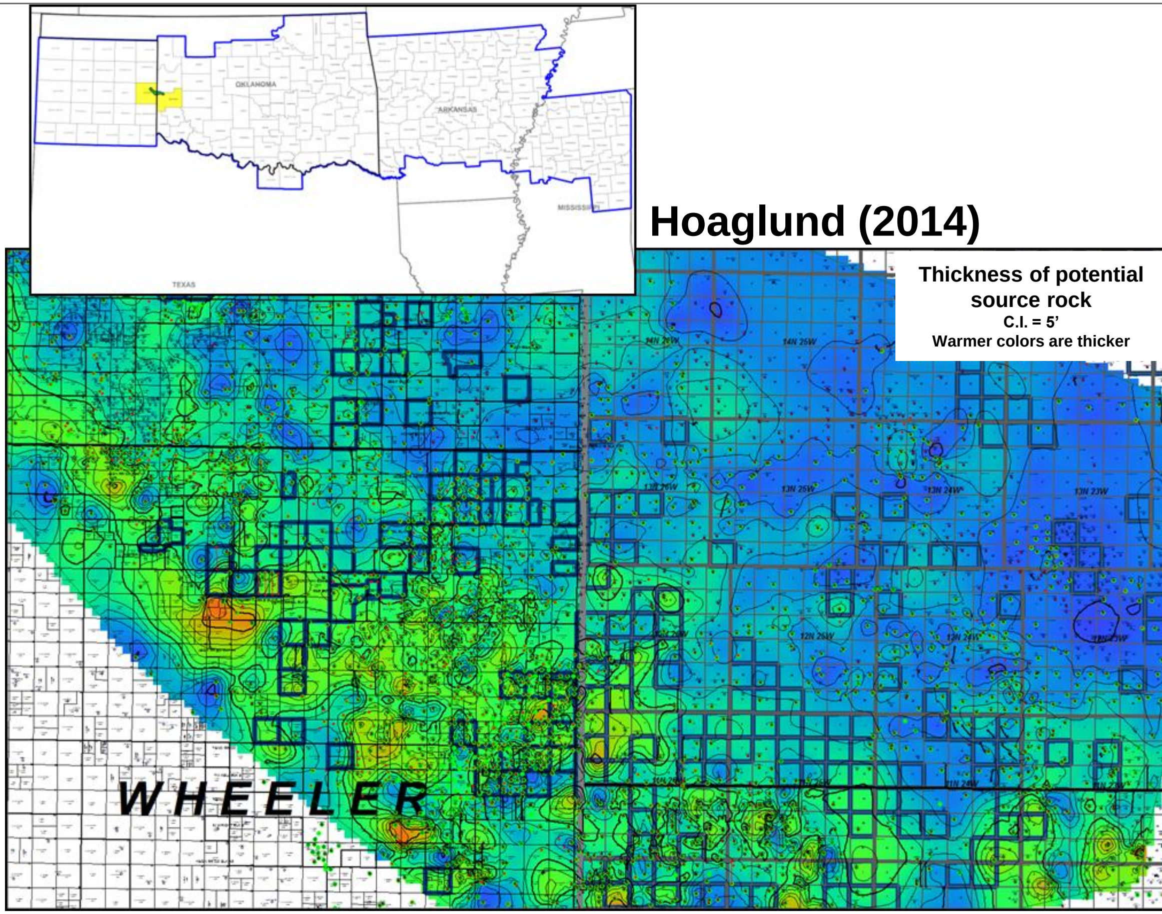
- Hogshooter oils are more closely related to the bitumen in the recovered Missourian core than oils or bitumen recovered in the Devonian system.

- Specifically, the high TOC/GR shales of the Hogshooter show the closest similarity to the Hogshooter oils in terms of molecular characteristics.

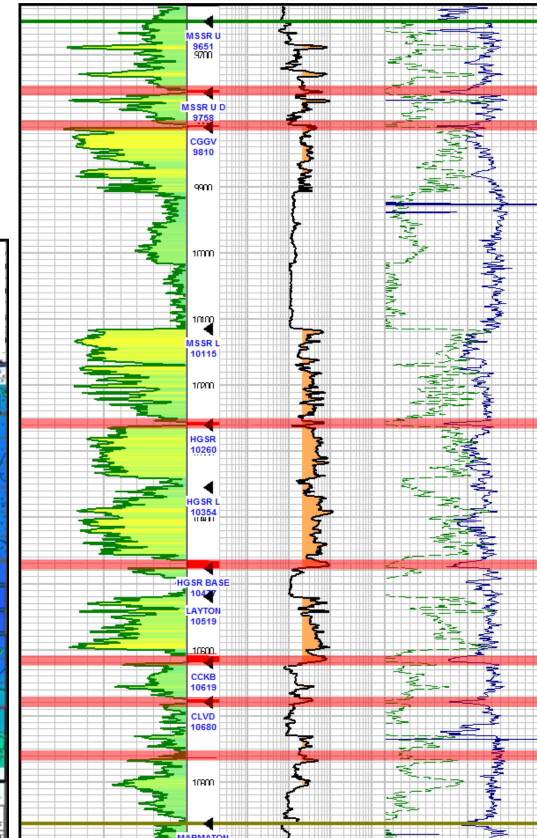
- There are about 20 net feet of these high TOC/GR shales in the cores recovered from the Hogshooter interval. However, there is much more present through the Missourian interval local to the Hogshooter productive zones.

NET THICKNESS OF HIGH GR HOGSHOOTER SHALES

Hoaglund (2014)



Missourian Interval Type Section



Volume of potential source rock

- This net thickness map of high GR shales shows that there is lateral and thickness potential for these primary petroleum source facies.

- These volumes can account for the Hogshooter in-place petroleum with conservative expulsion metrics.

THE (DEBATABLE) MASS BALANCE FOR GENERATED HYDROCARBONS USING PYROLYSIS DATA

- A mass balance method utilizing the algebraic scheme of Claypool from Peters et al. (2005; pg. 117-118) was used to estimate the amount of generated and expelled hydrocarbon from the Hogshooter shales. Values are corrected by a factor of 0.25 in loose accordance with recommendations by Lewan et al. (2002).
- Fortunately, we have low maturity samples for Pennsylvanian shales very similar to these so the upper bounds on HI original are well constrained.
- With these estimates it is thought likely that the Hogshooter shales have the capacity to source the adjacent sandstone reservoirs.
- It is within this portion of the analysis that we are most uncertain in regards to the characterization of the mudstones.

Case	TOC_{pd}	Hi_{pd}	HI_o	TOC_o	Gen. HC*
High TOC & HIo	6.5	200	700	12.0	375
High TOC & Low HIo	6.5	200	400	7.5	75
Mod TOC & High HIo	2.5	150	700	5.0	225
Mod TOC & Low HIo	2.5	150	400	3.0	50
Low TOC & High HIo	1.5	125	700	3.0	100
Low TOC & Low HIo	1.5	125	400	2.0	25

*per acre*ft shale of specified quality

pd = present day
o = original condition
TOC = Total Organic Carbon wt%
HI = Hydrogen Index mg HC/g TOC
Gen. HC = Total Generated HC-bbl light oil

IMPLICATIONS FOR PENNSYLVANIAN SHALE EXPLORATION AND EXPLOITATION

- Pennsylvanian shales have excellent source potential and accumulate to appreciable net thicknesses within the Anadarko basin.
- Historically, exploration of the mid-continent Pennsylvanian system has focused on sandstone-conglomerate reservoirs.
- Based on these findings certain shale intervals of the upper Pennsylvanian are oil-prone, and are also effective source-rocks in hybrid play situations and by extension, probably also in pure shale-play situations.
- Because of these qualities they deserve unique treatment within midcontinent exploration/exploitation portfolios.

FURTHER QUESTIONS FOR PENNSYLVANIAN SHALES

- What are the true oil and gas expulsion/retention metrics for various Pennsylvanian shale lithofacies?
- How do kinetics of oil and gas generation/expulsion vary by lithofacies?
- How does mudstone reservoir-quality vary with maturation by lithofacies?
- Answers to these questions will provide improved assessments of Pennsylvanian petroleum systems.

ACKNOWLEDGEMENTS

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- We thank the Chesapeake Reservoir Technology Center (CRTC), Chesapeake Mid-Continent business and Exploration units, and the Chesapeake Basin and Petroleum Systems Modeling Group (CHK-BPSMG) for review and input.

- We also wish to recognize David Jacobi for his mid-continent geochemistry work while at Chesapeake Energy prior to this study.