[PS]Using SARA Data to Reduce Uncertainty about the Type of Petroleum Fluid in the Woodford Formation and the Meramec Formation in the Anadarko Basin and the Arkoma Basin, Oklahoma*

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Abstract

The type of petroleum fluid in liquid-rich shale reservoirs that contain oil-prone kerogen typically changes from volatile oil to wet gas over a short distance. The production GOR provides insight about what kind of fluid is present in a shale reservoir. PVT analyses of shale reservoir fluids commonly are performed on recombined natural gas samples and the oil or condensate samples collected at a separator. Recombining separator samples properly requires knowing the GOR when they were collected – a value that may be difficult to measure accurately due to slugging or other processes. Geochemical properties of HC liquids can reduce uncertainty about the nature of the reservoir fluid in a shale reservoir. The abundance of saturate compounds relative to aromatic compounds and NSO compounds (resins) in the C15+ fraction of oil or condensate generally increases with increasing thermal maturity of the kerogen that generated it. Those trends are observed in oil and condensate samples produced from the Woodford Formation in the SCOOP area of the Anadarko Basin, and in the Arkoma Basin where oil in the Woodford reservoir dropped below its bubble point during basin uplift. Oil and condensate samples generated by Woodford source rock beds that subsequently migrated into the Meramec Formation in the STACK area of the Anadarko Basin exhibit similar trends. Black oil or volatile oil samples contain 62-75 wt% saturate compounds, 16-32 wt% aromatic compounds, and 2.8-7.6 wt% resins. Condensates from the SCOOP area contain 84-96 wt% saturate compounds, 3-14 wt% aromatic compounds, and 0.25-2.5 wt% resins. SARA data demonstrate that very light (40-45°API) liquid petroleum produced from Woodford gas wells in the Arkoma Basin actually is crude oil that dropped below its bubble point (not condensate that precipitated from wet gas generated at VR >1.2). The relatively low abundance of saturate compounds (~52 wt%) and the anomalously high abundance of aromatic compounds (~45 wt%) in "condensate" produced from a Woodford gas well in the SCOOP area indicate that liquid probably is crude oil that was converted into wet gas when an additional charge of dry gas migrated into the reservoir (a model supported by the C isotopic composition of methane). SARA data also were used to conclude that the Meramec Formation contains wet gas – rather than volatile oil – at a well location in the STACK area where ambiguous GOR data made it difficult to decide how to recombine separator samples.

ABSTRACT

The type of petroleum fluid in liquid-rich shale reservoirs that contain oil-prone kerogen typically changes from volatile oil to wet gas over a short distance. The production GOR provides insight about what kind of fluid is present in a shale reservoir. PVT analyses of shale reservoir fluids commonly are performed on recombined natural gas samples and the oil or condensate samples collected at a separator. Recombining separator samples properly requires knowing the GOR when they were collected – a value that may be difficult to measure accurately due to slugging or other processes. Geochemical properties of HC liquids can reduce uncertainty about the nature of the reservoir fluid in a shale reservoir. The abundance of saturate compounds relative to aromatic compounds and NSO compounds (resins) in the C_{15+} fraction of oil or condensate generally increases with increasing thermal maturity of the kerogen that generated it. Those trends are observed in oil and condensate samples produced from the Woodford Formation in the SCOOP area of the Anadarko Basin, and in the Arkoma Basin where oil in the Woodford reservoir dropped below its bubble point during basin uplift. Oil and condensate samples generated by Woodford source rock beds that subsequently migrated into the Meramec Formation in the STACK area of the Anadarko Basin exhibit similar trends. Black oil or volatile oil samples contain 62-74 wt% saturate compounds, 22-32 wt% aromatic compounds, and 2.8-5.6 wt% resins. Condensates from the SCOOP area contain 84-96 wt% saturate compounds, 3-13 wt% aromatic compounds, and 0.25-2.4 wt% resins. SARA data demonstrate that light (42-43°API) liquid petroleum produced from Woodford gas wells in the Arkoma Basin actually is crude oil that dropped below its bubble point – not higher-maturity condensate that precipitated from wet gas generated at VR >1.2. The relatively low abundance of saturate compounds (=52 wt%) and the anomalously high abundance of aromatic compounds (=44 wt%) in a 40°API condensate produced from a Woodford gas well in the SCOOP area indicate that liquid is crude oil that was converted into wet gas when an additional charge of dry gas migrated into the reservoir (a model supported by the C isotopic composition of methane). We used SARA data to conclude that the Meramec Formation contains wet gas – rather than volatile oil – at a well located in the STACK area where ambiguous GOR data made it difficult to decide how to recombine separator gas and liquid samples.

IA. INTRODUCTION: PETROLEUM FLUIDS. Petroleum engineers recognize five types of petroleum fluid: i.e., two types of oil and three types of natural gas (Figure 1)

Petroleum Fluids

Five fundamental types:

Liquid HCs
- Black Oil
- Volatile Oil

Gaseous HCs
- Gas Condensate
- Wet Gas
- Dry Gas

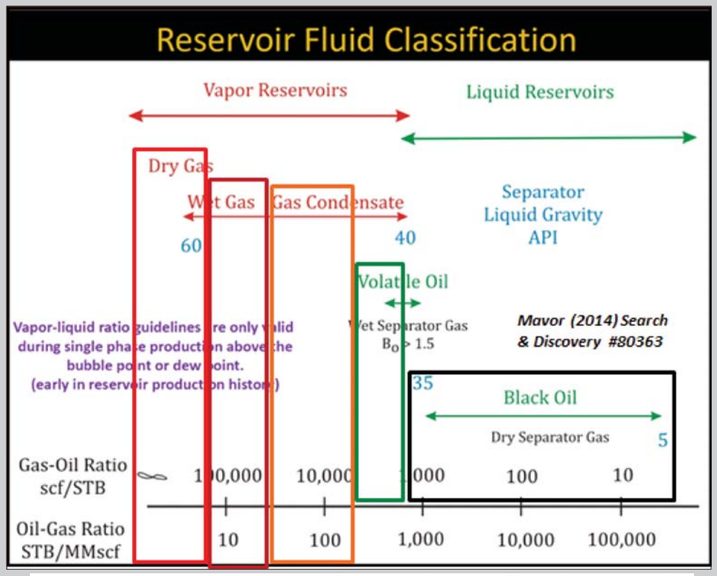

Figure 1. Each type of petroleum fluid typically has a distinct range of GOR/CGR and gravity.

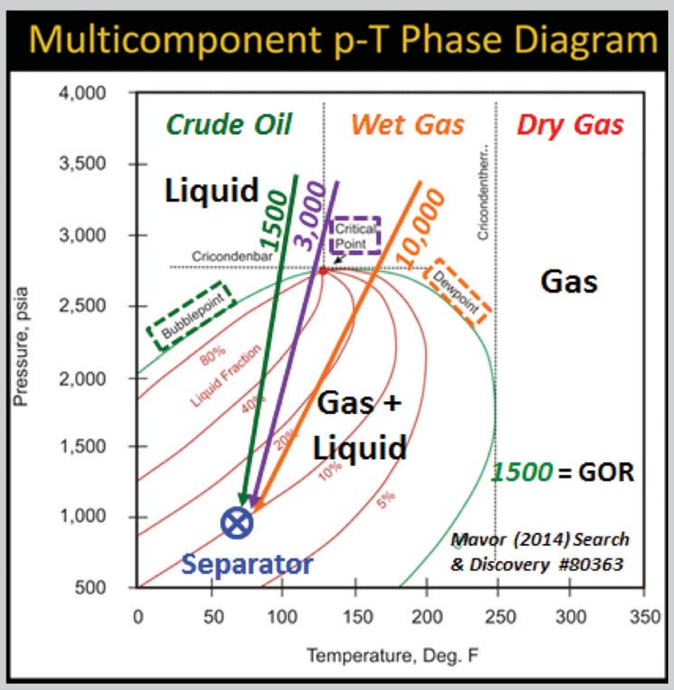

Figure 2. Pressure-temperature phase diagram for a HC system. Arrows show the path in p-T space during the production of oil (green), wet gas (orange), and near-critical fluid (purple).

Petroleum is a present in a permeable reservoir as a single phase (except at a GOC). When oil reaches its *bubble point*, dissolved gas forms a separate phase; condensate precipitates from wet gas when it reaches its *dew point* (Figure 2). *Near-critical fluids* exhibit more complex phase behavior that makes it difficult to study that unusual type of petroleum.

IB. INTRODUCTION: UNCONVENTIONAL OIL AND GAS RESERVOIRS IN THE ANADARKO BASIN AND ARKOMA BASON, OKLAHOMA (Figure 3)

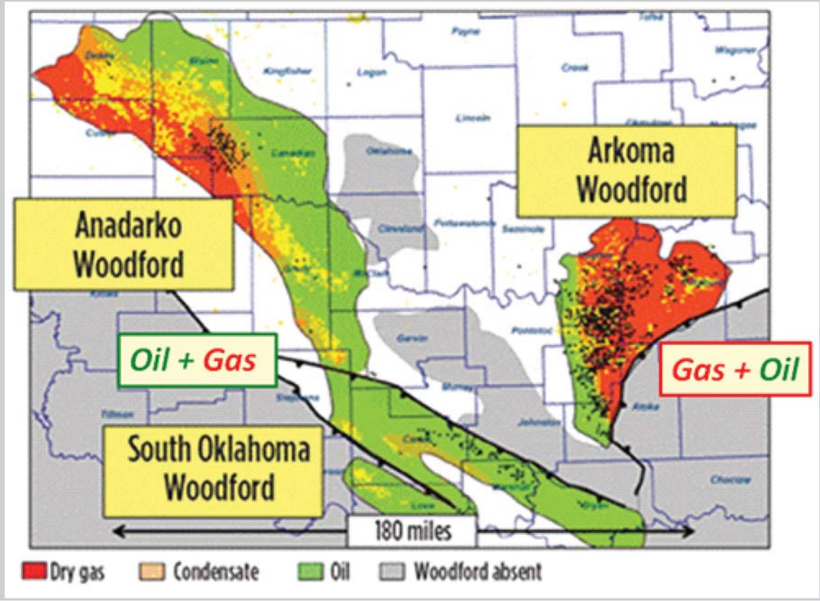

Figure 3. Map showing the type of oil and natural gas produced from the Woodford Formation in the Anadarko Basin and the Arkoma Basin.

Newfield Exploration Company is developing Woodford oil and wet-gas reservoirs in the South-Central Oklahoma Oil Province: i.e., SCOOP area of the Anadarko Basin. That company also is developing oil-shale resources in the same formation, and in the overlying Meramec Formation in the nearby STACK area (Figure 4).

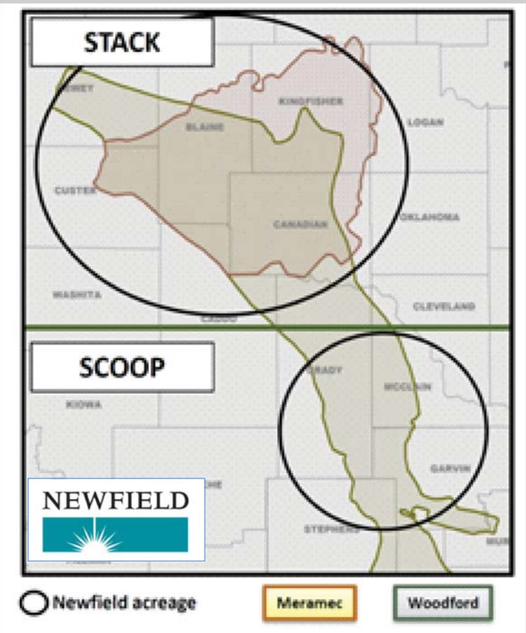

Figure 4. Map showing the location of the SCOOP area and the STACK area in the Anadarko Basin.

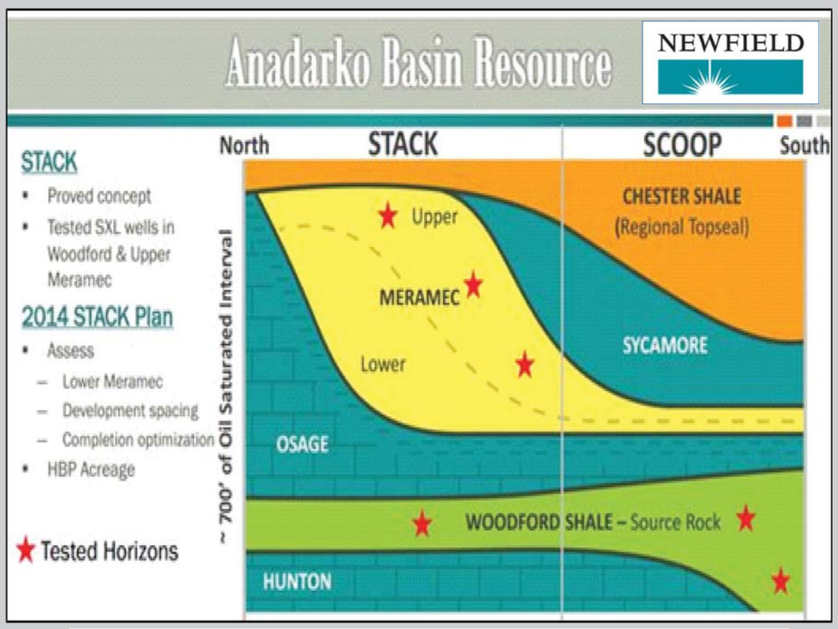

Figure 5. Stratigraphy of unconventional reservoirs in the SCOOP area and the STACK area of the Anadarko Basin.

Oil-prone source rock beds in the Woodford Formation generated the crude oil and wet gas produced from that reservoir. The oil in the Meramec Formation also was generated by Woodford source rocks (Figure 5).

Using SARA Data to Reduce Uncertainty About the Type of Petroleum Fluid in the Woodford Formation and the Meramec Formation in the Anadarko Basin and the Arkoma Basin, Oklahoma

2. DISTRIBUTION AND PROPERTIES OF OIL AND WET GAS SAMPLES PRODUCED FROM THE WOODFORD FORMATION IN THE SCOOP AREA OF THE ANADARKO BASIN

We studied the composition of separator oil, condensate, and gas samples collected at one Woodford oil well and five Woodford gas wells in the SCOOP area of the Anadarko Basin (Table 1).

Table 1. Gravity and GOR of volatile oil and wet gas samples obtained from the Woodford Formation (SCOOP area).

Well ID	Type of Fluid	Gravity (°API)	GOR (cf/bbl)	CGR (bbl/MMcf)
Well #1	Volatile oil	44	2,270	Not applicable
Well #3	Rich wet gas	47	4,560	219
Well #2	Rich wet gas	40	6,750	148
Well #4	Rich wet gas	52	12,490	80
Well #5	Lean wet gas	63	29,300	34
Well #6	Lean wet gas	59	50,200	20

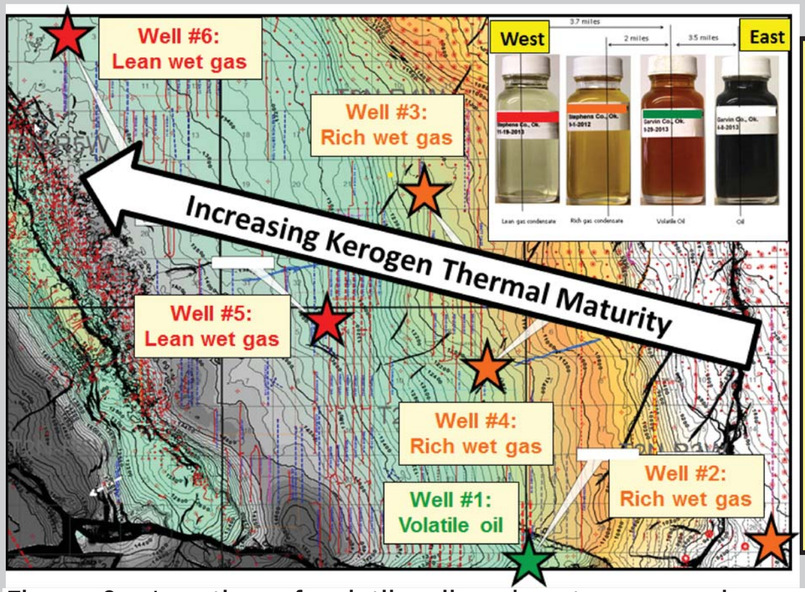

Figure 6. Location of volatile oil and wet gas samples produced from wells completed in the Woodford Formation in the SCOOP area of the Anadarko Basin.

The type of petroleum fluid changes from volatile oil to rich wet gas to leaner wet gas in an east to west direction in the SCOOP area (Figure 6). Is this explained by the increasing thermal maturity of oil-prone Woodford source rocks in the same direction?

3. THE TYPE AND THERMAL MATURITY OF KEROGEN IN THE WOODFORD FORMATION IN THE SCOOP AREA OF THE ANADARKO BASIN

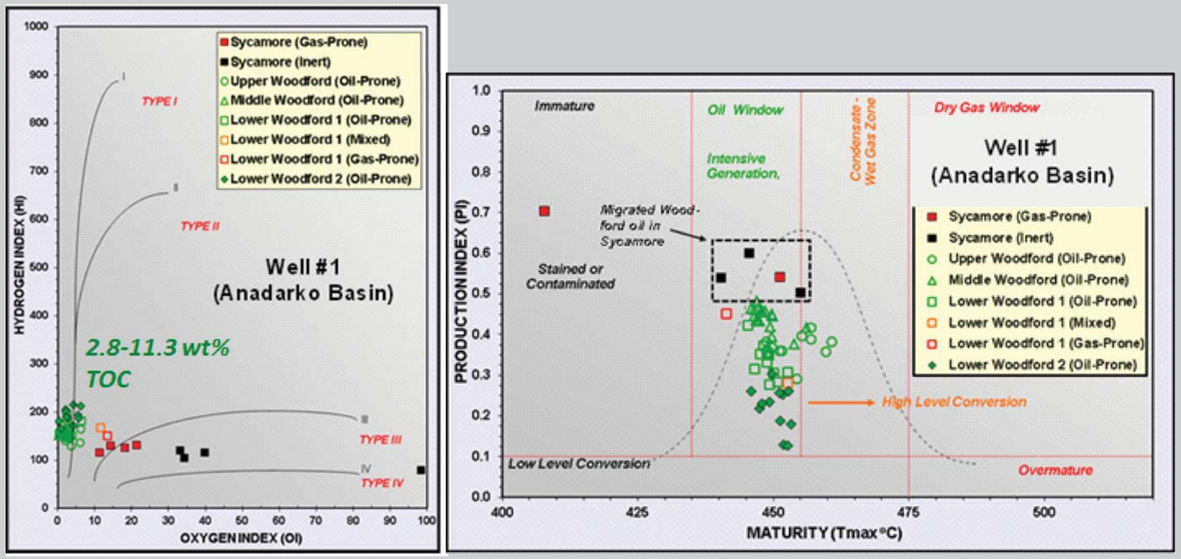

Figure 7. Modified van Krevelen diagram and Tmax data for core samples selected from the Woodford Formation and the Sycamore Formation at Well #1 in the SCOOP area. The Woodford Formation principally contains oil-prone kerogen that has reached the middle to high oil window.

4. GAS CHROMATOGRAMS AND SARA DATA MEASURED ON OIL AND CONDENSATE SAMPLES PRODUCED FROM THE WOODFORD FORMATION IN THE SCOOP AREA

The low values of pristane/phytane ratios indicate all of these samples were generated by the same type of oil-prone kerogen deposited in an anoxic environment: e.g., the lean wet gas at Well #5 was not generated by more gas-prone kerogen deposited under more oxidizing conditions (Figure 8).

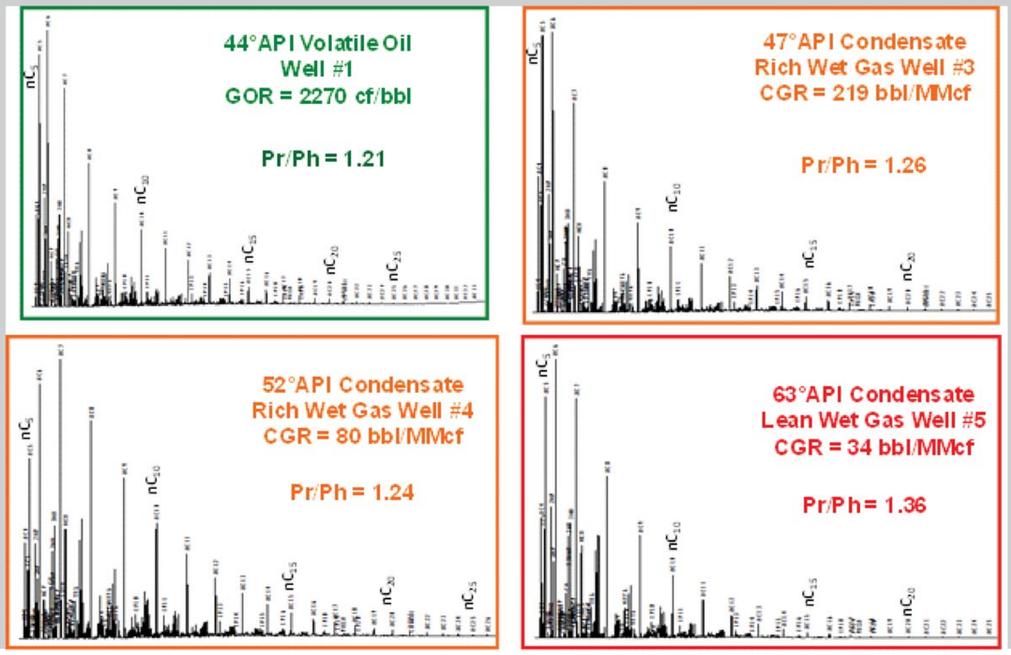

Figure 8. Gas chromatograms of a volatile oil sample (green) and three condensates (orange or red) produced from the Woodford Formation in the SCOOP area of the Anadarko Basin.

Aromatic compounds and resins crack to saturate compounds with increasing thermal maturity. Systematic changes in the abundance of saturate and aromatic compounds and resins demonstrate that the thermal maturity of Woodford source rocks controls the composition of these samples.

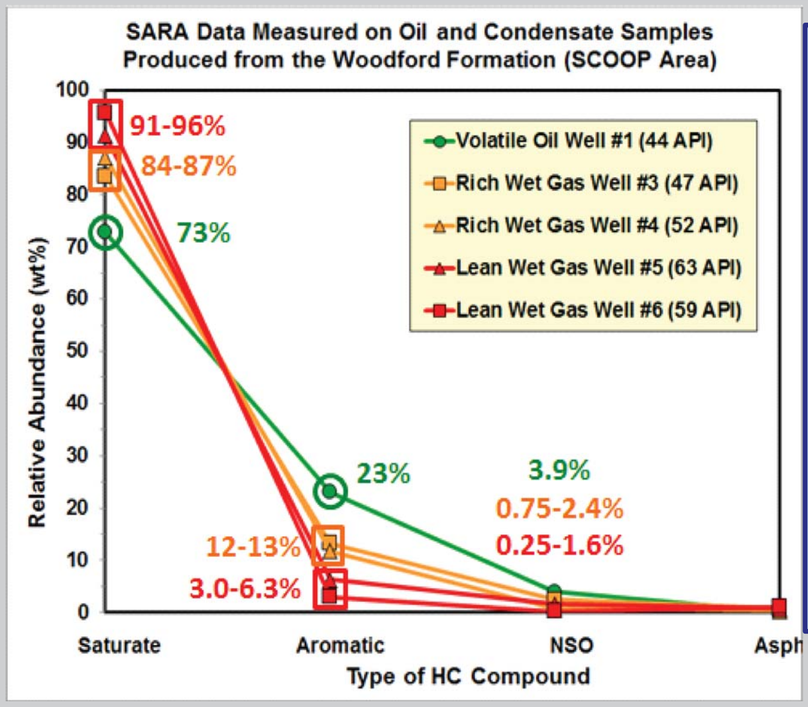

Figure 9. Abundance of SARA compounds in the C_{15+} fraction of oil and condensates produced from the SCOOP area of the Anadarko Basin.

For example, saturate compounds in volatile oil < saturate compounds in rich condensates < saturate compounds in lean condensates. Similarly, aromatic compounds and resins in volatile oil > aromatic compounds and resins in rich condensates > aromatic compounds and resins in lean condensates (Figure 9).

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5. PROPERTIES OF WET GAS SAMPLES PRODUCED FROM THE WOODFORD FORMATION IN THE ARKOMA BASIN

We also studied the composition of separator "condensate" and gas samples collected at three Woodford gas wells in the Arkoma Basin (Table 2).

Table 2. Gravity and GOR of gas samples obtained from the Woodford Formation in the Arkoma Basin.

Well ID	Type of Fluid	Gravity (°API)	GOR (cf/bbl)	CGR (bbl/MMcf)
Well #9	Rich wet gas	43	15,400	65
Well #8	Lean wet gas	43	24,400	41
Well #7	Lean wet gas	42	55,200	18

6. THE TYPE AND THERMAL MATURITY OF KEROGEN IN THE WOODFORD FORMATION AT A GAS WELL IN THE ARKOMA BASIN

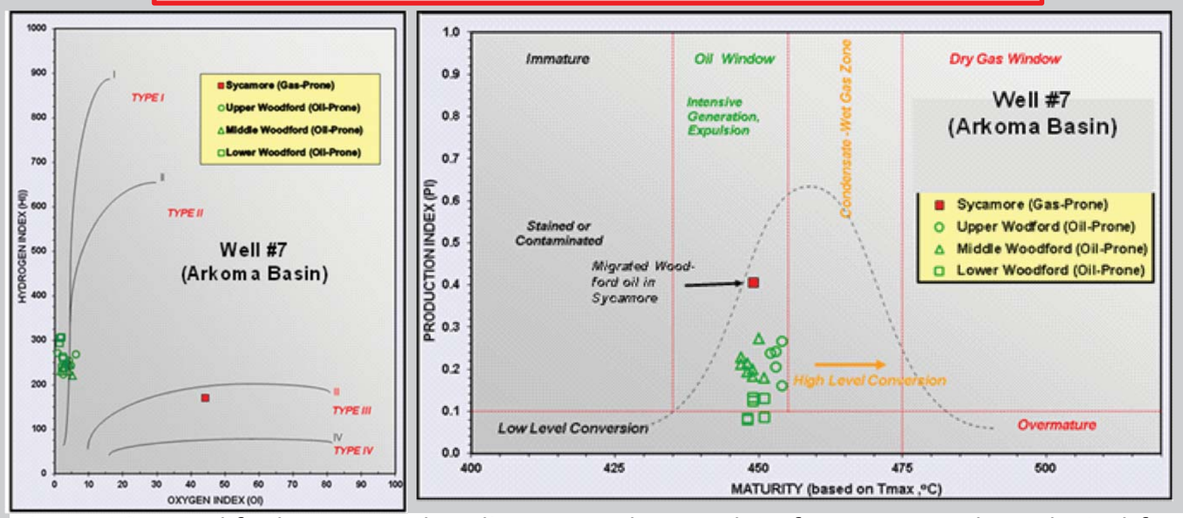
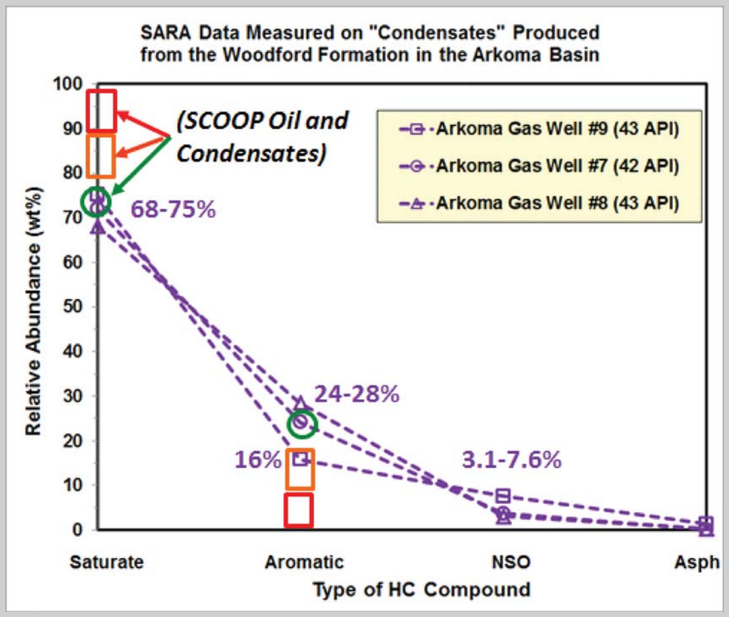


Figure 10. Modified van Krevelen diagram and Tmax data for core samples selected from the Woodford Formation and the Sycamore Formation at Well #7 in the Arkoma Basin. Woodford source rocks contain oil-prone kerogen that has reached only the middle to high oil window. Why does this well have a GOR = 55,200 cf/bbl – while volatile oil is produced from the Woodford Formation at Well #1 in the SCOOP area of the Anadarko Basin, where *the same type of kerogen has reached the same level of thermal maturity* (Figure 7)?

7. SARA DATA AND GAS CHROMATOGRAMS MEASURED ON "CONDENSATE" SAMPLES PRODUCED FROM THE WOODFORD FORMATION AT GAS WELLS IN THE ARKOMA BASIN



The abundance of saturate and aromatic compounds and resins in the 42-43°API liquids produced at these gas wells demonstrates they are oil samples – not condensates that formed when oil cracked to wet gas (Figure 11). Free gas formed when oil dropped below its bubble point during basin uplift.

Figure 11. Abundance of SARA compounds in the C_{15+} fraction of "condensates" produced from Woodford gas wells in the Arkoma Basin (purple symbols), and in a volatile oil (green circle) and bona-fide condensates (orange and red squares) produced from the same reservoir in the SCOOP area of the Anadarko Basin.

In fact, C_{20+} n-alkanes are more abundant in Arkoma oil samples than in a volatile oil sample from the SCOOP area (Figure 12). The low values of pristane/phytane ratios indicate the oil produced from Woodford gas wells in the Arkoma Basin was generated by oil-prone kerogen deposited in an anoxic environment.

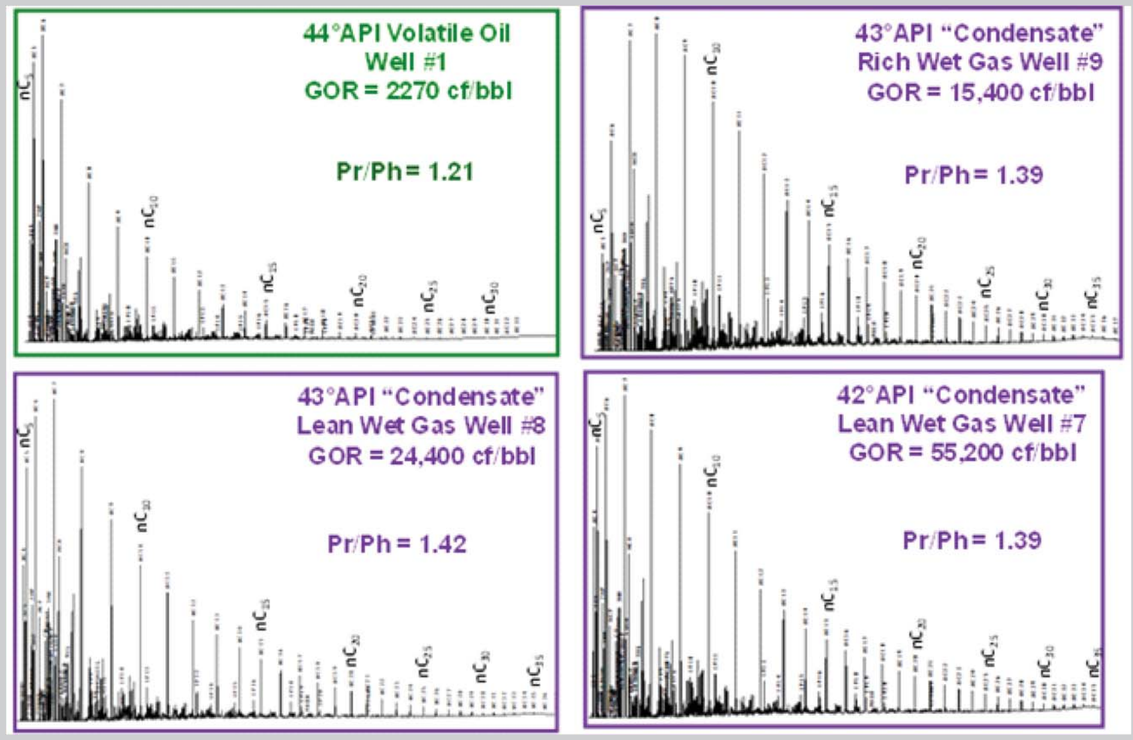


Figure 12. Gas chromatograms measured on "condensates" produced from the Woodford Formation at three gas wells in the Arkoma Basin (purple), and on a volatile oil sample produced in the SCOOP area of the Anadarko Basin (green).

8. IDENTIFYING THE TYPE OF PETROLEUM FLUID PRESENT IN THE MERAMEC FORMATION AT A WELL LOCATED IN THE STACK AREA OF THE ANADARKO BASIN

GORs measured at a separator commonly are used to determine what kind of fluid is present in a shale reservoir. In some cases, this leads to ambiguous results because that parameter changes during different periods due to slugging or well engineering decisions (Figure 13).

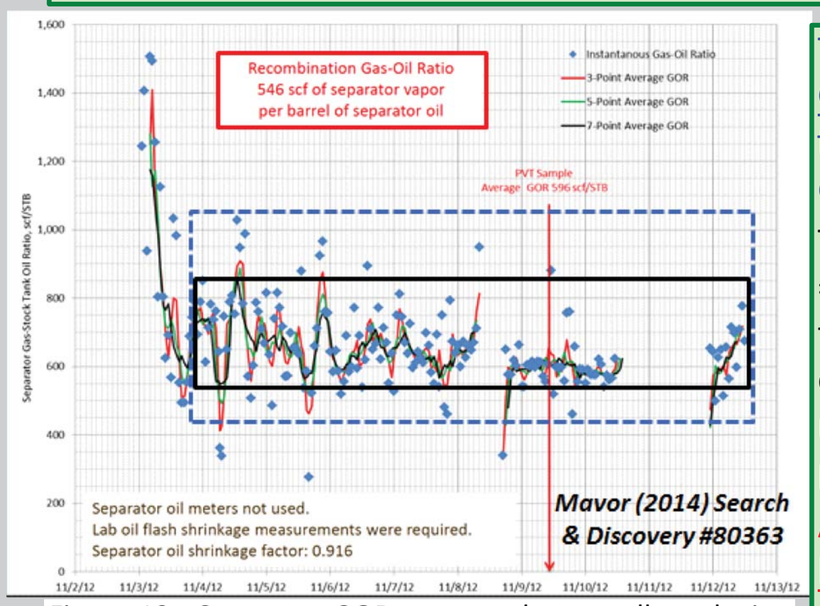


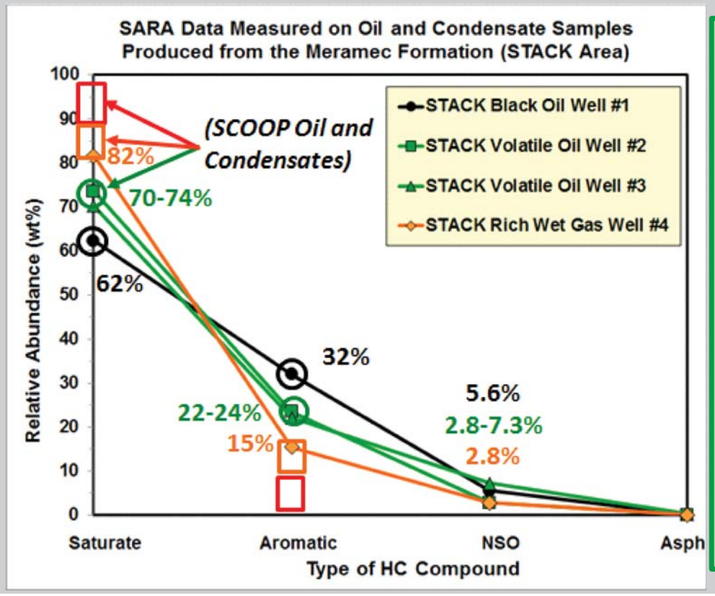
Figure 13. Separator GOR measured at a well producing black oil from a shale reservoir in the Permian Basin.

The instantaneous GOR at this well varied from = 450-1,050 cf/bbl during an 8-day period.

The GOR varied from =550-850 cf/bbl using the average of seven consecutive measurements during the same period.

A recombined PVT analysis was performed using a GOR=546 cf/bbl

Most wells completed in the Meramec Formation in the STACK area of the Anadarko Basin produce black oil or volatile oil (Figure 4). But the ambiguously high GOR at Well #4 in the STACK area suggests the Meramec reservoir contains wet gas at that location.



The abundance of SARA compounds in a liquid collected at Well #4 supports that interpretation. The composition of that sample and condensates from rich wet-gas wells in the SCOOP area is very similar (as is the composition of volatile oil samples in both areas) (Figure 14).

Figure 14. Abundance of SARA compounds in the C_{15+} fraction of liquid petroleum samples produced from the Meramec Formation in the STACK area of the Anadarko Basin. Rectangles and a green circle show the composition of saturate and aromatic compounds in various kinds of petroleum fluids in the SCOOP area (Figure 9). Note that a Meramec black oil sample contains more aromatic compounds and resins -- and less saturate compounds -- than do volatile oil samples produced in both areas.

9. COMPOSITION OF AN ANOMALOUS CONDENSATE PRODUCED FROM A WET GAS WELL IN THE SCOOP AREA OF THE ANADARKO BASIN

An anomalously heavy (40°API) condensate produced from the Woodford Formation at Well #2 in the SCOOP area (Figure 5) contains significantly less saturate compounds and significantly more aromatic compounds and resins than do other SCOOP condensates. The composition of that condensate and a Meramec volatile oil sample from the STACK area are similar -- indicating those liquids were generated at a lower level of thermal maturity than the STACK black oil sample (Figure 15).

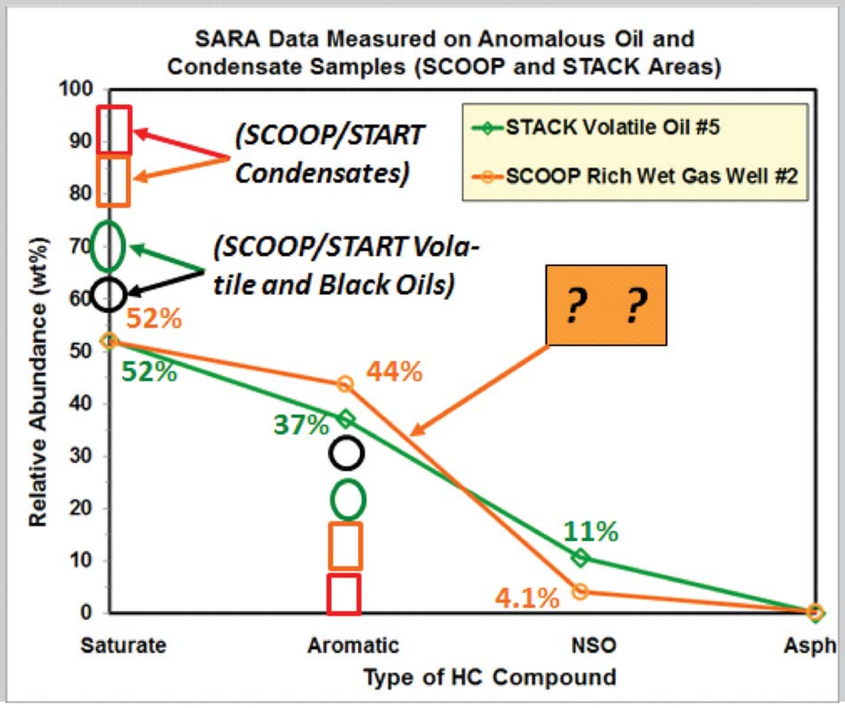
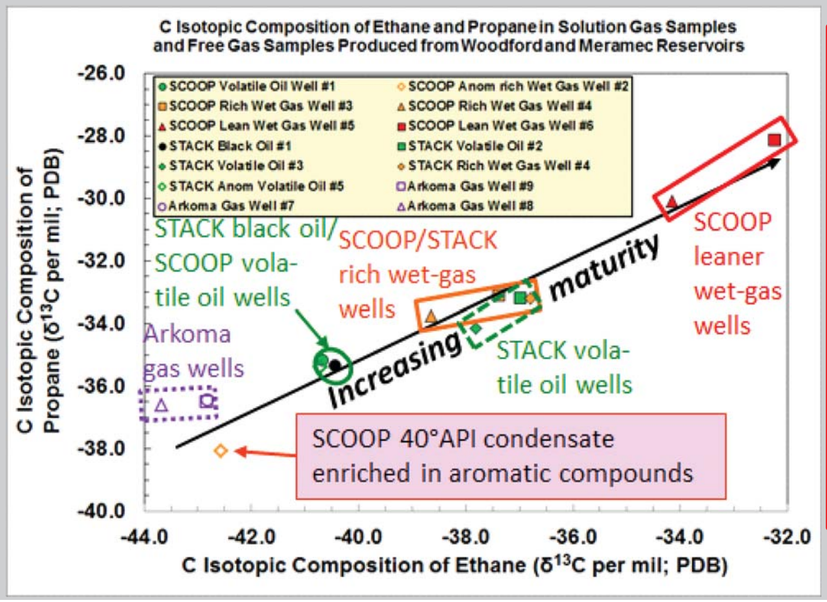


Figure 15. Abundance of SARA compounds in the C_{15+} fraction of a STACK volatile oil sample (green) and a SCOOP condensate (orange) that contain anomalously high aromatic compounds and anomalously low saturate compounds.

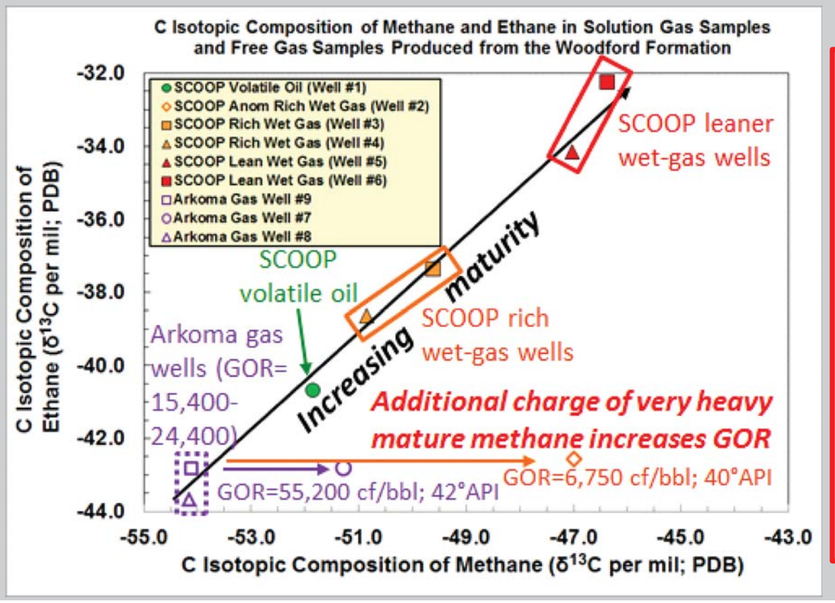
10. C ISOTOPIC COMPOSITION AND MATURITY OF GAS SAMPLES PRODUCED FROM WOODFORD AND MERAMEC RESERVOIRS IN THE ANADARKO AND ARKOMA BASINS

We used the C isotopic composition of separator gas samples to determine the level of thermal maturity at which they were generated. Thermogenic gas samples become drier as their thermal maturity increases, and the C isotopic composition of the HC gas compounds becomes heavier with increasing thermal maturity.



The C isotopic composition of ethane and propane in most gas samples changes systematically in a manner supporting our interpretation about the origin of oil and condensate samples (Figure 16).

Figure 16. The C isotopic composition of ethane and propane in gas samples produced from Woodford and Meramec reservoirs indicates samples obtained from Arkoma gas wells that produce light oil or from a SCOOP wet-gas well that produces relatively heavy condensate were generated at lower thermal maturity than gas samples obtained from wells that produce black oil, volatile oil, or wet gas.



The C isotopic composition of methane and ethane also changes systematically in most gas samples.

But methane in two of the gas samples is heavier than expected (Figure 17).

Figure 17. C isotopic composition of methane and ethane in gas samples produced from Woodford and Meramec reservoirs. The Woodford reservoir contains an additional charge of very dry thermogenic gas at two wells where gas samples contain anomalously heavy methane. That additional gas charge explains the very high GOR at Arkoma Gas Well #7. 40°API oil at SCOOP Well #2 was converted into rich wet gas when dry gas migrated into the reservoir, causing oil to dissolve into the gas phase.

Key Observation and Conclusions

Integrating PVT data and geochemical data demonstrates that:

- Liquid HCs produced from Woodford gas wells in the Arkoma Basin are **light oils** from which solution gas exsolved during basin uplift: i.e., PVT processes – not kerogen maturity – explain the presence of free gas.
- Rich wet gas – not volatile oil – is present in the Meramec reservoir at one well located in the STACK area.
- The 40°API condensate produced from a rich wet-gas well in the SCOOP area is **crude oil** that dissolved into a later dry gas charge.

The Woodford reservoir is **permeable** enough at some locations for very mature, dry thermogenic gas to migrate into it.

We thank Newfield Exploration Company and Weatherford Laboratories Inc. for permission to present these results