Woodford Shale Forum 2014 May 29, 2014

Woodford Shale Play Update: Expanded Extent in the Oil Window

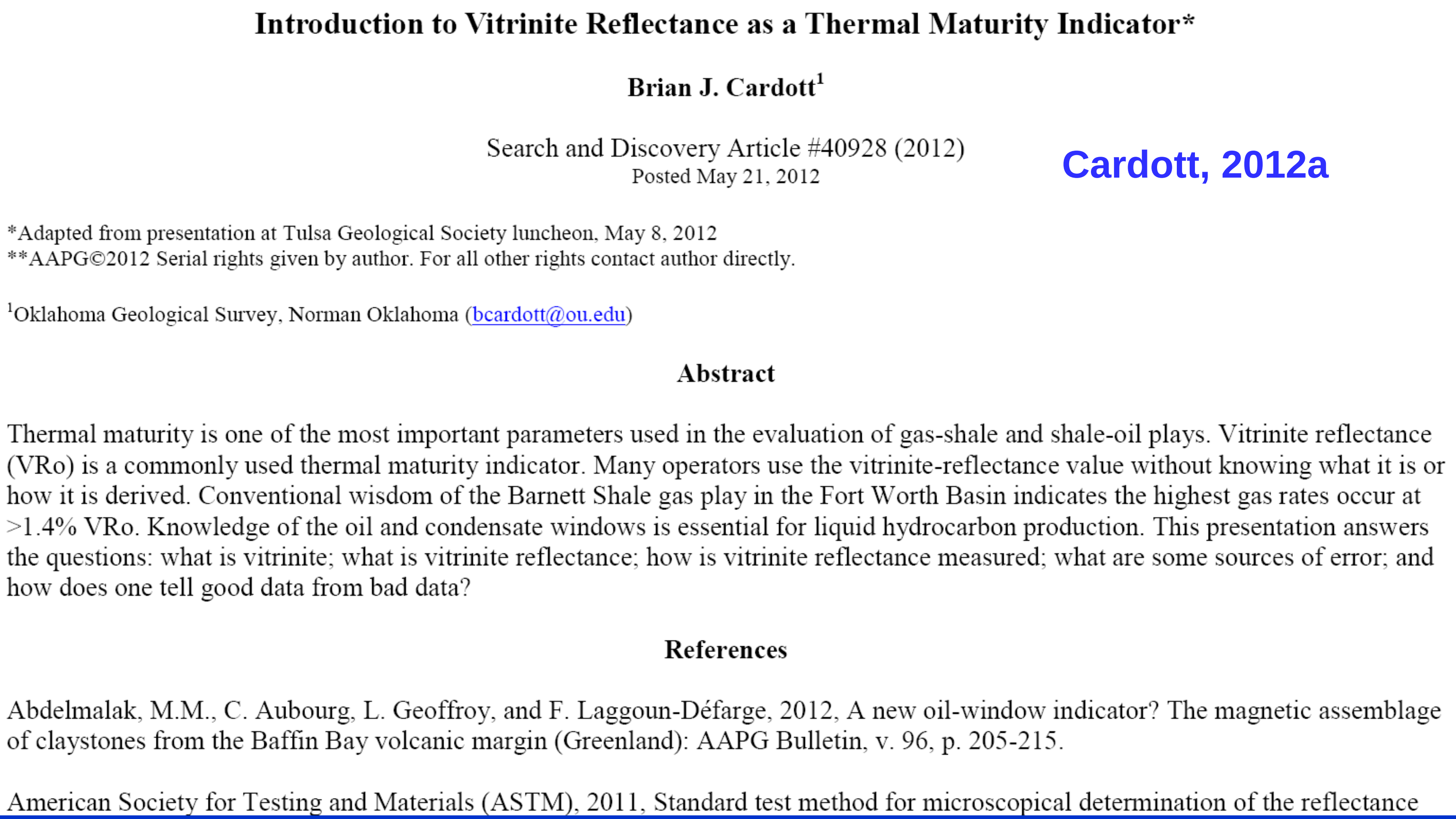
Brian J. Cardott

Oklahoma Geological Survey

Outline of Presentation

- Define the Oil Window, with an Emphasis on the Start of the Window
- Basic Parameters Needed for Oil Production from Shale Resource Plays
- Evaluation of Woodford Shale as a Liquid Hydrocarbon Reservoir

Useful Background Information on Vitrinite Reflectance is Available in AAPG Search and Discovery Article #40928



Introduction to Vitrinite Reflectance as a Thermal Maturity Indicator*

Brian J. Cardott[1]

Search and Discovery Article #40928 (2012)
Posted May 21, 2012

*Adapted from presentation at Tulsa Geological Society luncheon, May 8, 2012

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Abstract

Thermal maturity is one of the most important parameters used in the evaluation of gas-shale and shale-oil plays. Vitrinite reflectance (VRo) is a commonly used thermal maturity indicator. Many operators use the vitrinite-reflectance value without knowing what it is or how it is derived. Conventional wisdom of the Barnett Shale gas play in the Fort Worth Basin indicates the highest gas rates occur at >1.4% VRo. Knowledge of the oil and condensate windows is essential for liquid hydrocarbon production. This presentation answers the questions: what is vitrinite; what is vitrinite reflectance; how is vitrinite reflectance measured; what are some sources of error; and how does one tell good data from bad data?

References

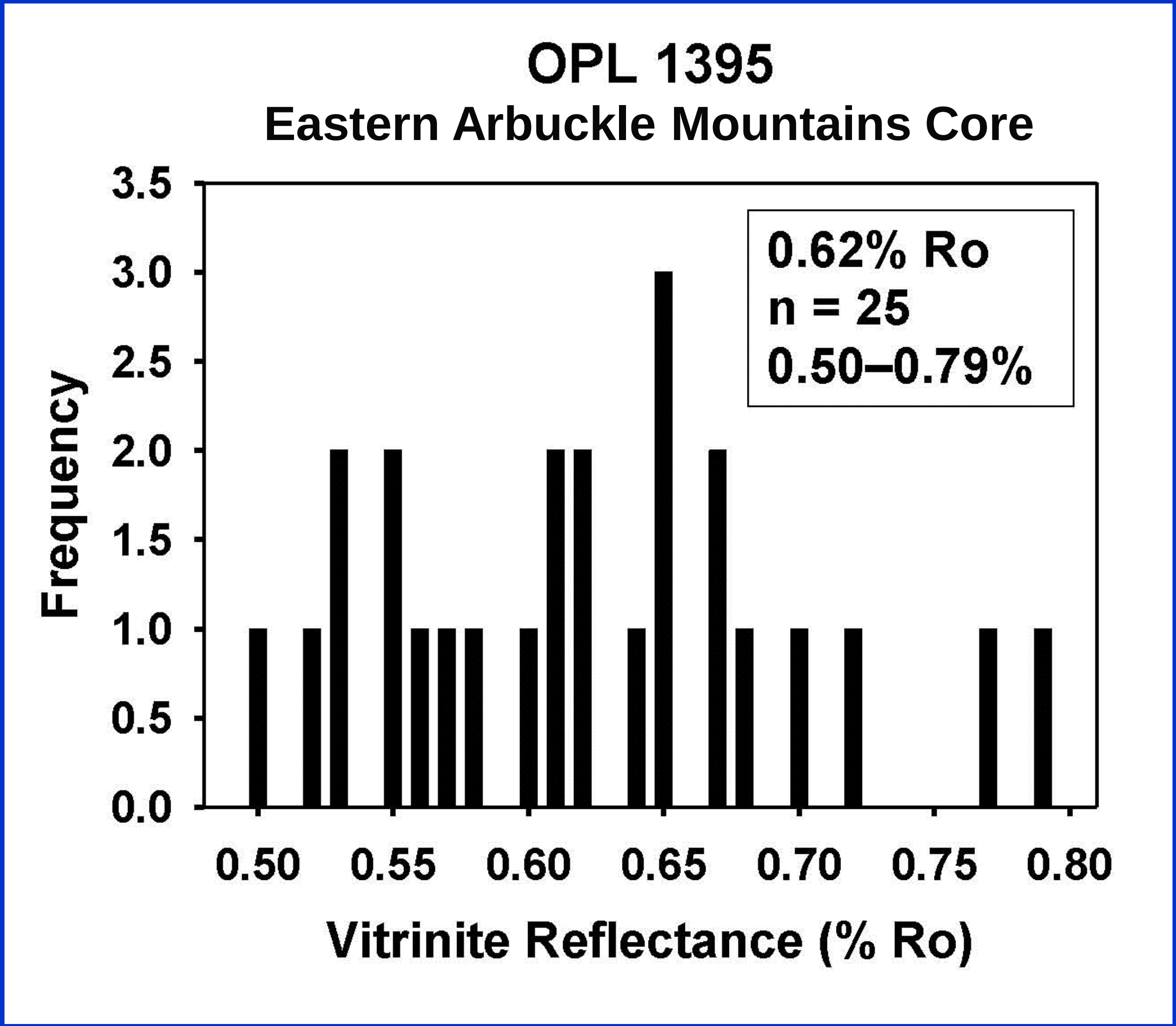
Abdelmalak, M.M., C. Aubourg, L. Geoffroy, and F. Laggoun-Défarge, 2012, A new oil-window indicator? The magnetic assemblage of claystones from the Baffin Bay volcanic margin (Greenland): AAPG Bulletin, v. 96, p. 205-215.

American Society for Testing and Materials (ASTM), 2011, Standard test method for microscopical determination of the reflectance

Cardott, 2012a

Vitrinite Reflectance Summary

The vitrinite-reflectance value is an average of >20 measurements typically following a normalized distribution over a range of ~0.3% Ro.

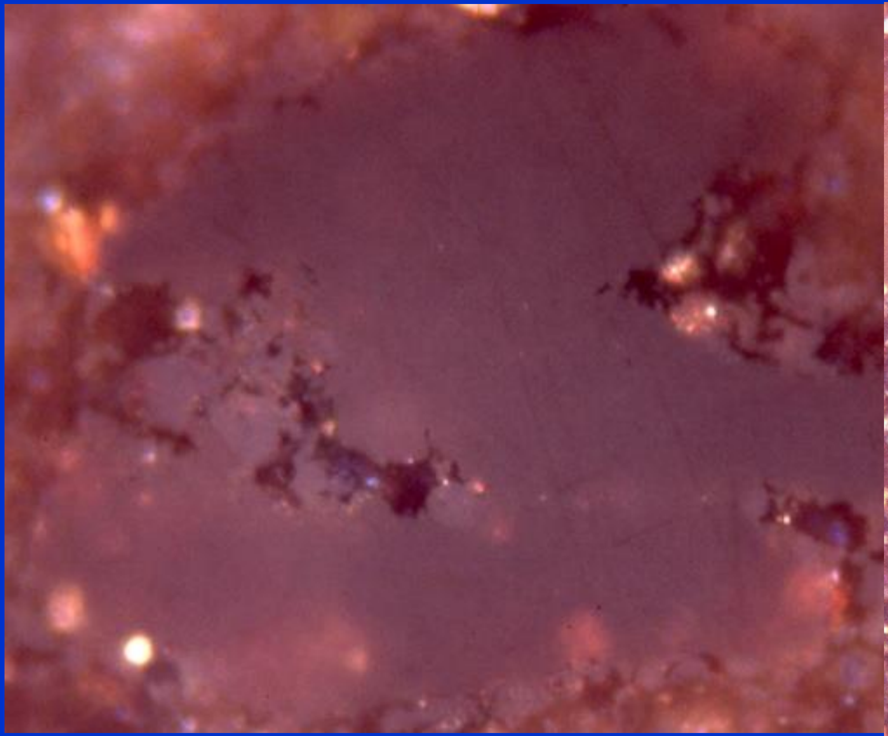


Part of the Problem of Determining the Vitrinite Reflectance of a Shale at the Start of the Oil Window (~0.5% Ro) is the presence of Vitrinite-Like Pre-Oil Solid Bitumen (genetic bitumen classification of Curiale, 1986)

- **Pre-Oil Solid Bitumen**: early-generation products of rich source rocks, probably extruded from their sources as a very viscous fluid, and migrated the minimum distance necessary to reach fractures and voids in the rock. [Kerogen → Bitumen → Oil (Lewan, 1983)]

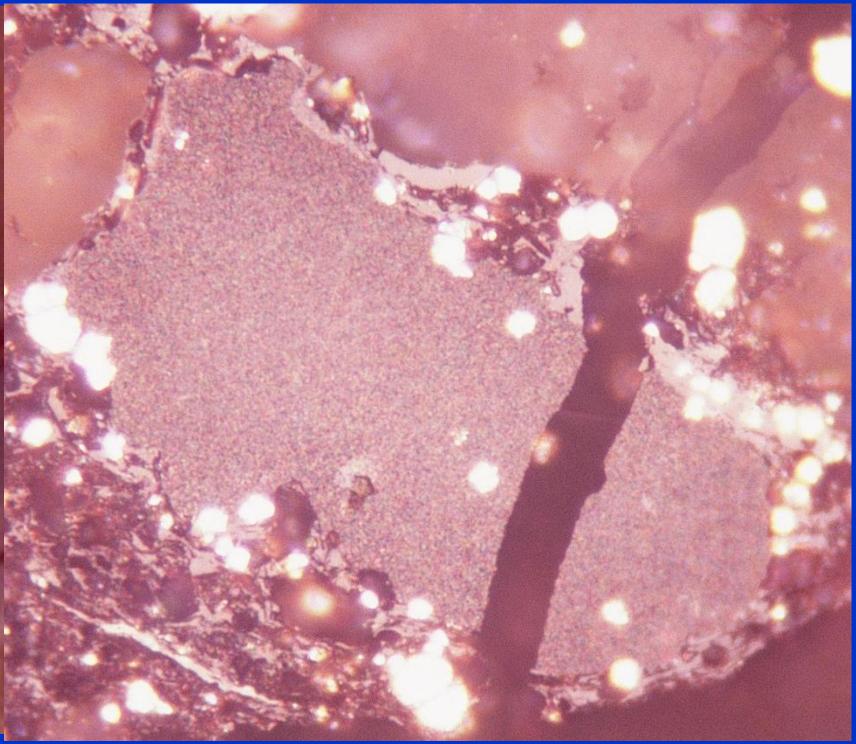
Two Common Pre-Oil Bitumen Optical Forms Based on Landis and Castaño (1994)
[regression equation is based on homogenous form]

Homogenous form



OPL 1333 500X

Granular form

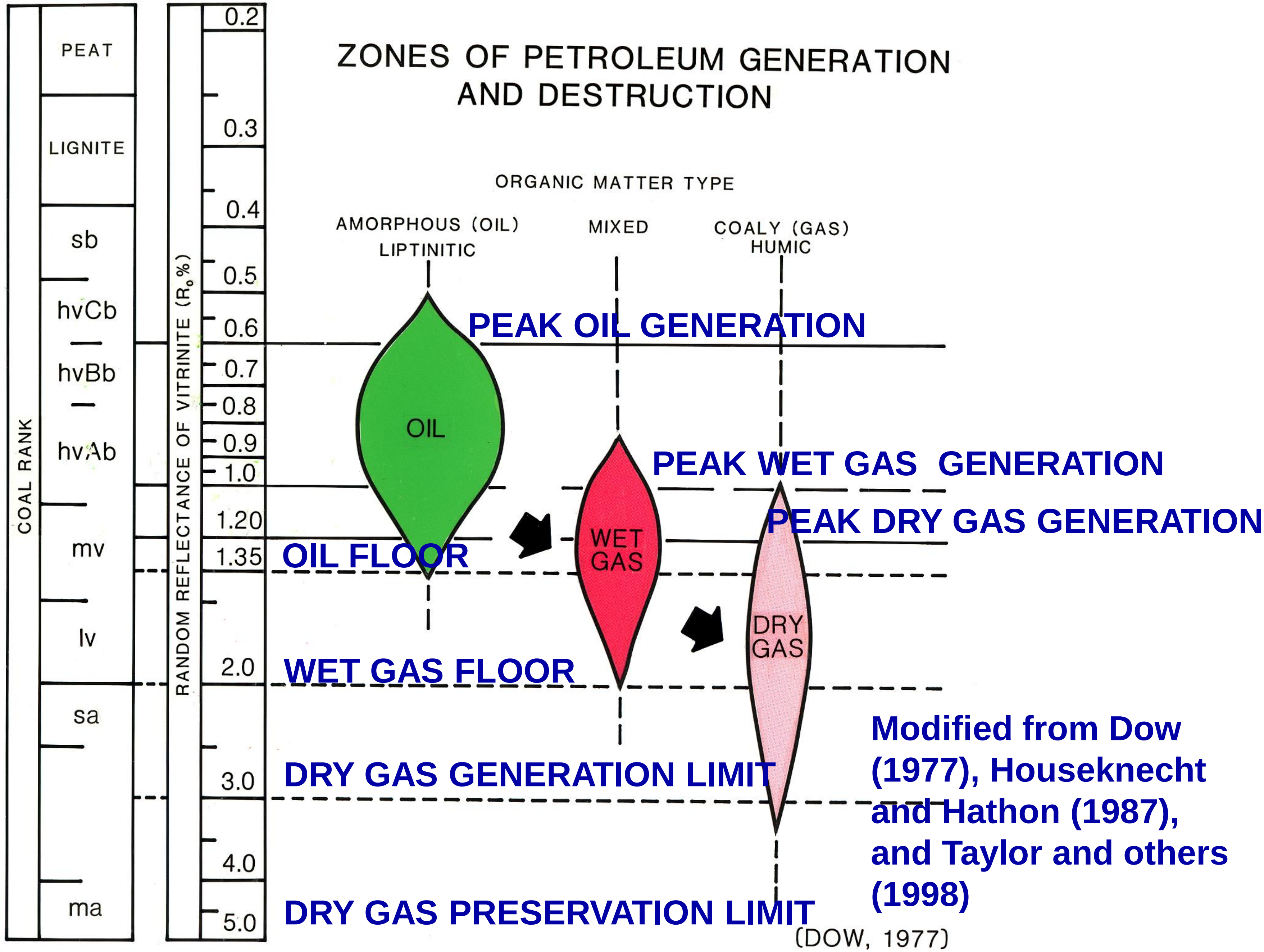


OPL 1076 500X

Vitrinite-like bitumen is the greatest source of error for low thermal maturity shales and possibly the source of reflectance suppression:

Hackley and others (2013) concluded that vitrinite reflectance measurements of early mature Devonian shales in the Appalachian Basin may erroneously include pre-oil solid bitumen reflectance measurements.

Even if some of the Woodford Shale vitrinite-reflectance values <0.5% Ro included lower bitumen-reflectance values, the influence would most likely lower the mean vitrinite-reflectance value by ~0.10-0.20% Ro (e.g., 0.48% Ro may actually be ~0.58-0.68% Ro at the start of the oil window), confirmed by other qualitative petrographic thermal maturity indicators.


ZONES OF PETROLEUM GENERATION AND DESTRUCTION
COAL RANK
PEAT
LIGNITE
sb
hvCb
hvBb
hvAb
mv
lv
sa
ma
RANDOM REFLECTANCE OF VITRINITE (R_o%)
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.20
1.35
2.0
3.0
4.0
5.0
ORGANIC MATTER TYPE
AMORPHOUS (OIL) LIPTINITIC
MIXED
COALY (GAS) HUMIC
PEAK OIL GENERATION
OIL
PEAK WET GAS GENERATION
PEAK DRY GAS GENERATION
WET GAS
OIL FLOOR
DRY GAS
WET GAS FLOOR
DRY GAS GENERATION LIMIT
DRY GAS PRESERVATION LIMIT
Modified from Dow (1977), Houseknecht and Hathon (1987), and Taylor and others (1998)
(DOW, 1977)

Guidelines for the Barnett Shale

VRo Values	Maturity
<0.55%	Immature
0.55-1.15%	Oil Window (peak oil at 0.90%VRo)
1.15-1.40%	Condensate–Wet-Gas Window
>1.40%	Dry-Gas Window

From Jarvie and others, 2005

Jarvie (2012, p. 91):

"…thermal maturity values from about 0.60 to 1.40% Ro are the most likely values significant for petroleum liquid generation. Regardless of thermal maturity, there must be sufficient oil saturation to allow the possibility of commercial production of oil".

Caution:
Vitrinite reflectance is applicable in coal only to ~0.47% Ro.

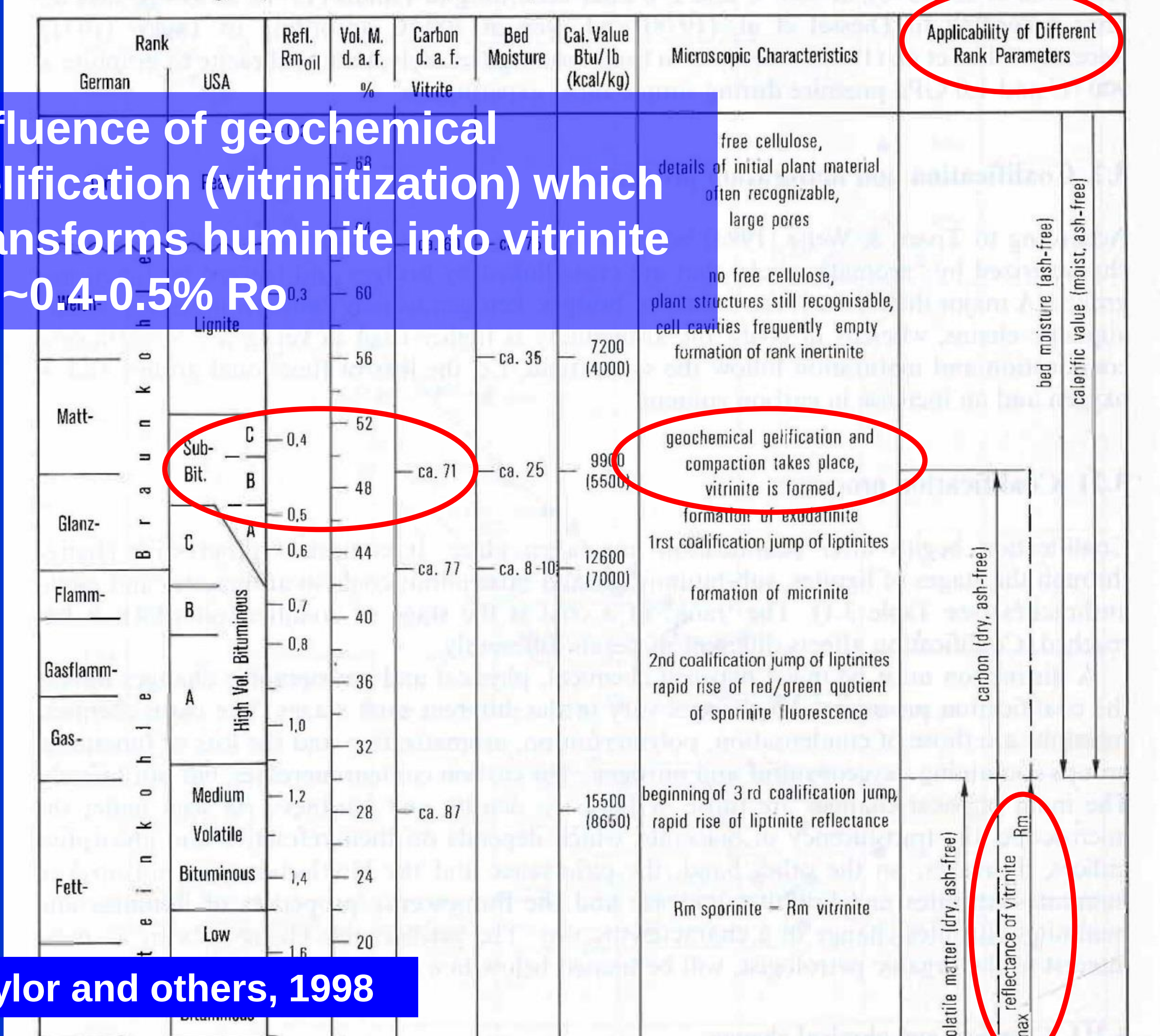
TABLE III *Oil Reflectance Limits of ASTM Coal Rank Classes*

Rank	Maximum reflectance (%)	Maximum reflectance (%)[a]	Random reflectance (%)[b]
Subbituminous	−0.47		
High volatile bituminous	C 0.47–0.57 B 0.57–0.71 A 0.71–1.10	<1.03	0.50–1.12
Medium volatile bituminous	1.10–1.50	1.03–(1.35–1.40)	1.12–1.51
Low volatile bituminous	1.50–2.05	>(1.35–1.40)	1.51–1.92
Semianthracite	2.05–3.00 (approx.)		1.92–2.50
Anthracite	>3.00 (approx.)		>2.50

[a] Procedure of Bethlehem Steel Corporation using "reactive vitrinite" reflectance.
[b] From McCartney and Teichmüller (1972, 1974).

Davis, 1978

Influence of geochemical gelification (vitrinitization) which transforms huminite into vitrinite at ~0.4-0.5% Ro



Taylor and others, 1998

Most petroleum geochemists use 0.6% Ro as the onset of oil generation (e.g., Peters and Cassa, 1994, Applied source rock geochemistry: AAPG Memoir 60, p. 93-117)

Table 5.3. Geochemical Parameters Describing Level of Thermal Maturation

	Maturation			Generation		
Stage of Thermal Maturity for Oil	R_o (%)	T_{max} (°C)	TAI[a]	Bitumen/ TOC[b]	Bitumen (mg/g rock)	PI[c] $[S_1/(S_1 + S_2)]$
Immature	0.2–0.6	<435	1.5–2.6	<0.05	<50	<0.10
Mature						
Early	0.6–0.65	435–445	2.6–2.7	0.05–0.10	50–100	0.10–0.15
Peak	0.65–0.9	445–450	2.7–2.9	0.15–0.25	150–250	0.25–0.40
Late	0.9–1.35	450–470	2.9–3.3	—	—	>0.40
Postmature	>1.35	>470	>3.3	—	—	—

[a]TAI, thermal alteration index.

[b]Mature oil–prone source rocks with type I or II kerogen commonly show bitumen/TOC ratios in the range 0.05–0.25. Caution should be applied when interpreting extract yields from coals. For example, many gas–prone coals show high extract yields suggesting oil–prone character, but extract yield normalized to TOC is low (<30 mg HC/g TOC). Bitumen/TOC ratios over 0.25 can indicate contamination or migrated oil or can be artifacts caused by ratios of small, inaccurate numbers.

[c]PI, production index.

Hunt (1996, p. 368):
“the lowest value associated with the known <u>generation</u> of conventional oil is about 0.5% [Ro], and 0.6% [Ro] is generally recognized as the beginning of <u>commercial oil accumulations</u>.”

What is the lowest thermal maturity to produce economic quantities of oil in the Woodford Shale?

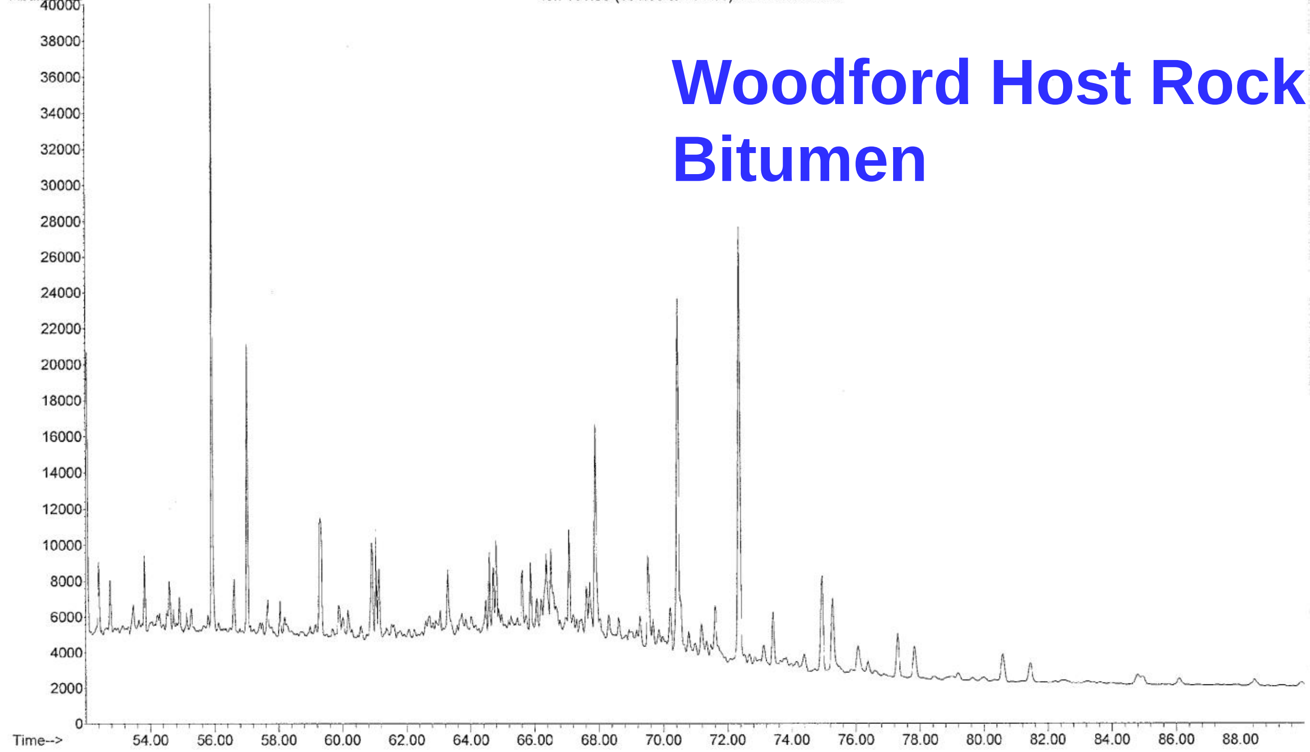
[Note: the start of the oil window is a zone rather than an exact number]

Example of “Solid hydrocarbon” filling fractures in Woodford Shale (exhumed reservoir) at the McAlister Cemetery Quarry in the Criner Hills Uplift of Southern Oklahoma

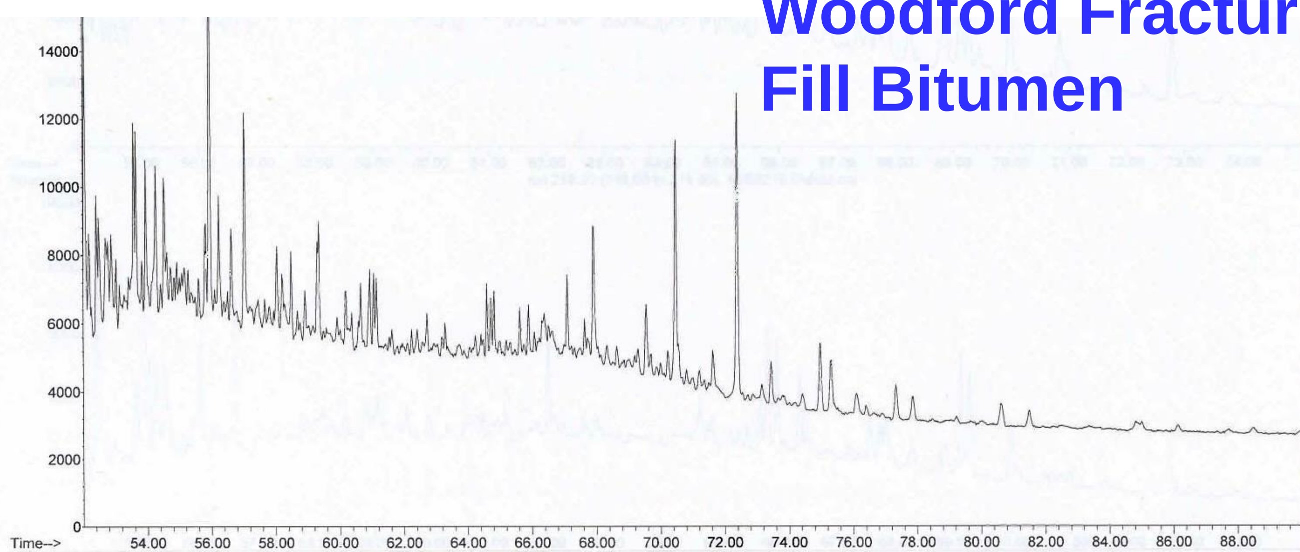
(what is the source of the “oil”?)

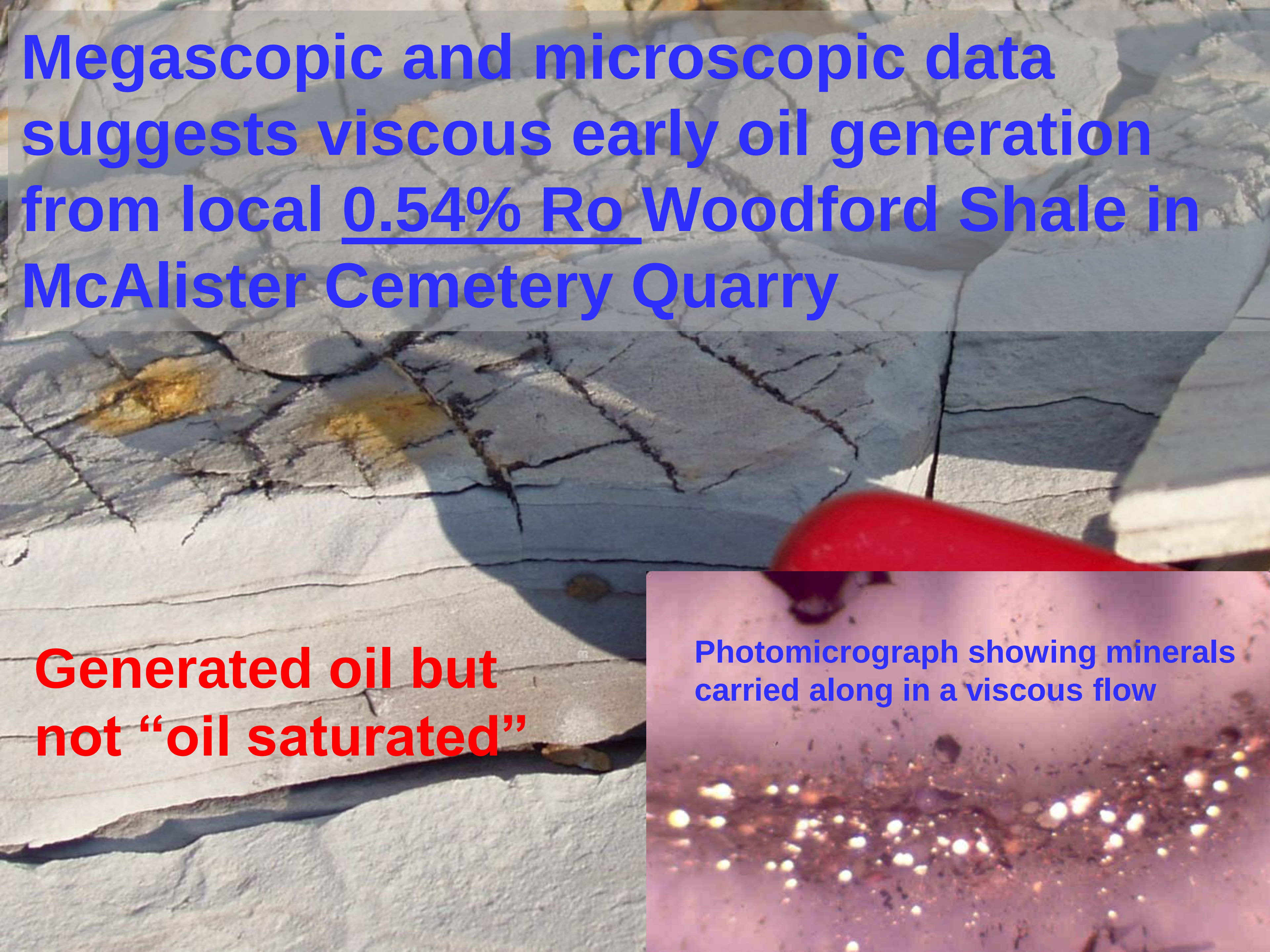
This Mass Spectrum (m/z 191 mass fragmentogram) indicates low thermal maturity “oil” from local Woodford Shale (data from Dr. R.P. Philp)

Woodford Host Rock Bitumen

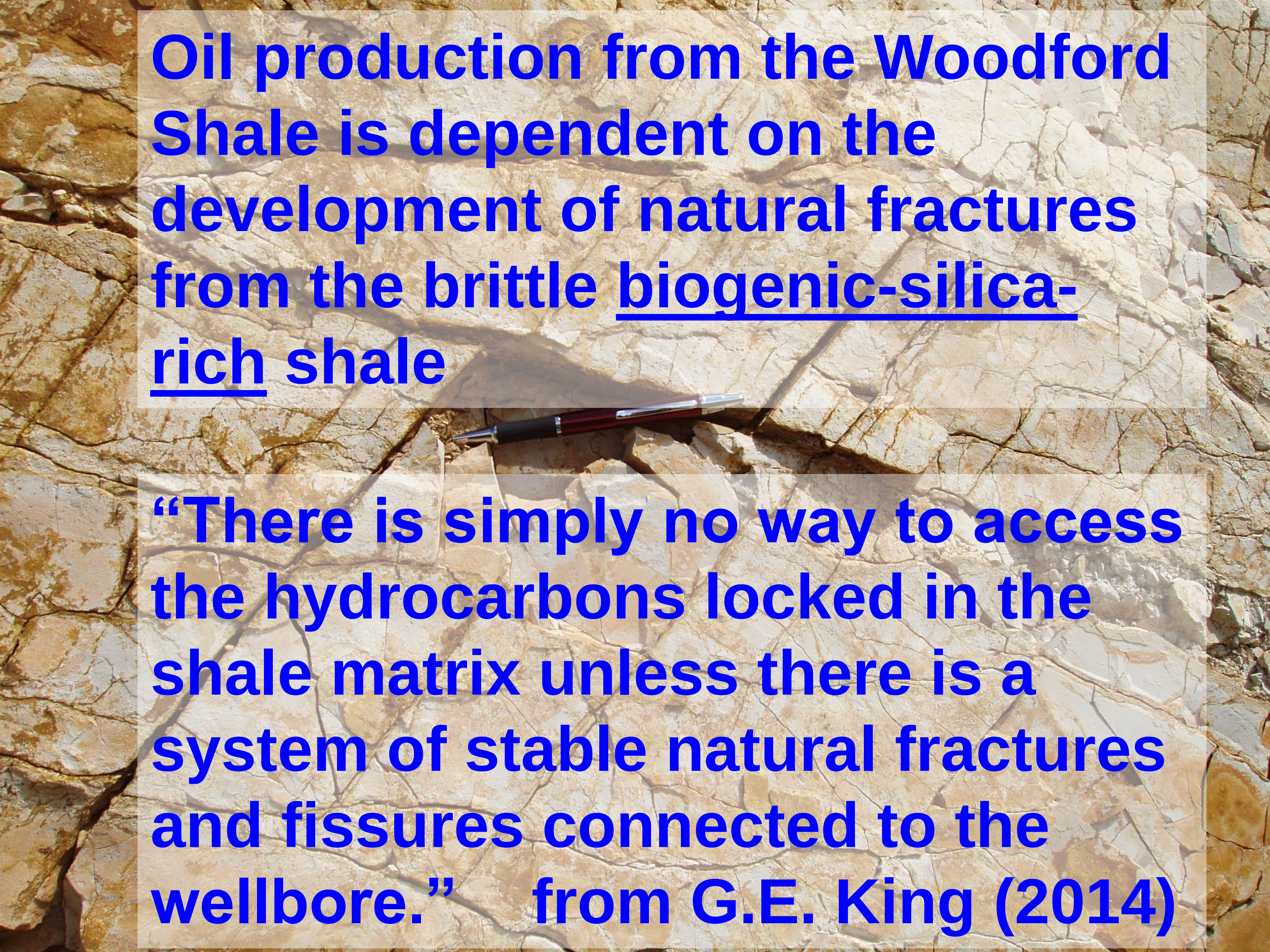


Woodford Fracture Fill Bitumen




Megascopic and microscopic data suggests viscous early oil generation from local 0.54% Ro Woodford Shale in McAlister Cemetery Quarry
Generated oil but not “oil saturated”
Photomicrograph showing minerals carried along in a viscous flow

Jarvie (2012, p. 91):
"Although an organic-rich source rock in the oil window with good oil saturation is the most likely place to have oil, it is also the most difficult to produce, unless it has open fractures or an organic-lean facies closely associated with it. This is due to molecular size, viscosity, and sorption of oil."

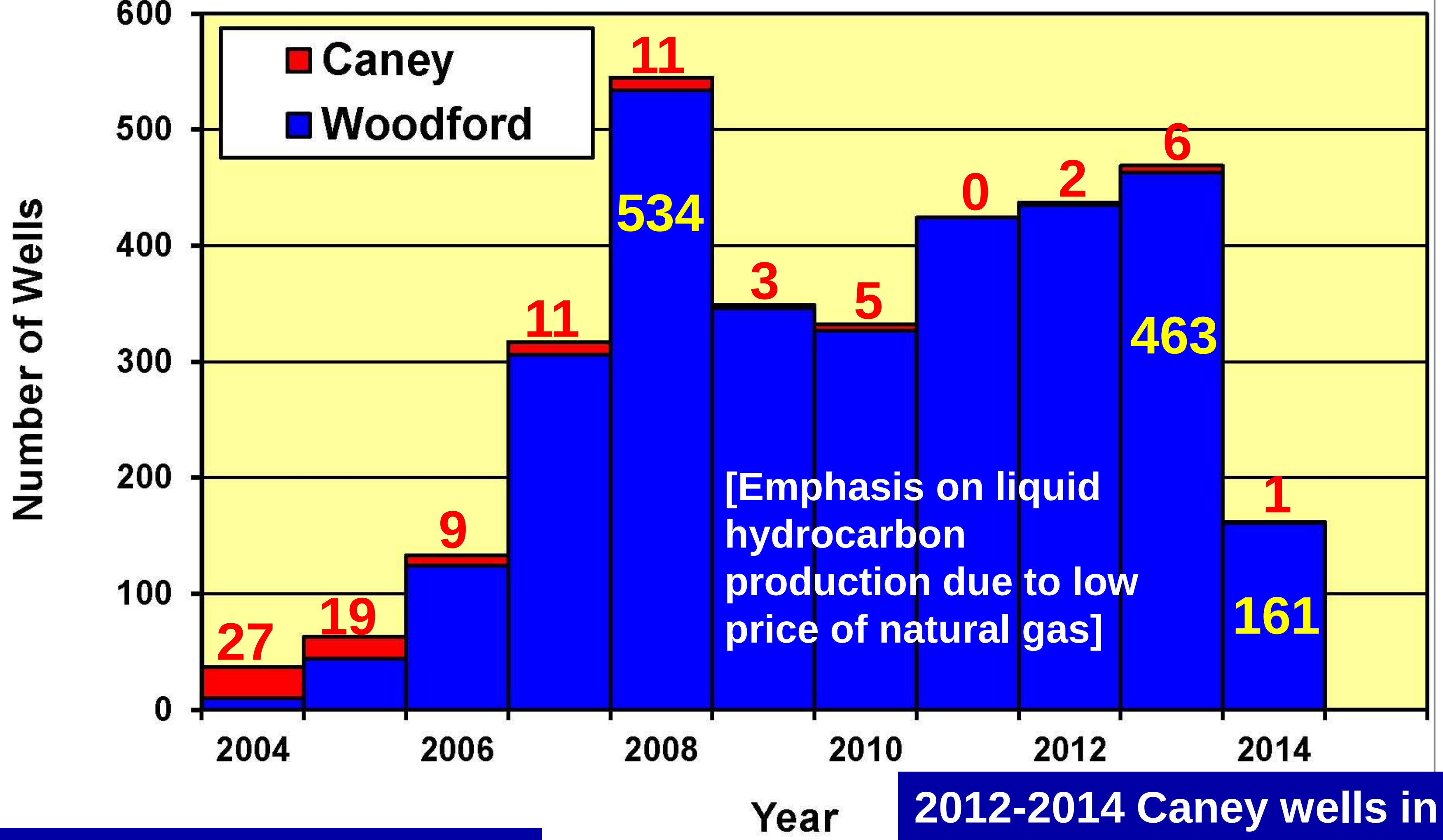


Oil production from the Woodford Shale is dependent on the development of natural fractures from the brittle biogenic-silica-rich shale

"There is simply no way to access the hydrocarbons locked in the shale matrix unless there is a system of stable natural fractures and fissures connected to the wellbore." from G.E. King (2014)

Oklahoma Shale-Gas Well History

3,174 Woodford + 94 Caney Wells, 2004–2014Q1



Caney/Woodford wells are included with Caney

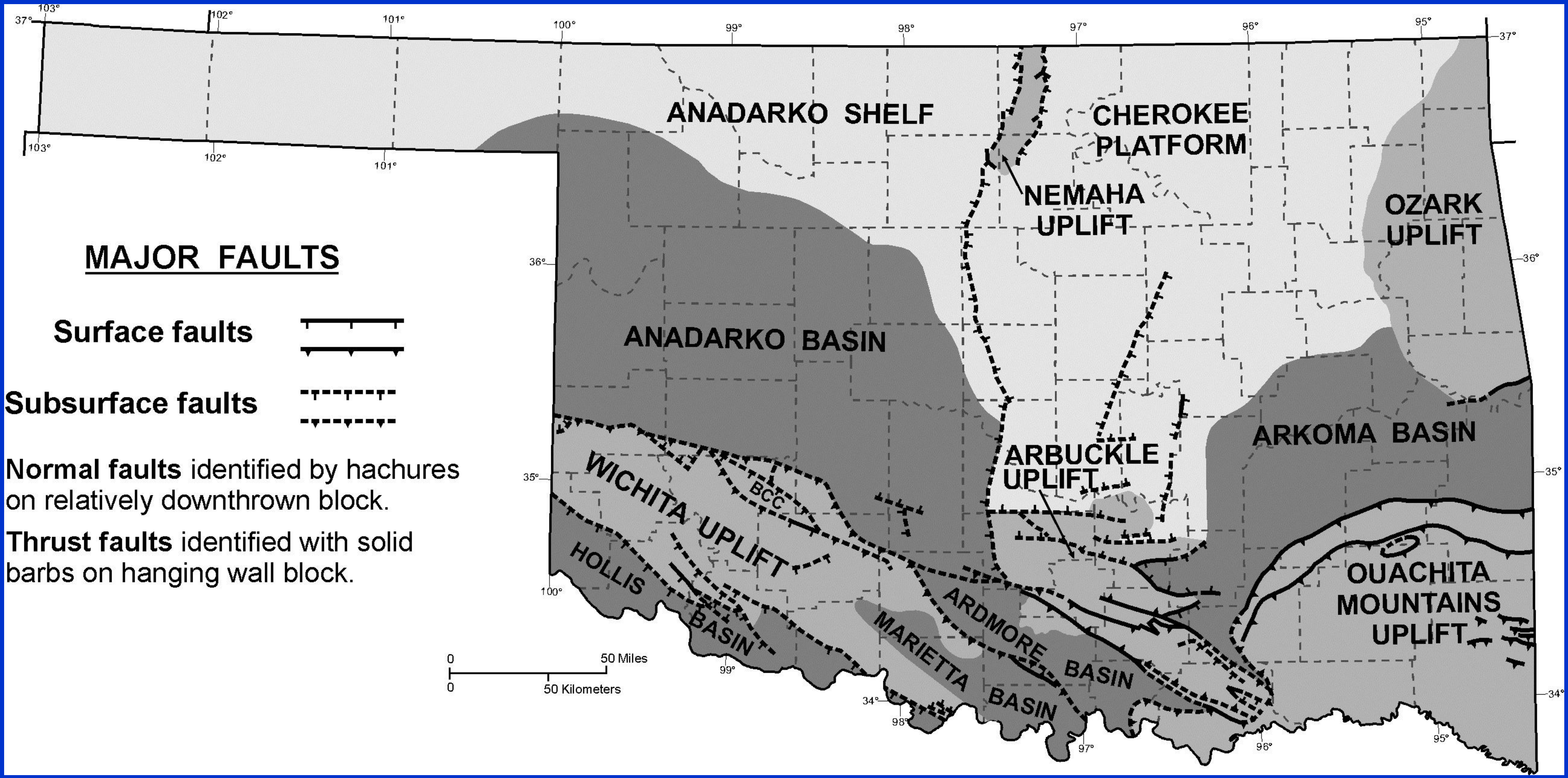
2012-2014 Caney wells in Carter, Love, Marshall & Stephens Cos

Oklahoma Oil/Condensate/Gas Production Caveat

- **Gas** production is reported by the Oklahoma Corporation Commission by **WELL**.
- **Oil/condensate** production is reported by the Oklahoma Tax Commission by **LEASE** [production by well is only on single-well leases]

(Production data supplied by PI/Dwights LLC, © 2014, IHS Energy Group)

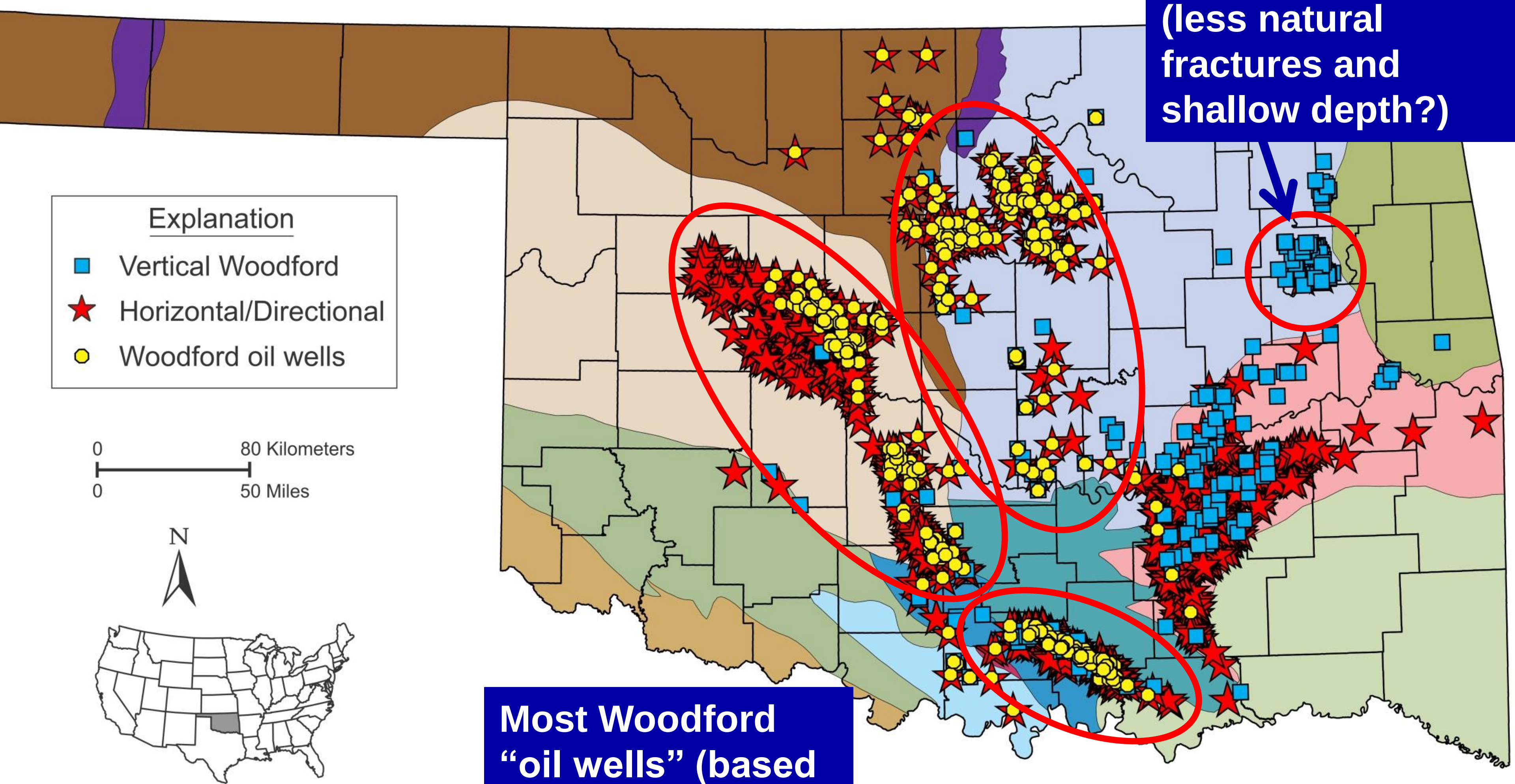
Oklahoma Geologic Provinces



Geologic provinces from Northcutt and Campbell, 1995

Woodford Shale (2004-2014 Q1)

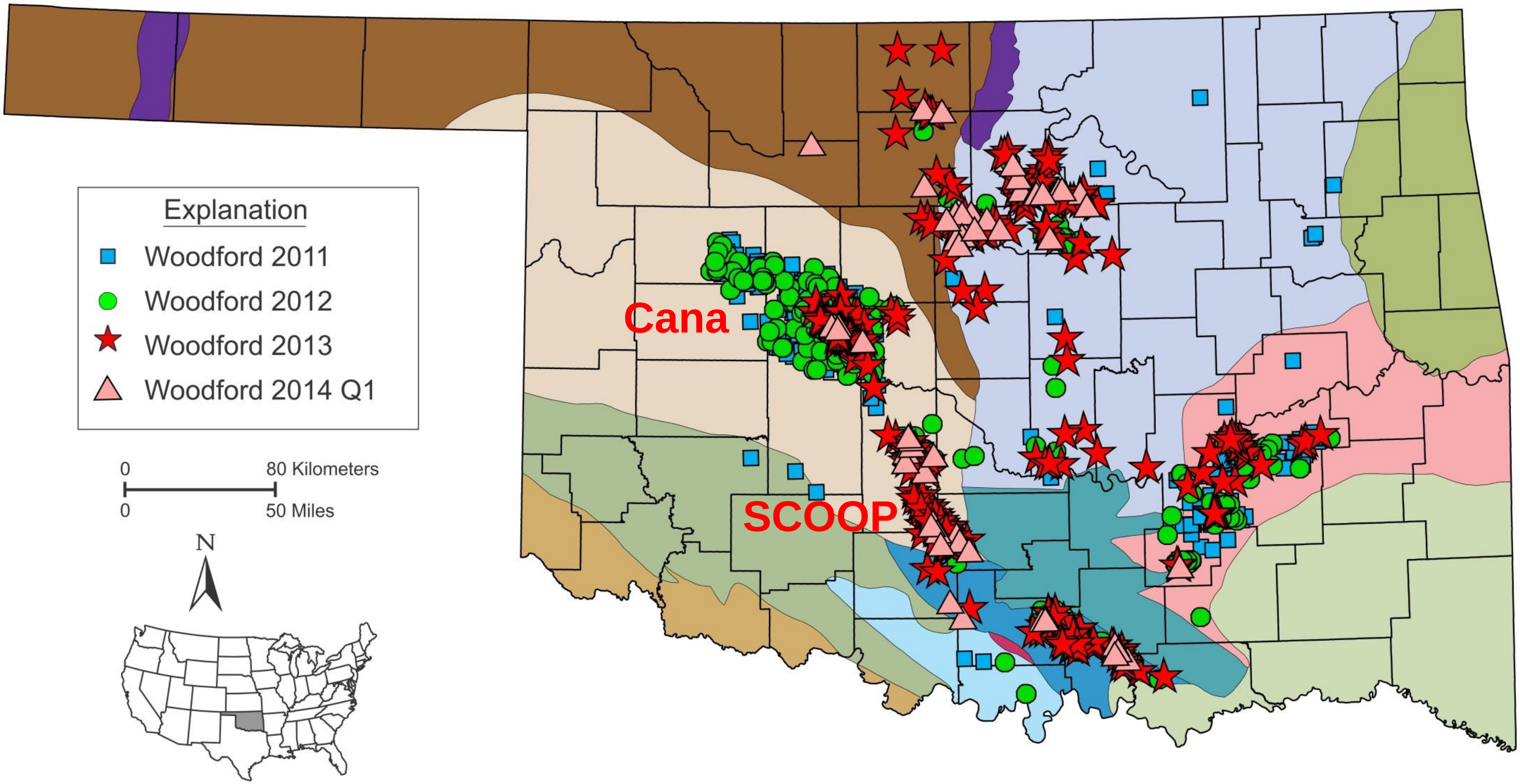
Wagoner Co. Woodford wells produce ONLY GAS in oil window (less natural fractures and shallow depth?)



Most Woodford "oil wells" (based on GOR <17,000) have low IP gas.

3,114 Woodford wells

Woodford Shale
(2011-2014 Q1)



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Thermal maturity of Woodford Shale gas and oil plays, Oklahoma, USA

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ABSTRACT

Being a hydrocarbon source rock and having a brittle (silica-rich) lithologic character makes the Woodford Shale (Late Devonian to Early Mississippian) an important oil and gas shale in Oklahoma. Since 2004, Woodford Shale plays have expanded from producing primarily thermogenic methane in one geologic province to producing thermogenic methane, condensate, oil and biogenic methane in four geologic provinces at thermal maturities from mature (>0.5% vitrinite reflectance, Ro) to post mature (2% to 3% Ro). Condensate is produced at a thermal maturity up to 1.67% Ro. Oil is produced from naturally-fractured, silica-rich shale. Biogenic methane is produced in shallow (<2000 ft, 610 m) reservoirs down dip from the outcrop in northeast Oklahoma.

1. Introduction

The Woodford Shale (Late Devonian to Early Mississippian) is an important hydrocarbon source rock in Oklahoma (Comer and Hinch, 1987; Johnson and Cardott, 1992). It is a black to dark-gray, marine, carbona-

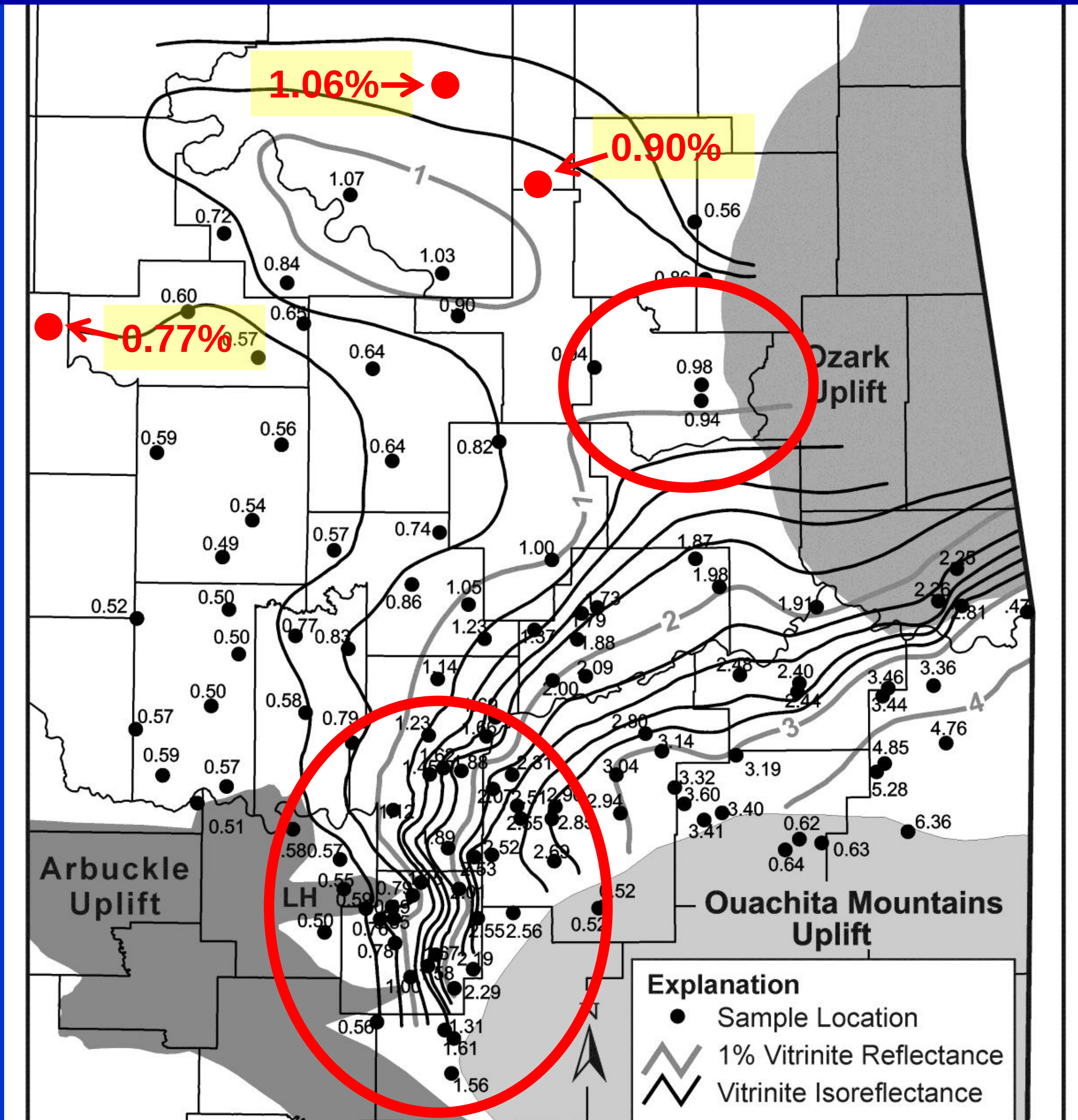
potential (e.g., high total organic carbon content with Type II kerogen), one advantage of the marine Woodford Shale as a gas shale is its quartz-rich composition, specifically rich primarily from Radiolaria and sponge spicule Kuuskraa et al. (2011) indicated that marine shales (common deposi-

Cardott, 2012b

Due to a number of variables, Woodford Shale vitrinite isoreflectance maps should be used as a qualitative thermal maturity indicator (e.g., start, middle, end of oil window; condensate window; gas window) and not as a "drill here" indicator because of the following factors:

- **Vitrinite reflectance is an average of many values and has some internal variation.**
- **Woodford Shale vitrinite reflectance was originally determined to estimate the general hydrocarbon source rock potential.**
- **The Woodford Shale is divided into three informal members: the lower member was deposited more near-shore marine and is where the most and largest vitrinite and petrified wood is found.**
- **The vitrinite reflectance value is extrapolated to the entire thickness even though the Woodford Shale may be up to 700 ft thick.**

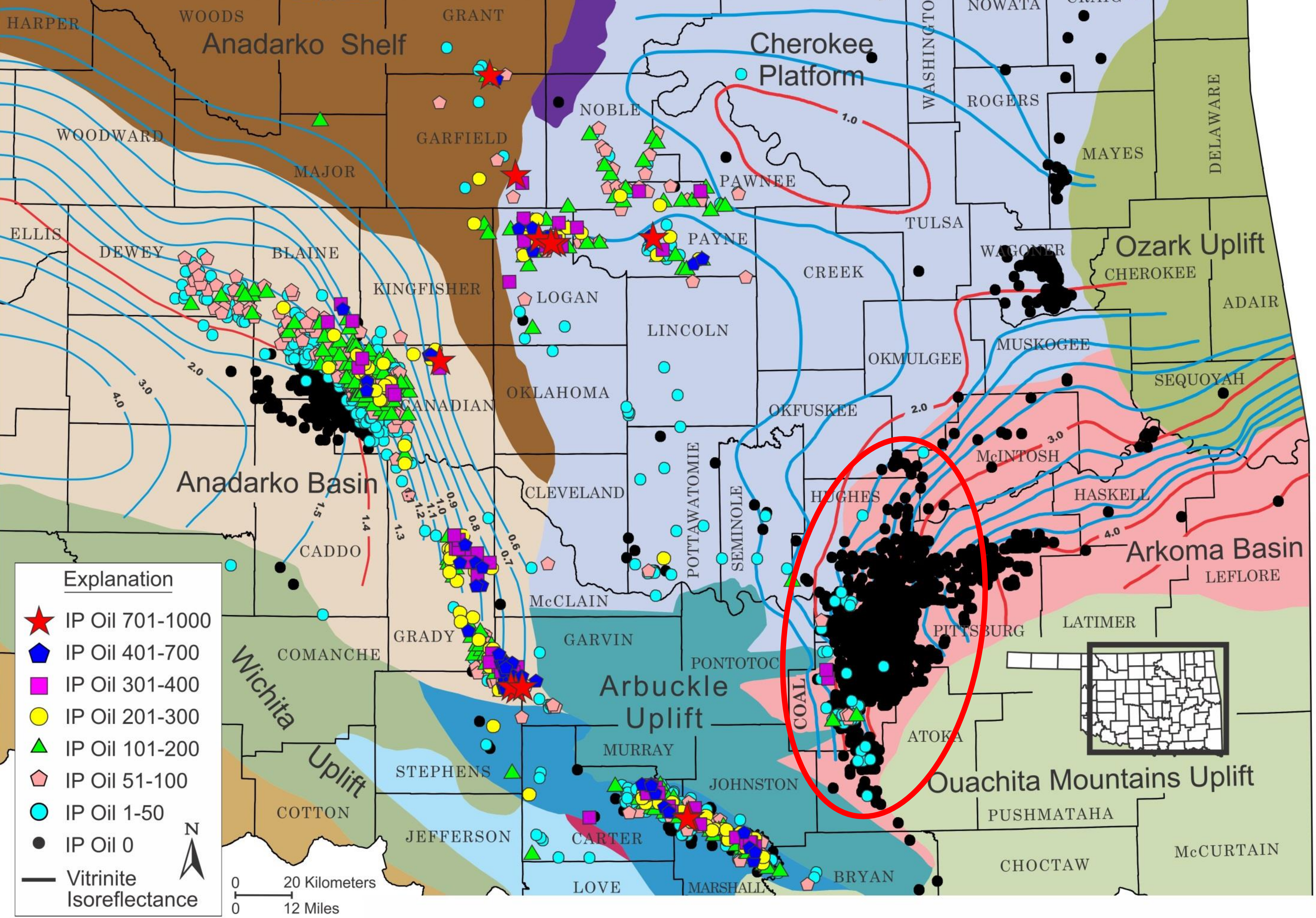
Isoreflectance Map of the Woodford Shale in Eastern Oklahoma (Updated November 2011)



Distribution of 117 Woodford Shale samples with vitrinite-reflectance data (n ≥20; whole-rock pellets)

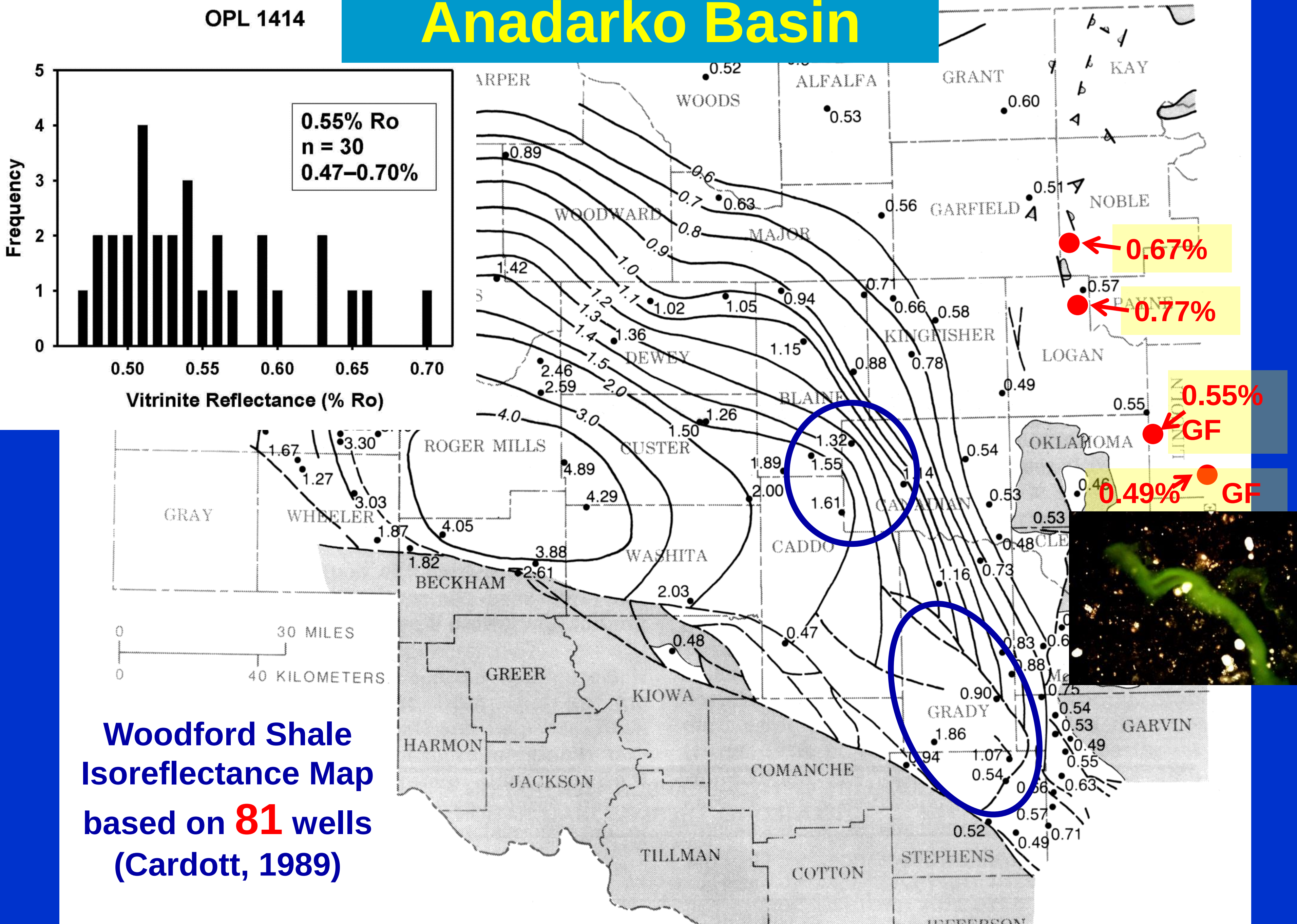
Cardott, in preparation

Woodford Shale Arkoma Basin IP Oil



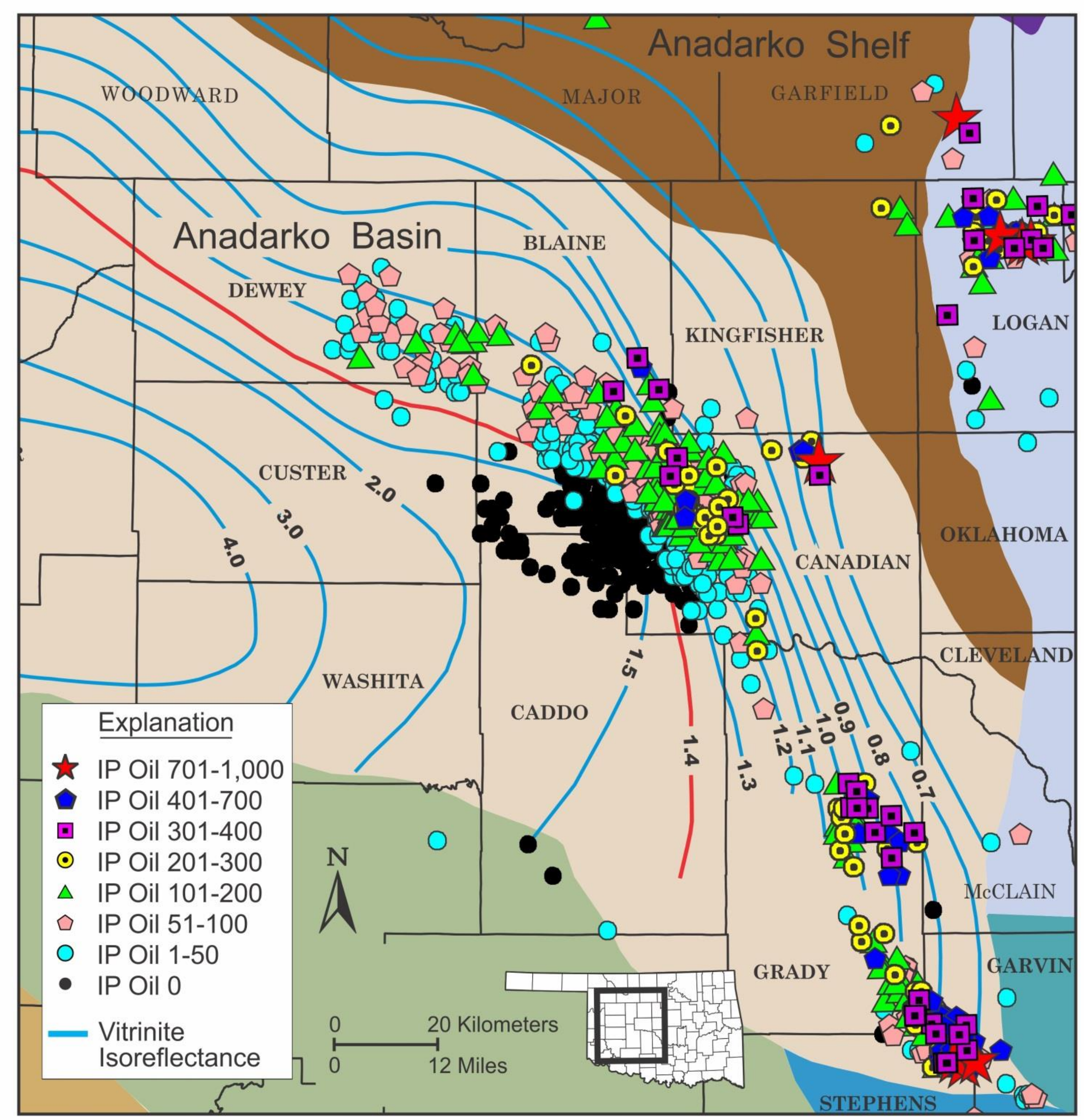
OPL 1414

Anadarko Basin

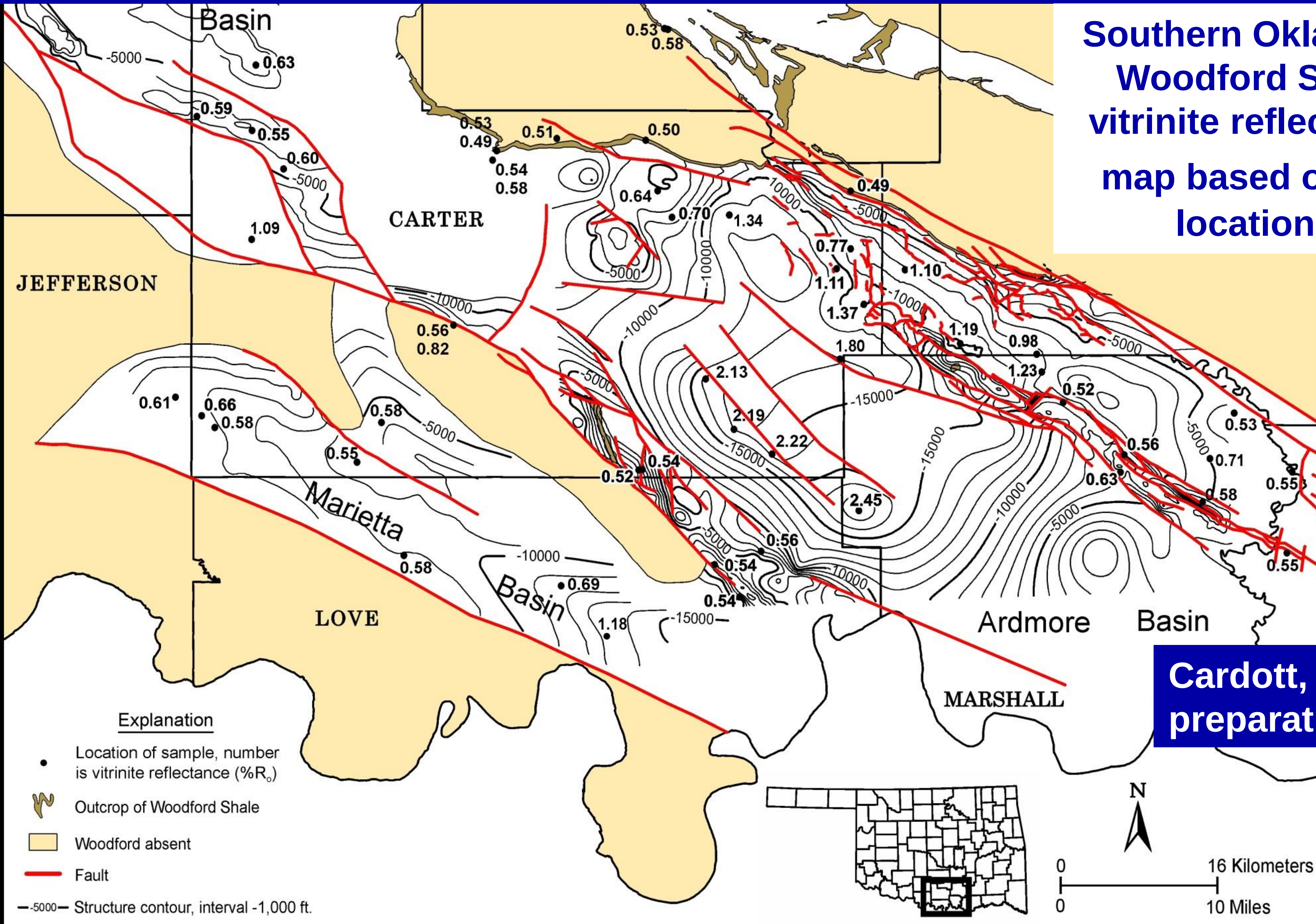


Woodford Shale Isoreflectance Map based on 81 wells (Cardott, 1989)

Woodford Shale Anadarko Basin IP Oil



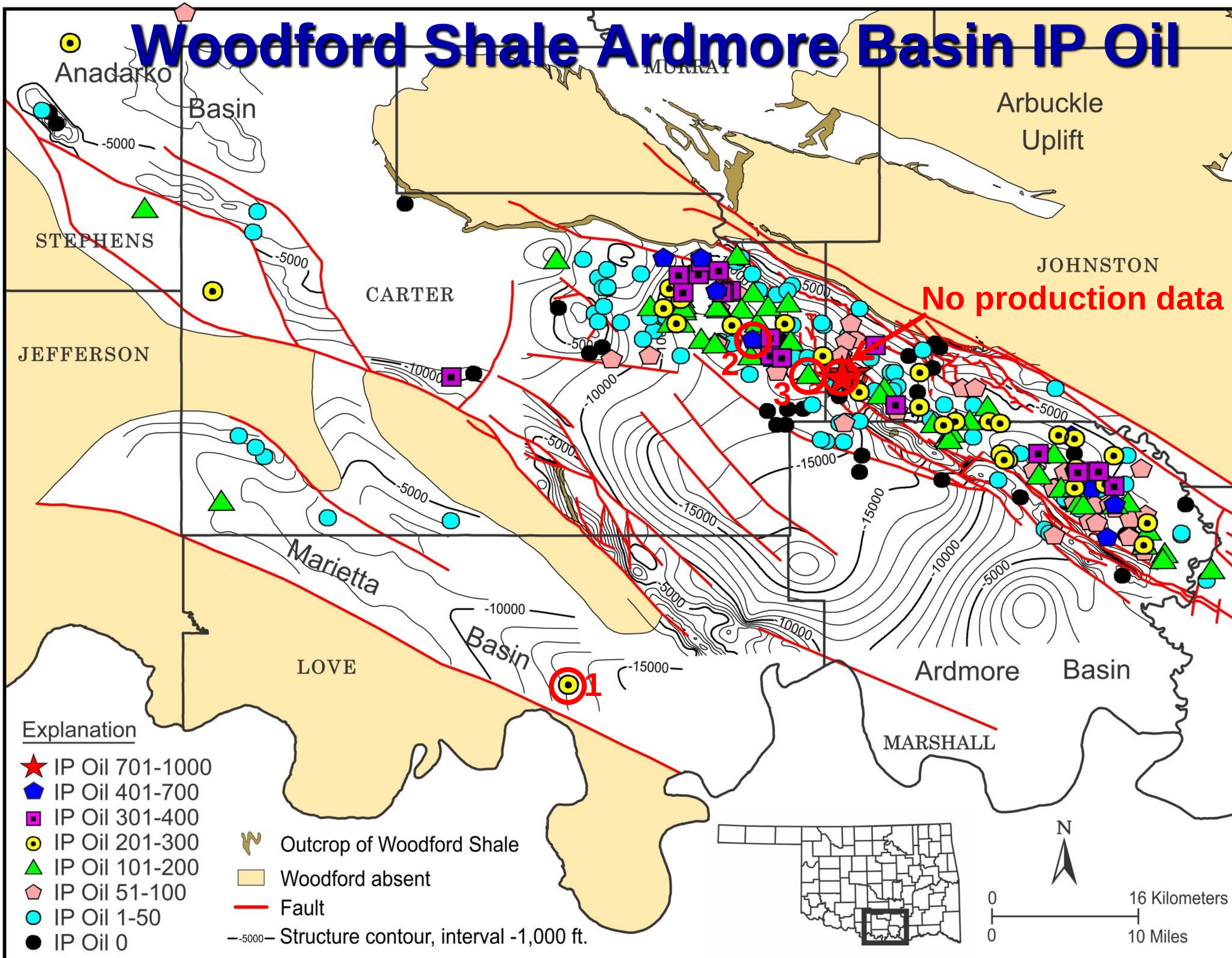
Woodford Shale Vitrinite Reflectance Data in Southern Oklahoma (Updated October 2013)



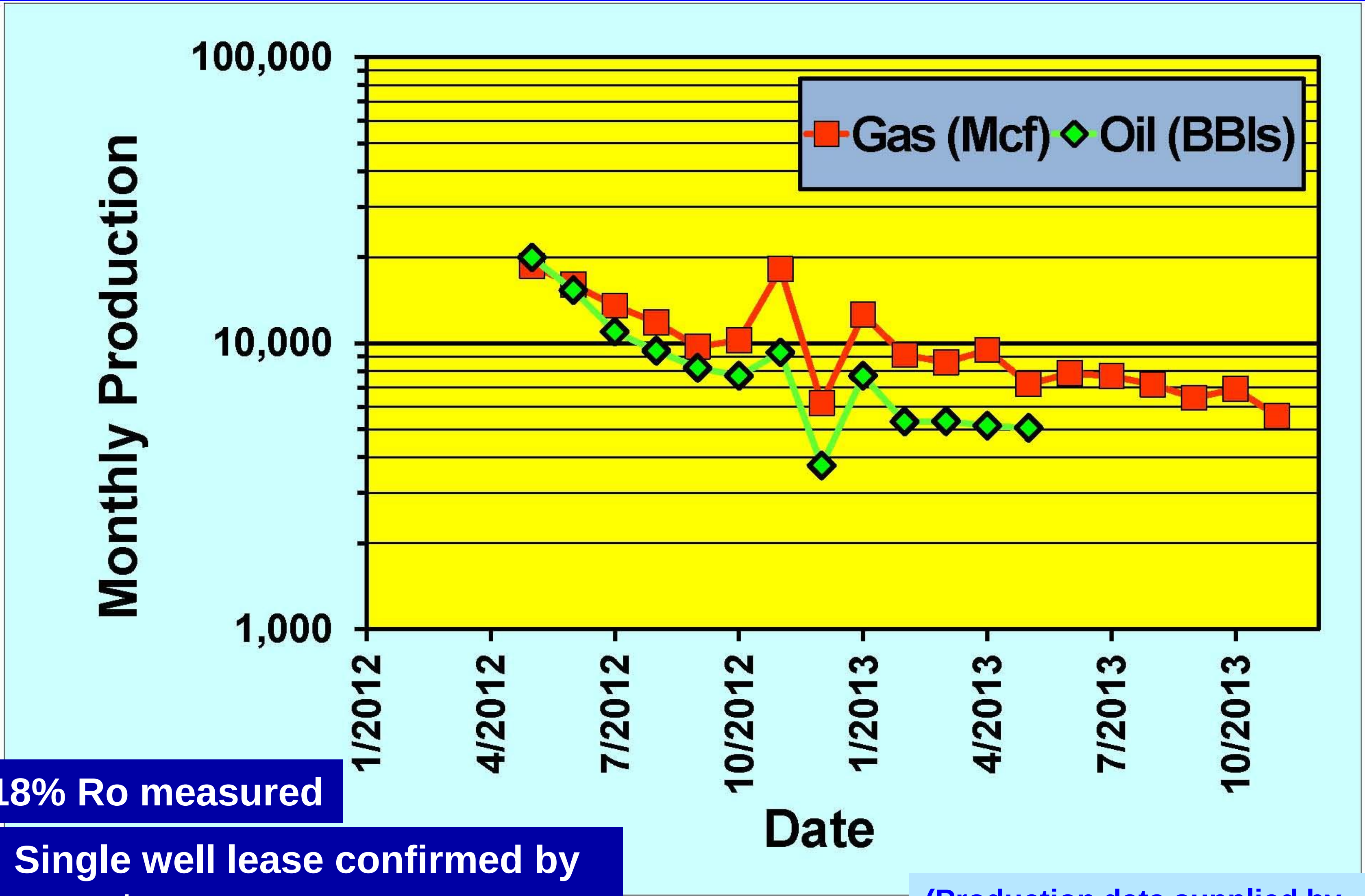
Southern Oklahoma Woodford Shale vitrinite reflectance map based on 51 locations

Cardott, in preparation

Woodford Shale Ardmore Basin IP Oil



1. XTO 1-22H15 McKay Horizontal Well
Love Co.; 22-7S-1E; IP 733 MCFD, 278 BOPD (41° API)

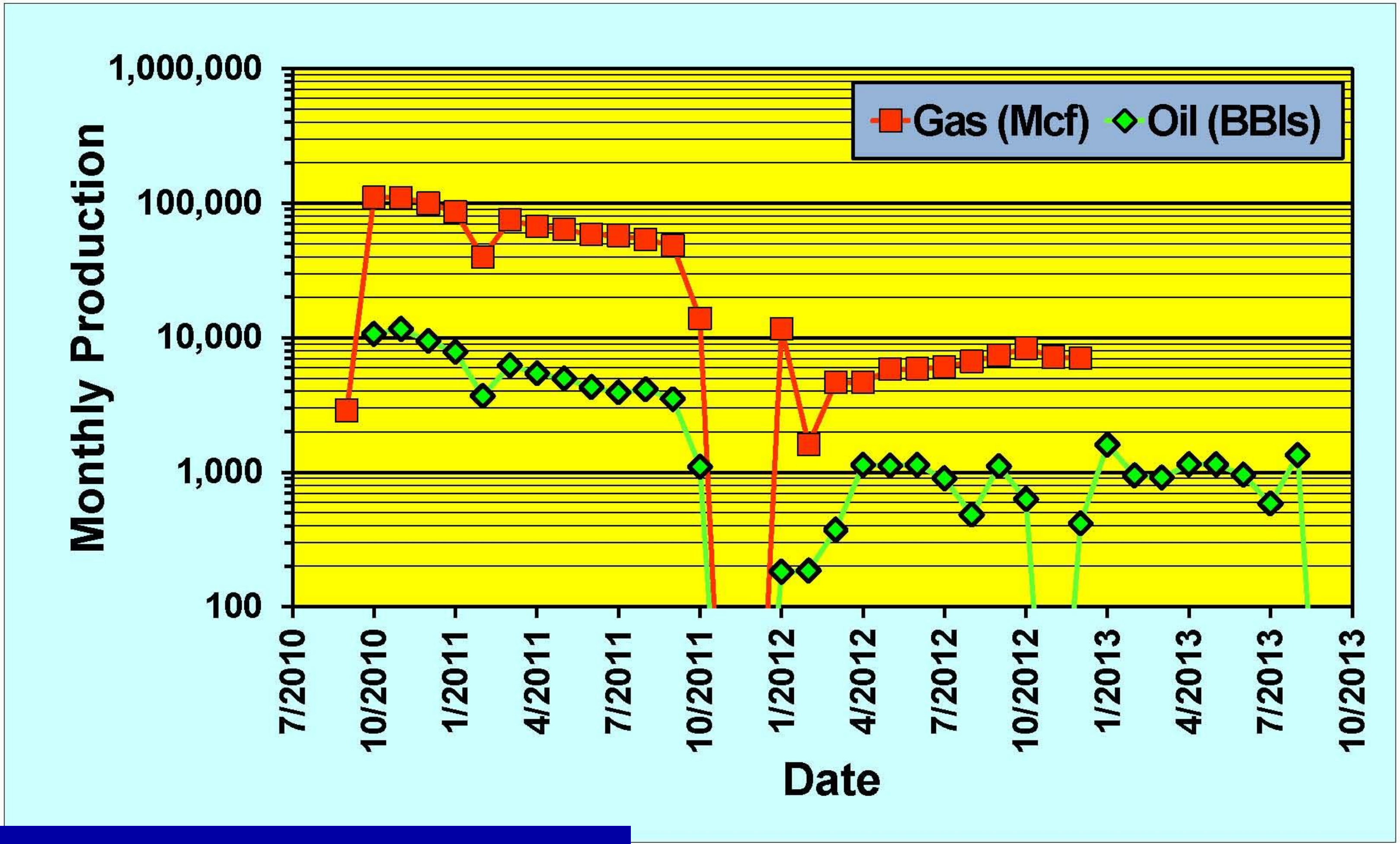


1.18% Ro measured

Single well lease confirmed by operator.
Cum: 113,102 BO; 192,898 MCF

(Production data supplied by Petroleum Information/Dwights LLC dba IHS Energy Group, © 2014)

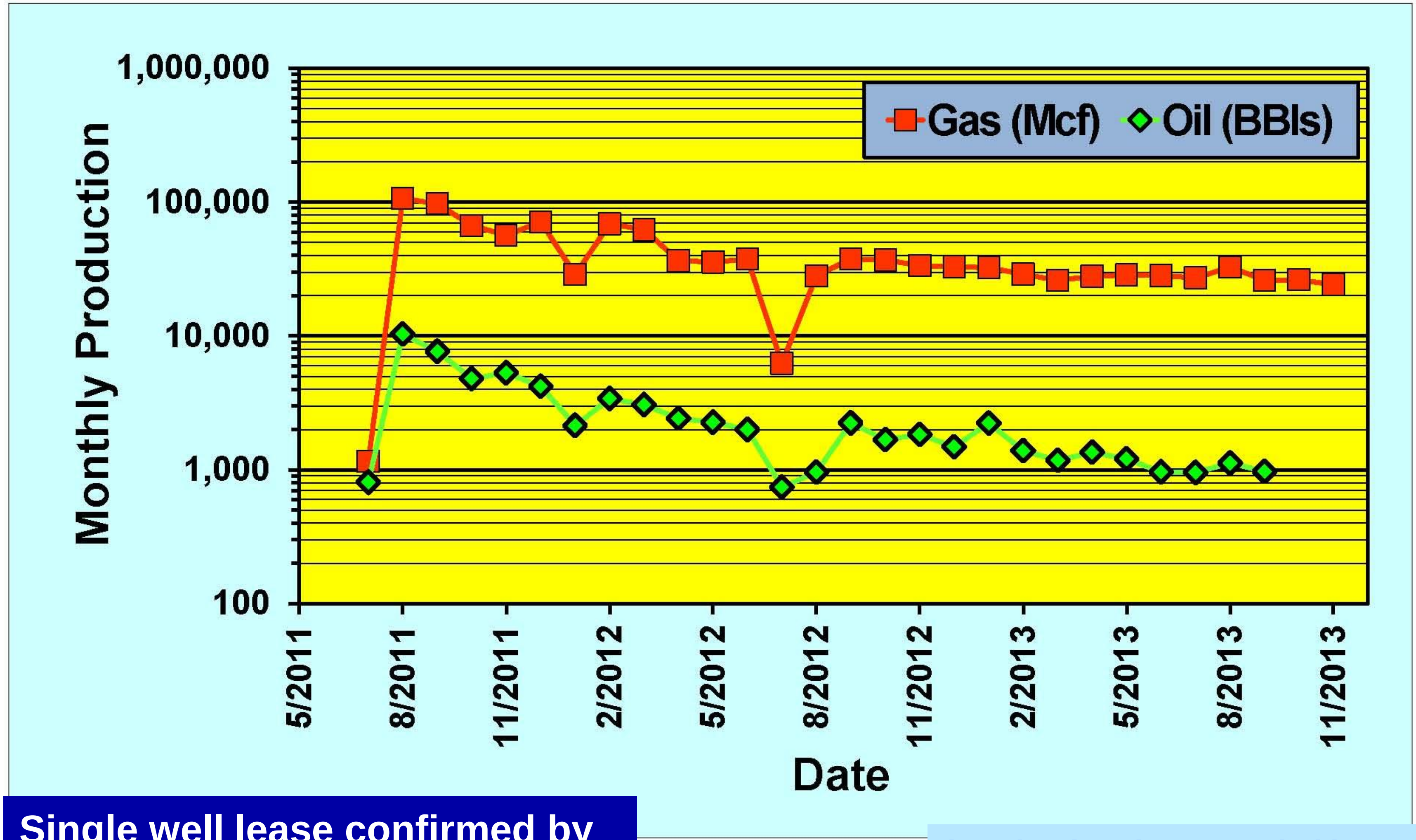
2. XTO 1-32H Owens Horizontal Well
Carter Co.; 32-3S-3E; IP 3,361 MCFD, 418 BOPD (50° API)



Single well lease confirmed by operator.
Cum: 93,131 BO; 963,655 MCF

(Production data supplied by Petroleum Information/Dwights LLC dba IHS Energy Group, © 2014)

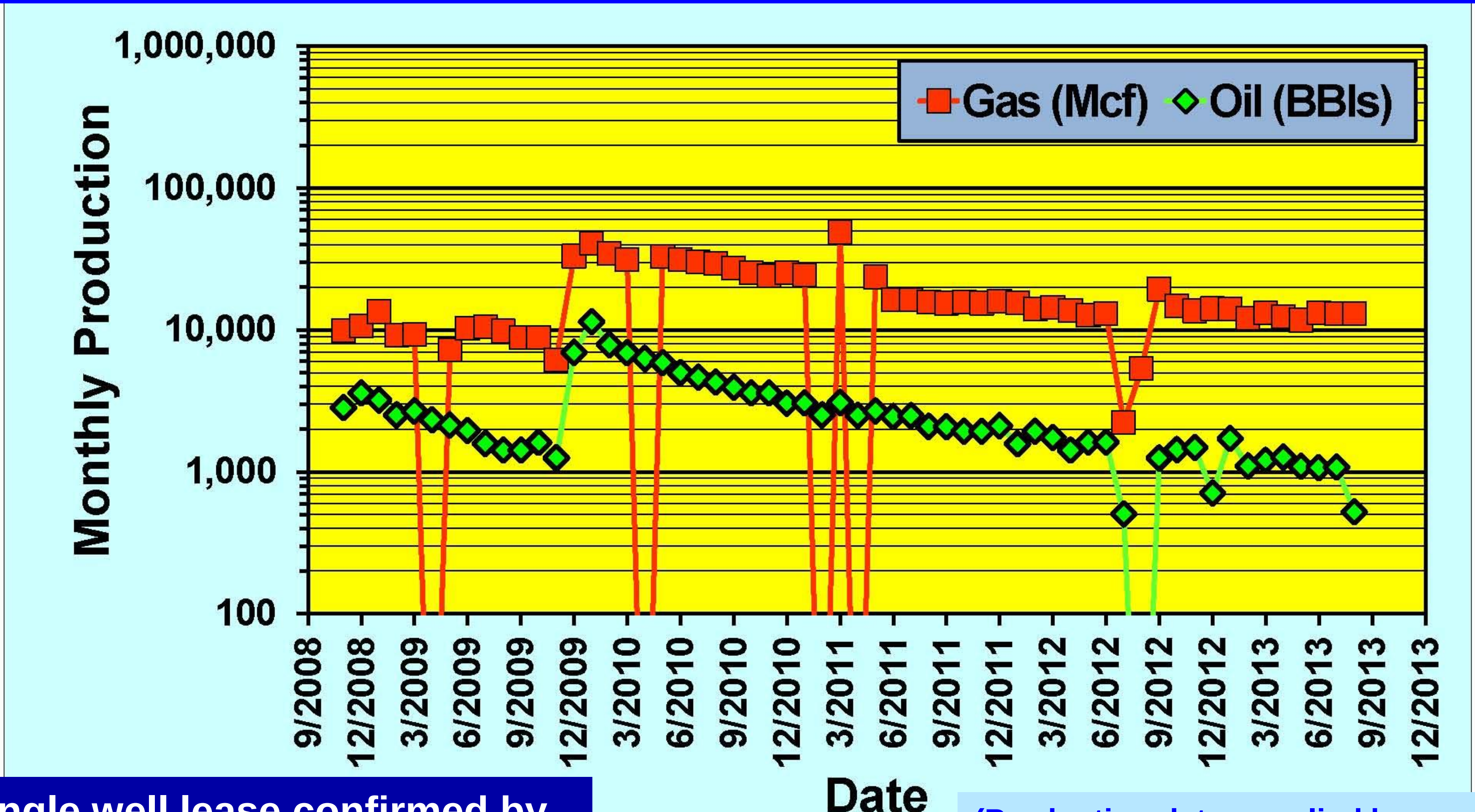
3a. XTO 1-12H Wiggins Horizontal Well
Carter Co.; 13-4S-3E; IP 1,285 MCFD, 150 BOPD



Single well lease confirmed by operator.
Cum: 68,657 BO; 1,153,080 MCF

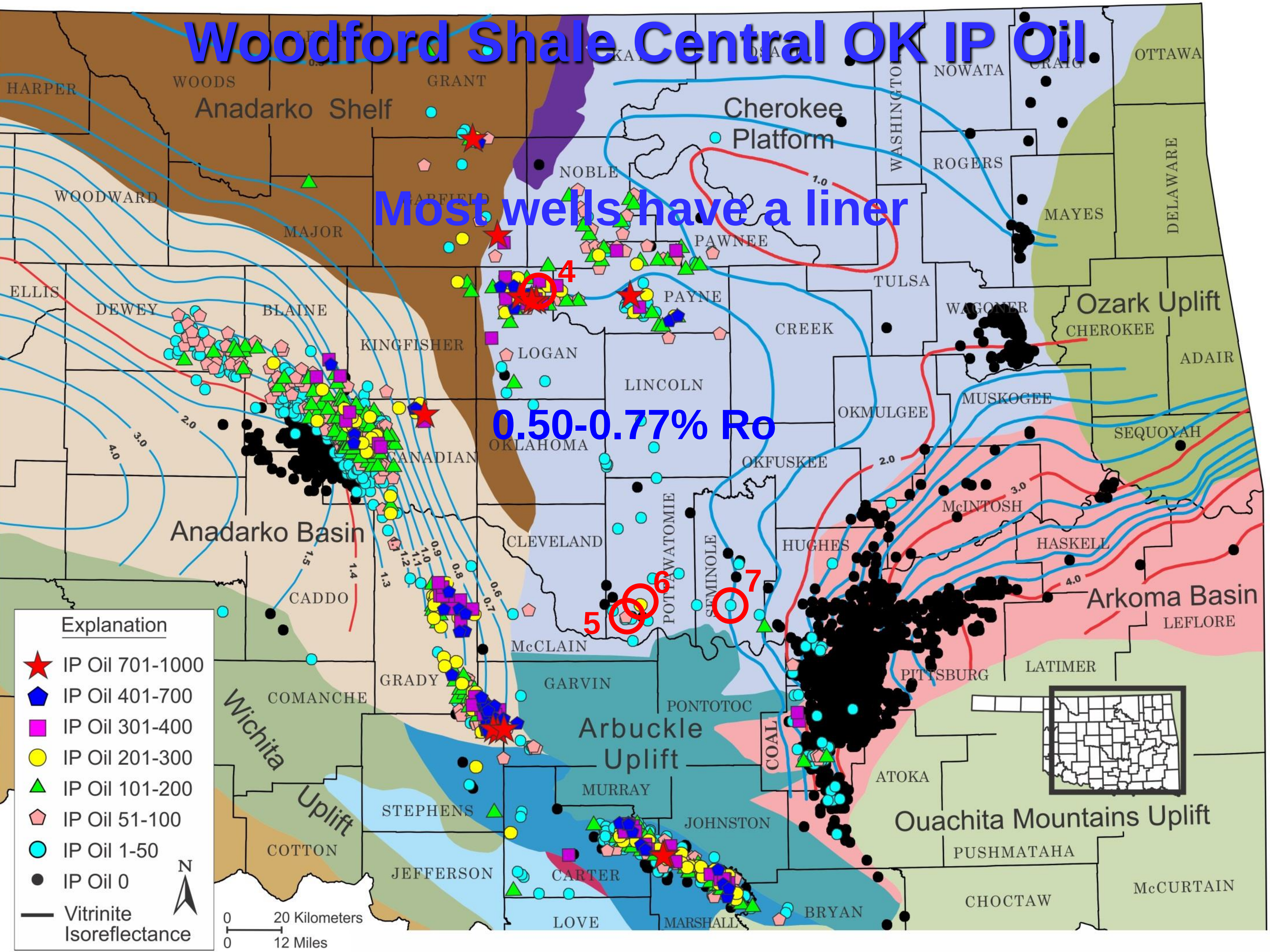
(Production data supplied by Petroleum Information/Dwights LLC dba IHS Energy Group, © 2014)

3b. Wagner & Brown 1H-1 Hartgraves Horizontal Well Carter Co.; 1-4S-3E; IP 243 MCFD, 252 BOPD [shut in for drilling/completion work on other wells on same pad]

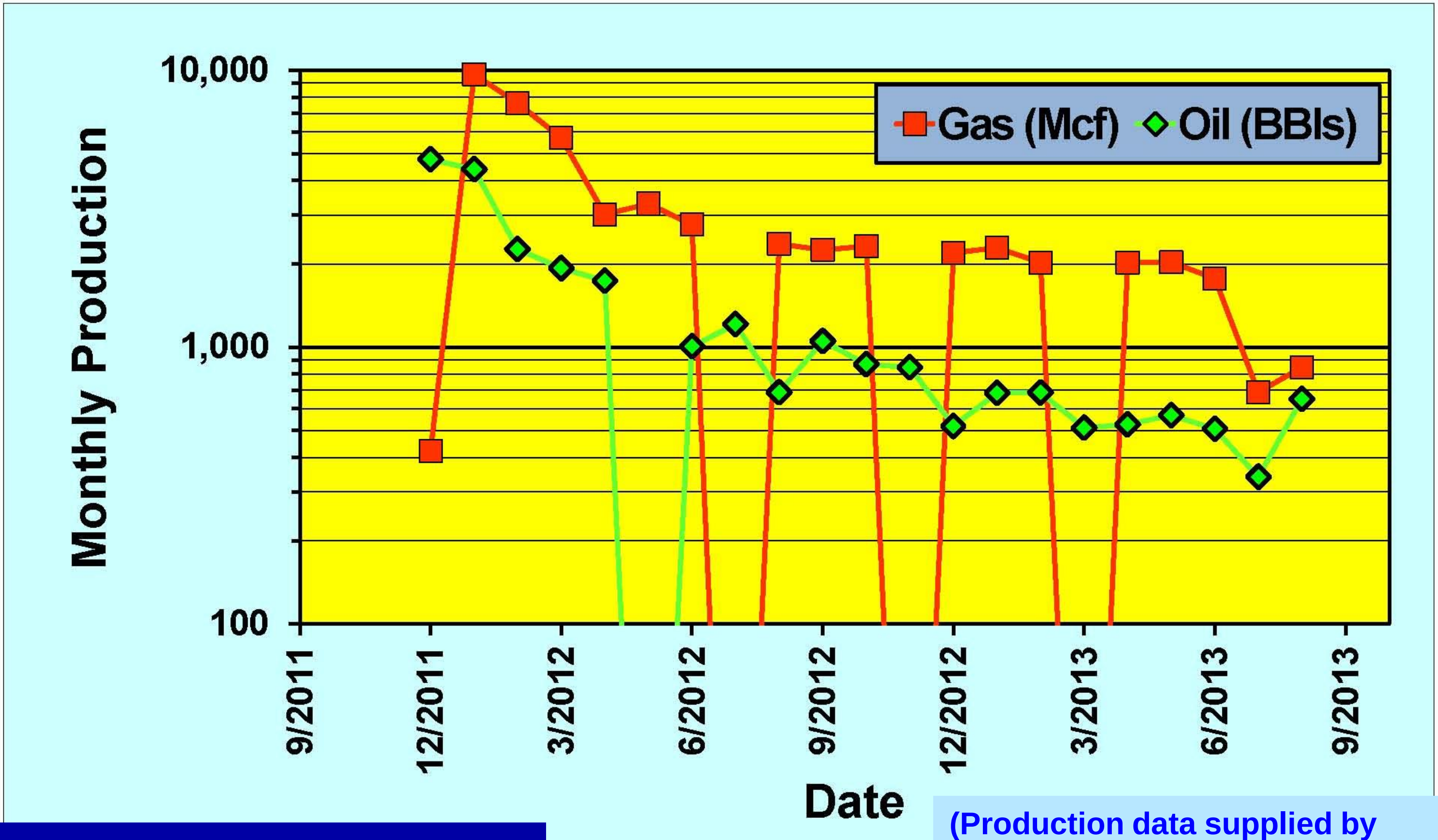


Single well lease confirmed by operator.
Cum: 154,994 BO; 943,423 MCF

(Production data supplied by Petroleum Information/Dwights LLC dba IHS Energy Group, © 2014)


Woodford Shale Central OK IP Oil
Most wells have a liner
0.50-0.77% Ro
4
5
6
7
Anadarko Shelf
Cherokee Platform
Ozark Uplift
Anadarko Basin
Arkoma Basin
Arbuckle Uplift
Wichita Uplift
Ouachita Mountains Uplift
HARPER
WOODS
GRANT
NOWATA
CRAIG
OTTAWA
WASHINGTON
NOBLE
ROGERS
MAYES
DELAWARE
WOODWARD
MAJOR
PAWNEE
TULSA
ELLIS
DEWEY
BLAINE
PAYNE
WAGONER
CHEROKEE
CREEK
ADAIR
KINGFISHER
LOGAN
LINCOLN
OKMULGEE
MUSKOGEE
SEQUOYAH
OKLAHOMA
CANADIAN
OKFUSKEE
McINTOSH
HASKELL
CLEVELAND
POTTAWATOMIE
SEMINOLE
HUGHES
CADDO
McCLAIN
LEFLORE
PITTSBURG
LATIMER
GRADY
GARVIN
COMANCHE
PONTOTOC
COAL
ATOKA
MURRAY
STEPHENS
JOHNSTON
COTTON
PUSHMATAHA
JEFFERSON
CARTER
McCURTAIN
CHOCTAW
BRYAN
LOVE
MARSHALL
1.0
2.0
3.0
4.0
1.5
1.4
1.3
1.2
1.1
0.9
0.8
0.7
0.6
Explanation
IP Oil 701-1000
IP Oil 401-700
IP Oil 301-400
IP Oil 201-300
IP Oil 101-200
IP Oil 51-100
IP Oil 1-50
IP Oil 0
Vitrinite Isoreflectance
N
0 20 Kilometers
0 12 Miles

4. Devon Energy 1-33H Johnson Horizontal Well; Logan Co.; 33-19N-2W; IP 242 MCFD, 285 BOPD

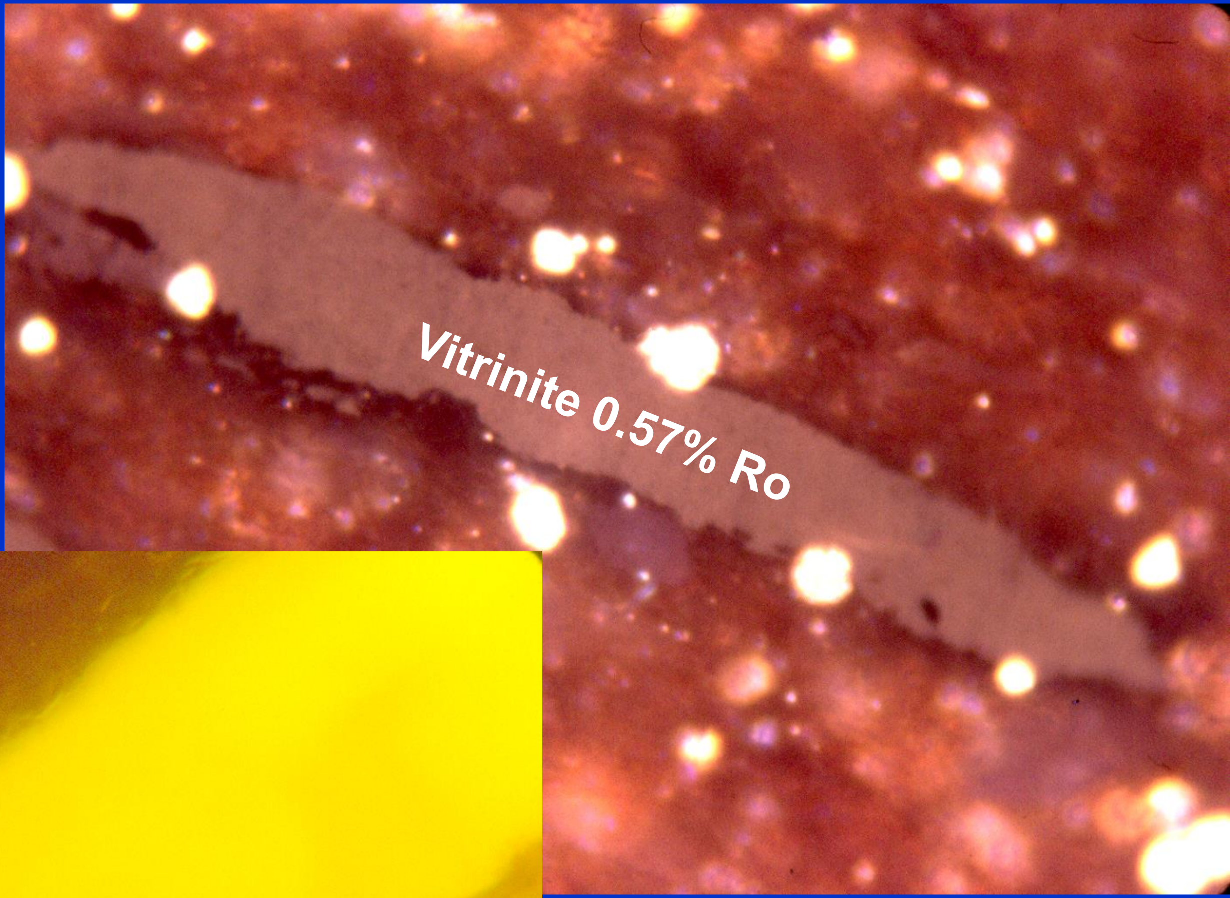


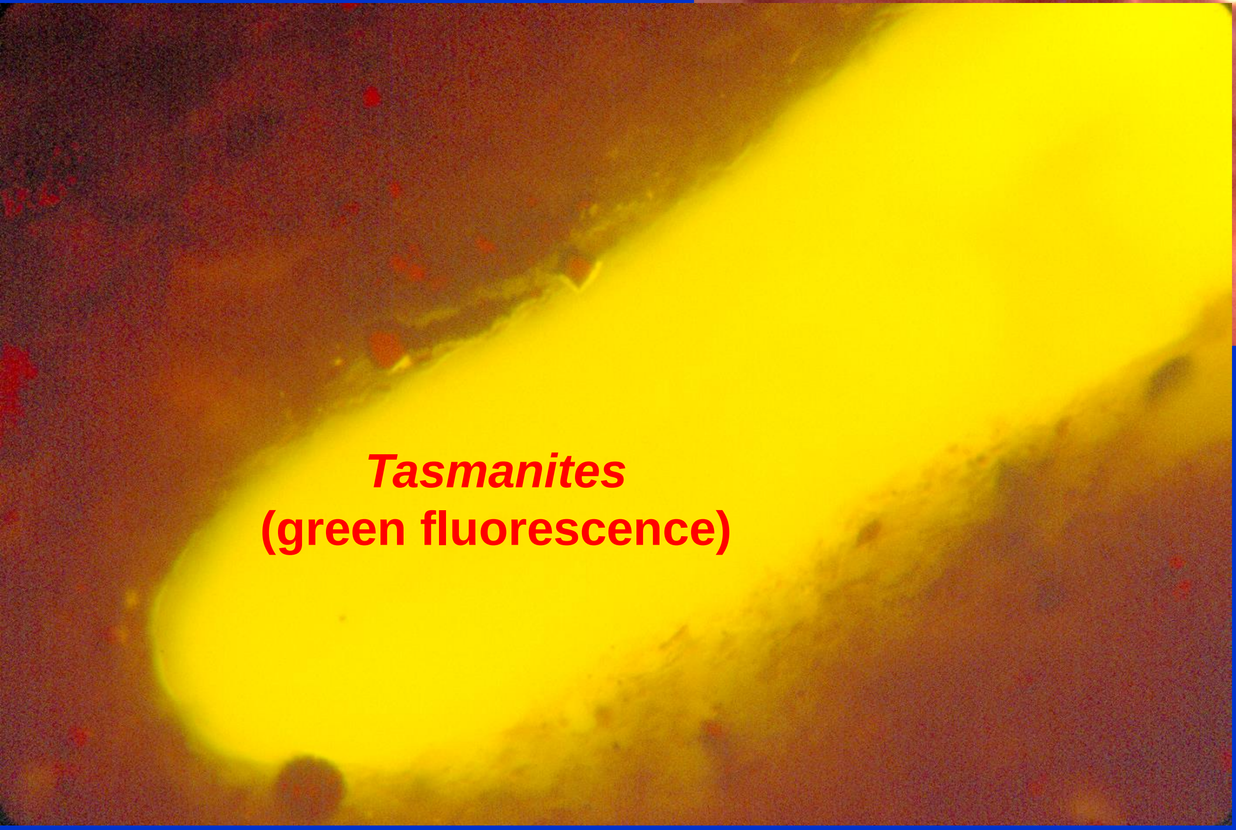
(Production data supplied by Petroleum Information/Dwights LLC dba IHS Energy Group, © 2014)

Single well lease confirmed by operator.
Cum: 25,761 BO; 53,415 MCF

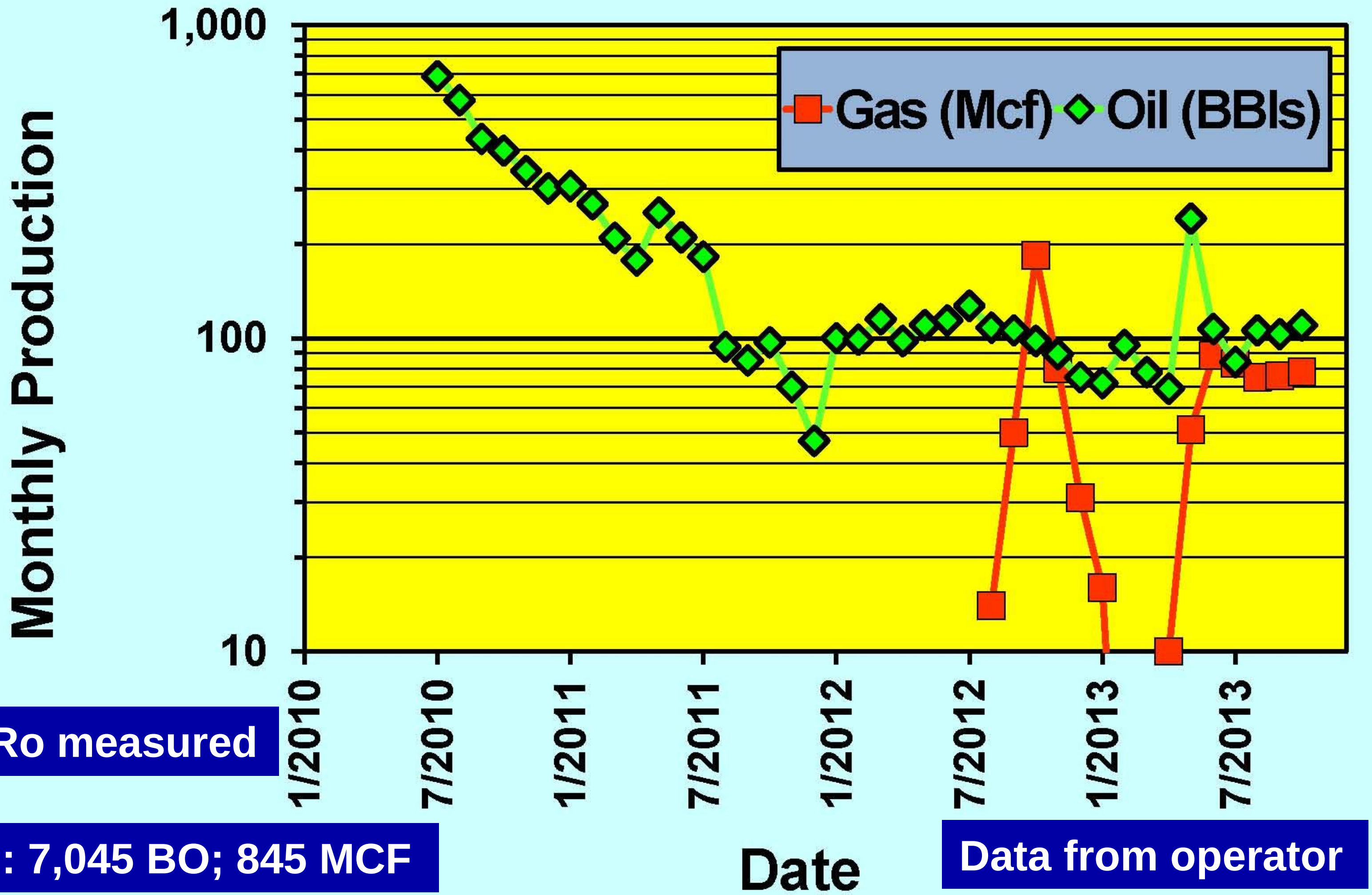
In an area recently measured 0.77% VRo

5. West Star Operating
1-13 Ray
Pottawatomie Co.
13-6N-2E
OPL 1333
VRo 0.59% Ro





5. West Star Operating 1-13 Ray Vertical Well Pottawatomie Co.; 13-6N-2E; IP not reported (delayed hook-up to gas pipeline)

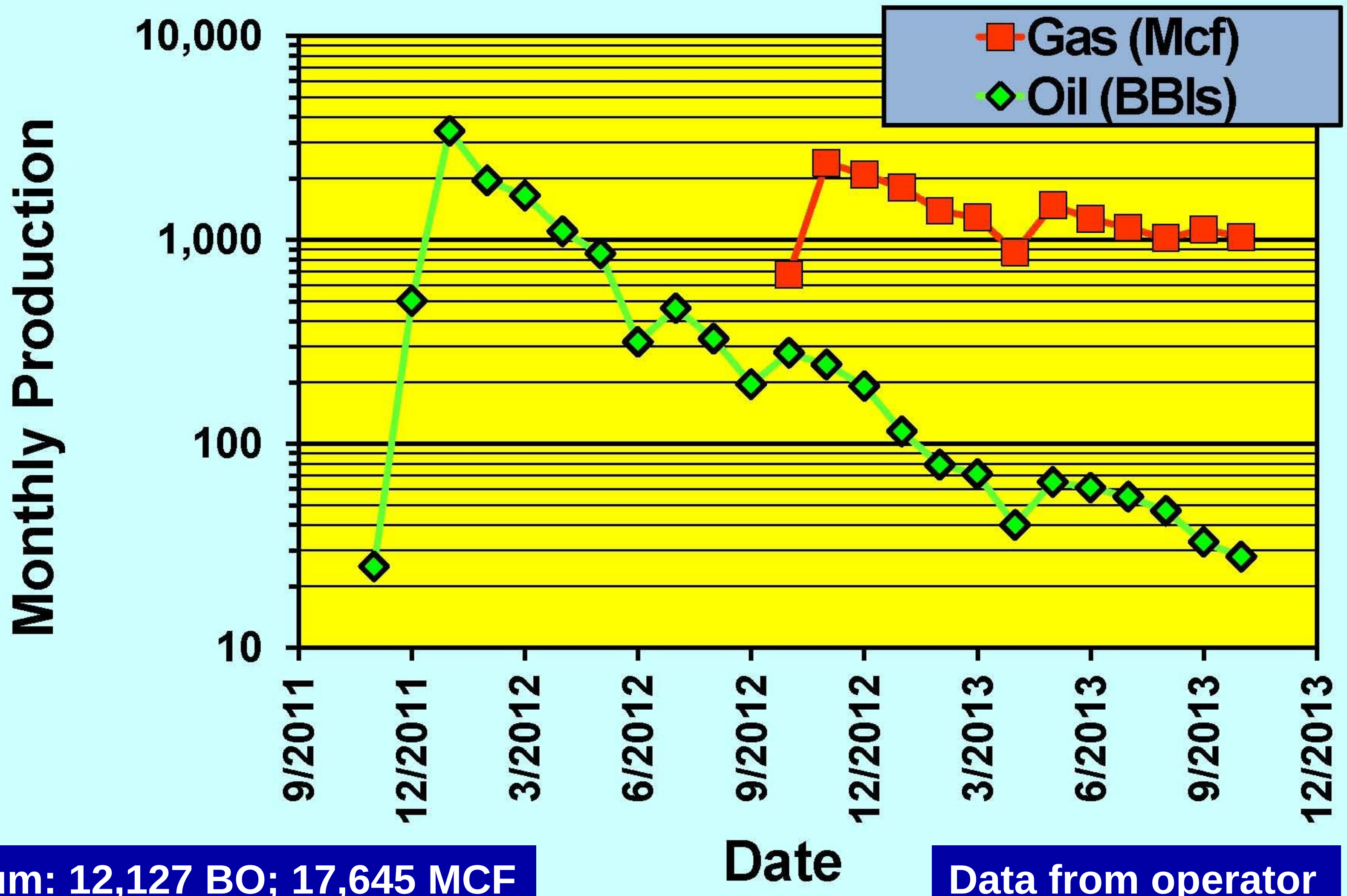


0.59% Ro measured

Cum: 7,045 BO; 845 MCF

Data from operator

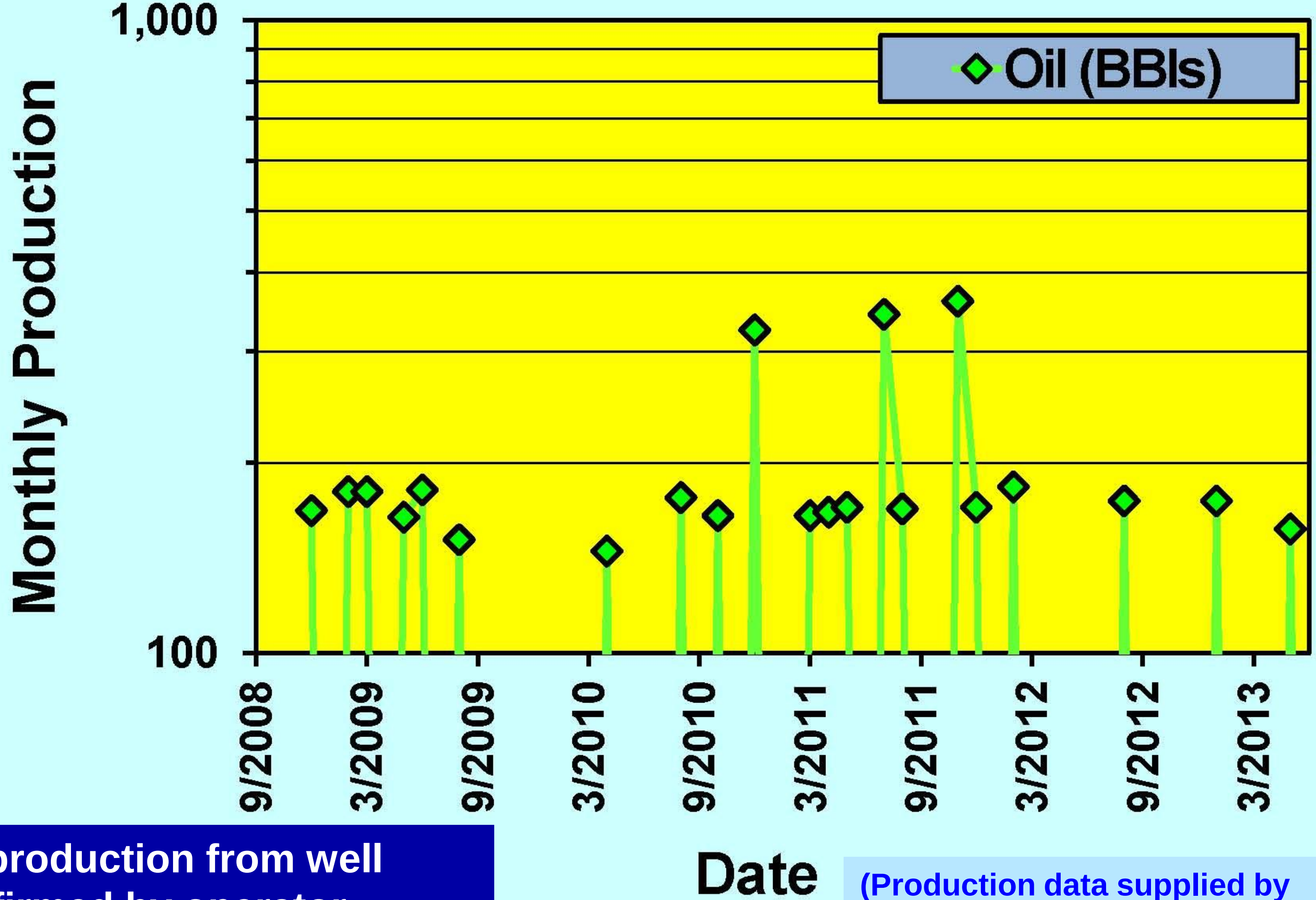
6. West Star Operating 1-33H Salt Creek Horizontal Well Pottawatomie Co.; 33-7N-3E; IP 256 MCFD, 215 BOPD (delayed hook-up to gas pipeline)



Cum: 12,127 BO; 17,645 MCF

Data from operator

7. Chesapeake Operating 1-36H Francisca Horizontal Well Seminole Co.; 36-7N-6E; IP 80 MCFD, 6 BOPD



Oil production from well confirmed by operator.
Cum: 4,066 BO

(Production data supplied by Petroleum Information/Dwights LLC dba IHS Energy Group, © 2014)

Conclusions

Vitrinite reflectance values <0.5% Ro may have errors because (1) pre-oil solid bitumen may be mistaken for vitrinite and (2) this is the level that vitrinite forms from huminite.

Oil production ranges from thermal maturities of ~0.59-1.18% Ro in the Anadarko, Ardmore, and Arkoma Basins and shelf areas (dependent on oil saturation).

Condensate production ranges from thermal maturities of ~1.15-1.67% Ro in the Anadarko, Ardmore, and Arkoma Basins.

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