Woodford Oil Congress 2014 January 29, 2013

Determining the Thermal Maturity Level at Which Oil Can Be Economically Produced in the Woodford Shale

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Outline of Presentation

- Brief Introduction to Vitrinite Reflectance as a Thermal Maturity Indicator
- Basic Parameters Needed for Shale Resource Plays
- Evaluation of Woodford Shale as a Liquid Hydrocarbon Reservoir

Modified from 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

Answer the following questions

- What is vitrinite?
- What is vitrinite reflectance?
- How is vitrinite reflectance measured?
- What are some sources of error?
- How do you tell good data from bad data?

Organic Matter Classifications

Coal Petrographers [reflected light]

Petroleum Geochemists [bulk geochemistry]

MACERAL GROUP (Teichmuller and Ottenjann)	PHYTOCLAST (Bostick)	PHYTOCLAST GROUP (Massoud and Kinghorn)	KEROGEN TYPE (Tissot and Welte; Harwood)	PALYNOLOGICAL KEROGEN (Hunt)
Liptinite (Exinite)	Algal bodies	Keroginite	I	Algal
	Floccules and Groundmass			Amorphous
	Liptinite	Liptinite	II	Herbaceous
Vitrinite	Low-gray Vitrinite	Vitrinite	III	Woody
Inertinite	High-gray Vitrinite and Fusinite	Inertinite	IV	Coaly

Taylor and others, 1998, p. 242-243

MACERAL

(from Latin: “macerare”, to soften)

Stopes, 1935

“Macerals are organic substances, or optically homogeneous aggregates of organic substances, possessing distinctive physical and chemical properties, and occurring naturally in the sedimentary, metamorphic, and igneous materials of the earth”

Spackman, 1958

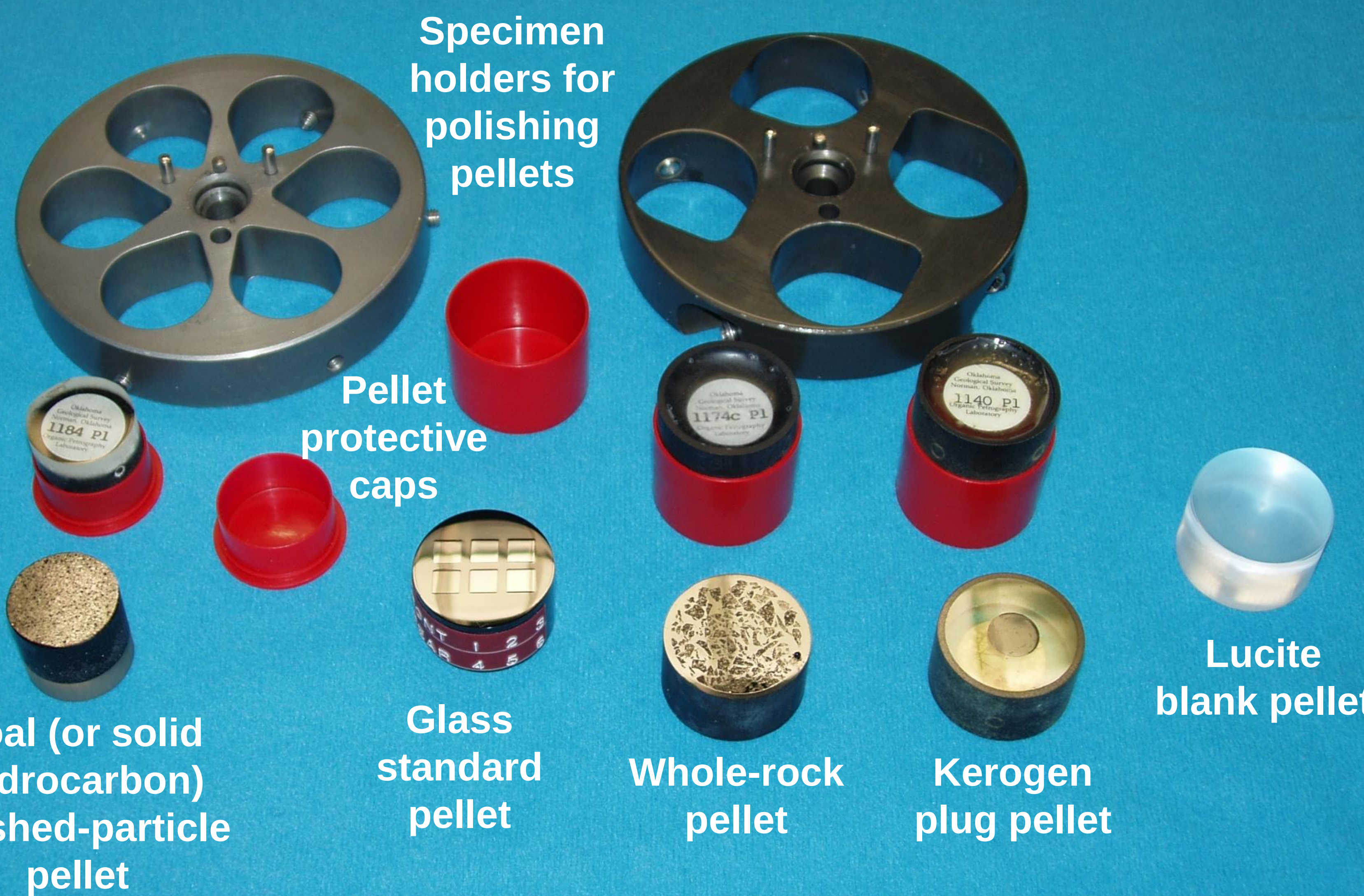
Microscopic Organic Composition (Maceral Classification)

MACERAL GROUP	ORIGIN	REFLECTANCE
VITRINITE	Cell wall material or woody tissue of plants.	Intermediate
LIPTINITE (EXINITE)	Waxy and resinous parts of plants (spores, cuticles, wound resin)	Lowest
INERTINITE	Plant material strongly altered and degraded in the peat stage of coal formation.	Highest

Crelling and Dutcher, 1980

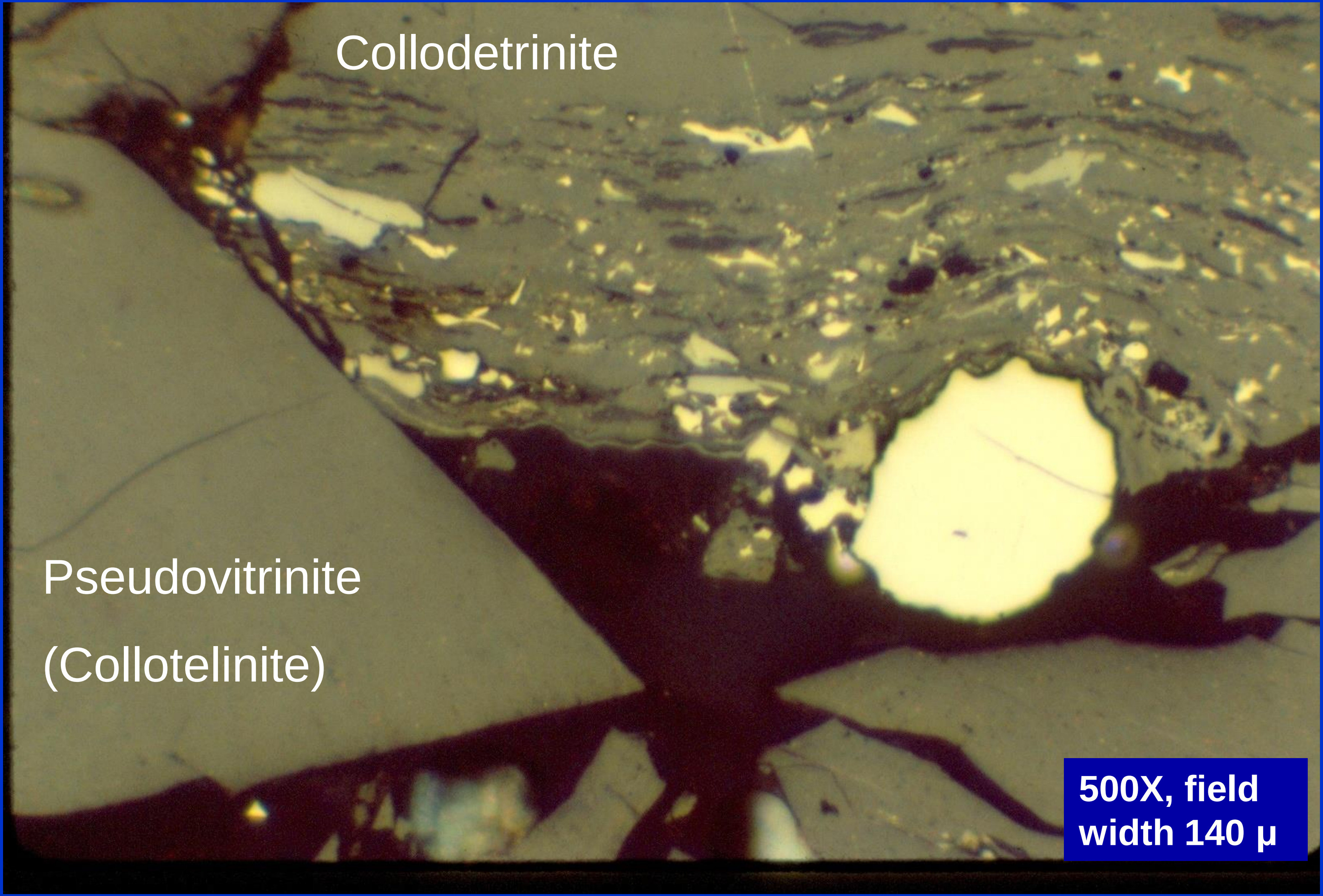
Vitrinite occurs in post Silurian- age rocks

Pellets are prepared and polished prior to the vitrinite reflectance analysis



Reflecting Light Microscope System

Coal in Reflected White Light



Vitrinite Reflectance (%Ro) is a measurement of the percentage of light reflected off the vitrinite maceral at 500X magnification in oil immersion

ASTM, 2011

Designation: D7708 – 11

Detailed procedure of reflectance analysis

Standard Test Method for Microscopical Determination of the Reflectance of Vitrinite Dispersed in Sedimentary Rocks[1]

This standard is issued under the fixed designation D7708; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the microscopical determination of the reflectance measured in oil of polished surfaces of vitrinite dispersed in sedimentary rocks. This test method can also be used to determine the reflectance of macerals other than vitrinite dispersed in sedimentary rocks.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D121 Terminology of Coal and Coke

D388 Classification of Coals by Rank

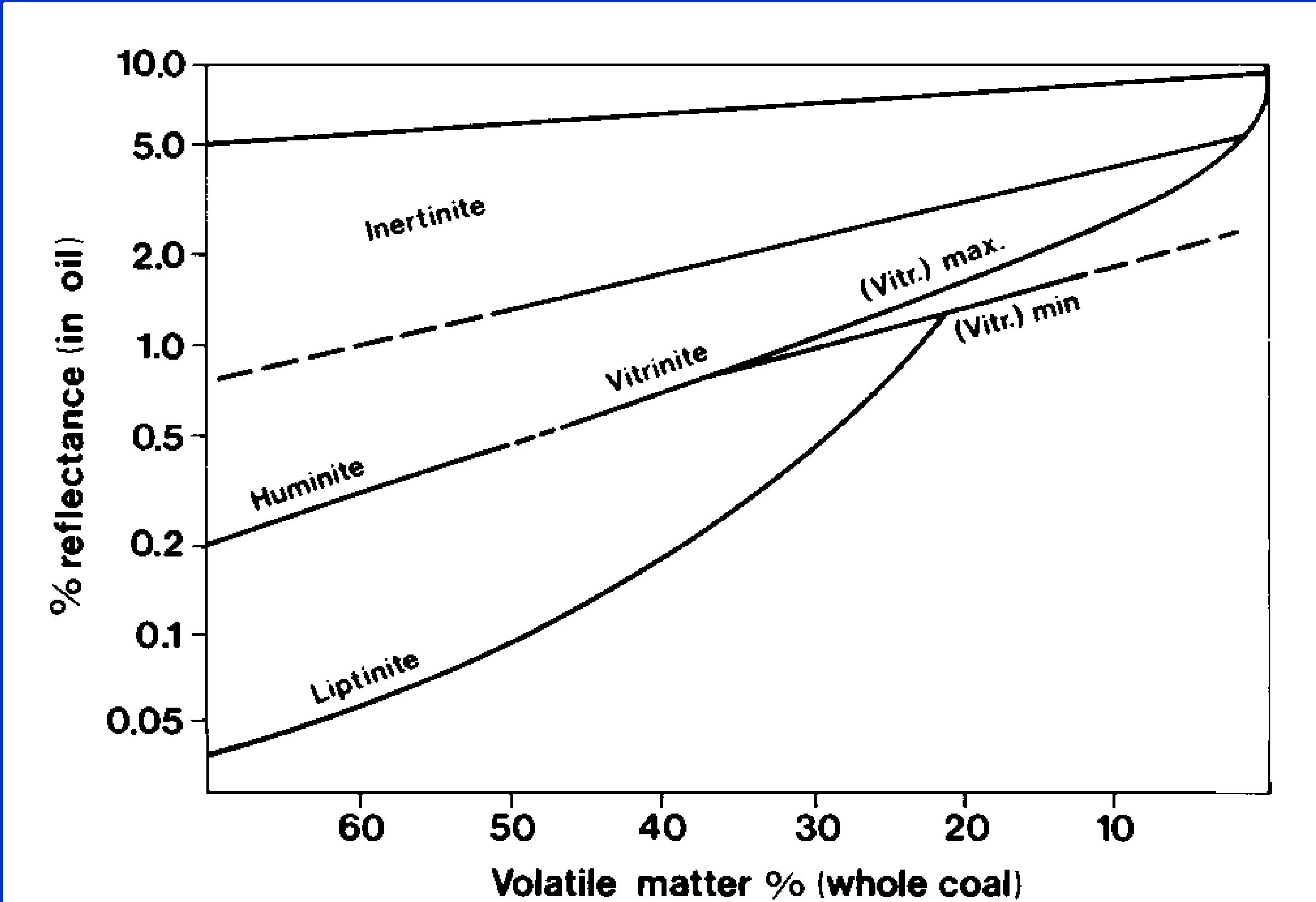
D2797 Practice for Preparing Coal Samples for Microscopical Analysis by Reflected Light

3.3.2 *bituminite, n*—an amorphous primary liptinite maceral with low reflectance, occasionally characterized by colored internal reflections and weak orange-brown fluorescence, derived from bacterial biomass and the bacterial decomposition of algal material and faunal plankton. Bituminite is equivalent to the amorphous organic matter recognized in strew slides of concentrated kerogen (**1**).[3]

3.3.2.1 *Discussion*—Bituminite may be distinguished from vitrinite by lower reflectance, as well as higher fluorescence intensity if fluorescence is present in vitrinite. Bituminite has poorly-defined wispy boundaries and may be speckled or unevenly colored whereas vitrinite has distinct boundaries and is blockier and evenly colored. The occurrence of bituminite in association with lamalginite and micrinite is common. Rock type, thermal maturity, and geologic occurrence can be used to interpret the potential presence of bituminite; for example, bituminite may be expected to occur in lacustrine or marine settings. It is less commonly present in fluvial or similar proximal depositional environments, where vitrinite may be expected to occur in greater abundance.

3.3.3 *chitinozoan, n*—a group of flask-shaped, sometimes

Coalification Curves



Alpern and Lemos de Sousa, 1970, in Tissot and Welte, 1984, p. 243.

Dispersed Vitrinite in Shale

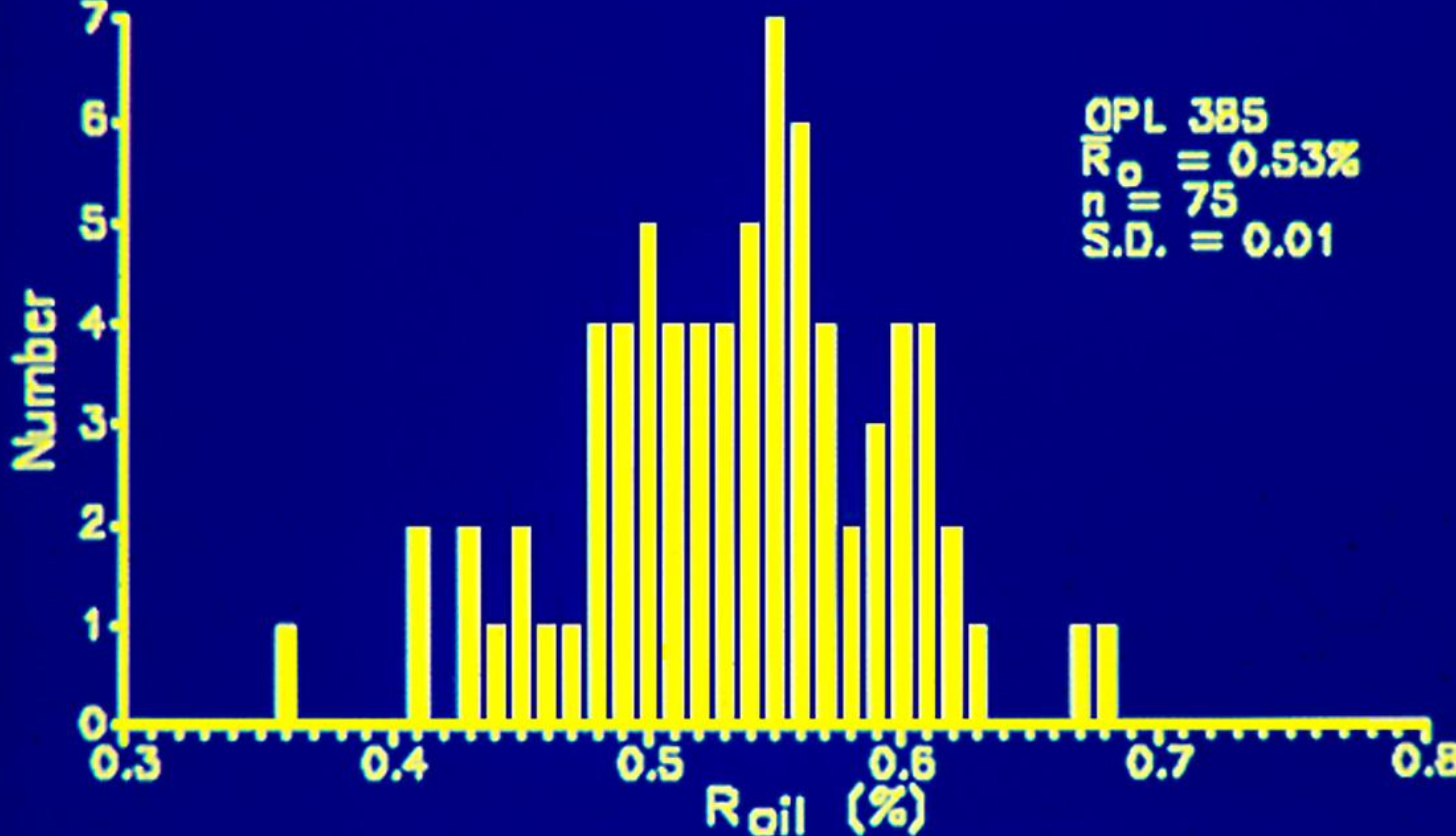
500X, field width 140 μ

PETROGRAPHER	VRo	SAMPLE IDENTIFICATION
DATE	[mean____________] nonpolarized light	PELLET NUMBER

V		PV	V		PV	V		PV	V		PV	V		PV
	0.30			0.60			0.90			1.20			1.50	
	0.31			0.61			0.91			1.21			1.51	
	0.32			0.62			0.92			1.22			1.52	
	0.33			0.63			0.93			1.23			1.53	
	0.34			0.64			0.94			1.24			1.54	
	0.35			0.65			0.95			1.25			1.55	
	0.36			[illegible]			[illegible]			[illegible]			1.56	
	0.37			[illegible]			[illegible]			[illegible]			1.57	
	0.38			[illegible]			[illegible]			[illegible]			1.58	
	0.39			0.69			0.99			1.29			1.59	
	0.40			0.70			1.00			1.30			1.60	
	0.41			0.71			1.01			1.31			1.61	
	0.42			0.72			1.02			1.32			1.62	
	0.43			0.73			1.03			1.33			1.63	
	0.44			0.74			1.04			1.34			1.64	
	0.45			0.75			1.05			1.35			1.65	
	0.46			0.76			1.06			1.36			1.66	
	0.47			0.77			1.07			1.37			1.67	
	0.48			0.78			1.08			1.38			1.68	
	0.49			0.79			1.09			1.39			1.69	
	0.50			0.80			1.10			1.40			1.70	
	0.51			0.81			1.11			1.41			1.71	
	0.52			0.82			1.12			1.42			1.72	
	0.53			0.83			1.13			1.43			1.73	
	0.54			0.84			1.14			1.44			1.74	
	0.55			0.85			1.15			1.45			1.75	
	0.56			0.86			1.16			1.46			1.76	
	0.57			0.87			1.17			1.47			1.77	

Precision to 0.01%

<u>Random</u> Vitrinite Reflectance of Woodford Shale from Arbuckle Mountains



Vitrinite-like organic matter

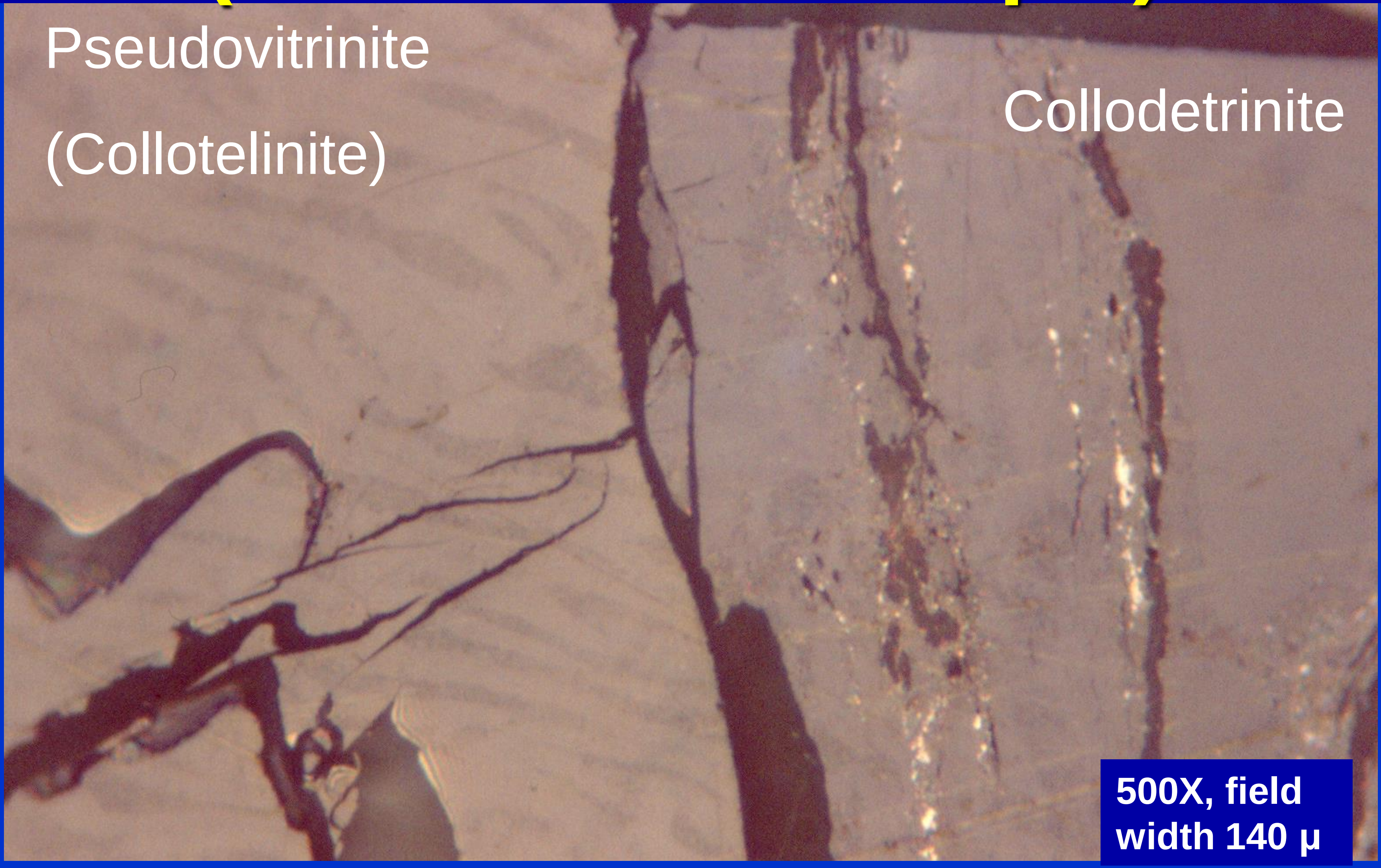
Vitrinite subtypes

Inertinite macerals

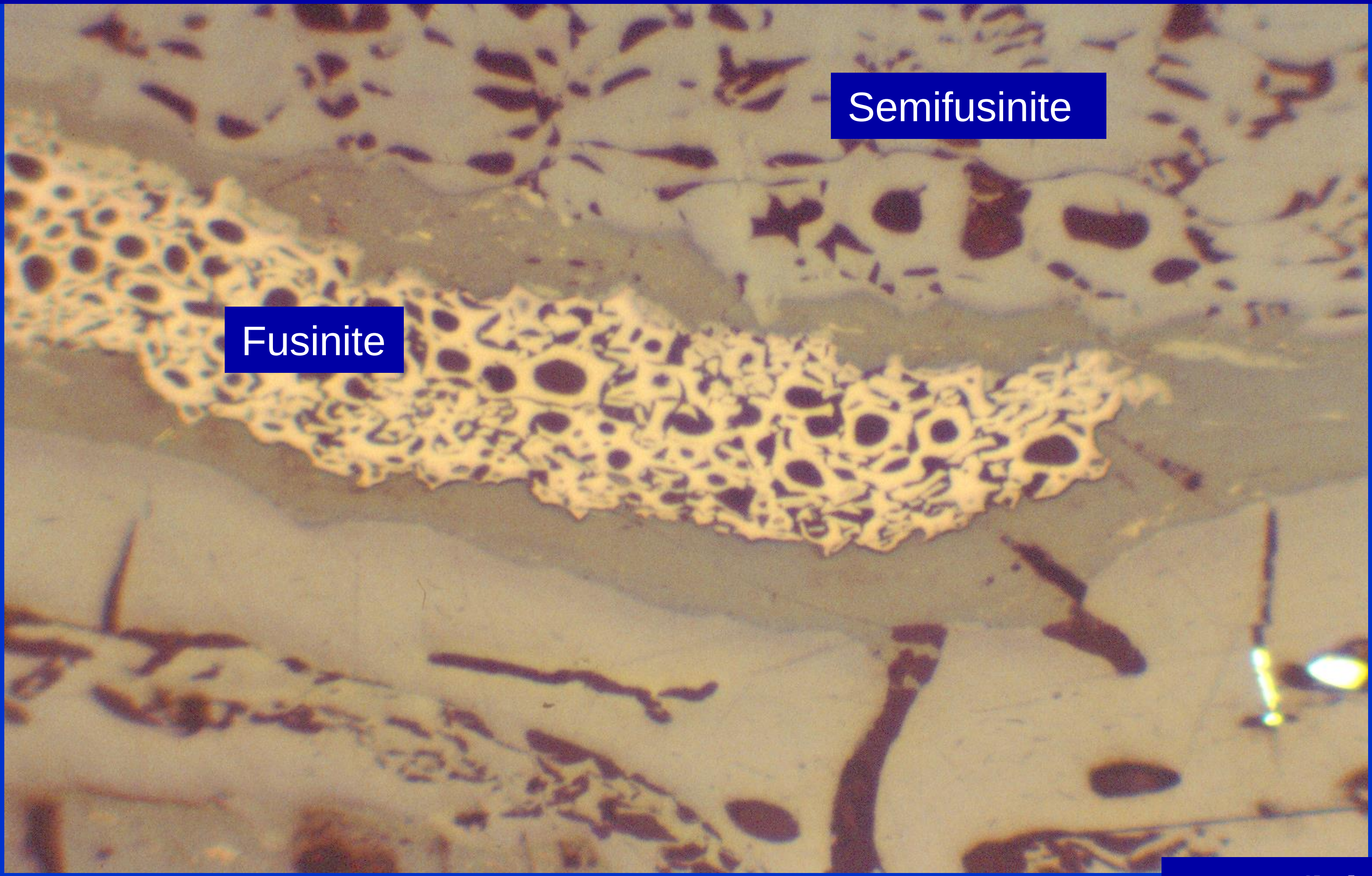
Solid bitumen (several types)

Graptolites

Vitrinite Subtypes (in same coal sample)



Inertinite Macerals



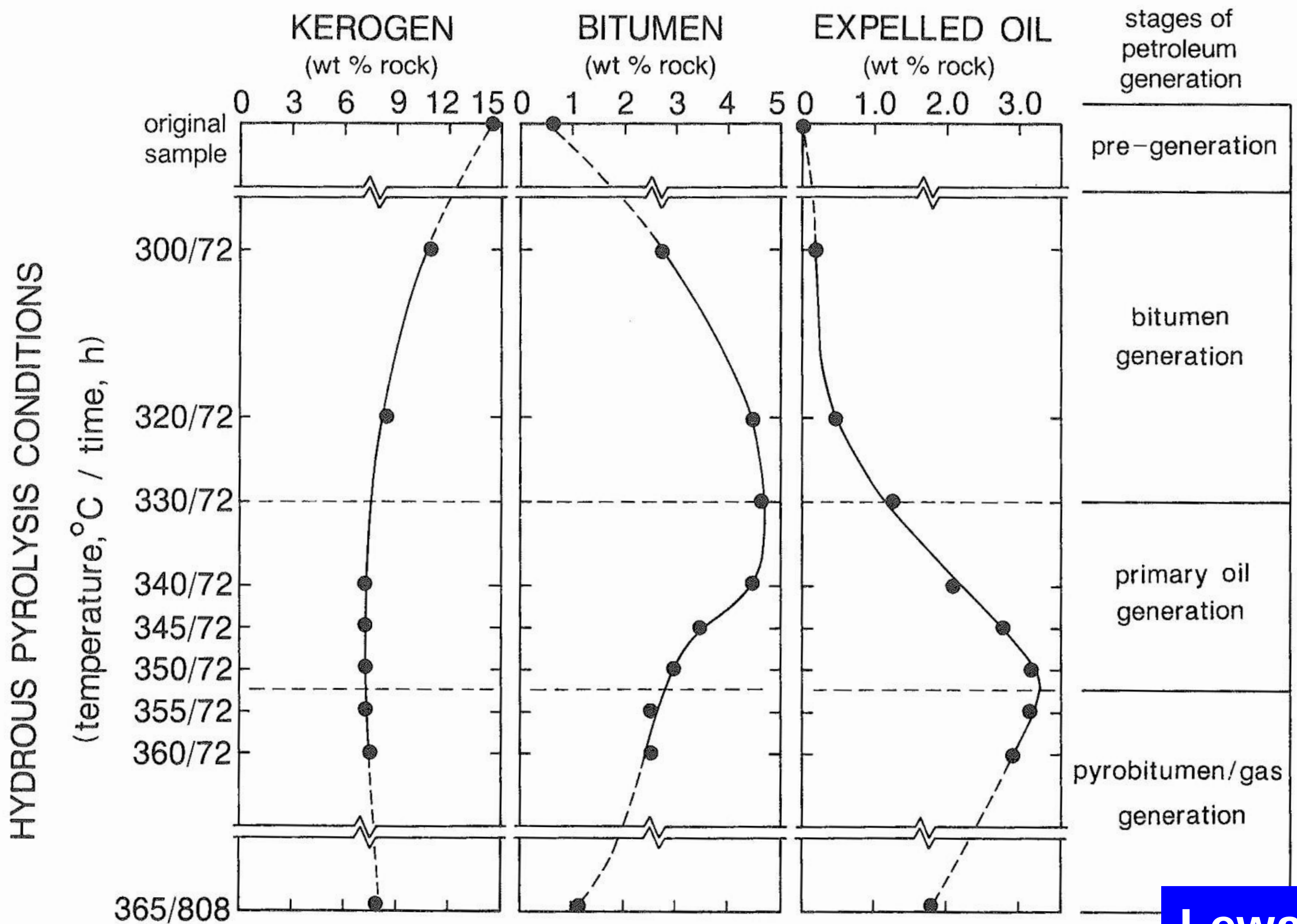
200X, field width 320 μ

Genetic Solid Bitumen Classification

- **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)]
- **Post-Oil Solid Bitumen**: products of the alteration of a once-liquid crude oil, generated and migrated from a conventional oil source rock, and subsequently degraded. [includes vein deposits and solid residue of primary oil migration]

Curiale (1986)

Pre-Oil Solid Bitumen Generation from Kerogen

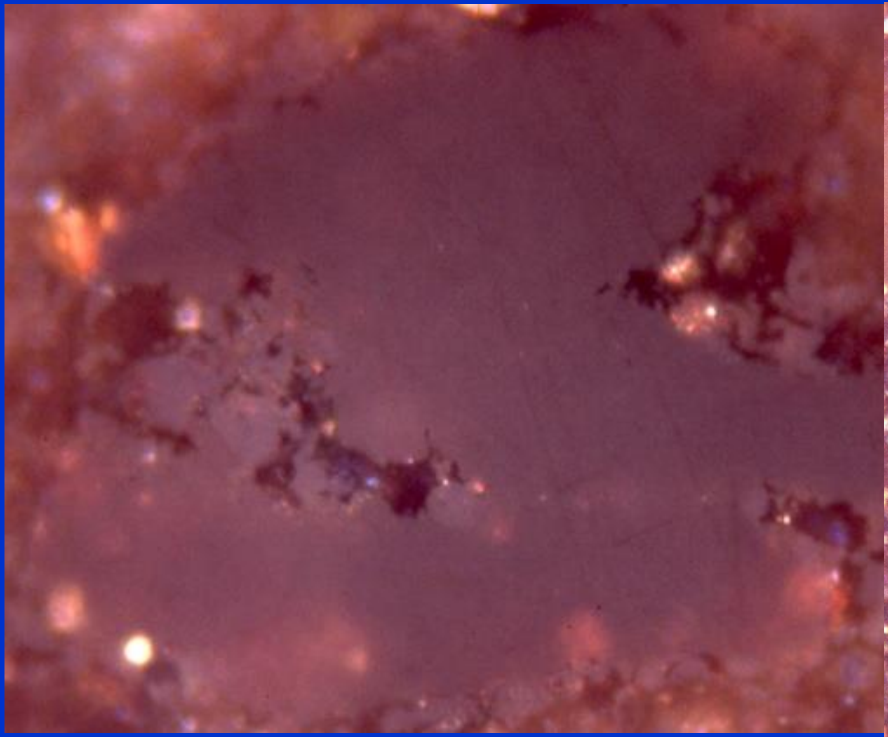


Lewan, 1994

Figure 11.1. Amounts of kerogen, bitumen, and expelled oil collected after conducting isothermal hydrous pyrolysis experiments on aliquots of a Woodford Shale sample (WD-5) at temperatures ranging from 300° to 360°C for 72 hr, and at 365°C for 808 hr. Each experiment consists of heating 500 g of a separate aliquot of the original sample with 260 g of distilled water in a 1-L reactor at the temperature and time specified along the vertical axis. The bitumen generation stage represents the partial decomposition of kerogen to bitumen through the cleavage of weak noncovalent bonds. The primary oil generation stage represents the partial decomposition of bitumen to an immiscible expelled oil through cleavage of covalent bonds. The pyrobitumen/gas generation stage represents the decomposition of expelled oil and bitumen to insoluble organic matter (pyrobitumen) and gas.

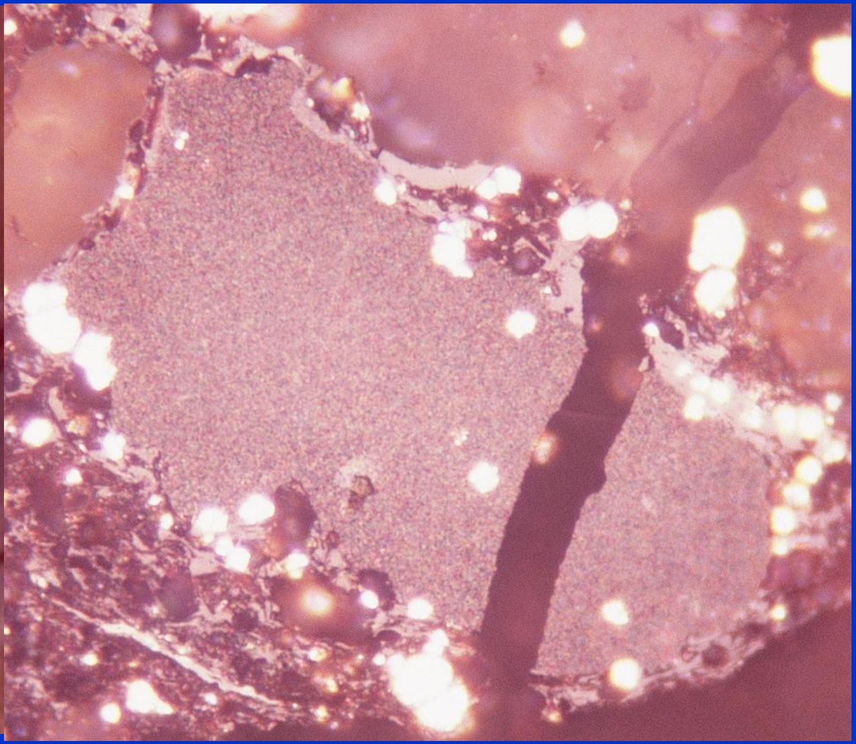
Two Common Pre-Oil Bitumen Optical Forms Based on Landis and Castaño (1994)
[regression equation is based on homogenous form]

Homogenous form



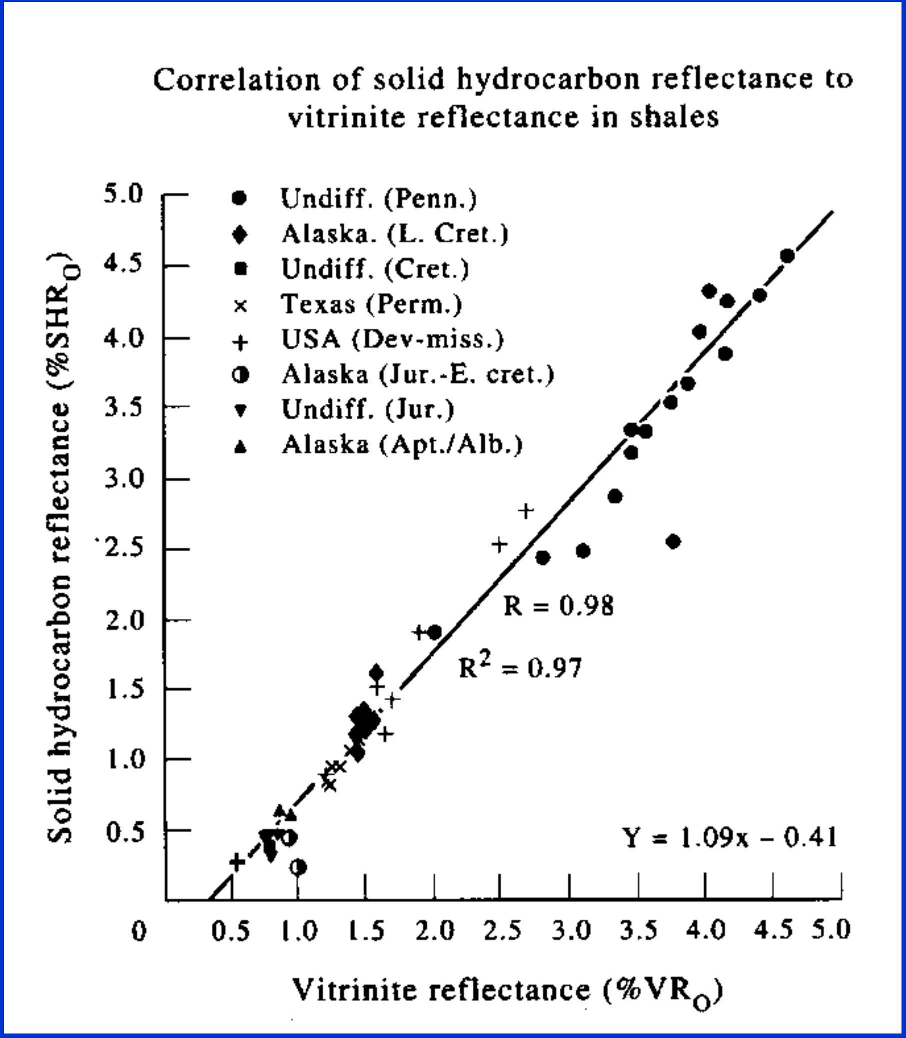
OPL 1333 500X

Granular form



OPL 1076 500X

Use of pre-oil solid bitumen as thermal maturity indicator following "solid hydrocarbon" reflectance to vitrinite reflectance equivalent regression equation of Landis and Castaño (1994)



$$VRE = (BRo + 0.41)/1.09$$

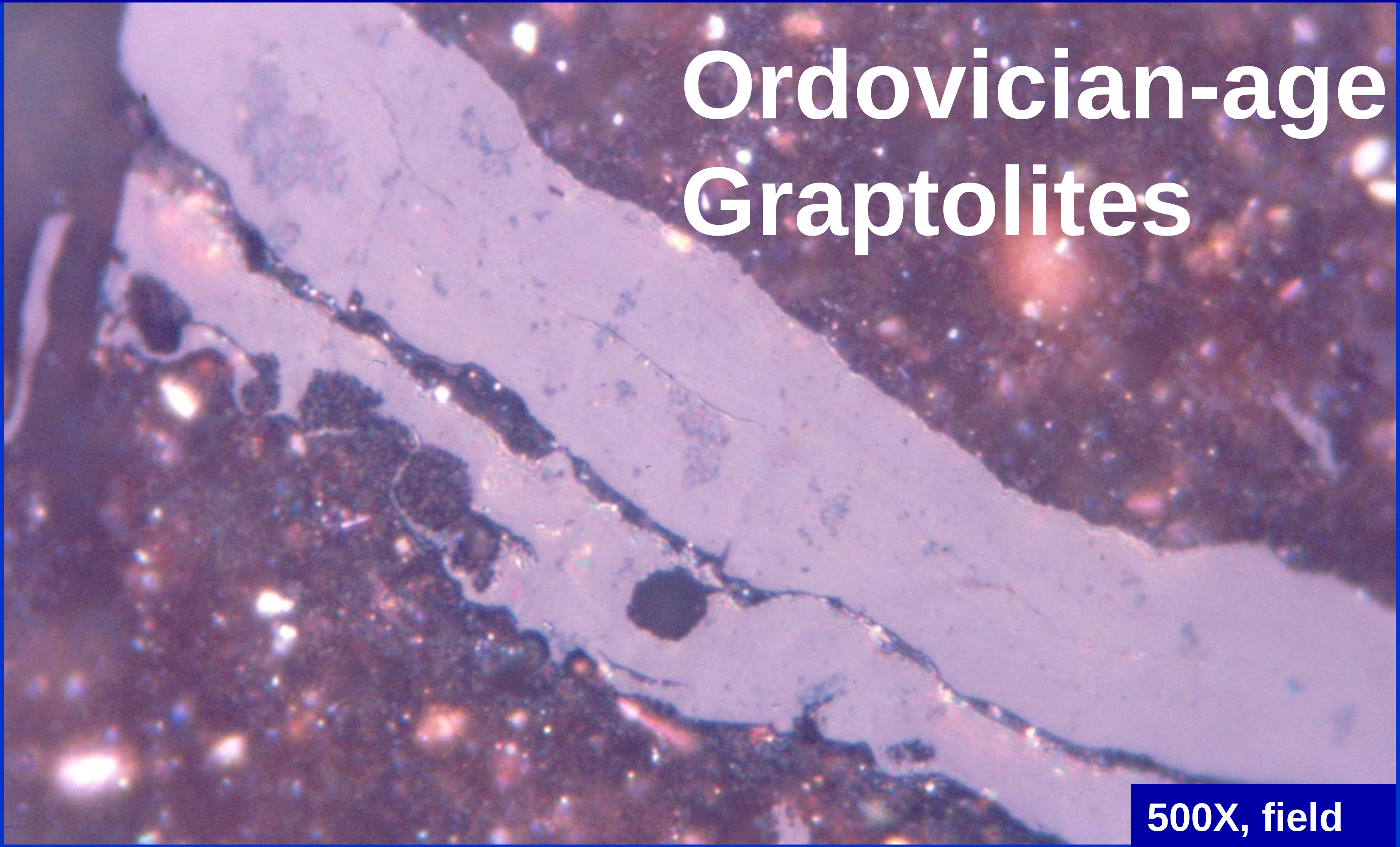
For additional references visit http://www.tsop.org/refs/bitref.htm

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 may erroneously include pre-oil solid bitumen reflectance measurements.

Hackley, P.C., R.T. Ryder, M.H. Trippi, and H. Alimi, 2013, Thermal maturity of northern Appalachian Basin Devonian shales: Insights from sterane and terpane biomarkers: Fuel, v. 106, p. 455-462.

Vitrinite-Like Organic Matter



500X, field width 140 µ

Cardott and Kidwai, 1991

VITRINITE-REFLECTANCE ANALYSIS
SOURCES OF ERROR

- Samples
- Equipment

SAMPLES

- **SAMPLE TYPE (core, outcrop, well cuttings)**
- **LITHOLOGY (coal, shale, siltstone, sandstone)**
- **SAMPLE HANDLING (oil-based drilling mud, kerogen isolation, oxidation, heating)**
- **ORGANIC MATTER (quantity, quality, size, type, thermal maturity, reflectance suppression/enhancement)**

CORE >> **OUTCROP** > **WELL CUTTINGS**

(Weathering) (Caving)

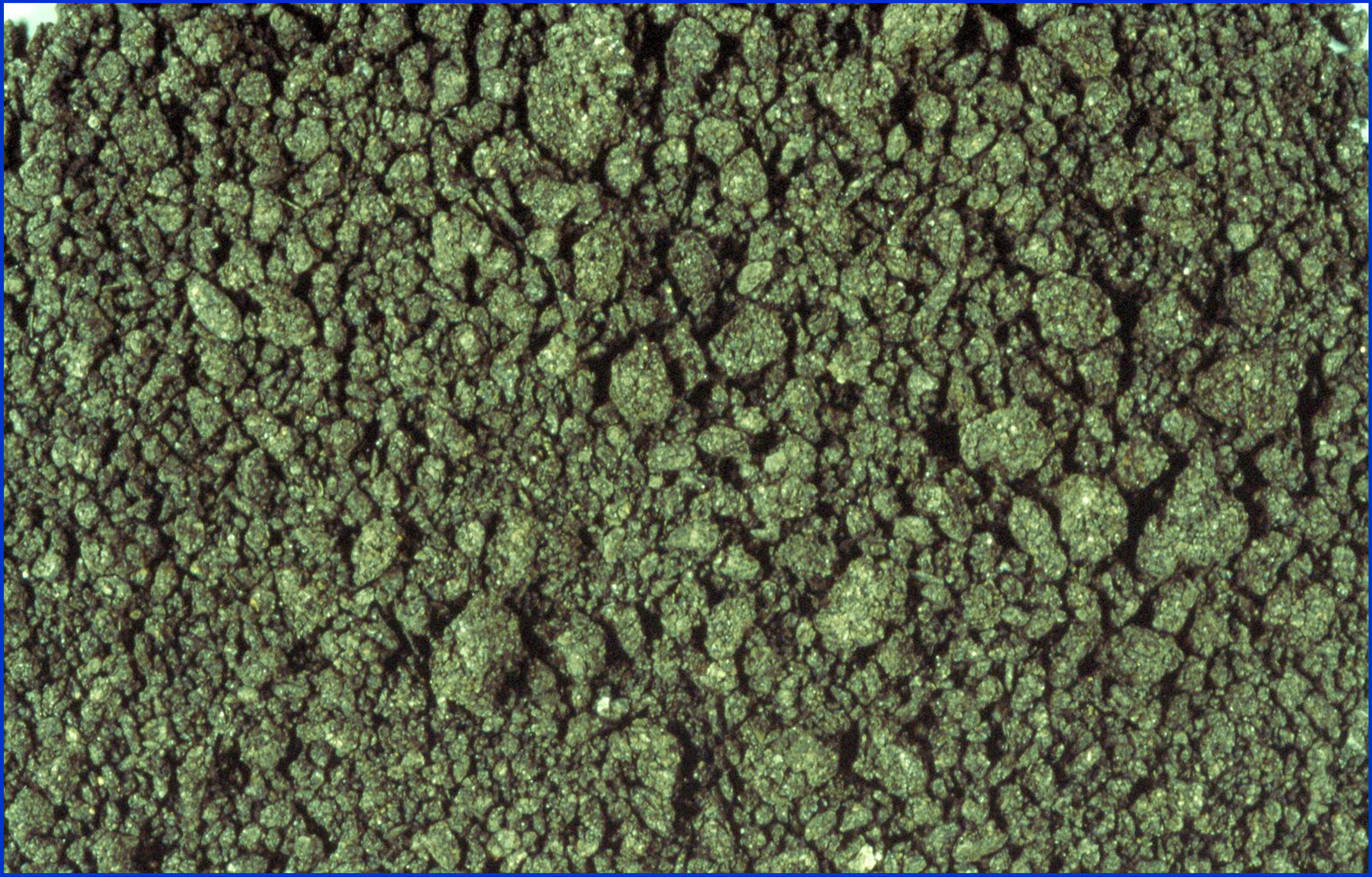
(Recycled Vitrinite)

(Vitrinite - Like Organic Matter)

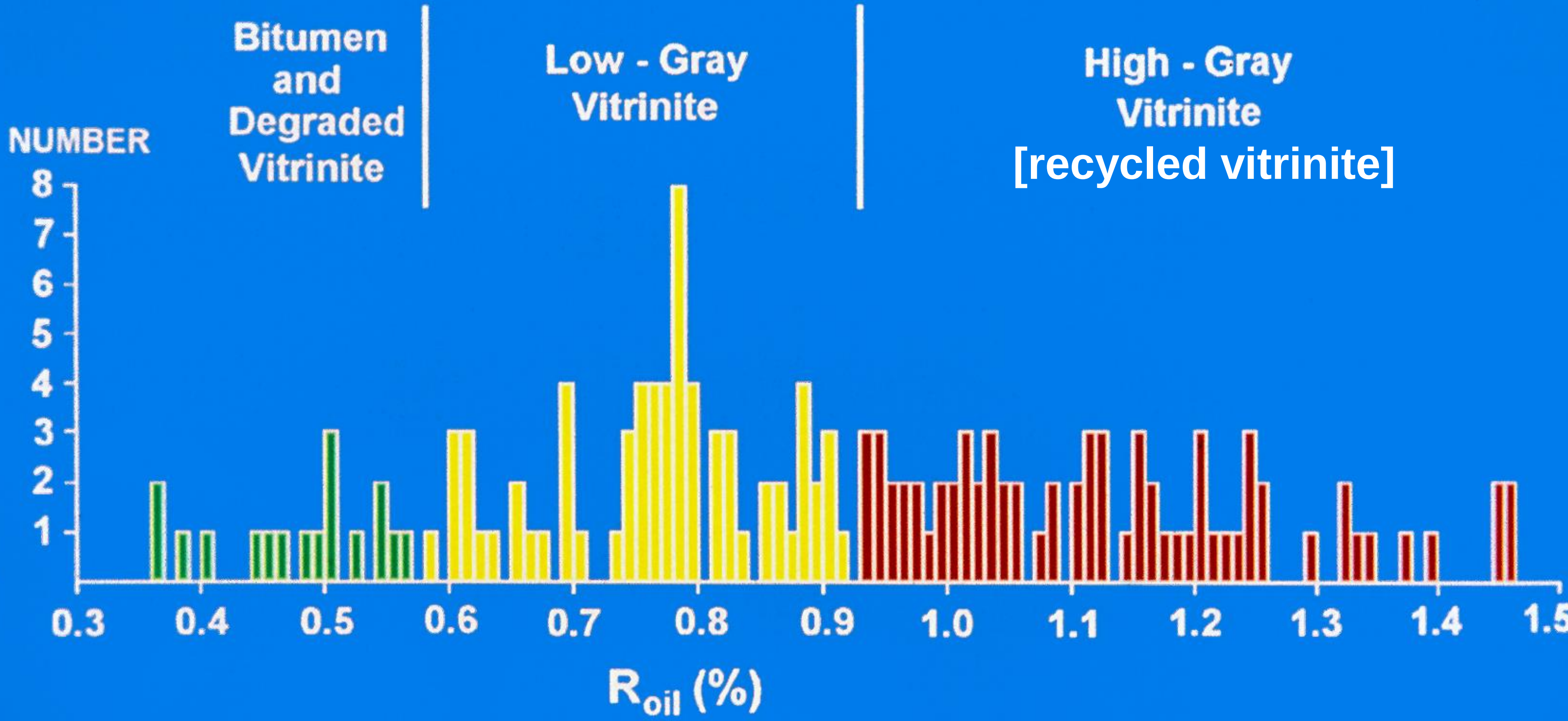

Drilling Mud
Additive

Caving Contamination

Oil-Based Mud



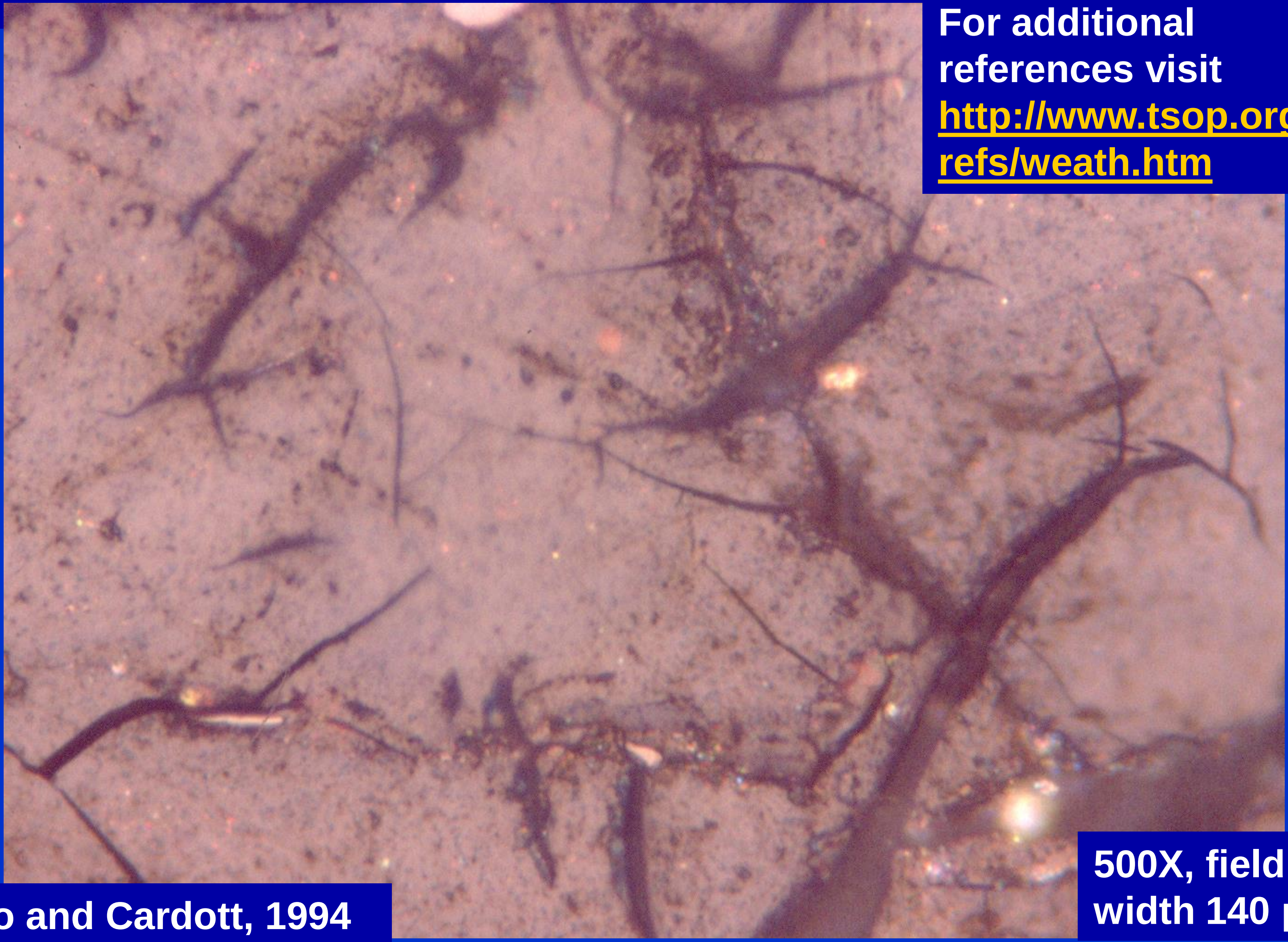
Measure and Interpret Everything



Cardott, 1994

Weathered Coal

For additional references visit http://www.tsop.org/refs/weath.htm



Lo and Cardott, 1994

500X, field width 140 µ

Weathered Shale

500X, field width 140 μ

Cardott, 1994

SAMPLES

- **SAMPLE TYPE** (core, outcrop, well cuttings)
- **LITHOLOGY** (coal, shale, siltstone, sandstone)
- **SAMPLE HANDLING** (oil-based drilling mud, kerogen isolation, oxidation, heating)
- **ORGANIC MATTER** (quantity, quality, size, type, thermal maturity, reflectance suppression/enhancement)

SAMPLES

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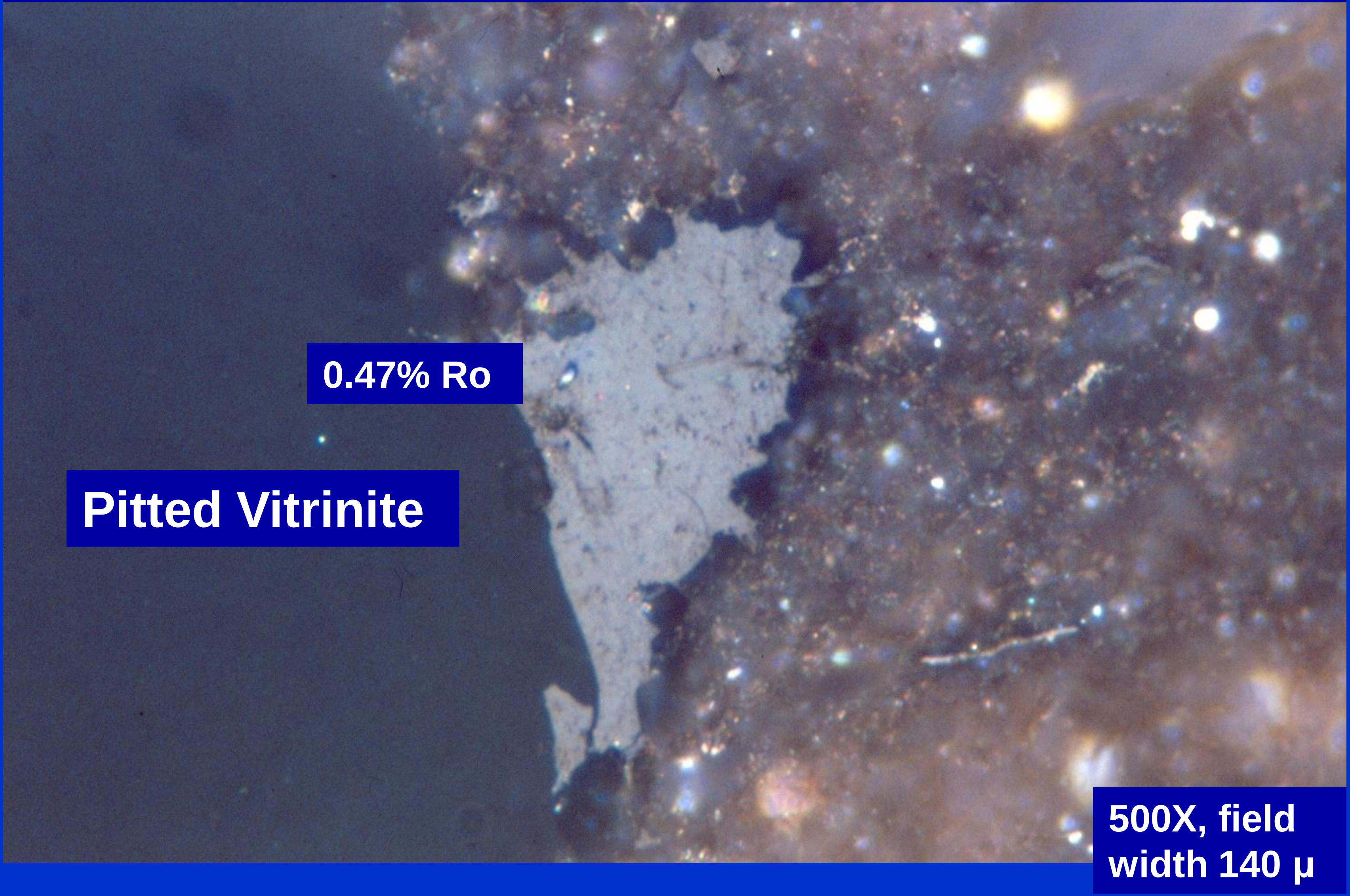
ORGANIC MATTER ERRORS

- Quantity (minimum of 20) (Barker and Pawlewicz, 1993)
- Quality (e.g., pitted vitrinite)(ICCP)
- Size (larger than measuring spot, >10 microns) [can not use powdered well cuttings]
- Type (vitrinite-like organic matter)
- Thermal maturity (anisotropy, >1% VRo)
- Reflectance suppression/enhancement (e.g., alginite; oxidizing environment)

Vitrinite Surface Quality

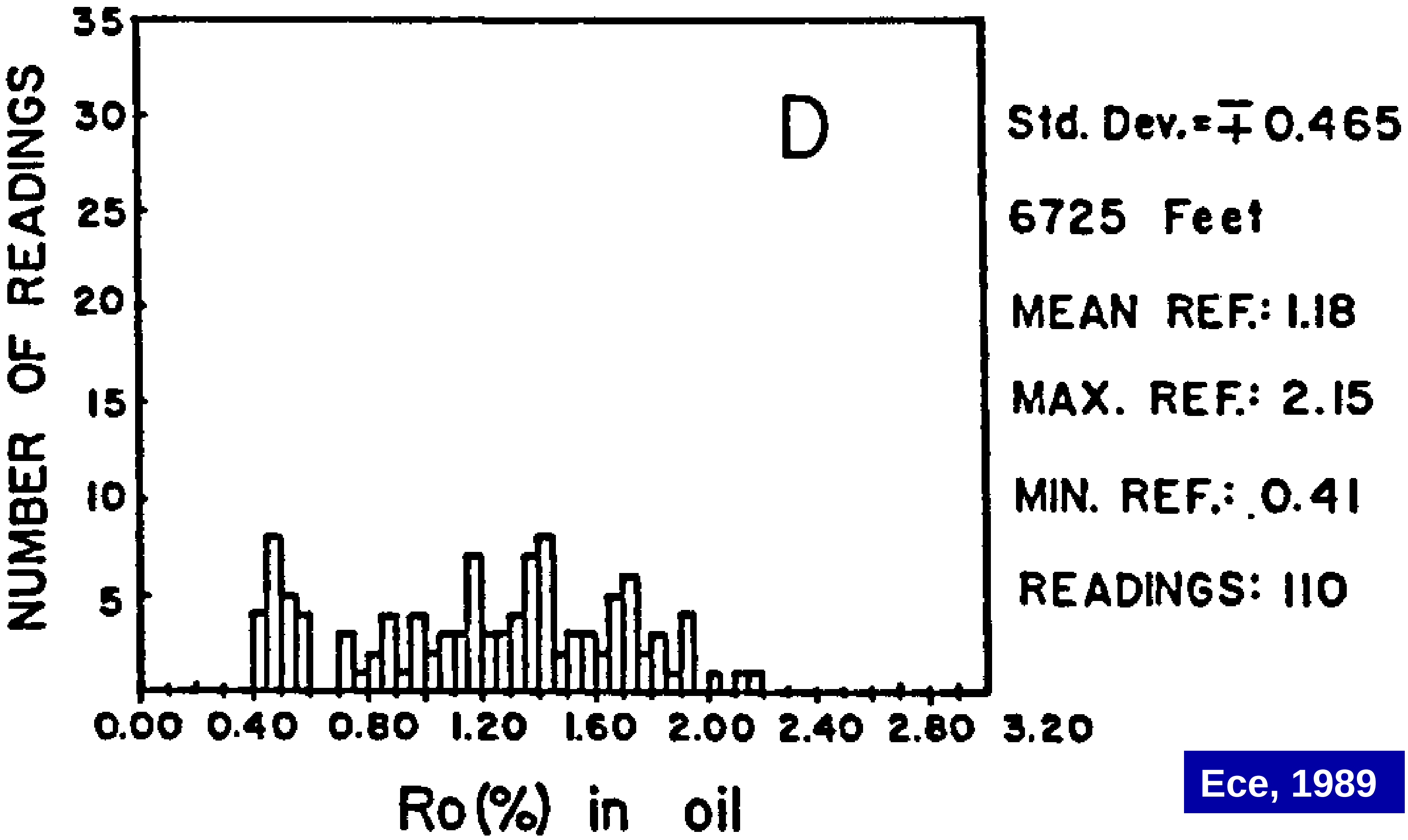


Summary of How to Tell Good Data from Bad Data

- **Number of Measurements** (minimum of 20; otherwise, qualitative)
- **Reflectance Histogram**

  (shape of distribution and spread of values)
- **Photomicrographs** (quality and size of clasts; surrounding minerals [kerogen concentrate vs. whole-rock]; correct identification of low-gray [primary] vitrinite vs high-gray [recycled] vitrinite or inertinite)

Example of Poor Interpretation from Core Sample



Ece, 1989

EQUIPMENT

- **POLISHING EQUIPMENT** (quality of polish; relief-free, scratch-free surface)
- **GLASS STANDARDS/CALIBRATION**

  (Ro range; immersion-oil contamination; air bubbles)
- **MICROSCOPE/PHOTOMETER** (quality of photometer/optics; stability to 0.01% Ro; frequency of calibration)

Importance of petrographic QUALITATIVE thermal maturity indicators to check accuracy of vitrinite-reflectance value:

- Vitrinite Reflectance Equivalent (VRE) from **bitumen** reflectance values.
- **Fluorescence** of liptinite macerals (e.g., algae): fluorescence color changes from green, greenish-yellow, yellow, orange with increasing thermal maturity before it is extinguished (0.9-1.0% VRo for Tasmanites)

SUMMARY

Vitrinite is a coal maceral derived from wood.

Vitrinite reflectance is a measurement of the percentage of light reflected from the vitrinite maceral.

Vitrinite reflectance value is an average of many measurements.

Disadvantages

Vitrinite reflectance can not tell you whether or not a rock generated oil or gas

Limitations

Post Silurian-age rocks

Dependent on sample quality, size, and contamination

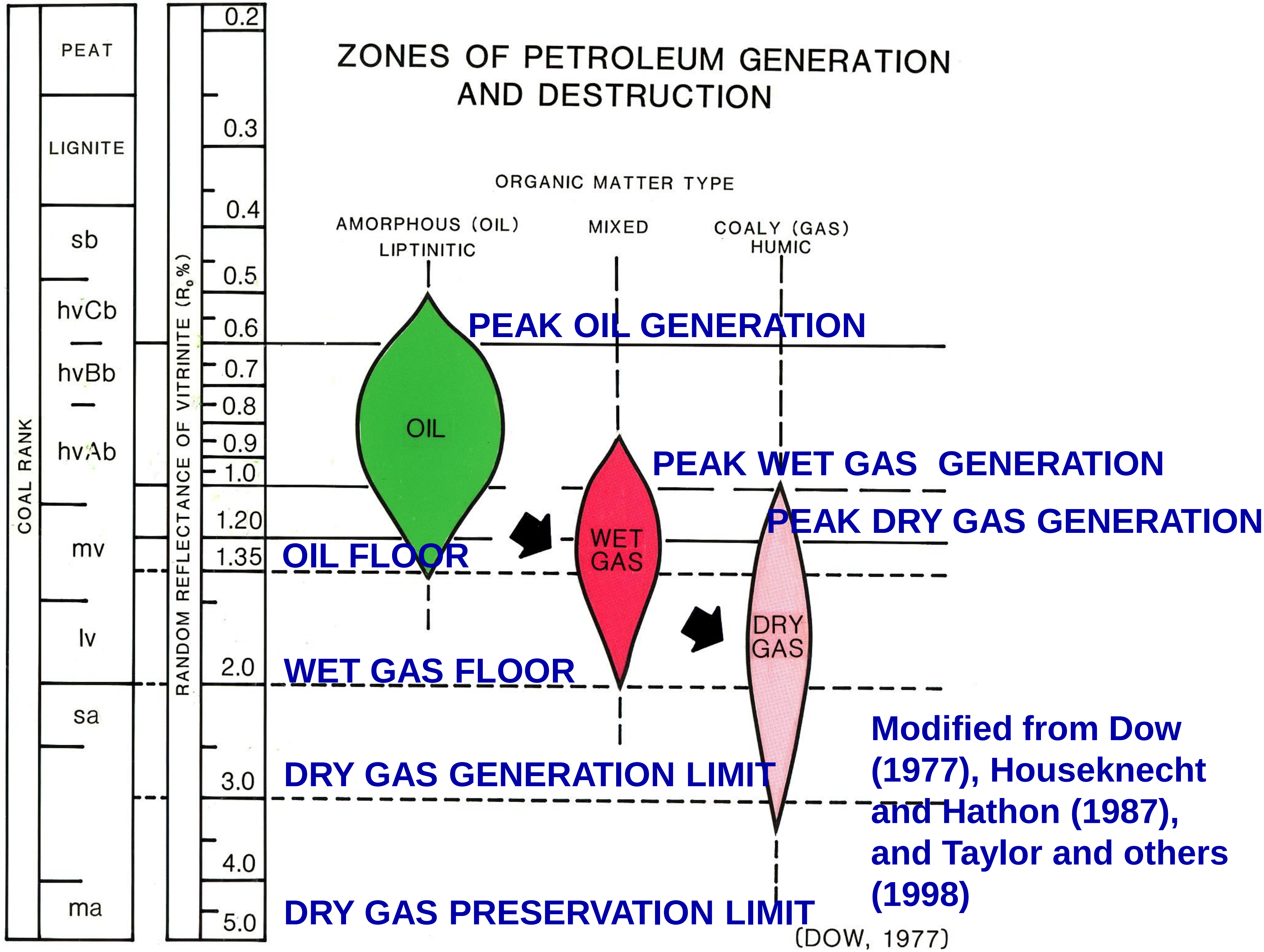
Conventional Wisdom [Non-Negotiable Parameters] Necessary for Gas Shales

- Hydrocarbon Source Rock (Hydrocarbon Generation, Storage, and Preservation)
- Brittle lithology to generate fractures (permeability) or "conventional" reservoir lithology

Hydrocarbon Generation: Organic-Rich Black Shale

- **Organic Matter Type**:

  Type II (oil generative) Kerogen
  [All gas shales have Type II Kerogen]
- **Organic Matter Quantity**: minimum of 2% TOC (depends on thermal maturity since TOC decreases with increasing thermal maturity)
- **Thermal Maturity**: oil, condensate, or dry gas windows



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
OIL
WET GAS
DRY GAS
PEAK OIL GENERATION
PEAK WET GAS GENERATION
PEAK DRY GAS GENERATION
OIL FLOOR
WET GAS FLOOR
DRY GAS GENERATION LIMIT
DRY GAS PRESERVATION LIMIT
(DOW, 1977)
Modified from Dow (1977), Houseknecht and Hathon (1987), and Taylor and others (1998)

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".

What is the lowest vitrinite reflectance for oil production?

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

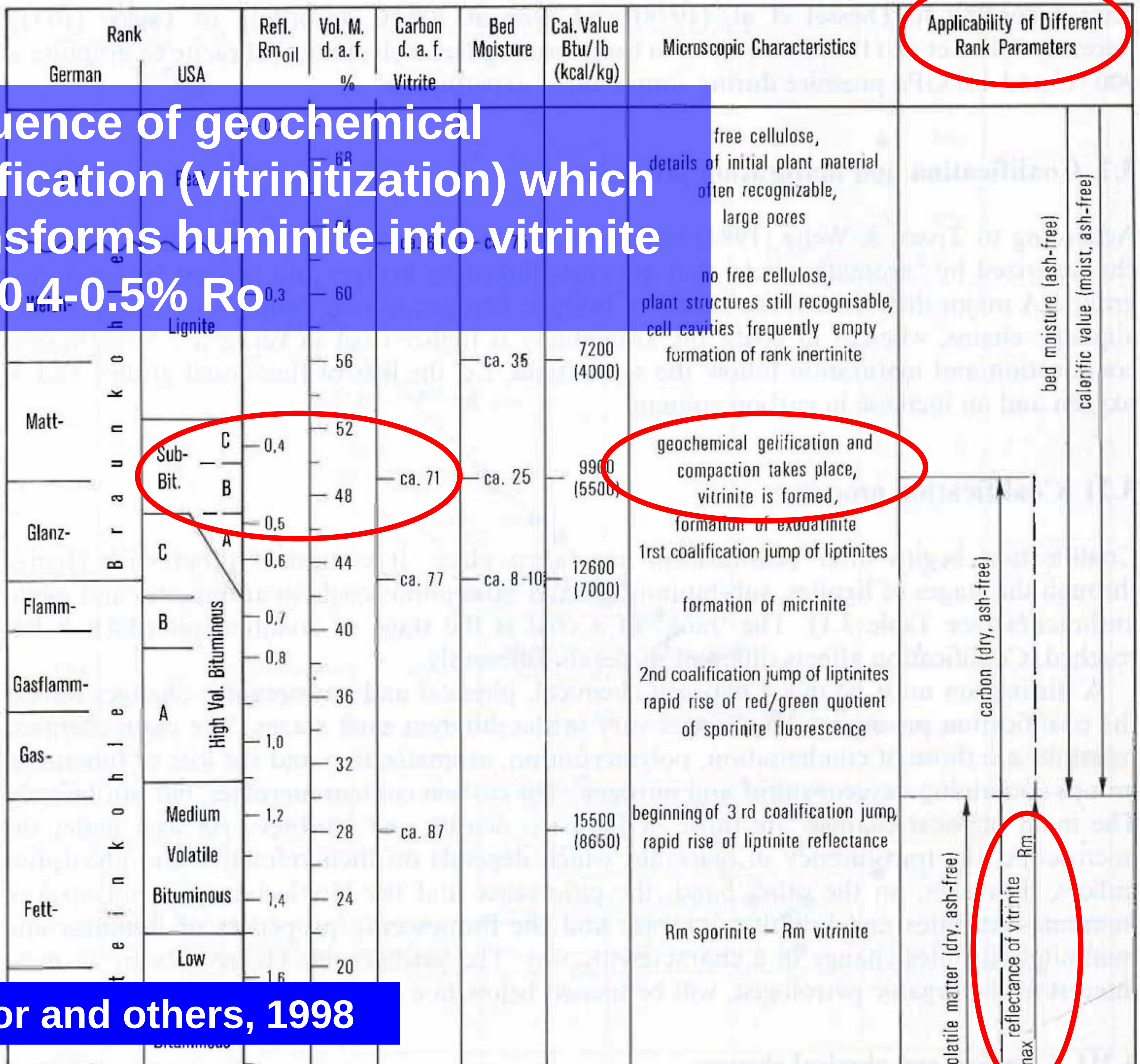
TABLE III *Oil Reflectance Limits of ASTM Coal Rank Classes*

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.

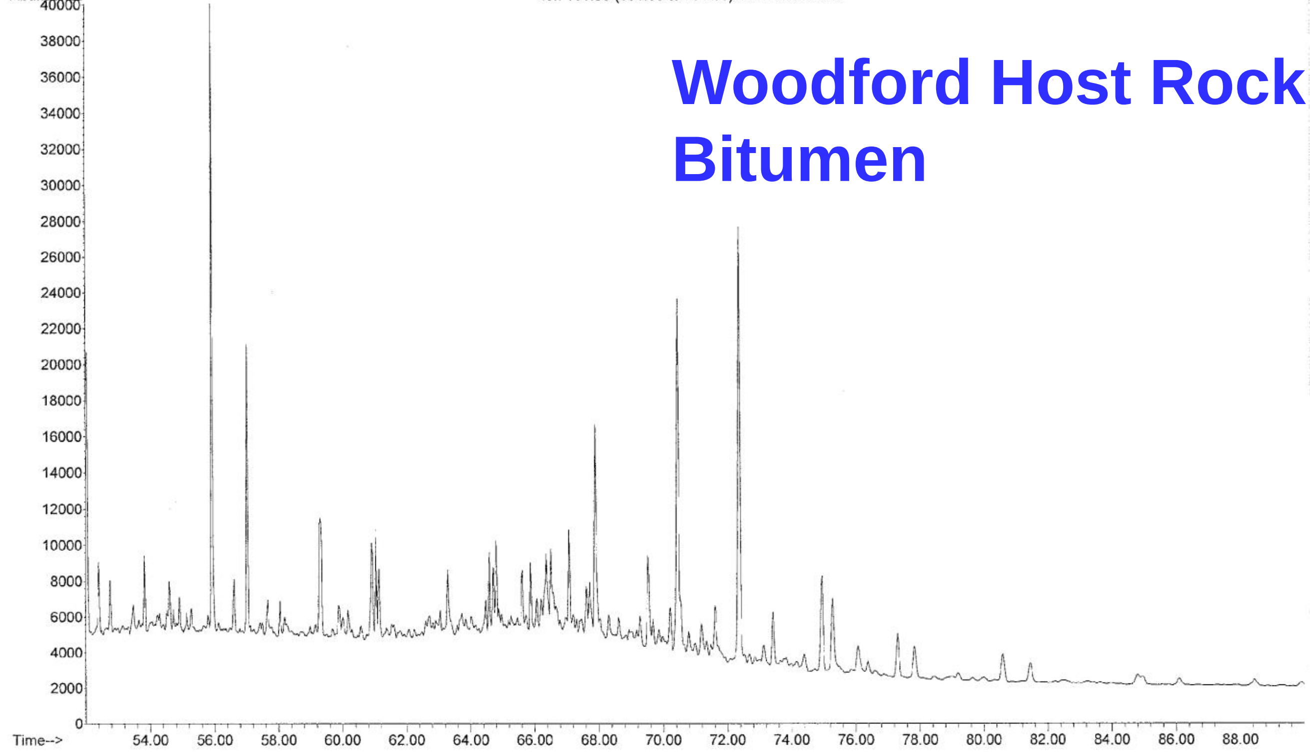
Hunt (1996, p. 368):
“the lowest value associated with the known <u>generation</u> of conventional oil is about 0.5% [Ro], and 0.6% [Ro] is generally recognized as the beginning of <u>commercial oil accumulations</u>.”

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

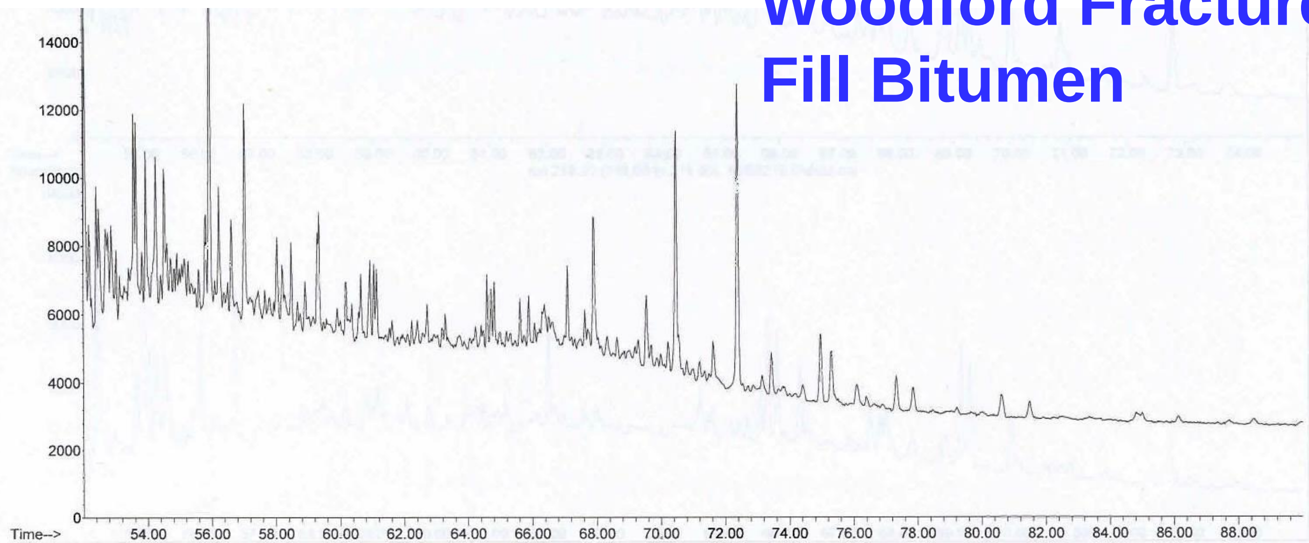
Example of “Solid hydrocarbon” filling fractures in Woodford Shale (exhumed reservoir) at the McAlister Cemetery Quarry in the Criner Hills Uplift of Southern Oklahoma
(what is the source of the “oil”?)

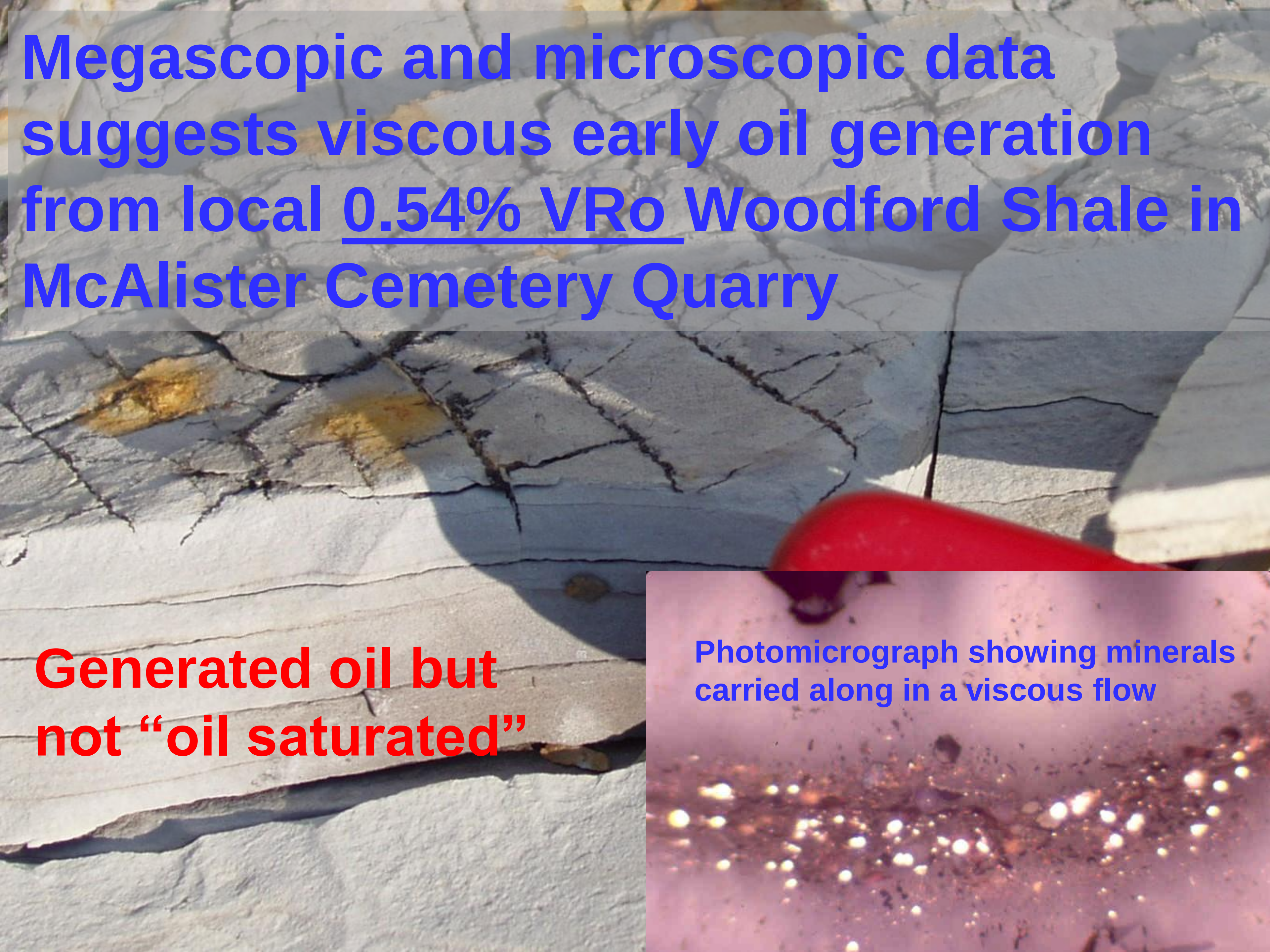
This Mass Spectrum (m/z 191 mass fragmentogram) indicates low thermal maturity “oil” from local Woodford Shale (data from Dr. R.P. Philp)

Woodford Host Rock Bitumen



Woodford Fracture Fill Bitumen



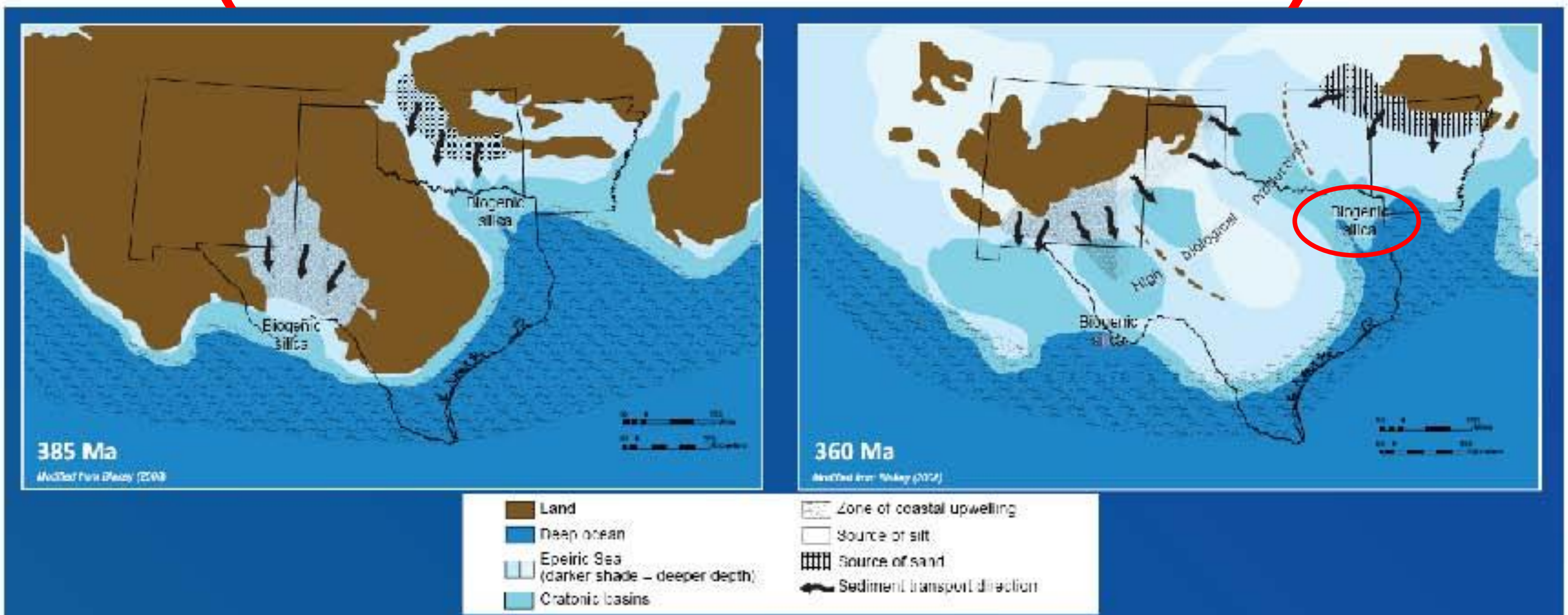

Megascopic and microscopic data suggests viscous early oil generation from local 0.54% VRo Woodford Shale in McAlister Cemetery Quarry
Generated oil but not “oil saturated”
Photomicrograph showing minerals carried along in a viscous flow

Answer two basic questions:

1. what is the source of permeability in the silica-rich Woodford Shale?
2. what thermal maturity range is optimal for liquid hydrocarbon production?

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."

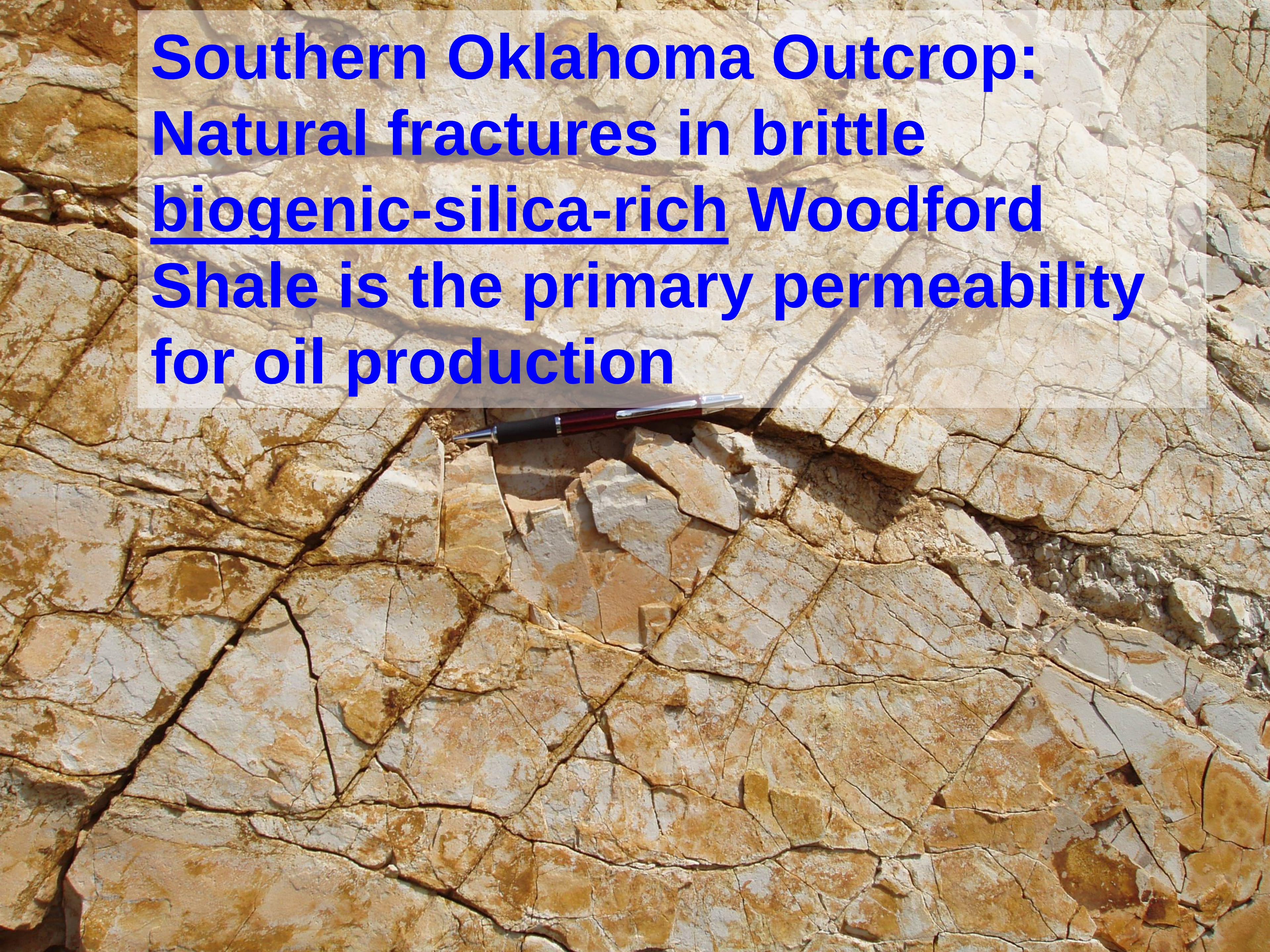
Importance of Biogenic-Silica Formation in Woodford Shale (derived from Radiolarian ooze)



Paleogeography of North America (Laurentia) at the beginning of the Late Devonian (Frasnian). Reconstructions show that Laurentia moved northward during this time and they place the Southern Midcontinent along the western or southwestern continental margin near 15° to 20° south latitude. Prior to the beginning of the Late Devonian epoch much of the Southern Midcontinent was subaerially exposed, and this extensively eroded and dissected landscape became a major regional unconformity surface. Worldwide Late Devonian marine transgression flooded the craton, creating an extensive epeiric sea that covered all but a few isolated areas during eustatic highstand. Thick accumulations of biogenic silica (Novaculite) document persistent coastal upwelling along the Late Devonian continental margin, while sand dispersed southward toward the subsiding Anadarko Basin from Ordovician sandstone exposures flanking the Ozark Uplift and silt dispersed southward from shoals and emergent parts of the Transcontinental Arch into the Delaware and Midland Basins.

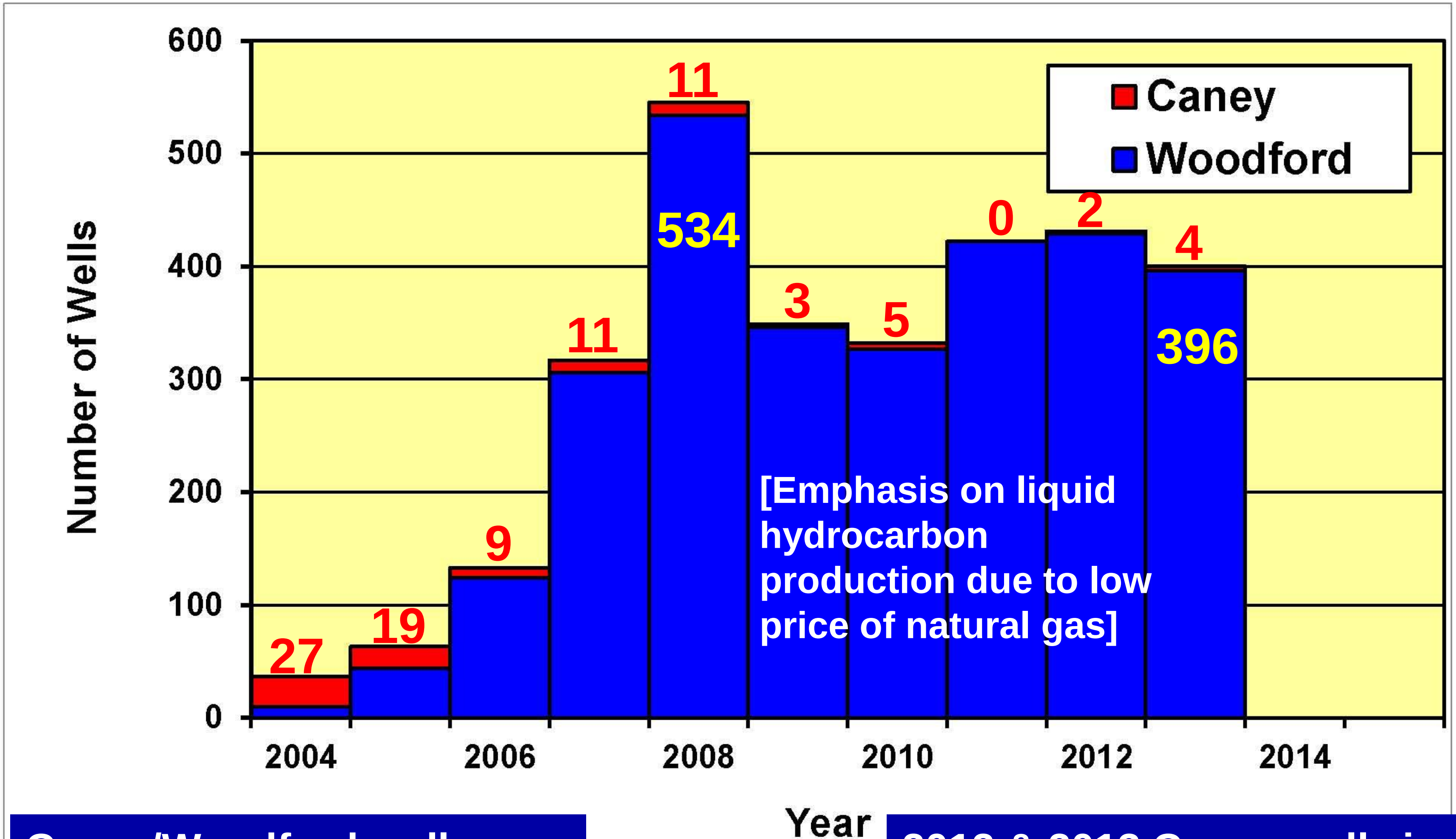
From Comer, 2008

Chattanooga Shale outcrop in northeast Oklahoma showing lack of chert beds


Southern Oklahoma Outcrop:
Natural fractures in brittle biogenic-silica-rich Woodford Shale is the primary permeability for oil production

Oklahoma Shale-Gas Well History

2,940 Woodford + 91 Caney Wells, 2004–2013



Caney/Woodford wells are included with Caney

2012 & 2013 Caney wells in Carter, Love, and Marshall Co

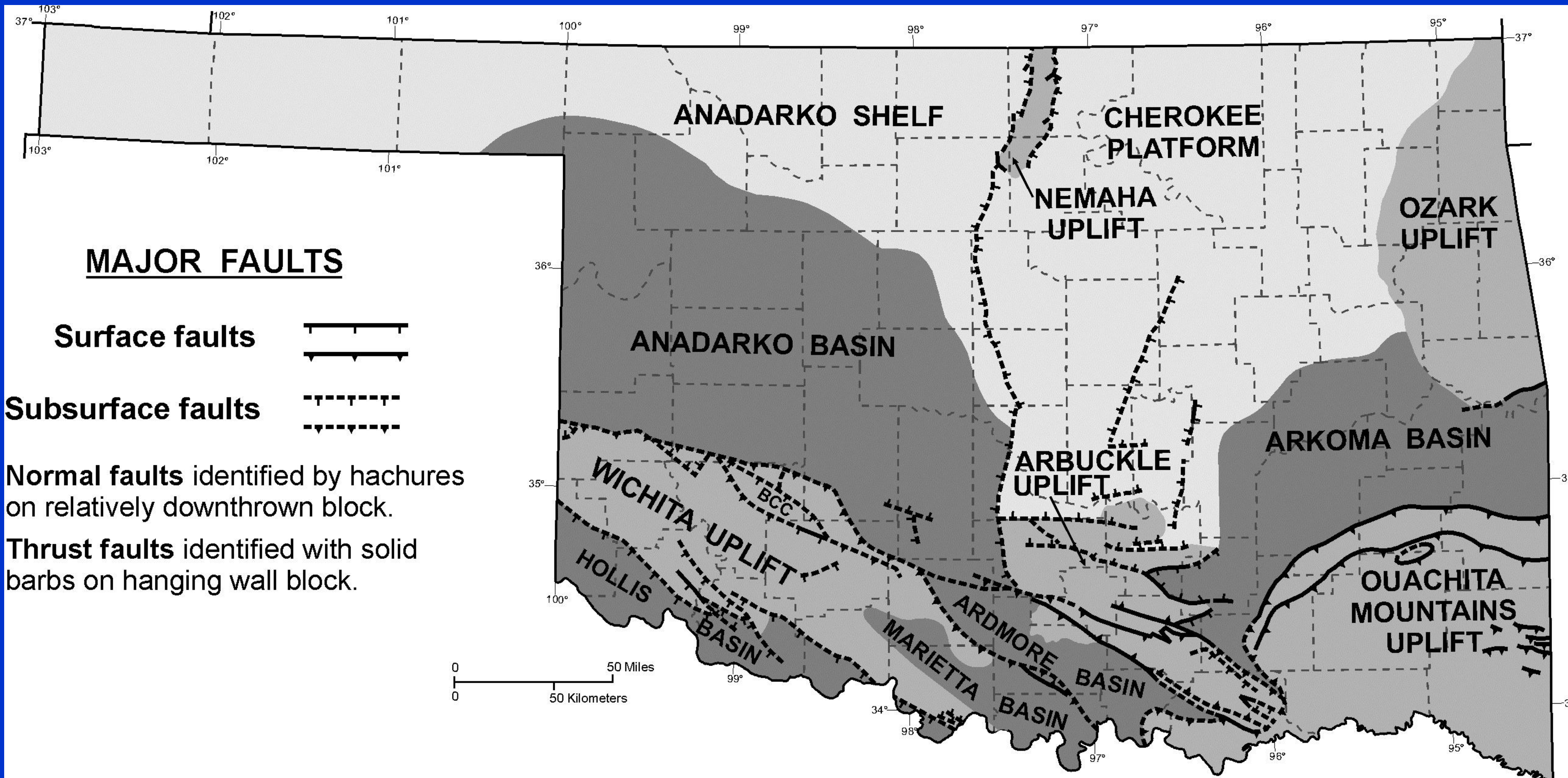
Oklahoma Oil/Condensate/Gas Production Caveat

- 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)

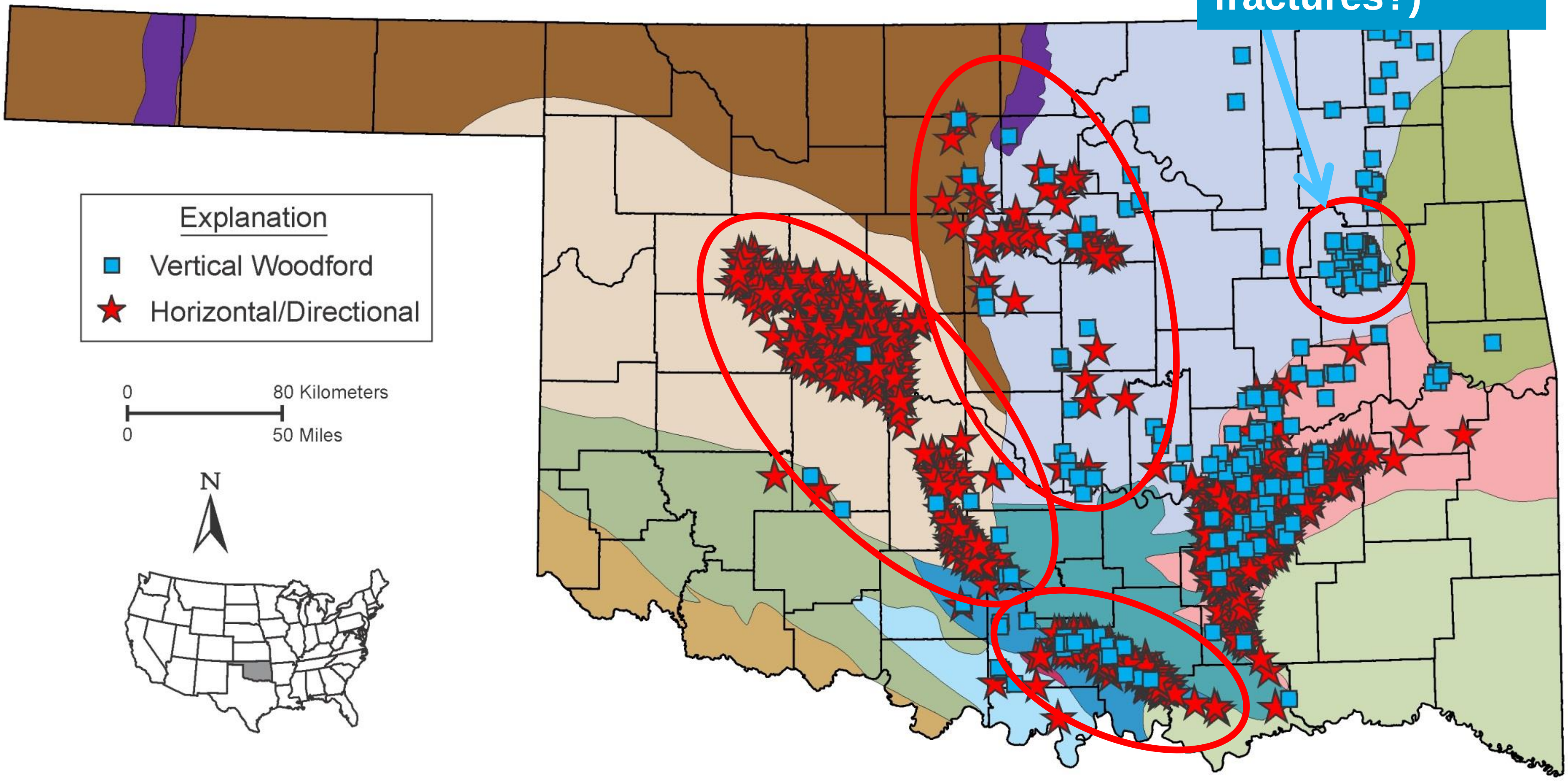
Oklahoma Geologic Provinces



Geologic provinces from Northcutt and Campbell, 1995

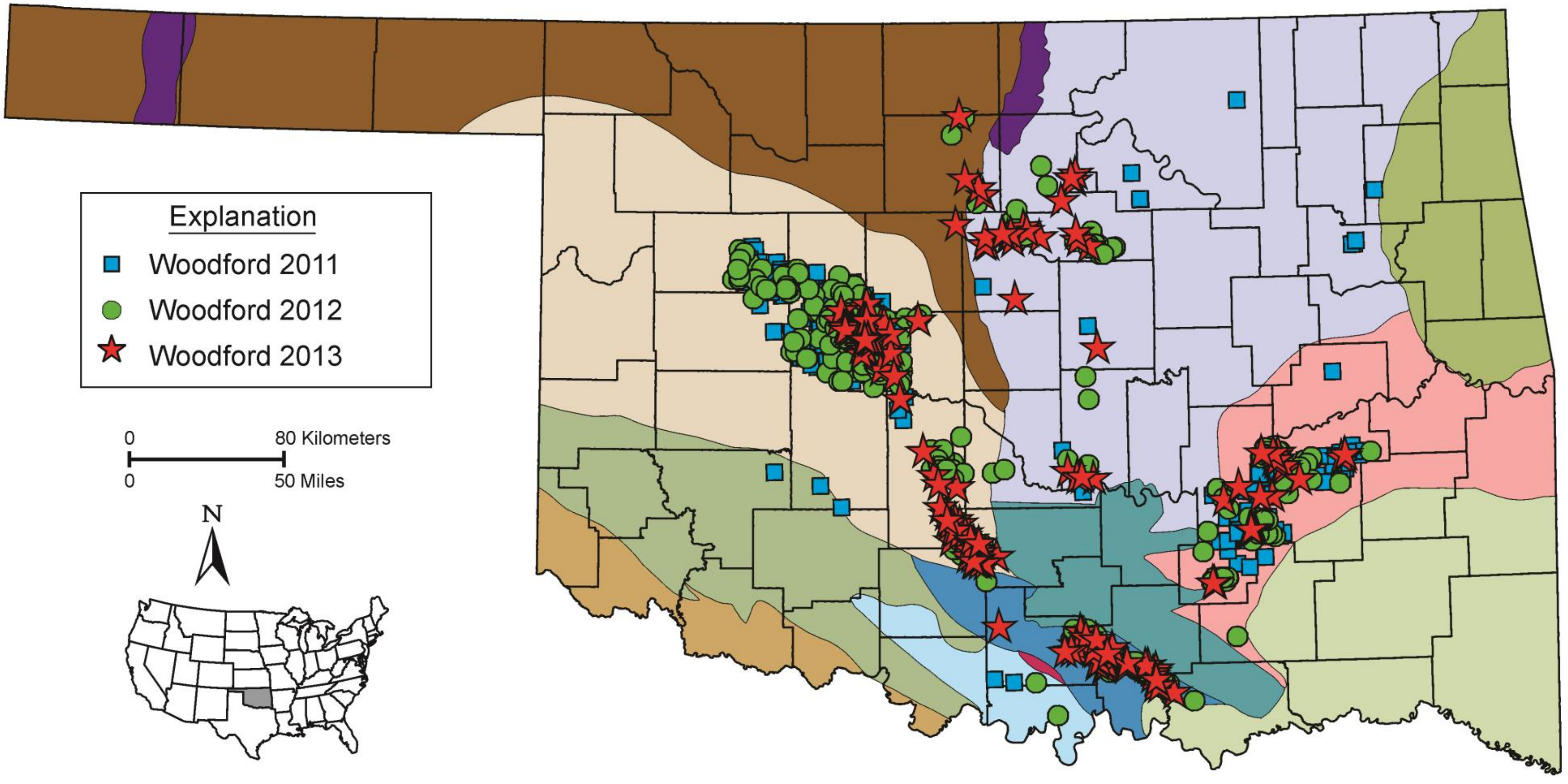
Woodford Shale (2004-2013)

Wagoner Co. Woodford wells produce ONLY GAS (less natural fractures?)

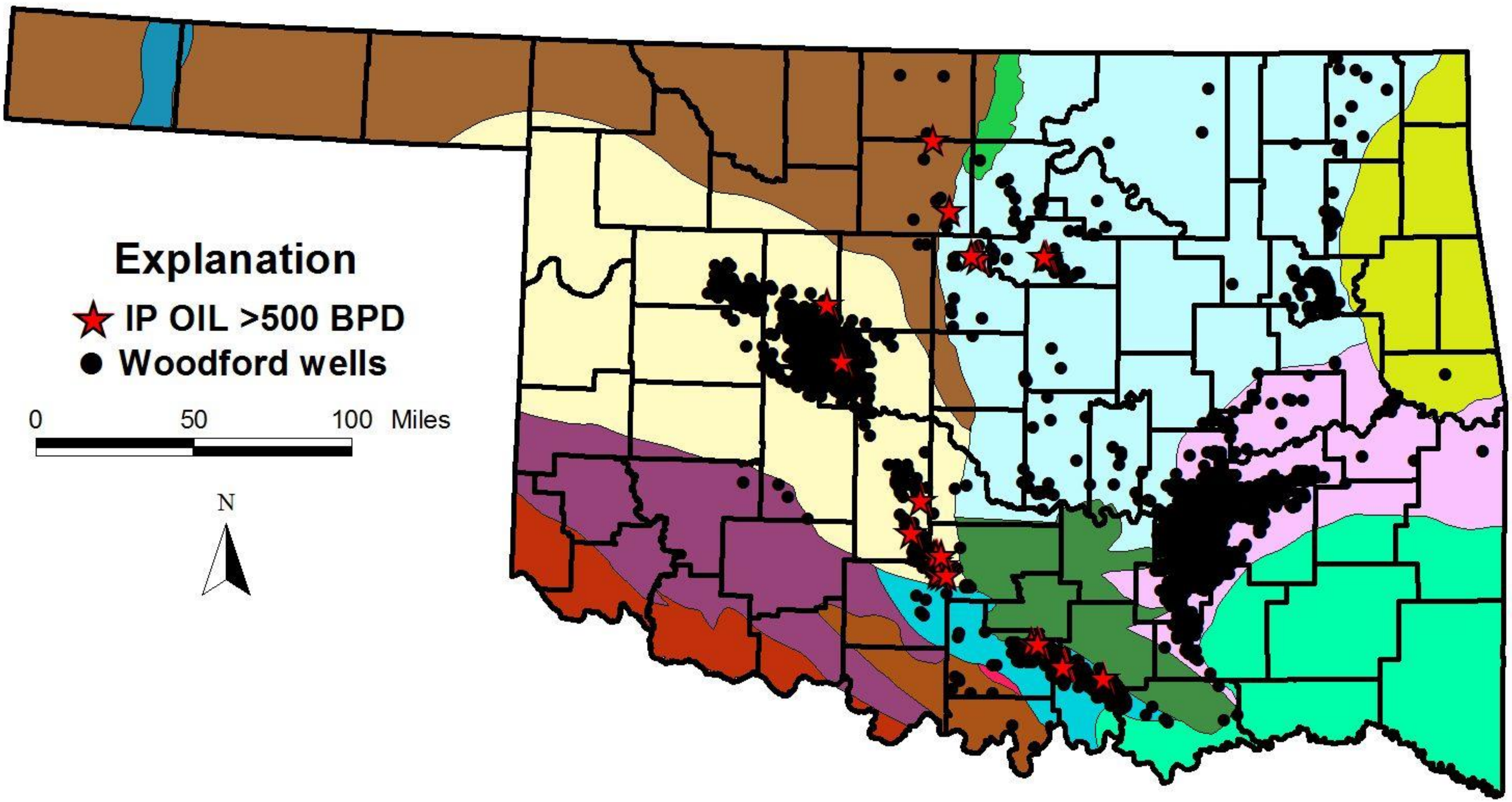


2,822 Woodford wells

Woodford Shale
(2011-2013)



Woodford Shale Well Completions Highlighting Wells with IP Oil >500 BPD (2012-2013)



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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-

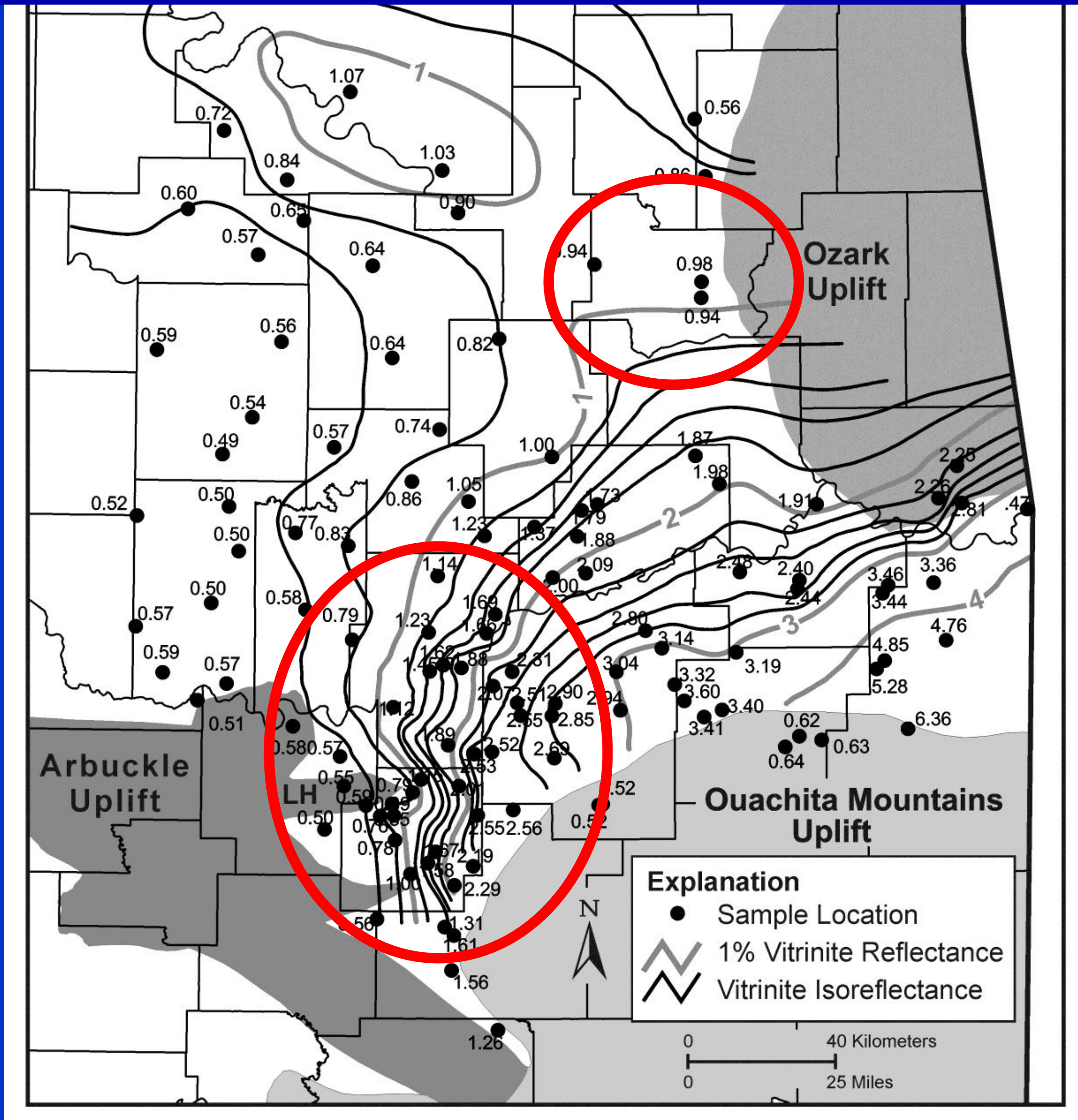
potential (e.g., high total organic carbon content with Type II kerogen), one advantage of the marine Woodford Shale as a gas shale is its quartz-rich composition, specifically rich primarily from Radiolaria and sponge spicule Kuuskraa et al. (2011) indicated that marine shales (common deposi-

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 hydrocarbon source rock potential.
- The Woodford Shale is dividied into three informal members: the lower member was 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.

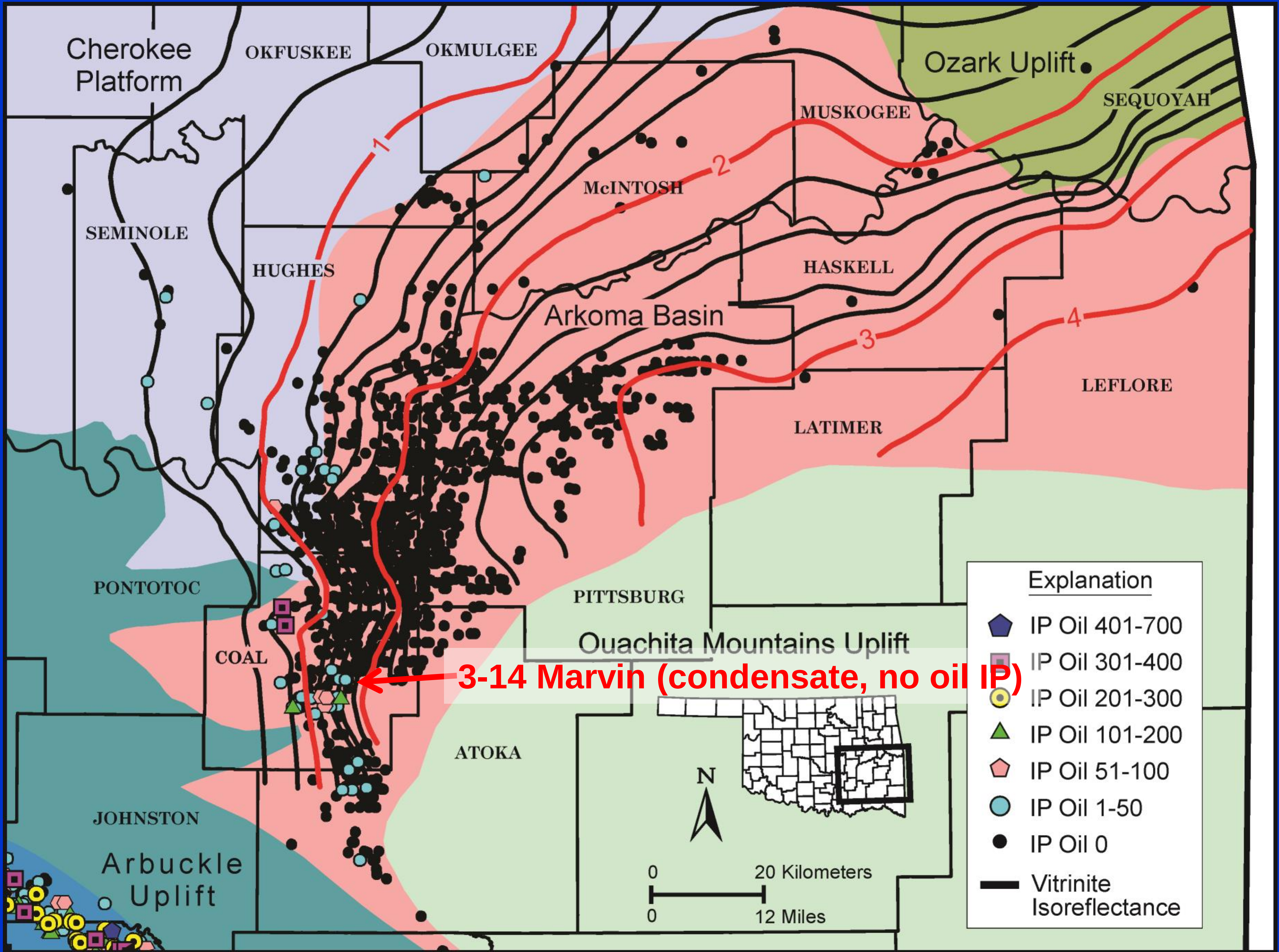
Isoreflectance Map of the Woodford Shale in Eastern Oklahoma (Updated November 2011)



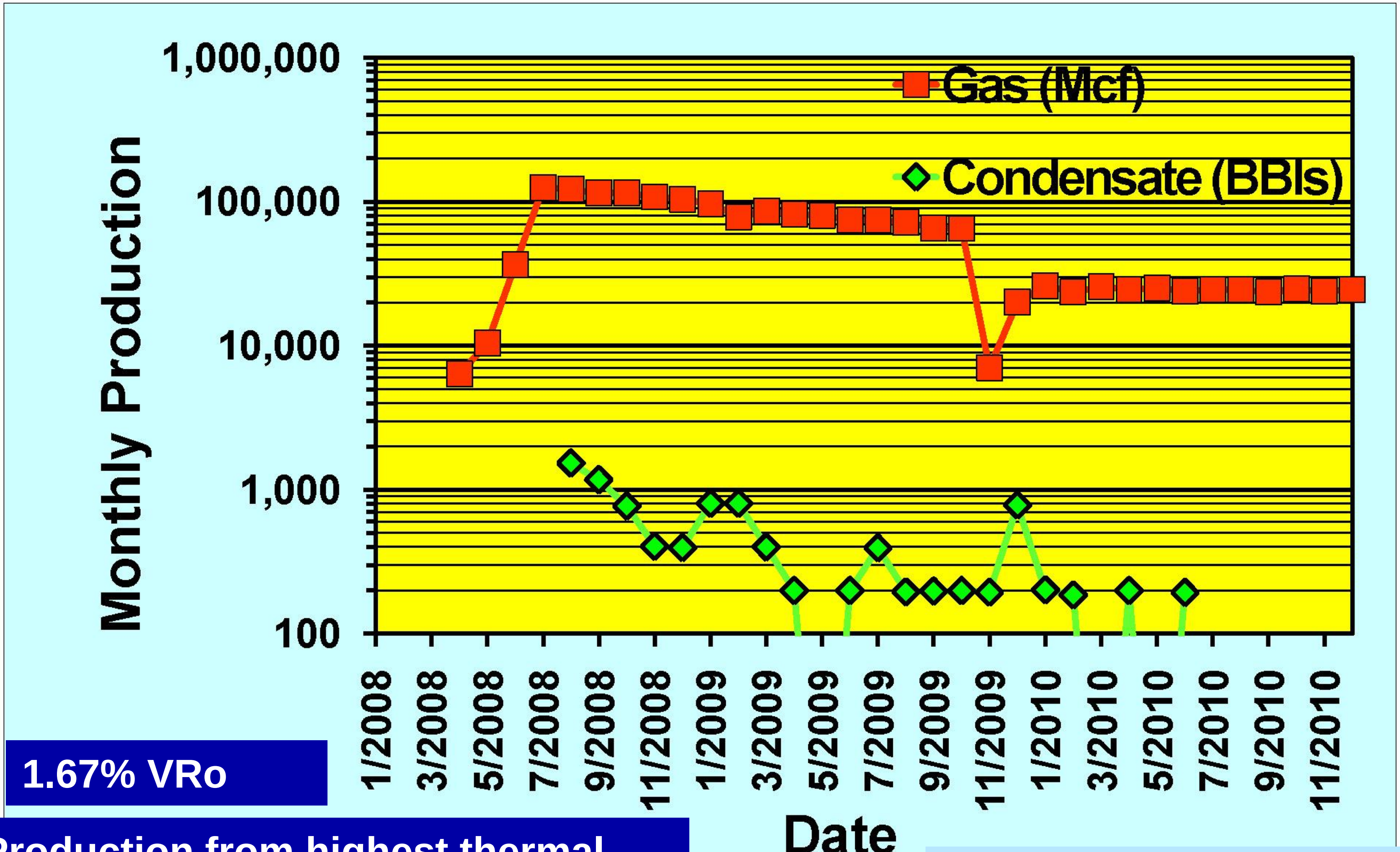
Distribution of 117 Woodford Shale samples with vitrinite-reflectance data (n ≥20; whole-rock pellets)

Cardott, in preparation

Woodford Shale Arkoma Basin Oil IP



St. Mary Land & Exploration 3-14 Marvin (14-1N-10E; Coal Co.; IP 3,125 Mcfd)

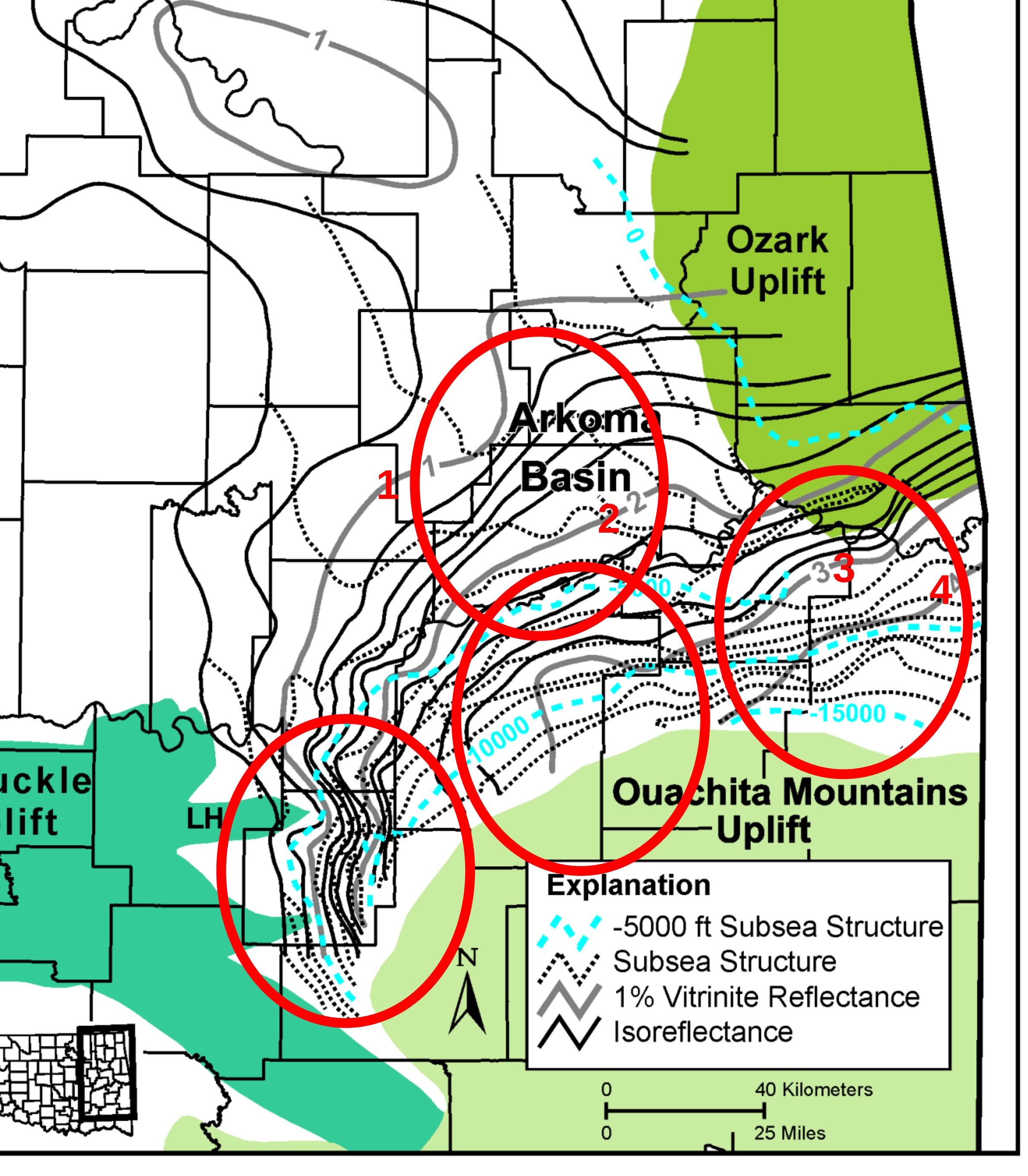


1.67% VRo

Production from highest thermal maturity Woodford well producing condensate

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

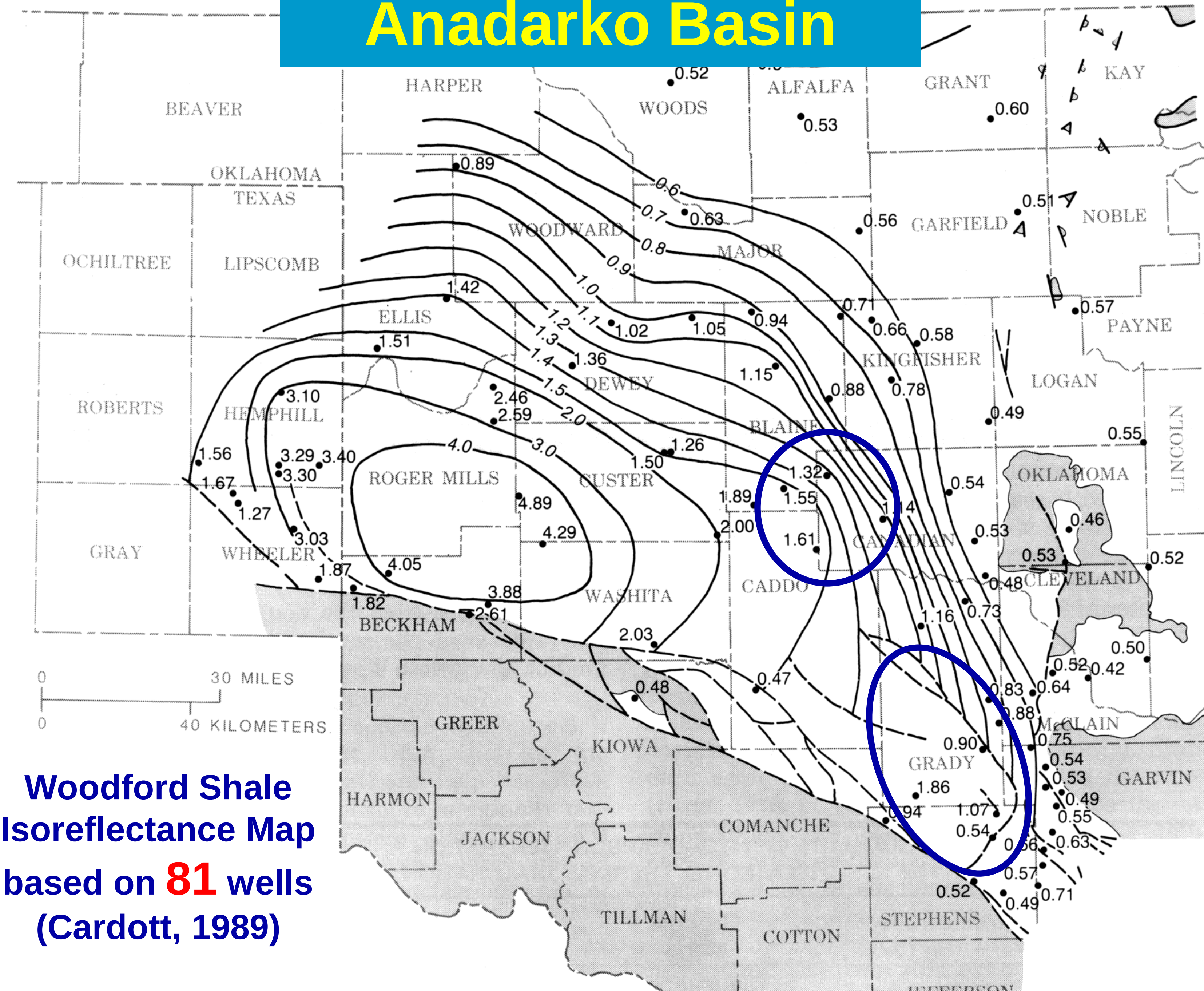
Woodford Shale Structure & Vitrinite Isoreflectance Map



Maps prepared by R. Vance Hall using Petra

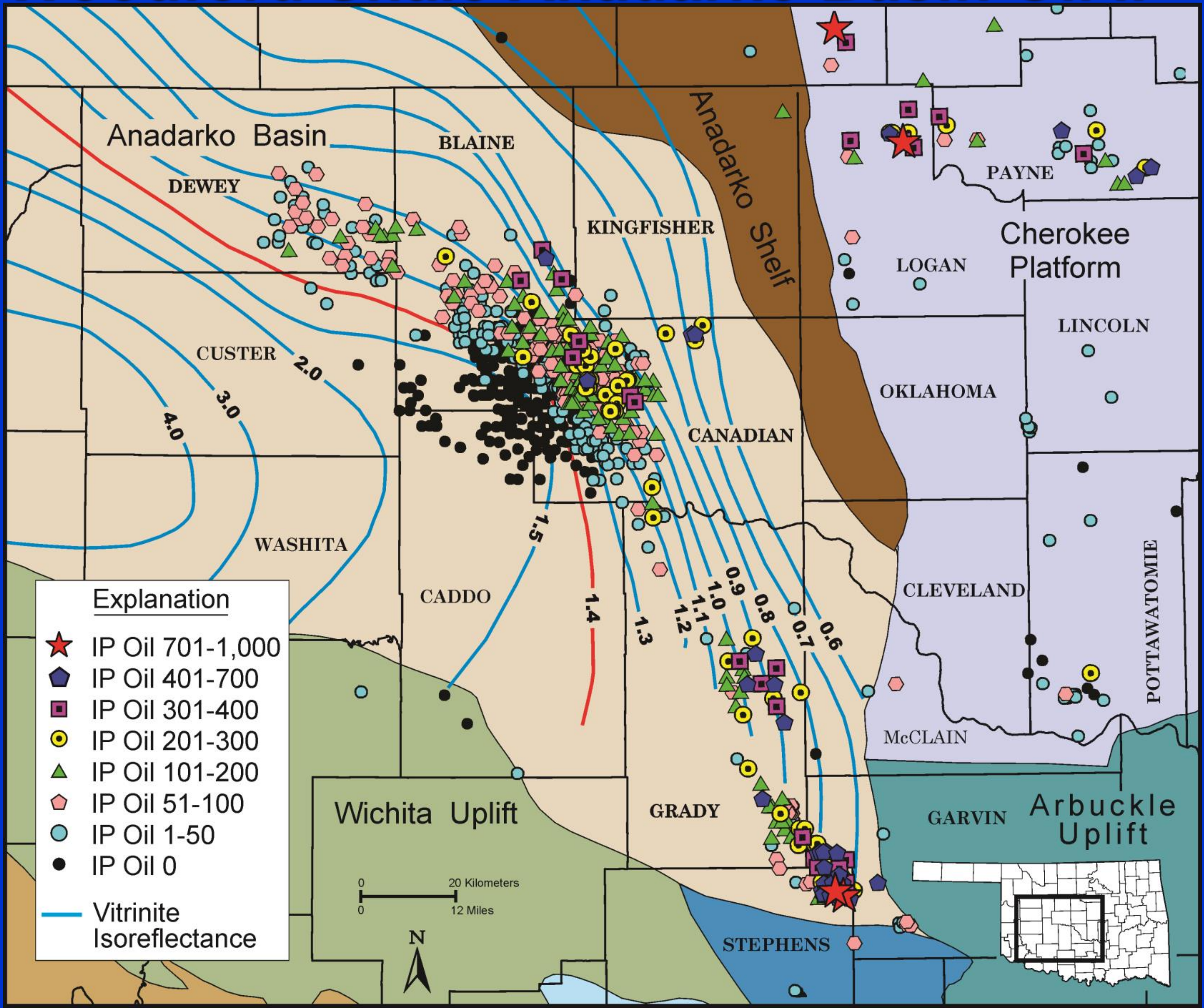
Cardott, 2012

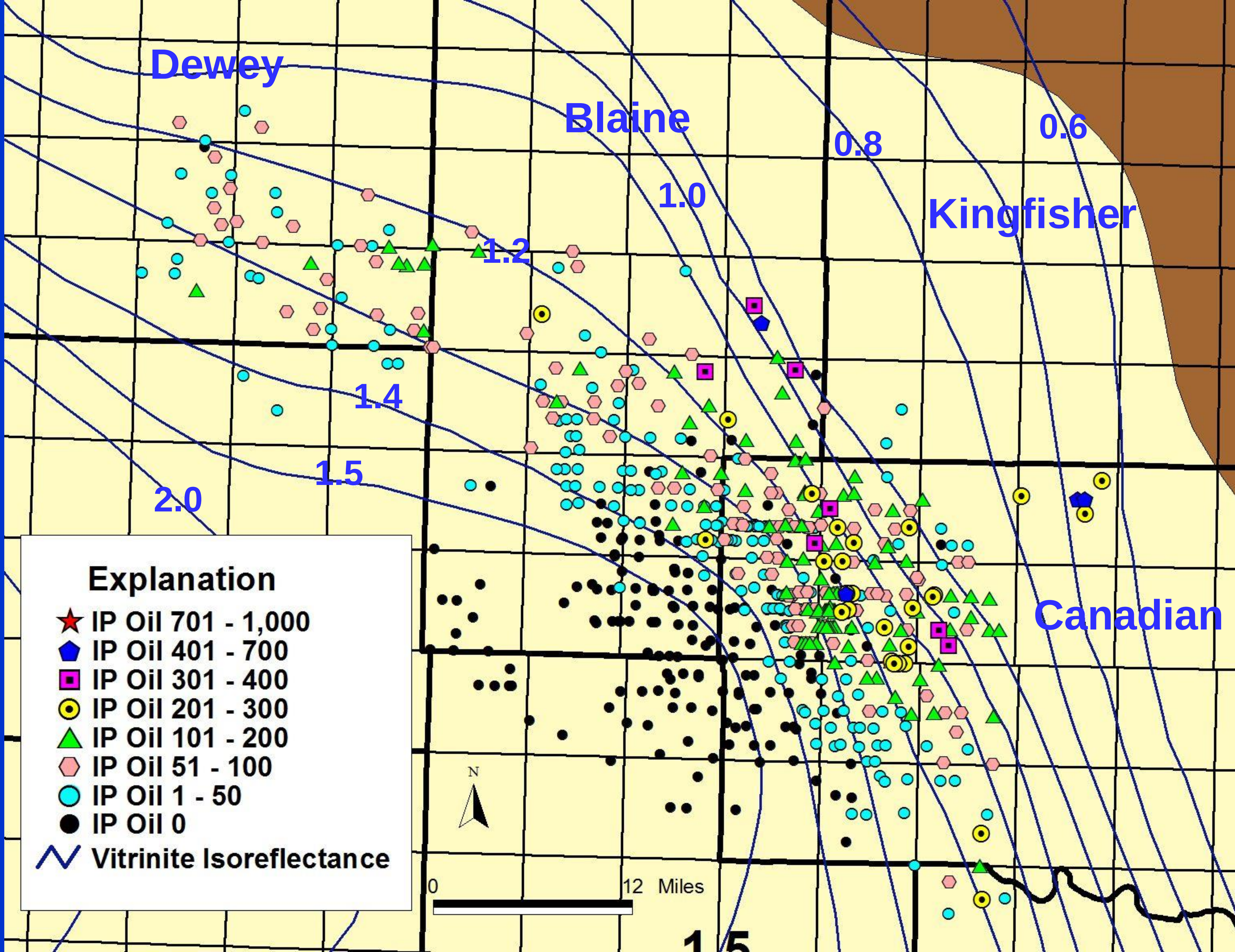
Anadarko Basin



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

Woodford Shale Anadarko Basin Oil IP

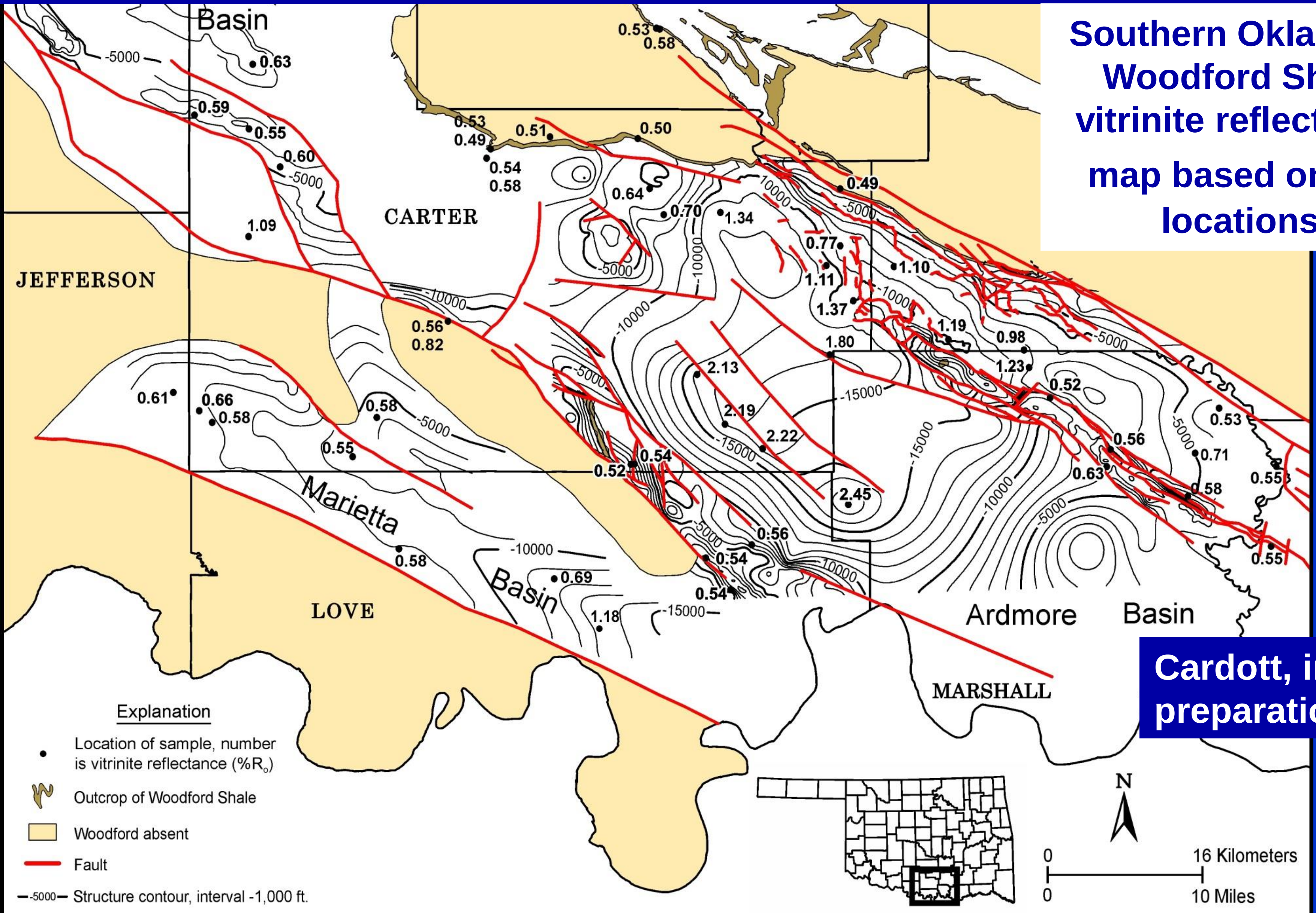




Dewey
Blaine
Kingfisher
Canadian
0.6
0.8
1.0
1.2
1.4
1.5
2.0
Explanation
IP Oil 701 - 1,000
IP Oil 401 - 700
IP Oil 301 - 400
IP Oil 201 - 300
IP Oil 101 - 200
IP Oil 51 - 100
IP Oil 1 - 50
IP Oil 0
Vitrinite Isoreflectance
N
0
12 Miles

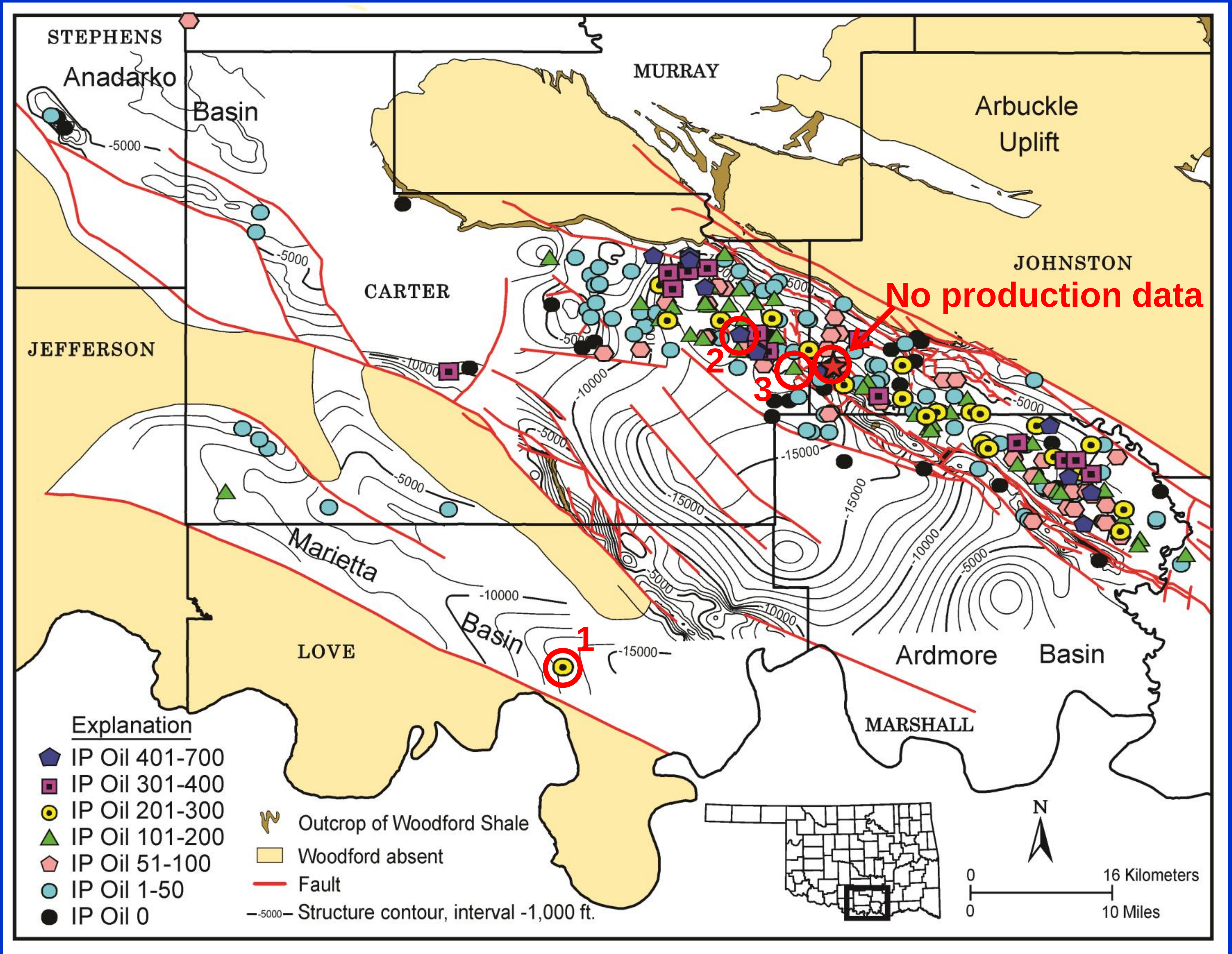
Woodford Shale Vitrinite Reflectance Data in Southern Oklahoma (Updated October 2013)

Southern Oklahoma Woodford Shale vitrinite reflectance map based on 51 locations

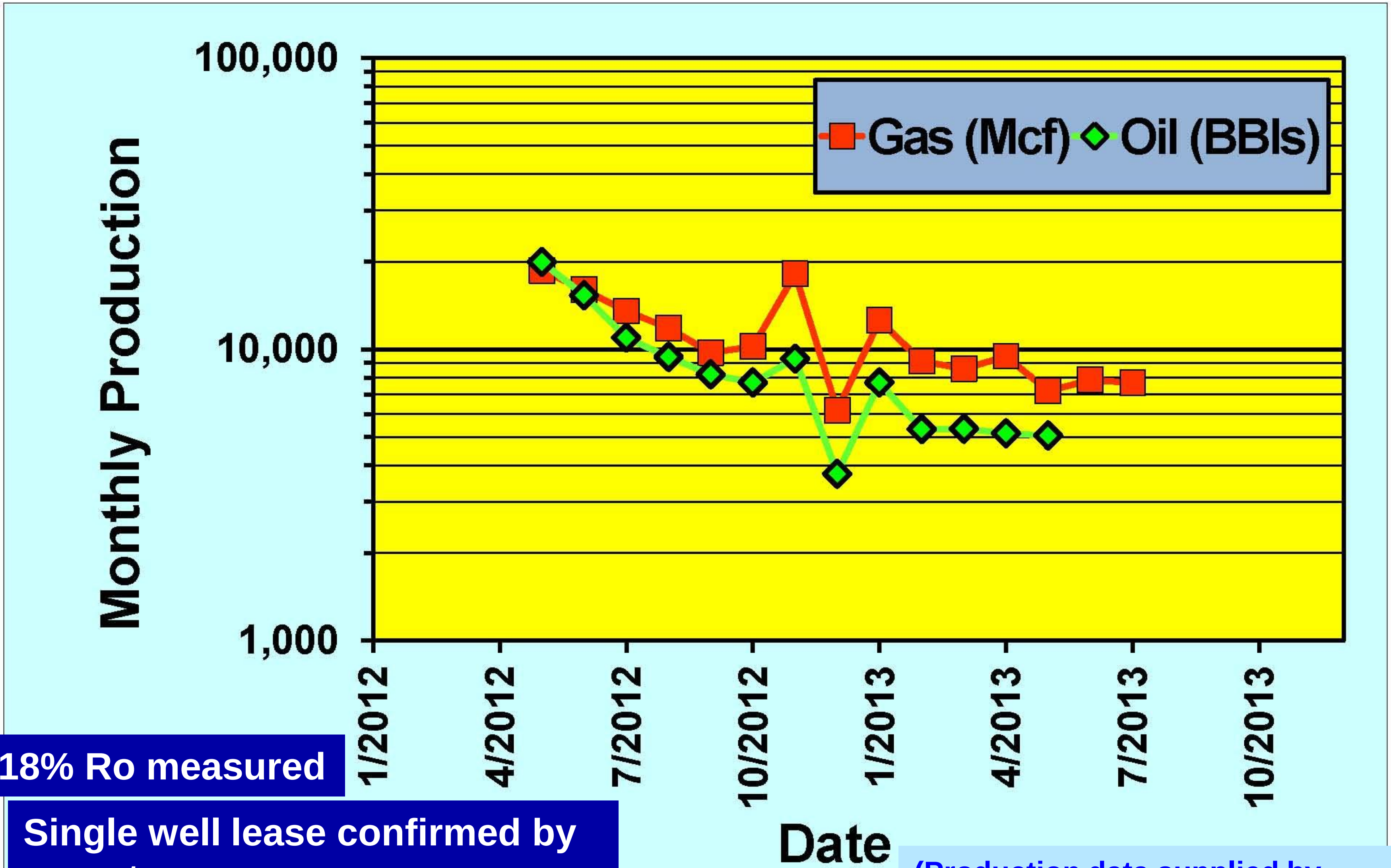


Cardott, in preparation

Woodford Shale Ardmore Basin Oil IP



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

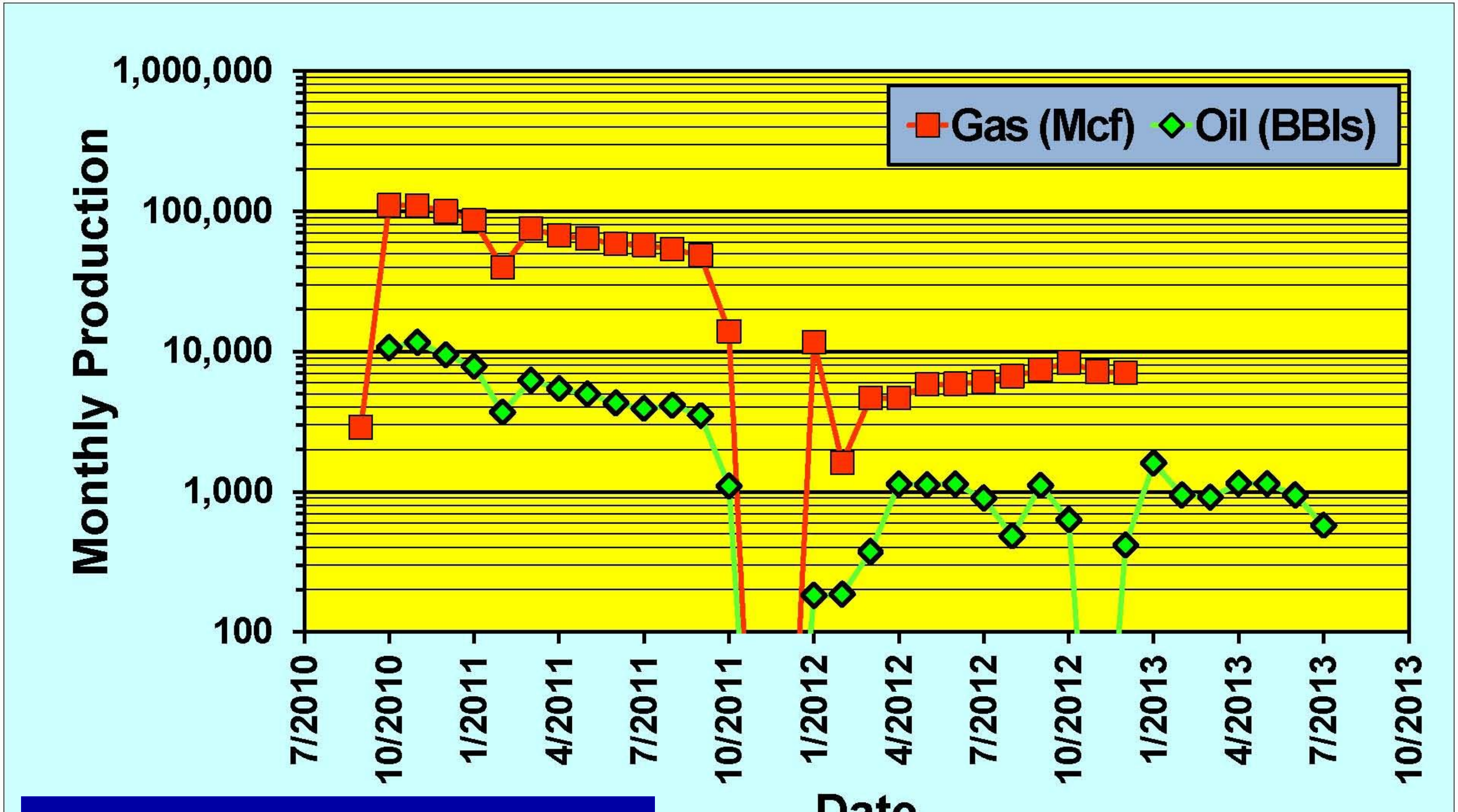


1.18% Ro measured

Single well lease confirmed by operator.
Cum: 113,102 BO; 166,780 MCF

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

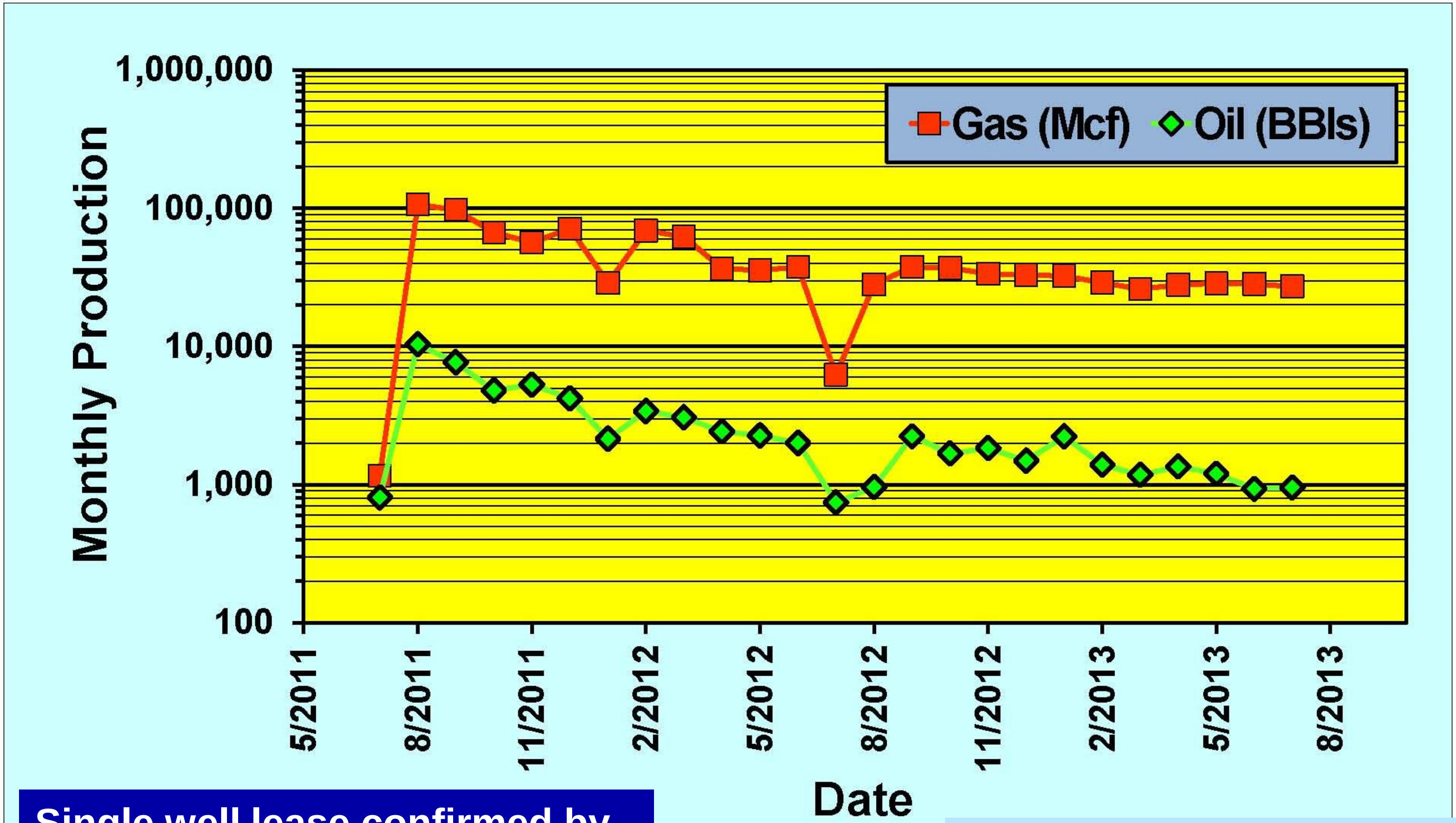
2. XTO 1-32H Owens Horizontal Well
Carter Co.; 32-3S-3E; IP 3,361 MCFD, 418 BOPD (50° API)



Single well lease confirmed by operator.
Cum: 91,768 BO; 963,655 MCF

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

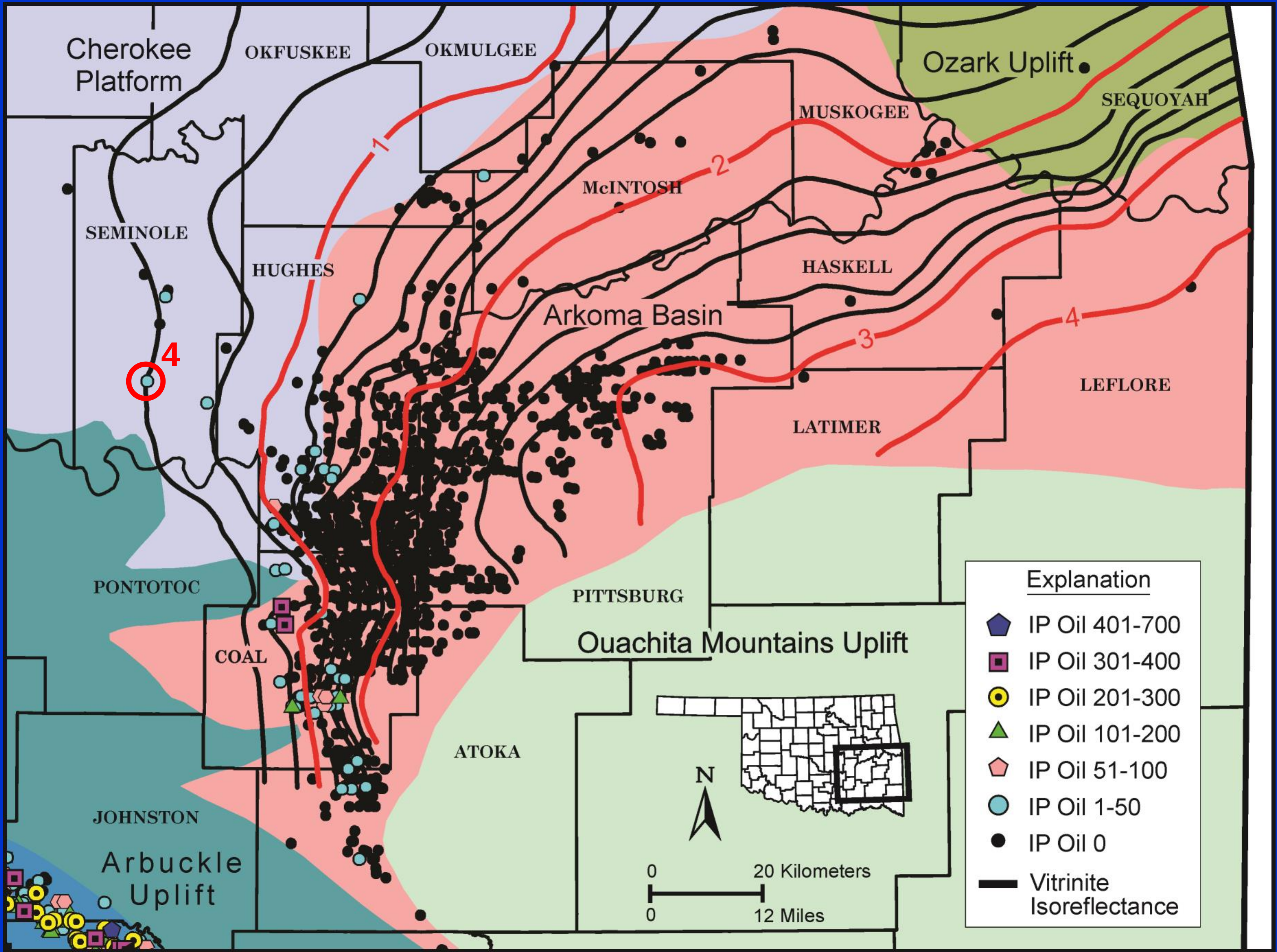
3. XTO 1-12H Wiggins Horizontal Well
Carter Co.; 13-4S-3E; IP 1,285 MCFD, 150 BOPD



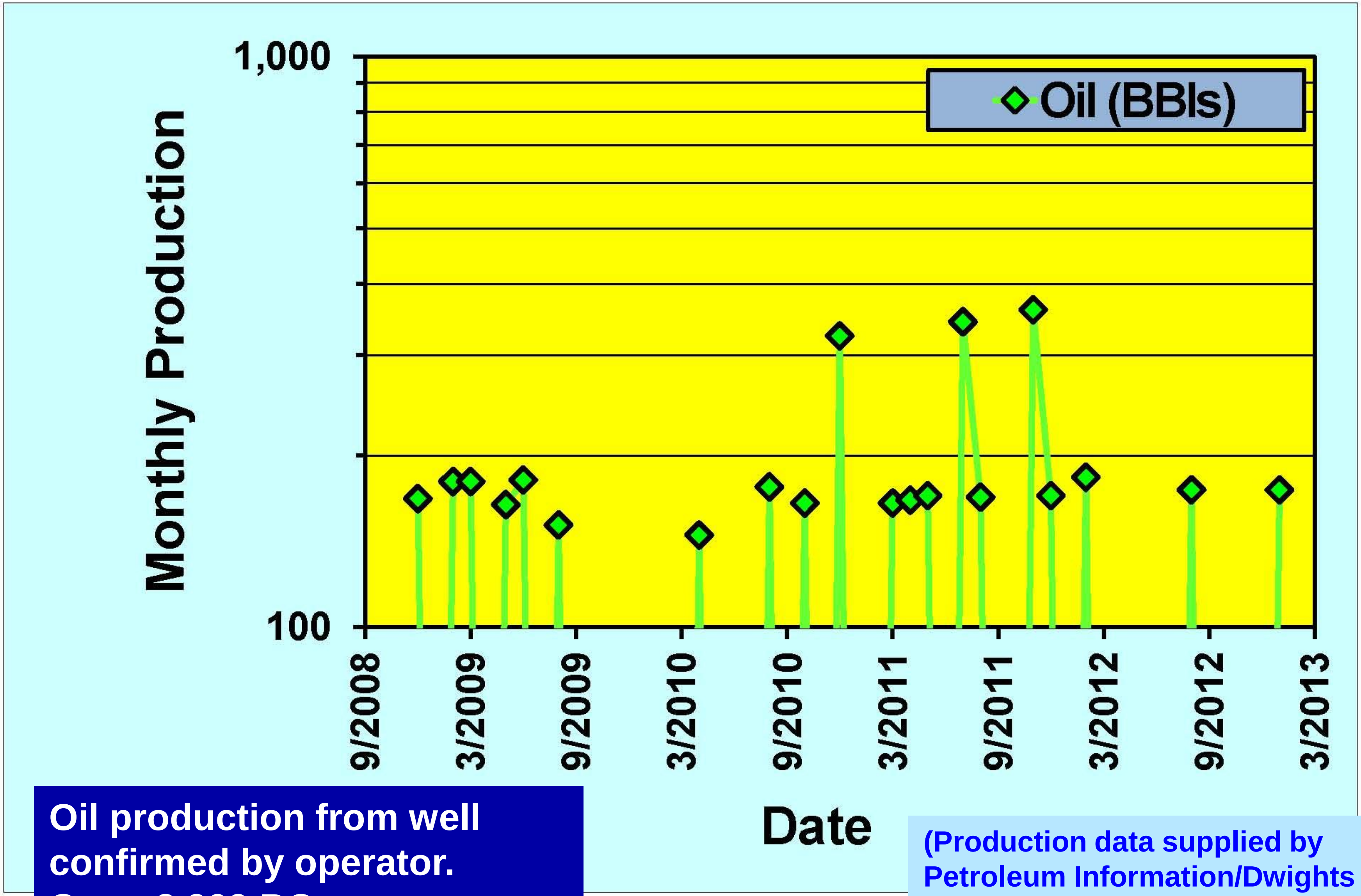
Single well lease confirmed by operator.
Cum: 66,532 BO; 1,043,812 MCF

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

Woodford Shale Arkoma Basin Oil IP



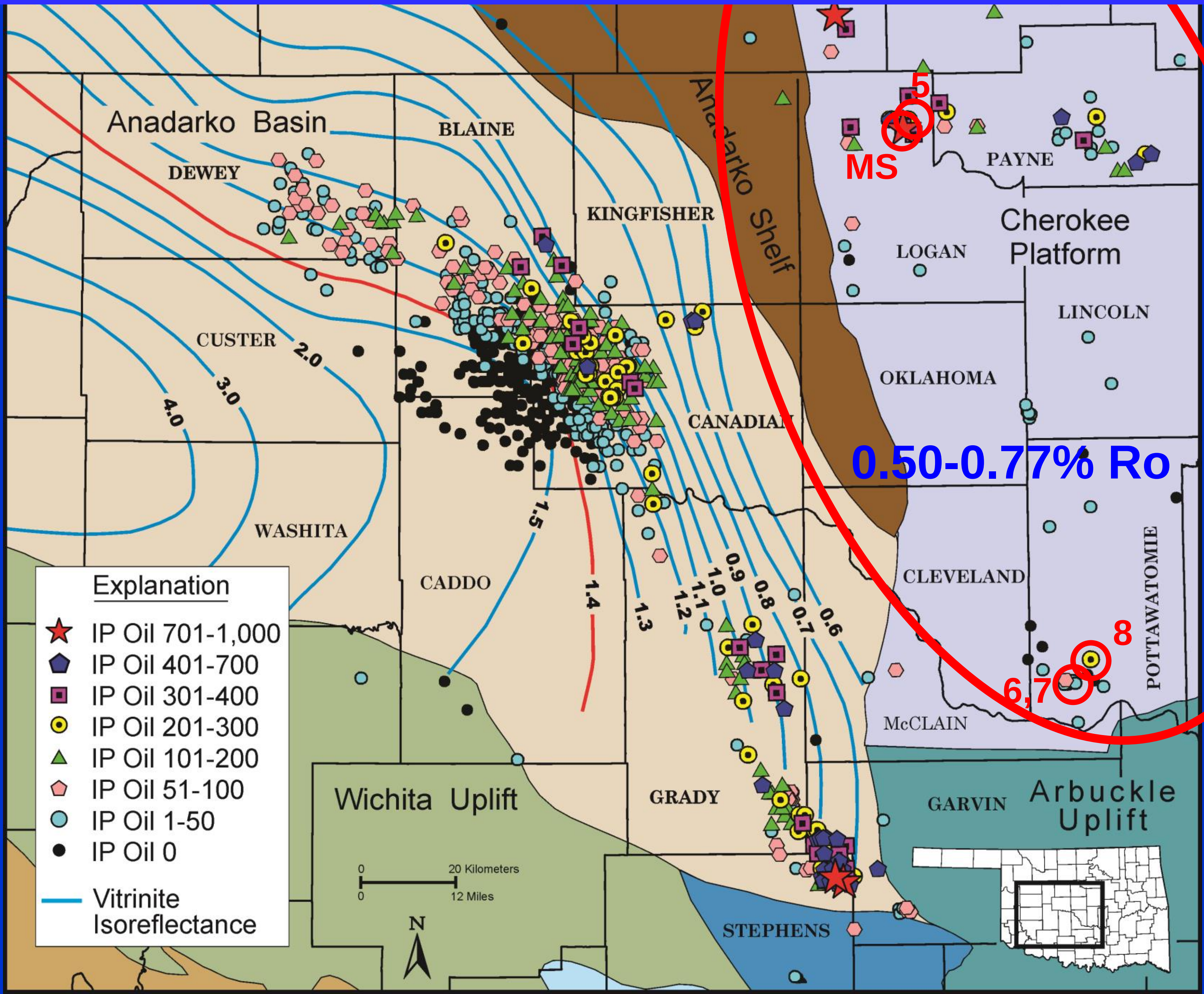
4. Chesapeake Operating 1-36H Francisca Horizontal Well Seminole Co.; 36-7N-6E; IP 80 MCFD, 6 BOPD



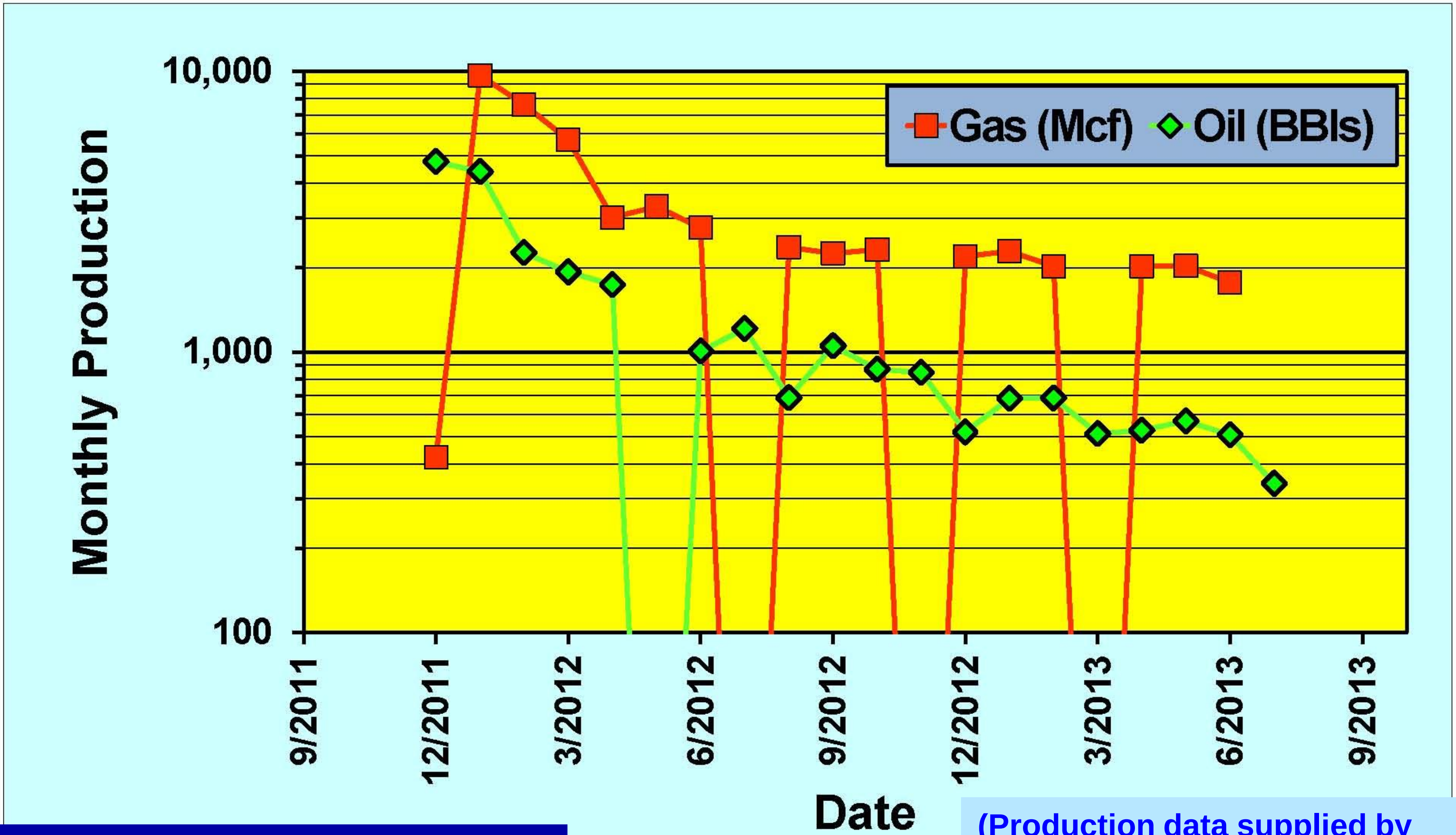
Oil production from well confirmed by operator.
Cum: 3,909 BO

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

Woodford Shale North Central OK Oil IP



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

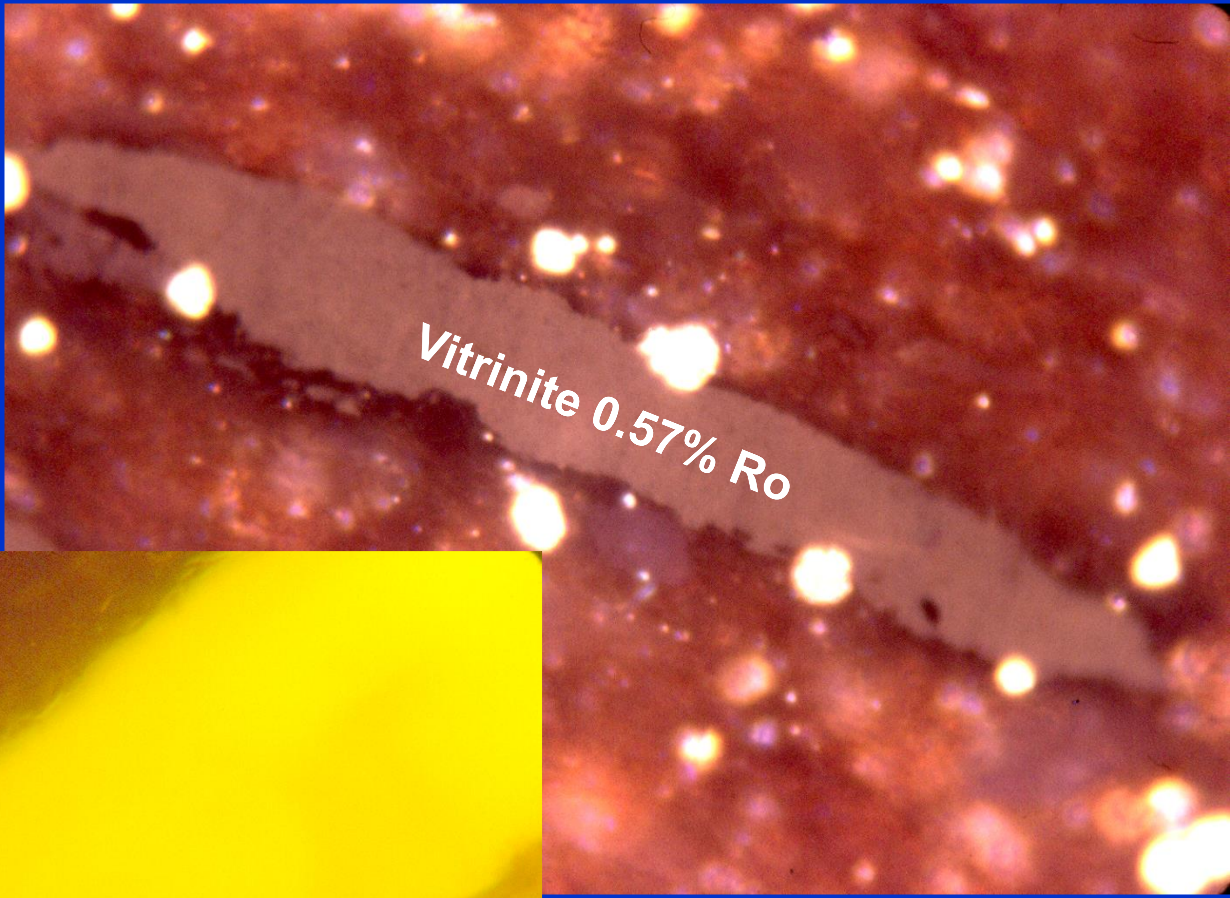


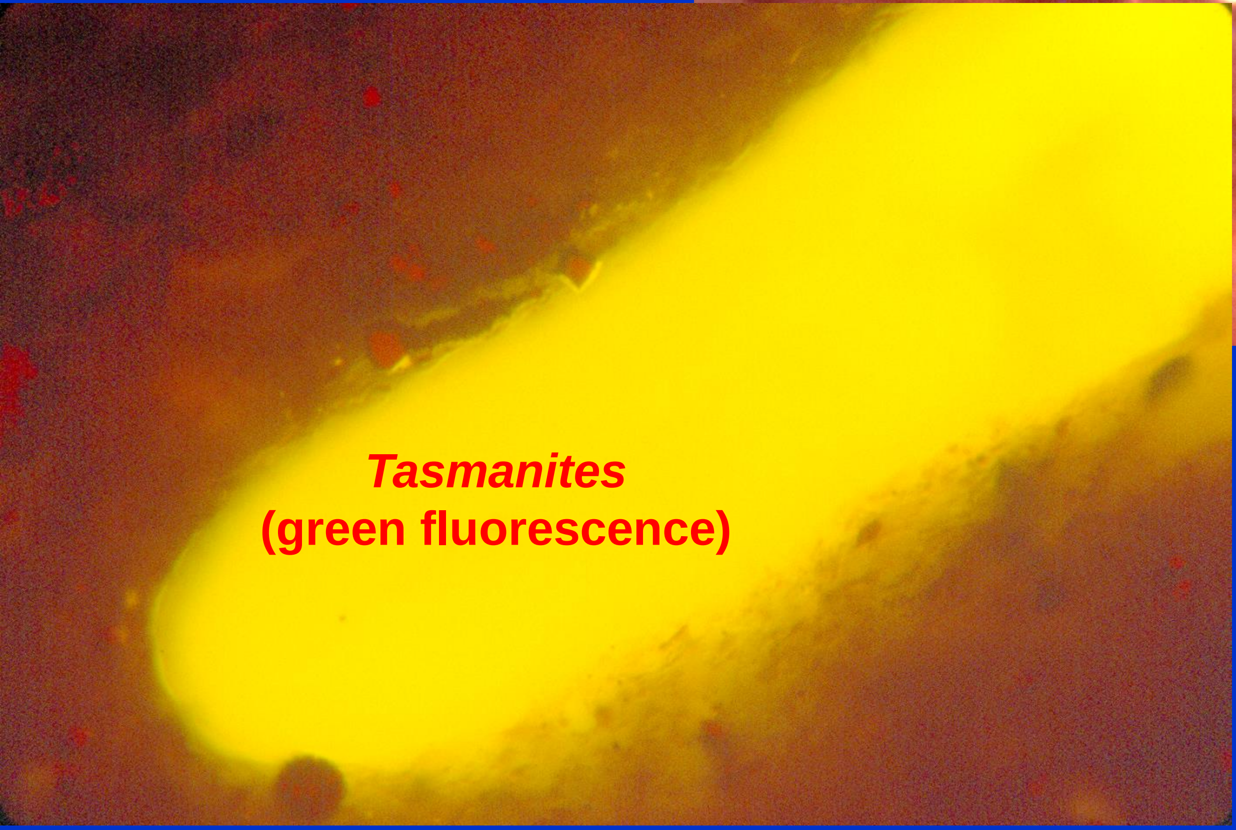
(Production data supplied by Petroleum Information/Dwights LLC dba IHS Energy Group, © 2014)

Single well lease confirmed by operator.
Cum: 25,110 BO; 51,755 MCF

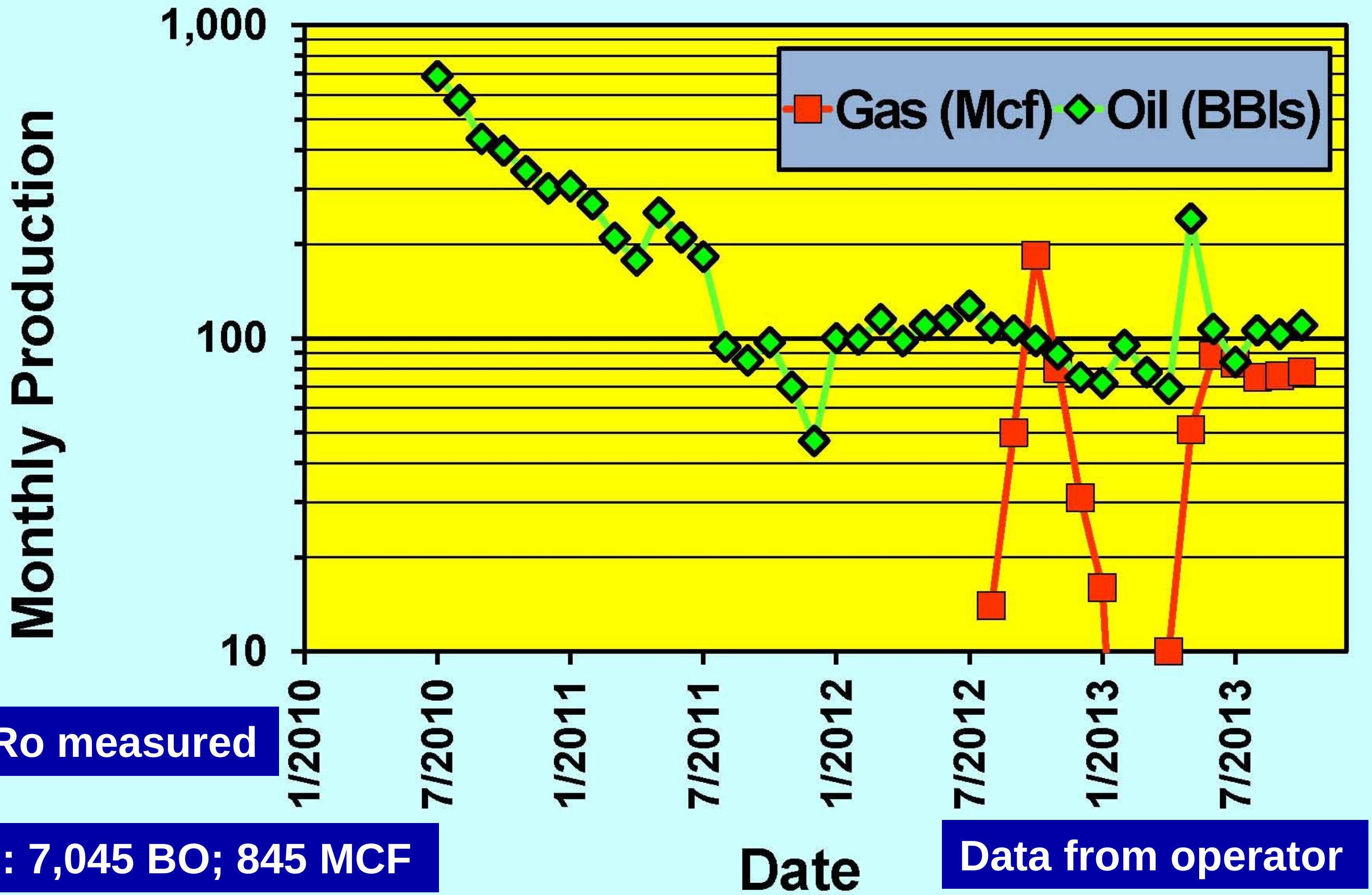
In an area recently measured 0.77% VRo

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





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

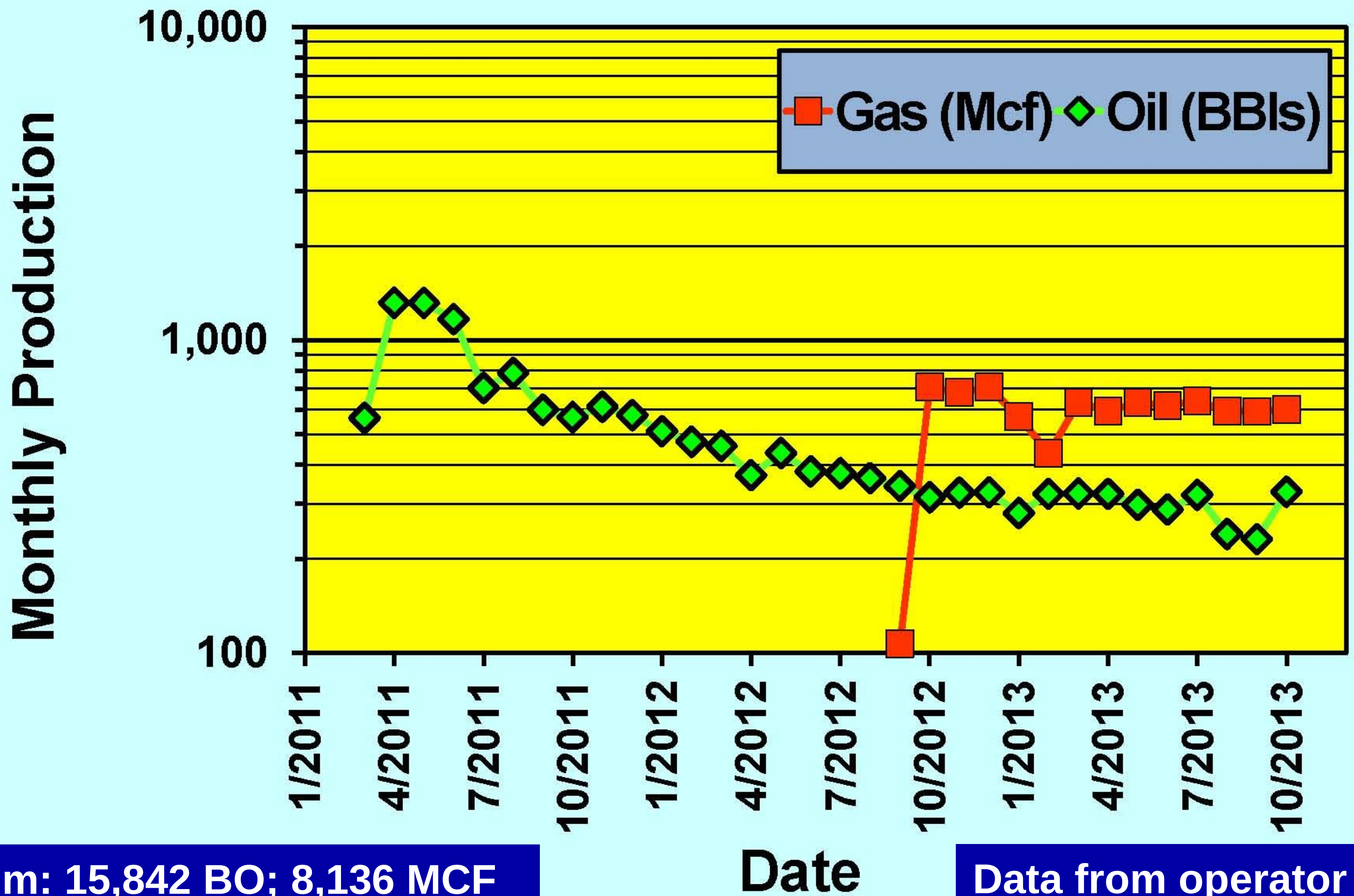


0.59% Ro measured

Cum: 7,045 BO; 845 MCF

Data from operator

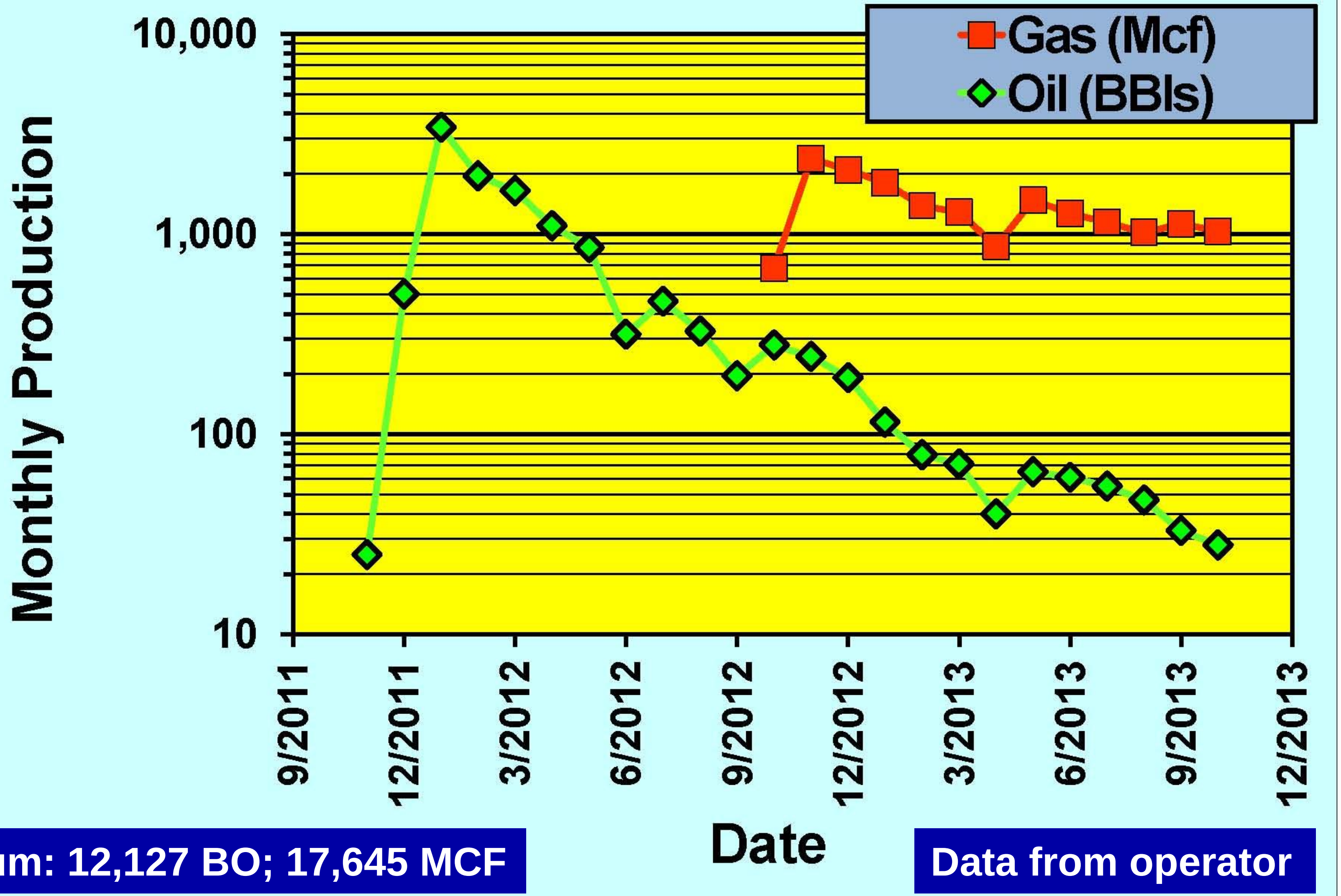
7. West Star Operating 1-12 Schoemann Vertical Well Pottawatomie Co.; 12-6N-2E; IP 85 MCFD, 38 BOPD (delayed hook-up to gas pipeline)



Cum: 15,842 BO; 8,136 MCF

Data from operator

8. 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

Conclusions

Oil and condensate have been produced from naturally- and induced-fractured Woodford Shale wells in Oklahoma.

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.