TSOP Annual Meeting August 1, 2011

Application of Organic Petrology to Shale Oil and Gas Potential of the Woodford Shale, Oklahoma, USA

Brian J. Cardott

Oklahoma Geological Survey

Three Basic Factors Necessary for a Successful Gas Shale Play

- **Hydrocarbon Source Rock:**
  Organic Matter TYPE, QUANTITY, AND THERMAL MATURITY.
- **Mineralogy:** **quartz and carbonate vs. clays. Mineralogy and rock fabric influence porosity and mechanical strength (brittleness vs. ductile)**
- **Stress:** **rock is difficult to break and fractures may close in high stress; low stress regions result in better stimulation.**

Modified from Norton and Tushingham, 2011)

Criteria from U.S. Energy Information Administration "World Shale Gas Resources: An Initial Assessment of 14 Regions Outside the United States"

- Higher thermal maturity shales may contain nanopores that contribute to additional porosity in the shale matrix.

[What is the effect of thermal maturity and OM type on porosity?]

- Marine shales [e.g., Type II Kerogen] tend to have less clay and more brittle minerals (e.g., quartz, feldspar, carbonate) that respond well to hydraulic fracturing.
- Non-marine shales [e.g., Type I Kerogen] tend to have more clay, are more ductile, and absorb frac energy.

All gas shales have marine Type II Kerogen bulk composition

'Magnificent Seven' Gas Shale Basins of the U.S. and Canada

UNITED STATES

- Barnett
- Fayetteville
- Haynesville
- Marcellus
- Woodford (Late Devonian-Early Mississippian)

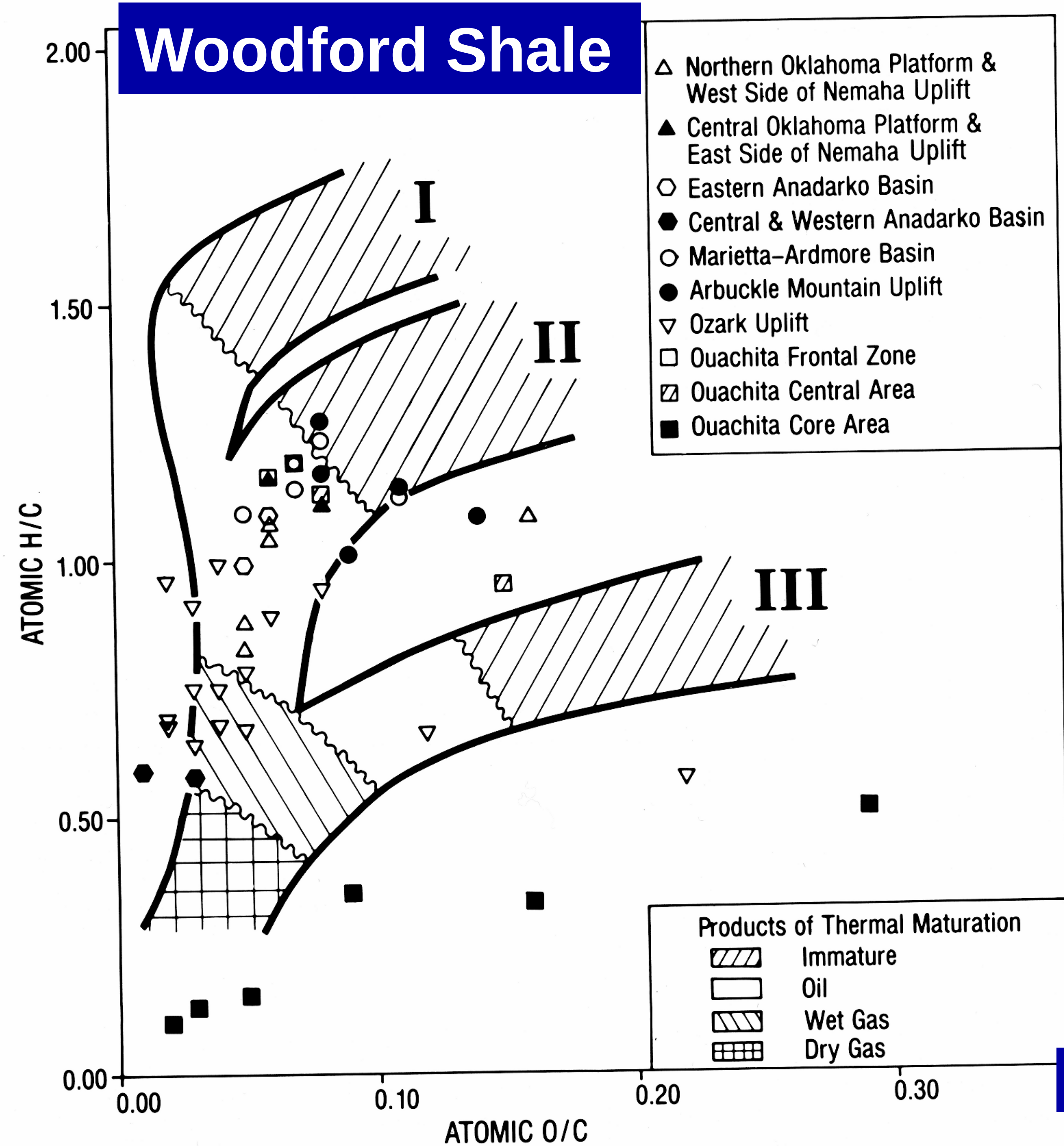
CANADA

Horn River

Montney

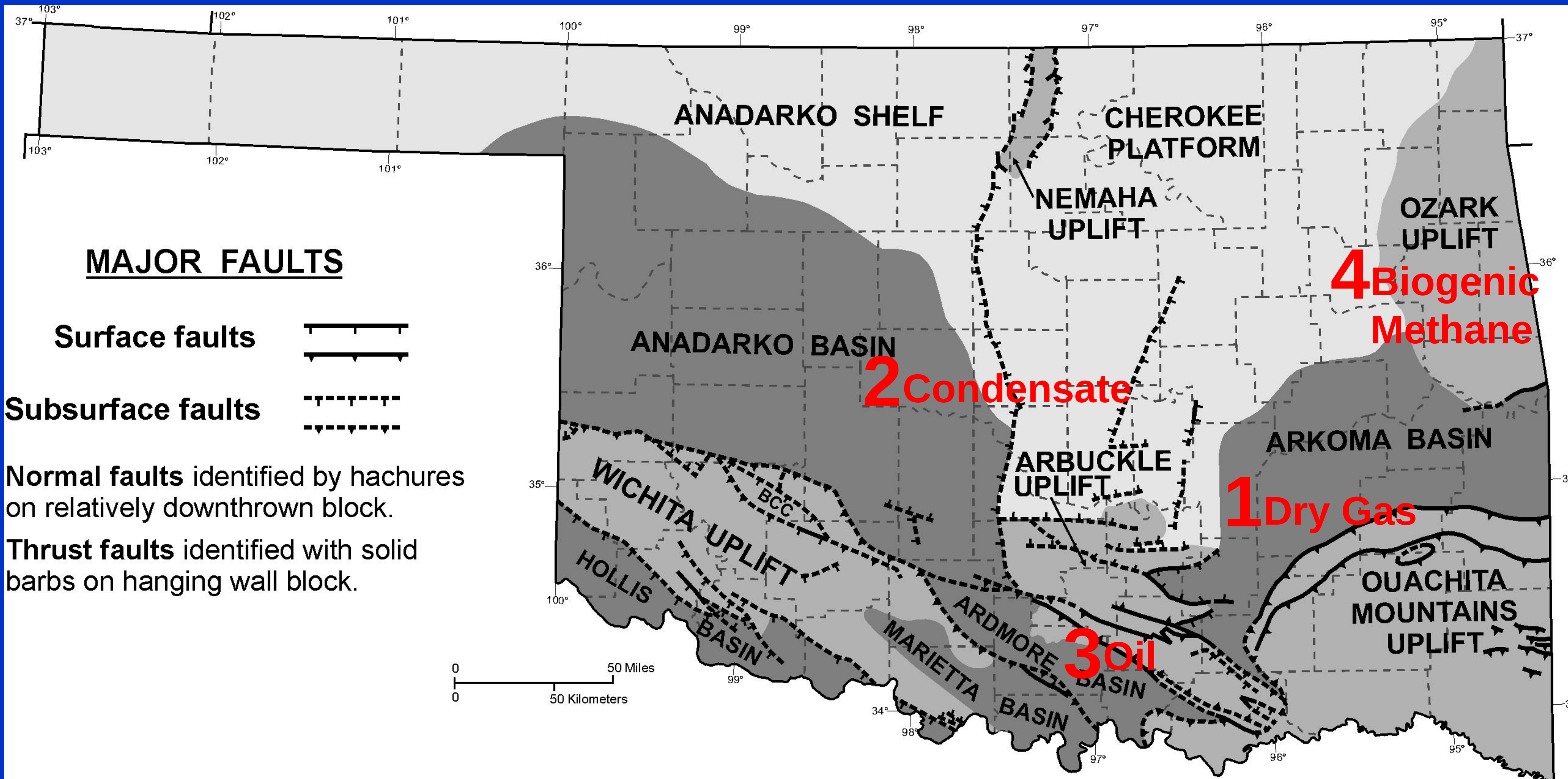
From Kuuskraa, 2011

Woodford Shale



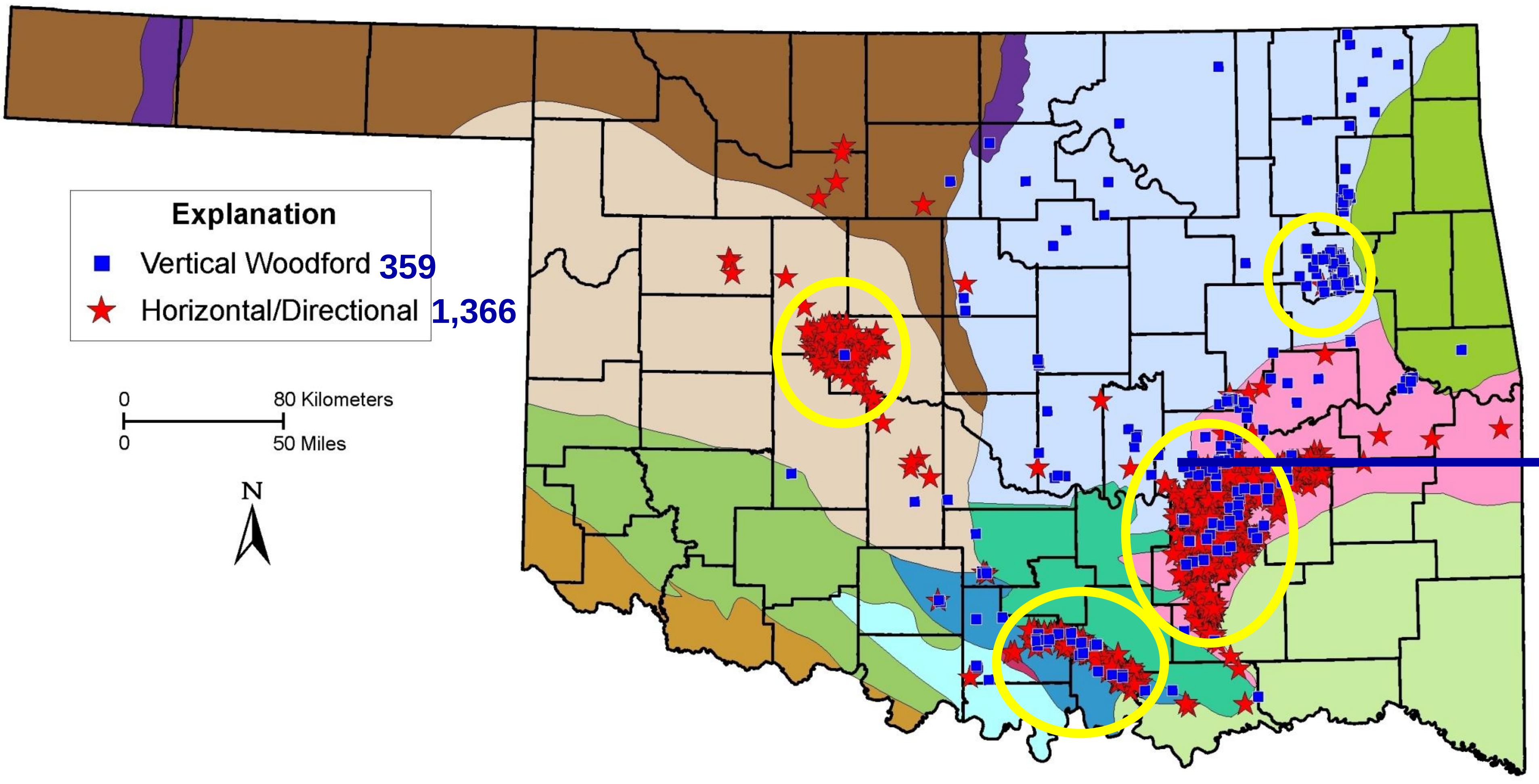
Comer (1992)

Woodford Shale Plays



Geologic provinces from
Northcutt and Campbell, 1995

1,725 Woodford Shale Wells (2004-2011)



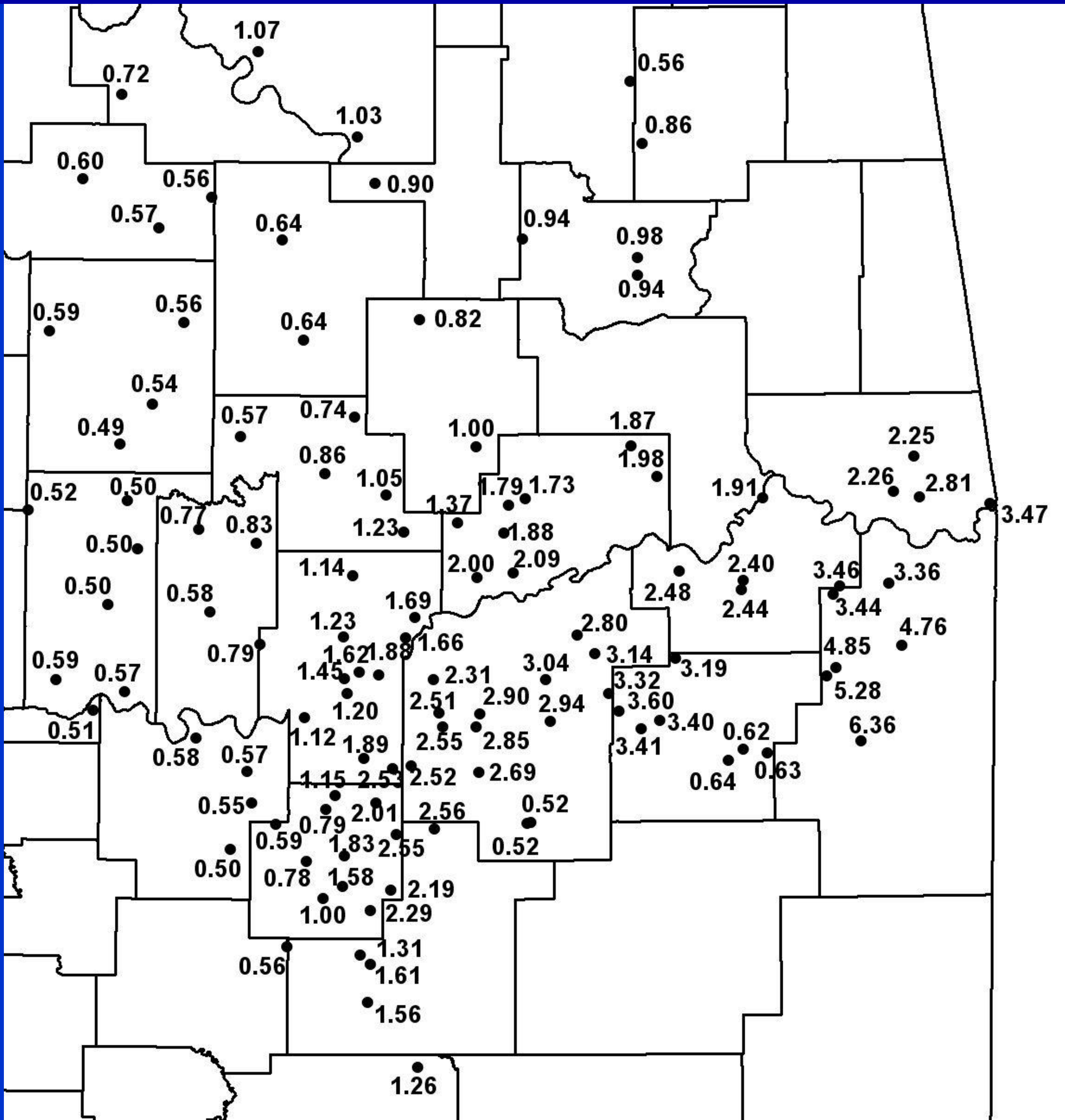
Importance of thermal maturity (by vitrinite reflectance) on the Woodford Shale oil and gas plays.

Guidelines for the Barnett Shale (Based on Rock-Eval Pyrolysis)

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

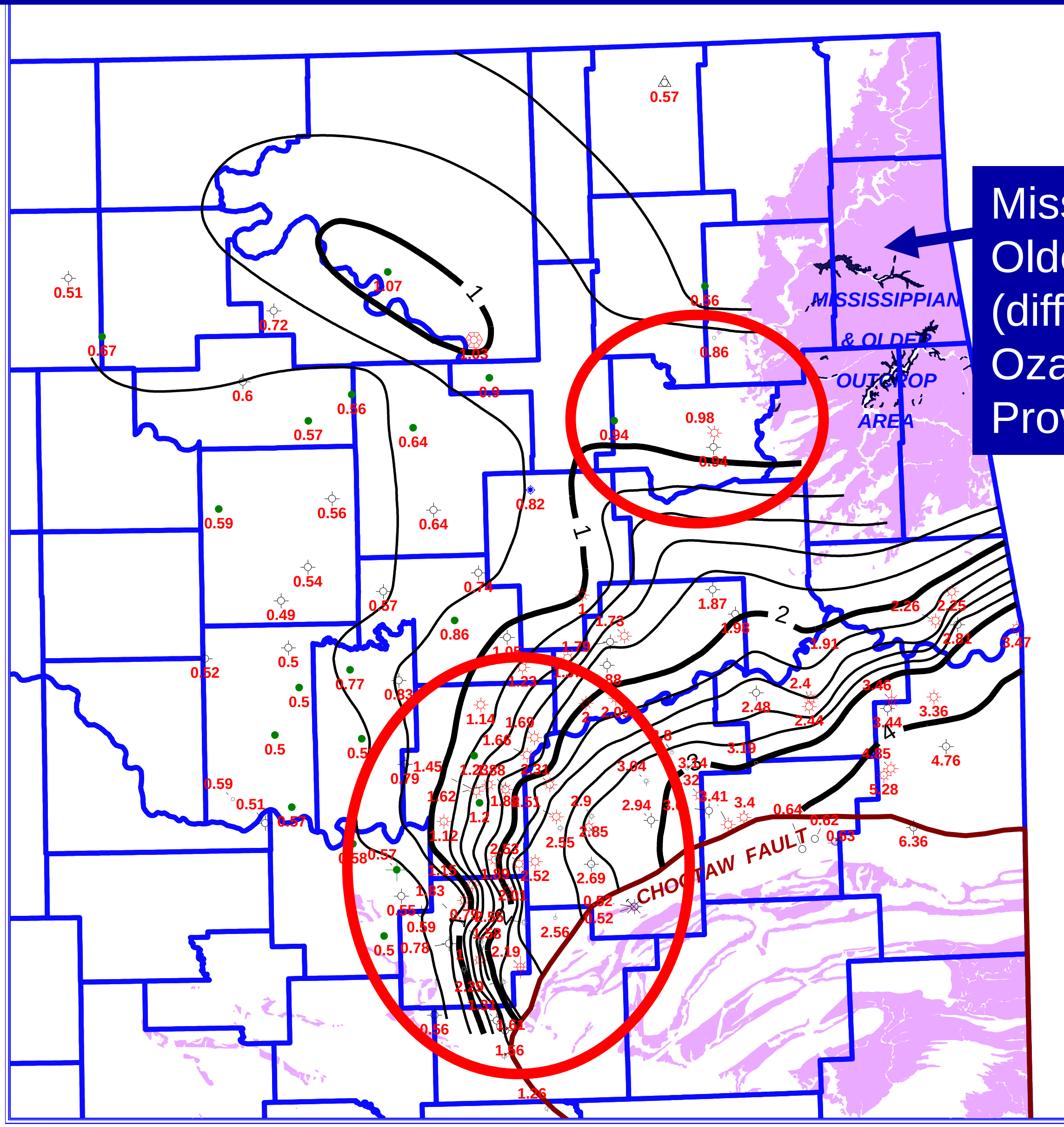
Eastern Oklahoma



Distribution of 112 Woodford Shale samples with vitrinite-reflectance data (n ≥20; whole-rock pellets)

Cardott, in preparation

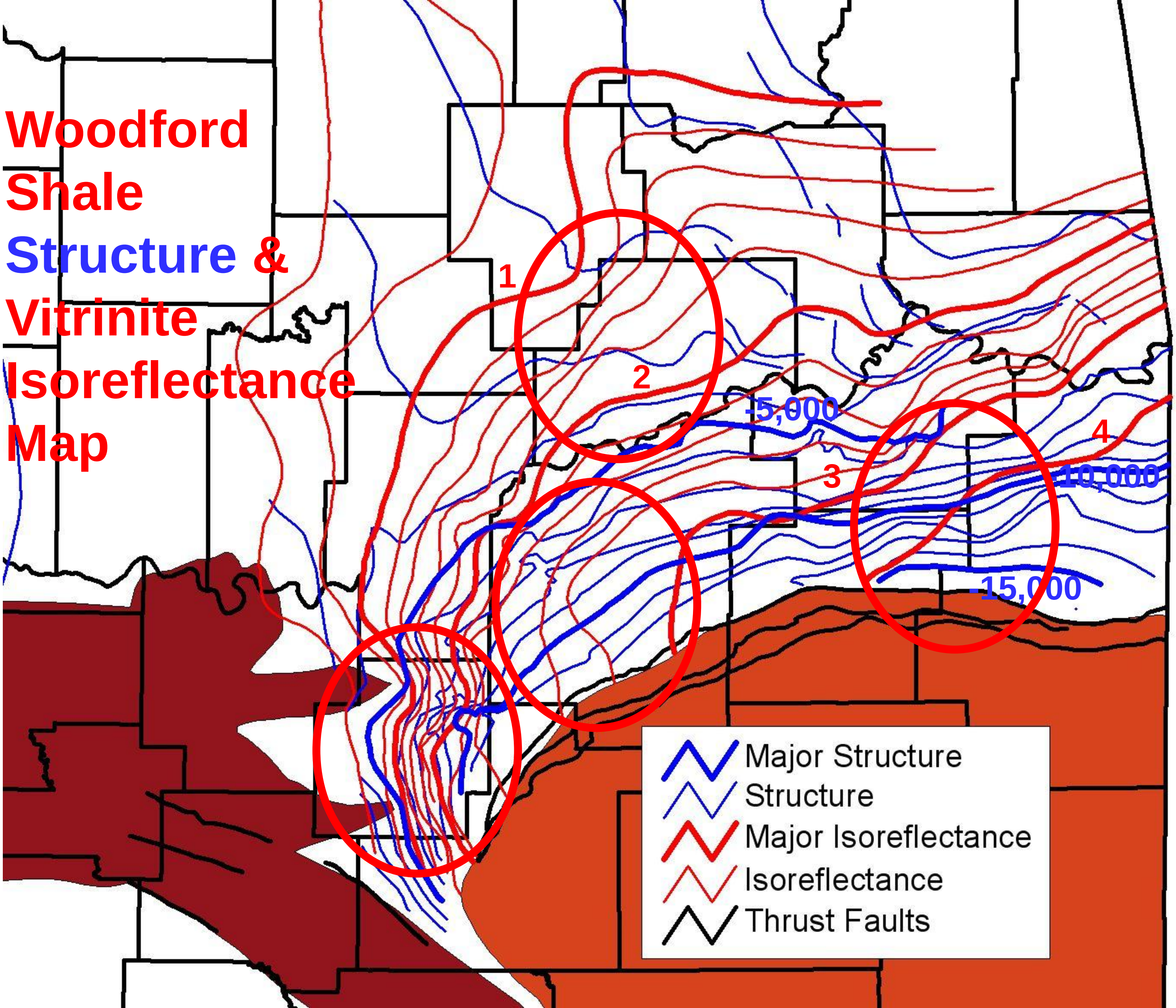
Isoreflectance Map of the Woodford Shale in Eastern Oklahoma (Updated October 2009)



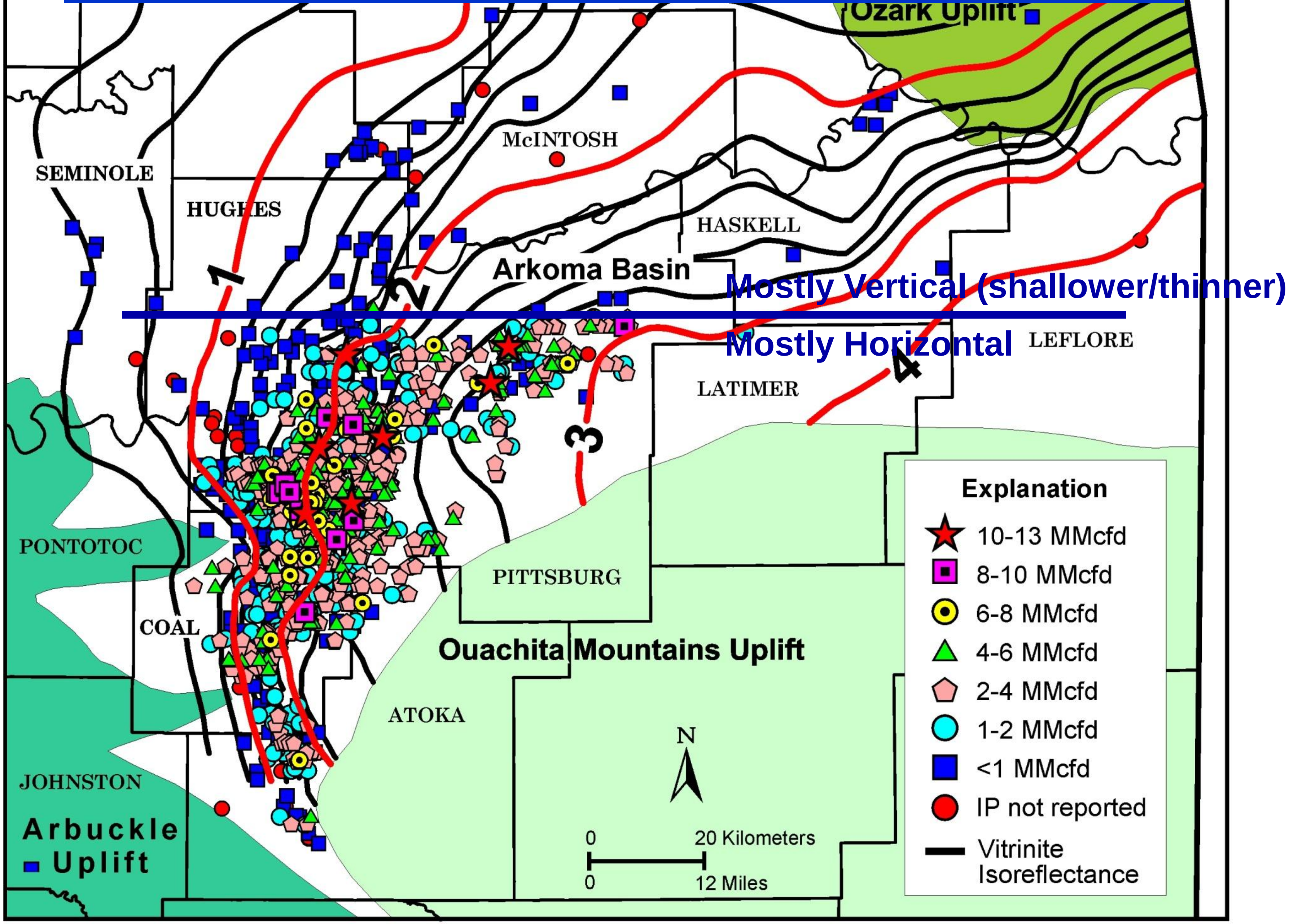
Mississippian and Older Outcrop Area (different than Ozark Uplift Province boundary)

Map prepared by R. Vance Hall using Petra

Cardott, in preparation


Woodford Shale
Structure &
Vitrinite Isoreflectance Map
1
2
3
4
-5,000
-10,000
-15,000
Major Structure
Structure
Major Isoreflectance
Isoreflectance
Thrust Faults

Arkoma Basin Initial Potential

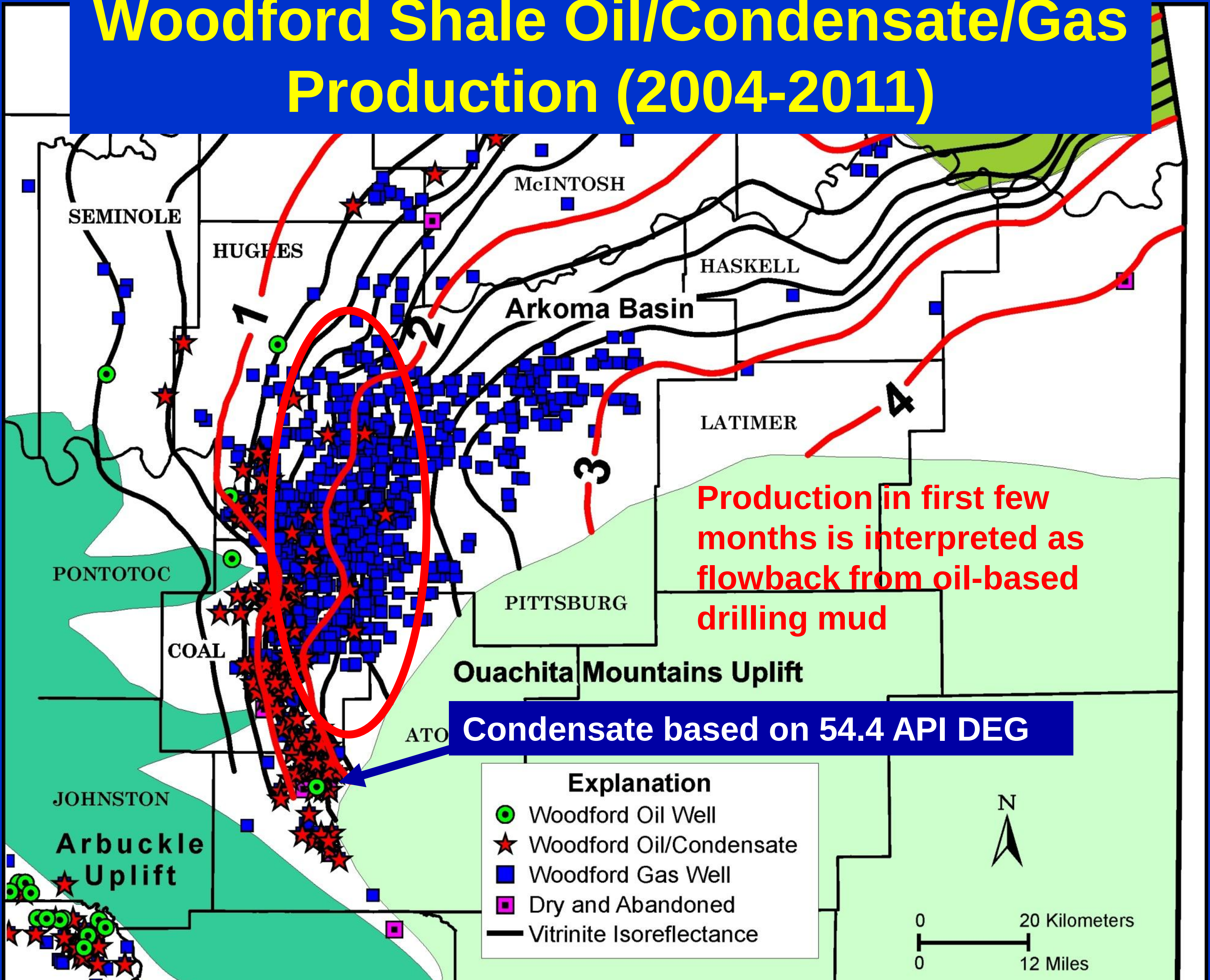


Woodford Oil/Condensate/Gas Production Caveat

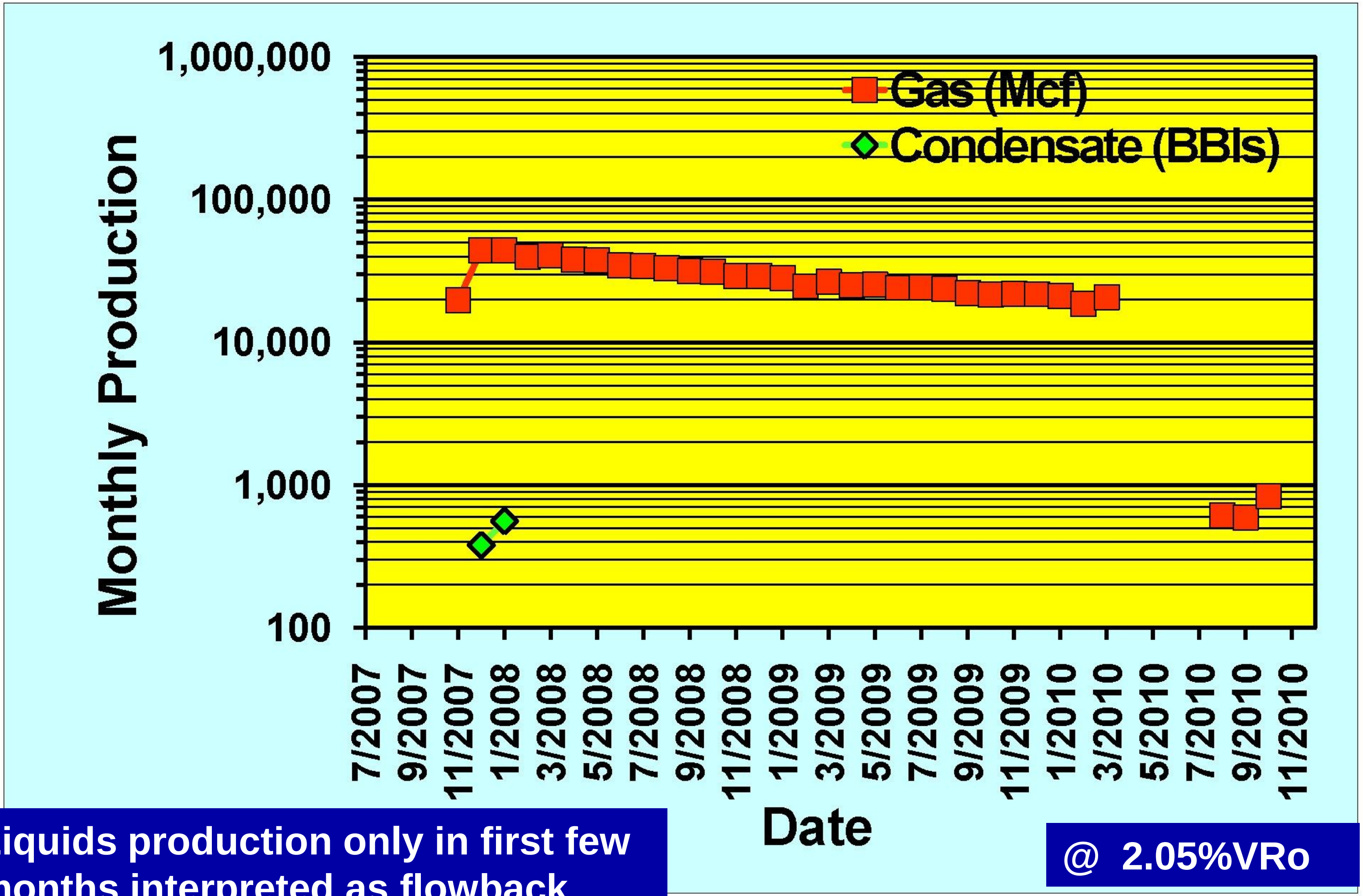
- **Gas** production is reported by the Oklahoma Corporation Commission by **WELL**.
- **Oil/condensate** production is reported by the Oklahoma Tax Commission by **LEASE** [production by well is only on single-well leases]

(Production data supplied by PI/Dwights LLC, © 2011, IHS Energy Group)

Woodford Shale Oil/Condensate/Gas Production (2004-2011)



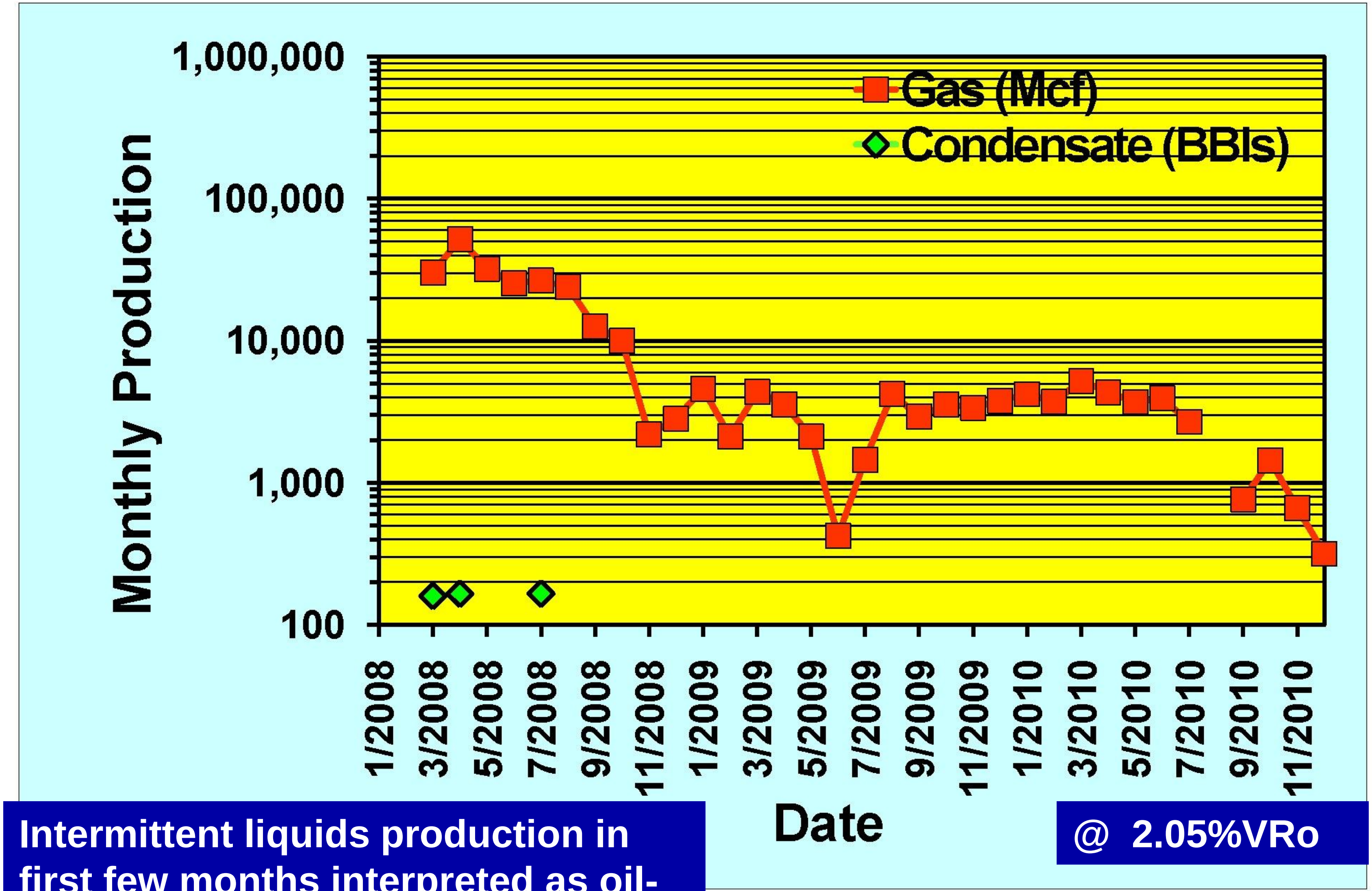
(1) Newfield 3H-36 Genevieve (36-6N-11E; Hughes Co.; IP 2,118 Mcfd)



Liquids production only in first few months interpreted as flowback

@ 2.05%VRo

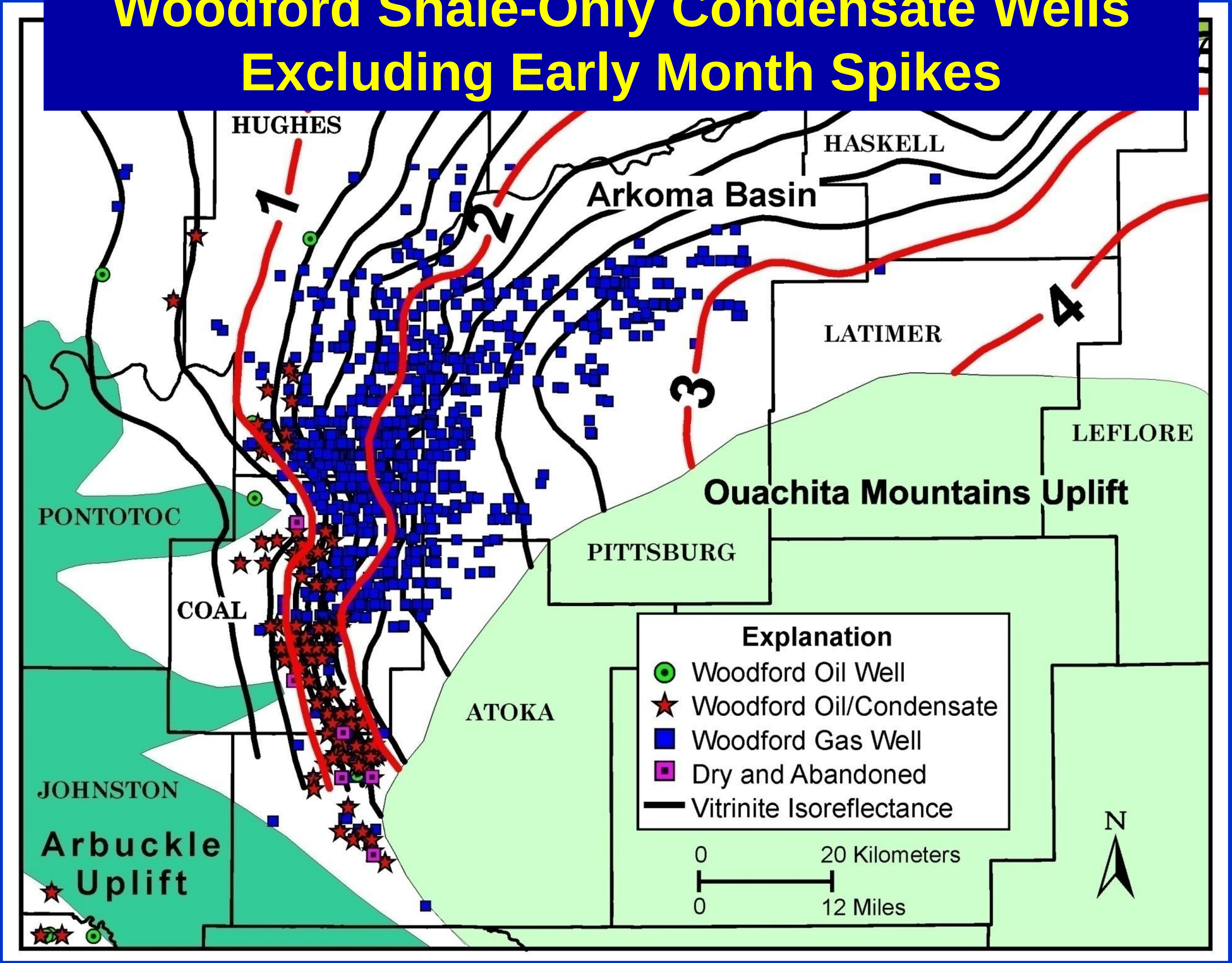
(2) Cimarex 3-34H Hall
(34-3N-11E; Coal Co.; IP 1,740 Mcfd)

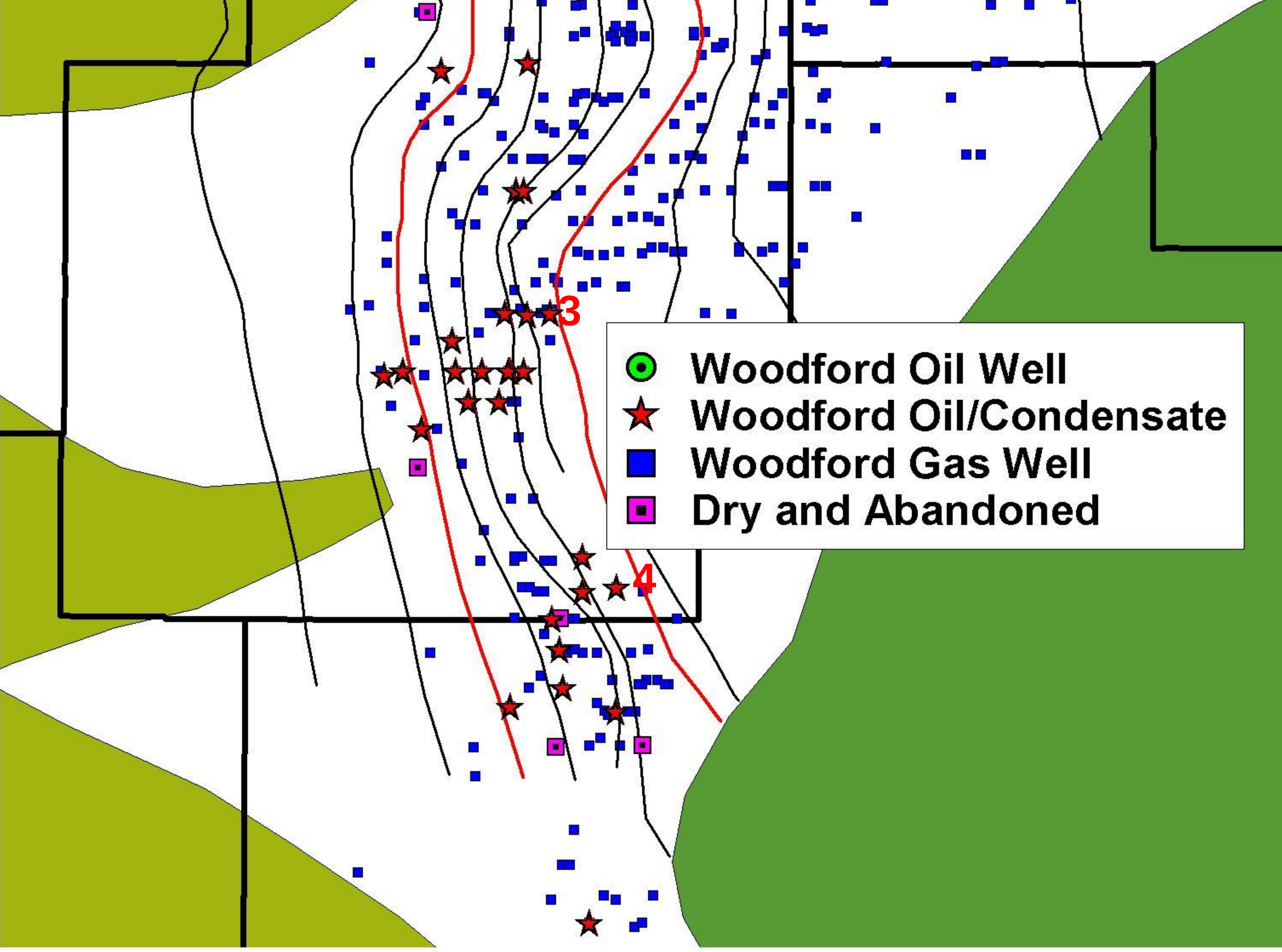


Intermittent liquids production in first few months interpreted as oil-based drilling mud flowback

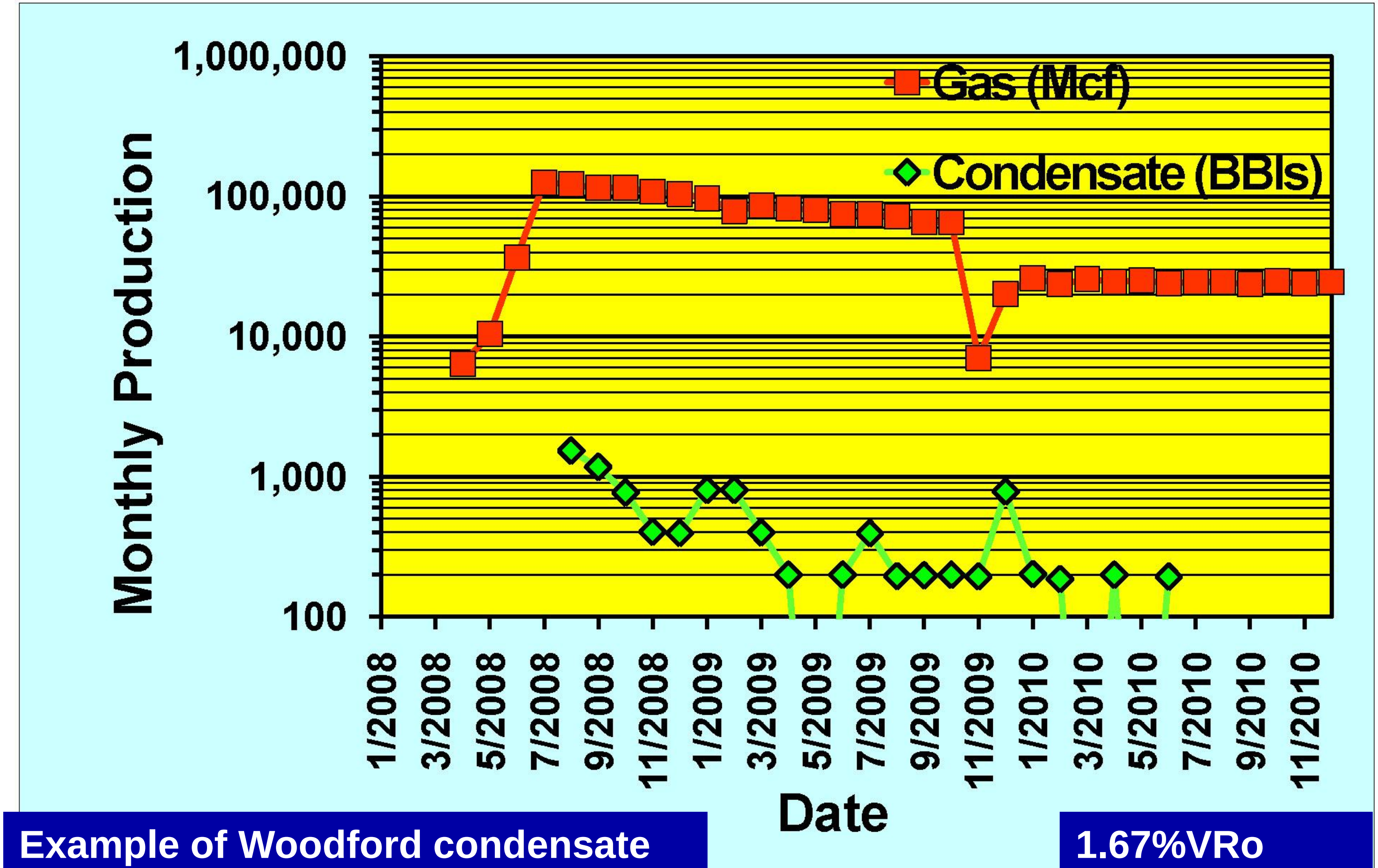
@ 2.05%VRo

Woodford Shale-Only Condensate Wells Excluding Early Month Spikes




3
4
Woodford Oil Well
Woodford Oil/Condensate
Woodford Gas Well
Dry and Abandoned

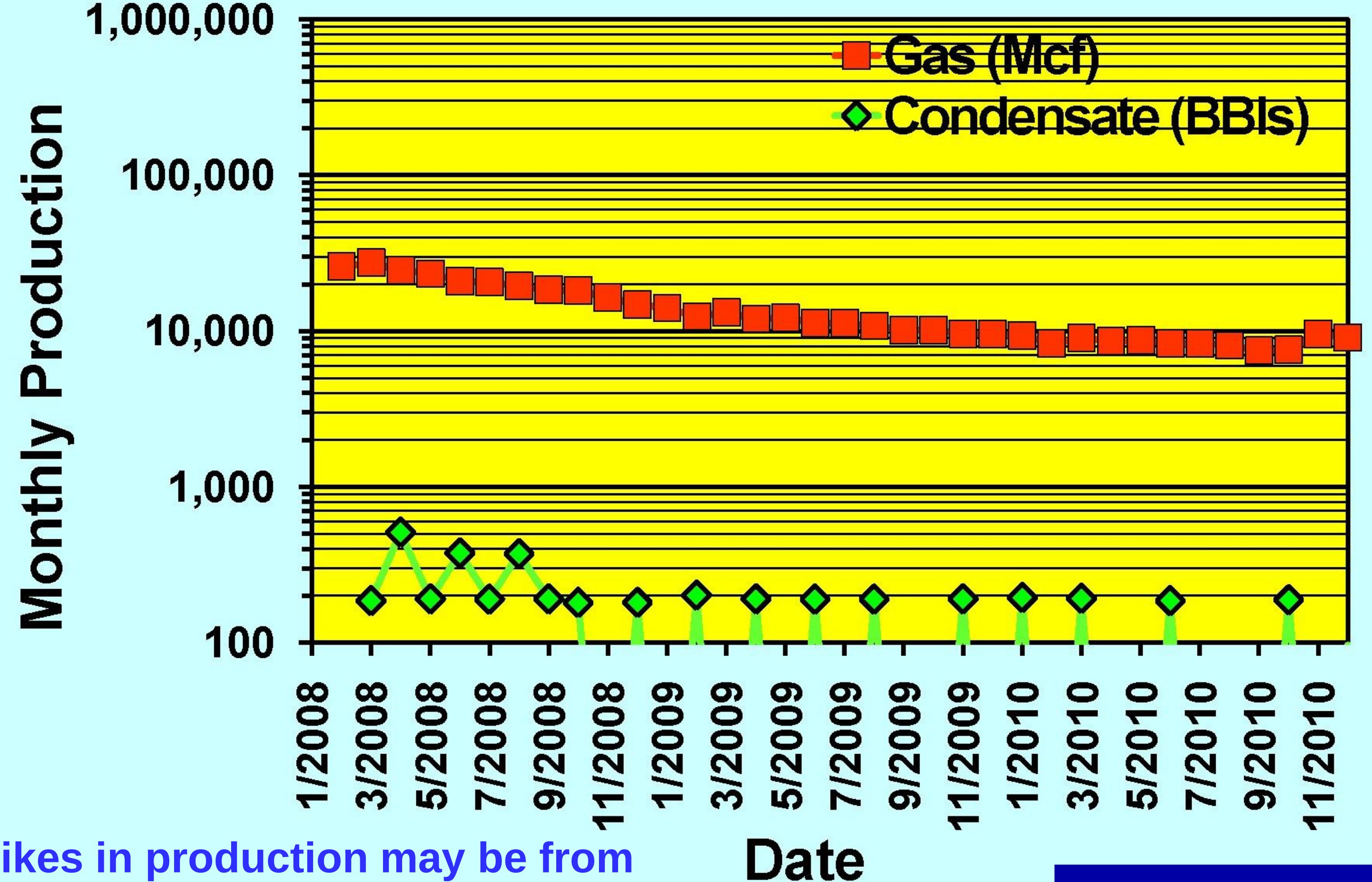
(3) St. Mary Land & Exploration 3-14 Marvin (14-1N-10E; Coal Co.; IP 3,125 Mcfd)



Example of Woodford condensate produced later in well's life

1.67%VRo

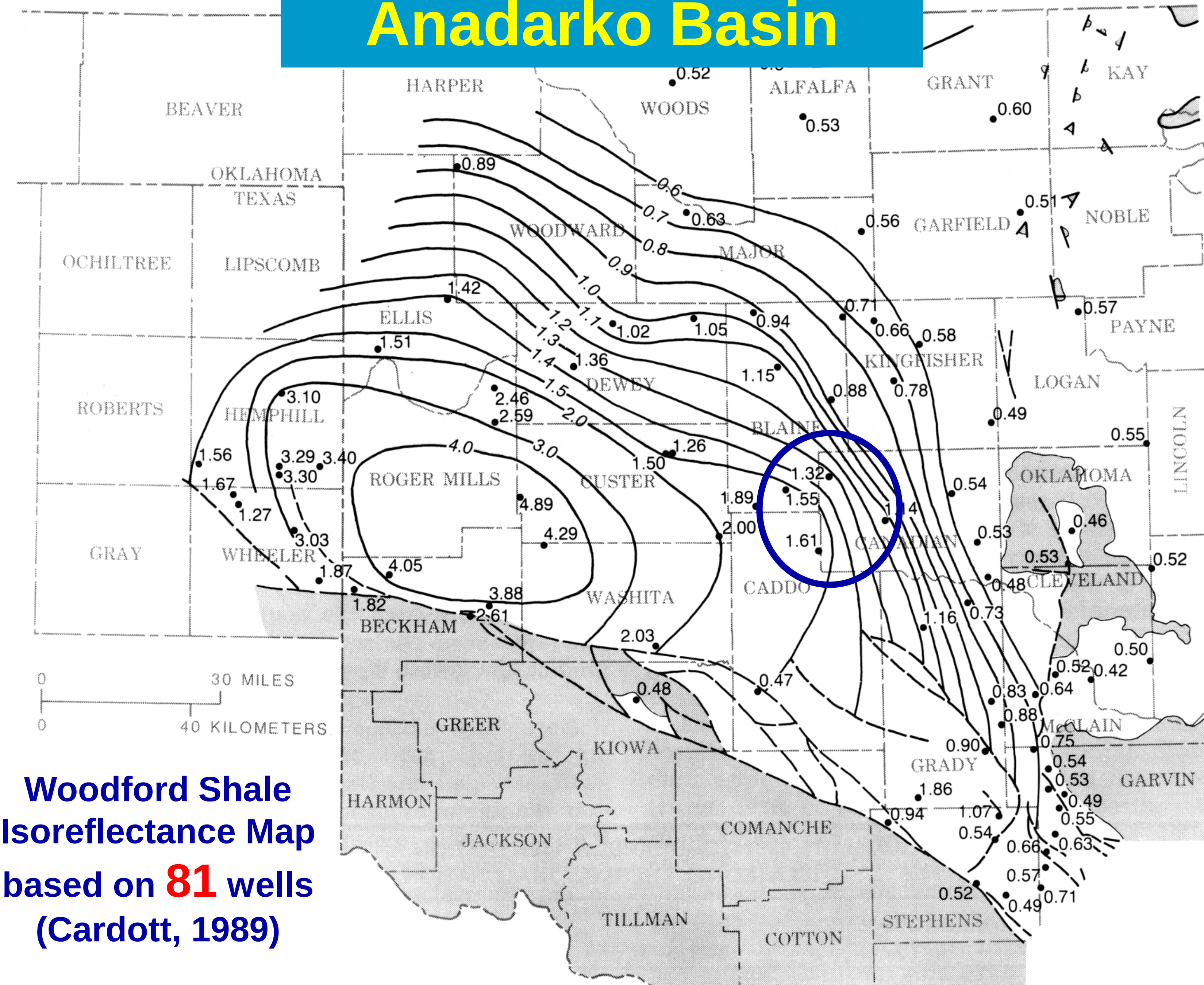
(4) Antero 30-1H Harris
(30-1S-11E; Coal Co.; IP 1,334 Mcfd)



Spikes in production may be from intermittent trucking

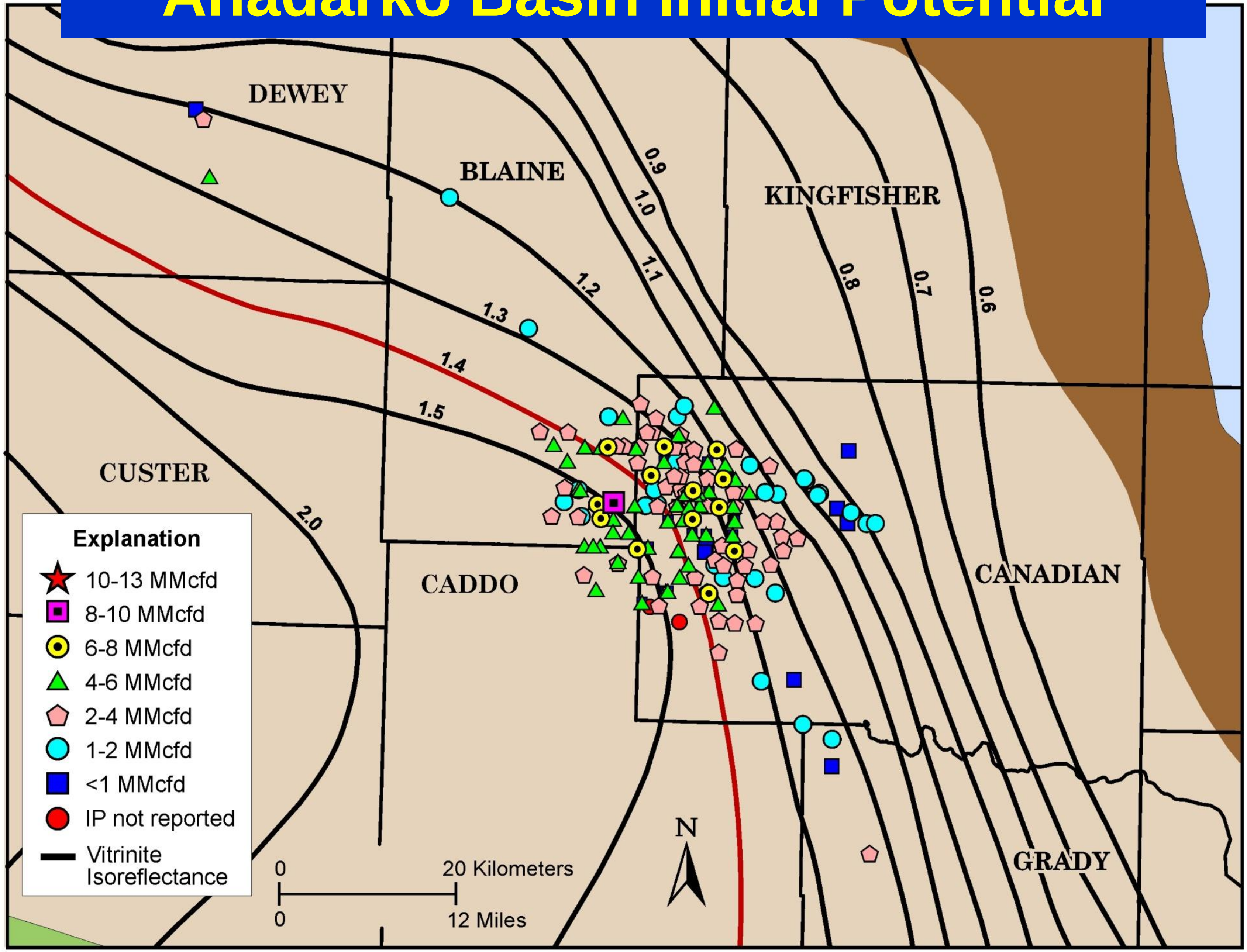
@ 1.6%VRo

Anadarko Basin

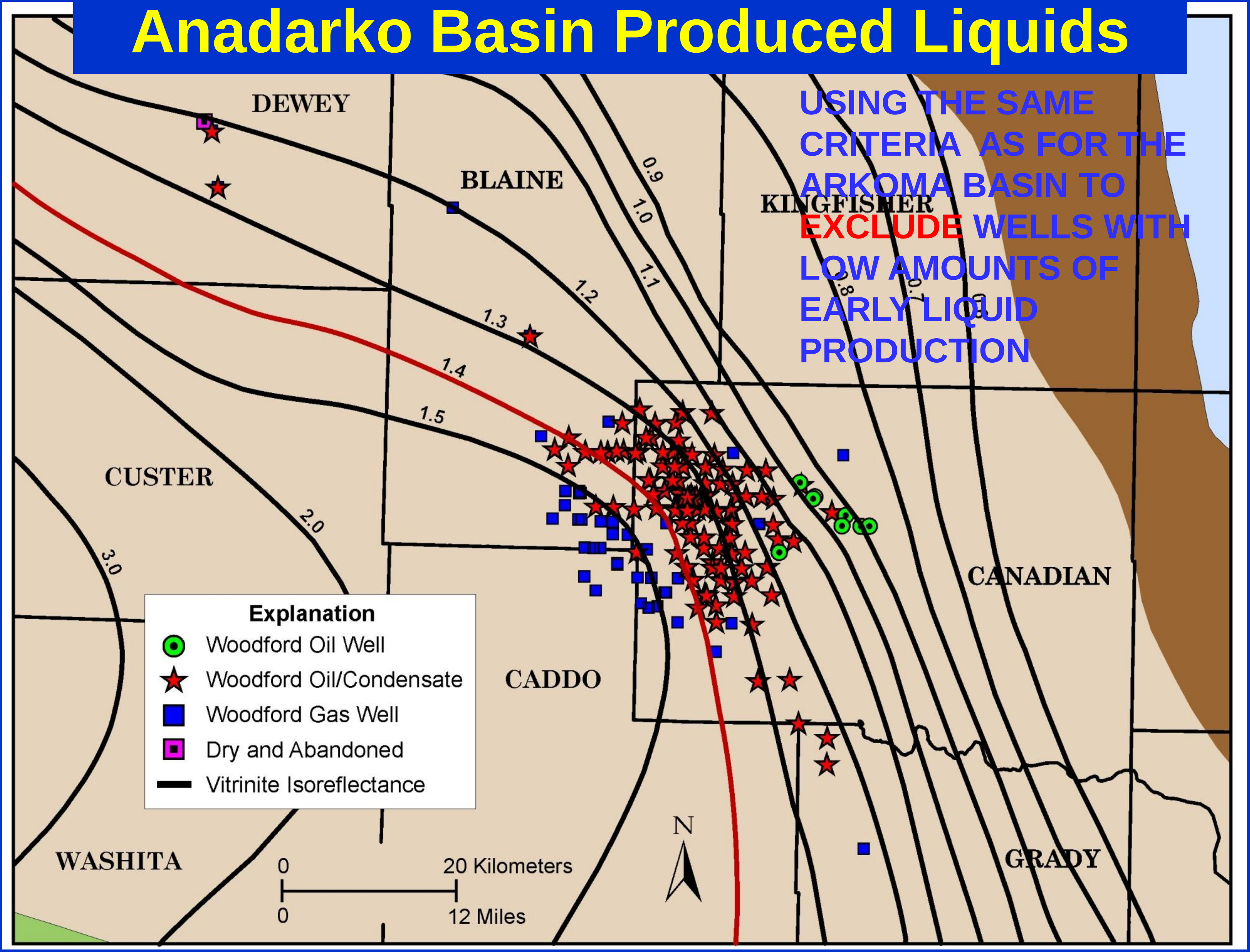


Woodford Shale Isoreflectance Map based on **81 wells (Cardott, 1989)**

Anadarko Basin Initial Potential

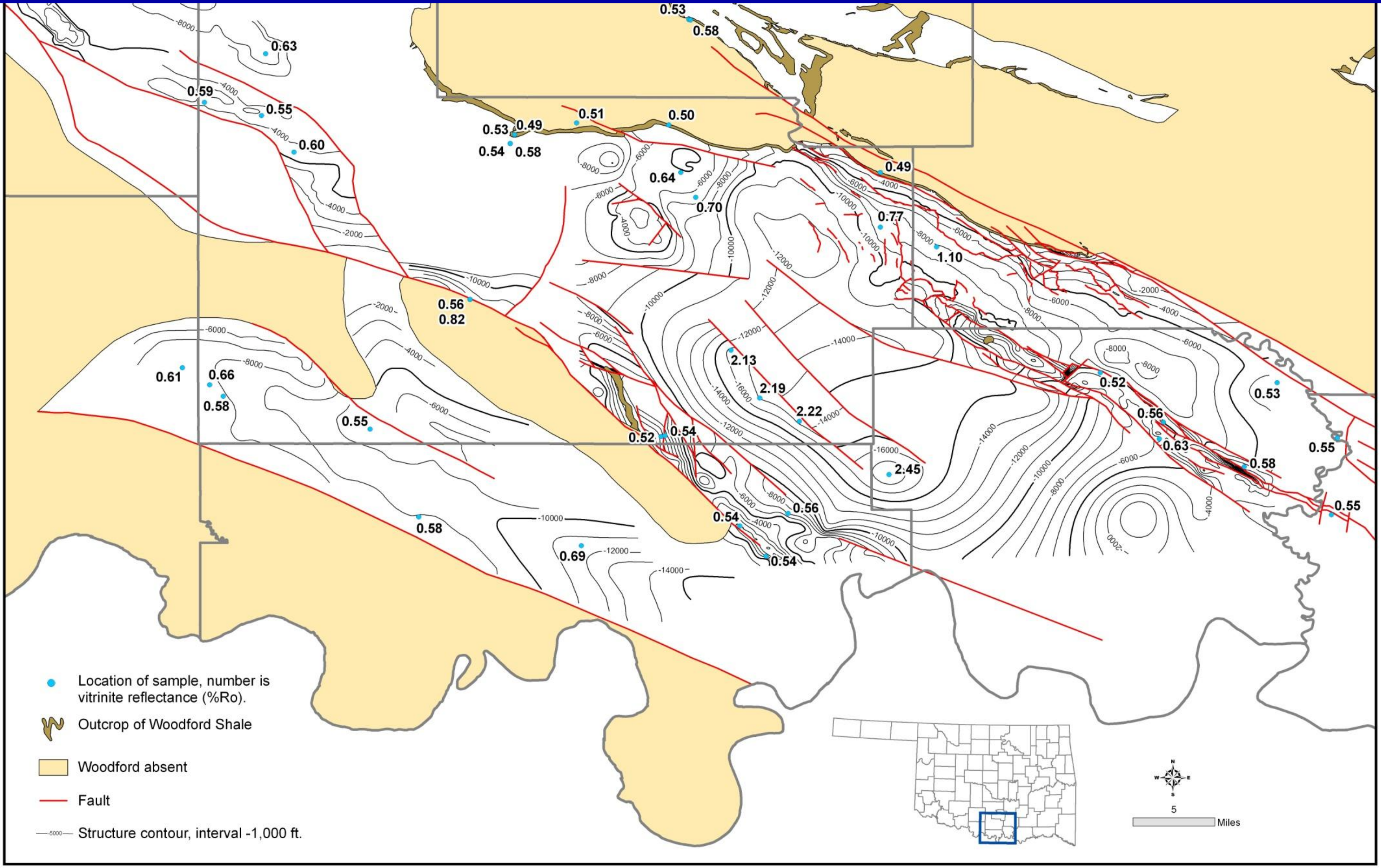


Anadarko Basin Produced Liquids



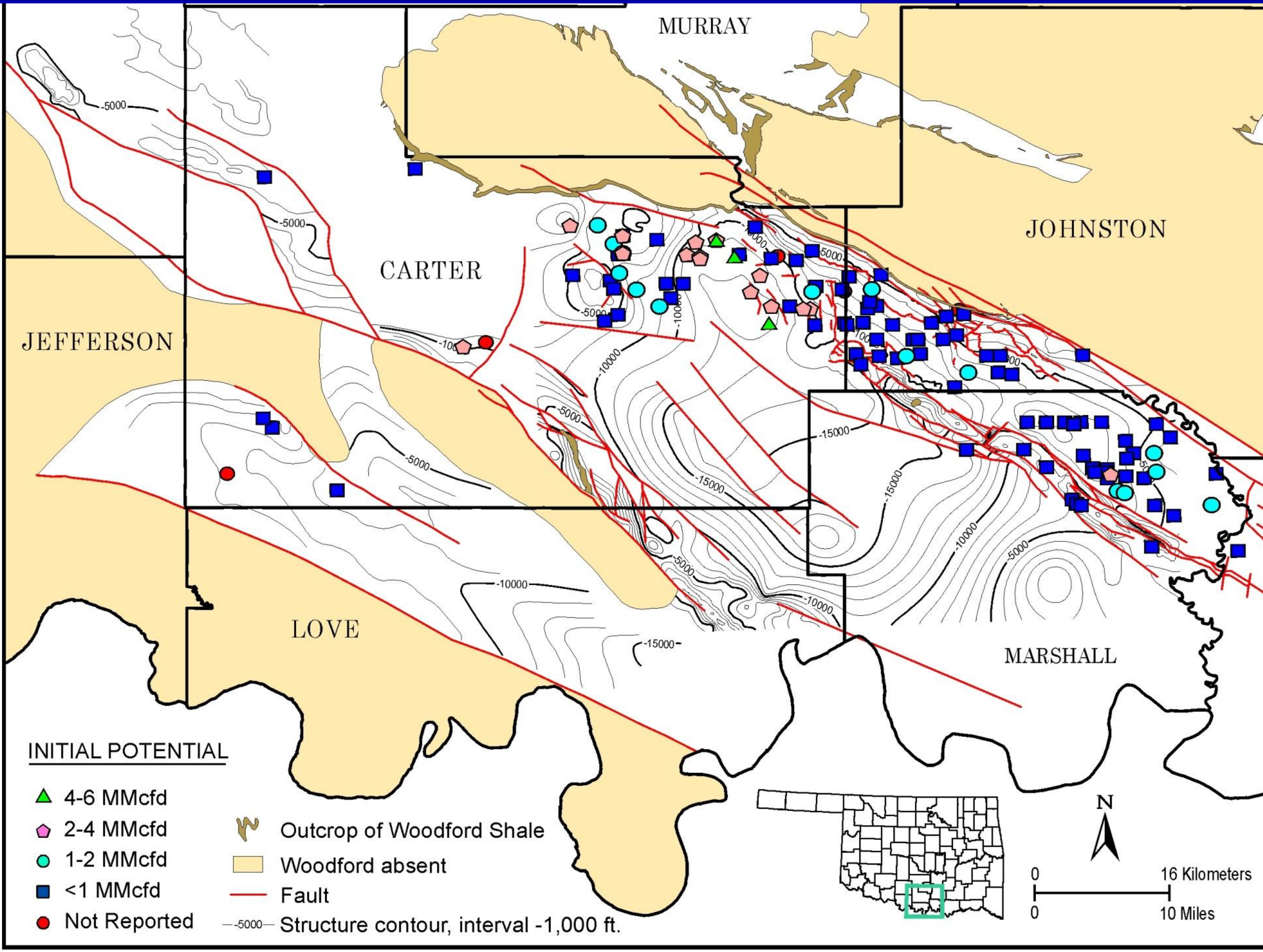
USING THE SAME CRITERIA AS FOR THE ARKOMA BASIN TO EXCLUDE WELLS WITH LOW AMOUNTS OF EARLY LIQUID PRODUCTION

Woodford Shale VRo on Structure



Vitrinite reflectance of Woodford Shale in southern Oklahoma on Woodford Shale structure map (structure modified from Carlyle Hinshaw (1999) and Wagner & Brown (2010); VRo data by Cardott).

Woodford Shale IPs on Structure



Shale Oil Plays

The Bakken Shale (Late Devonian-Early Mississippian; North Dakota & Montana) is the analog for shale oil plays. However, the reservoir of the Bakken is a permeable, non-shale middle member.

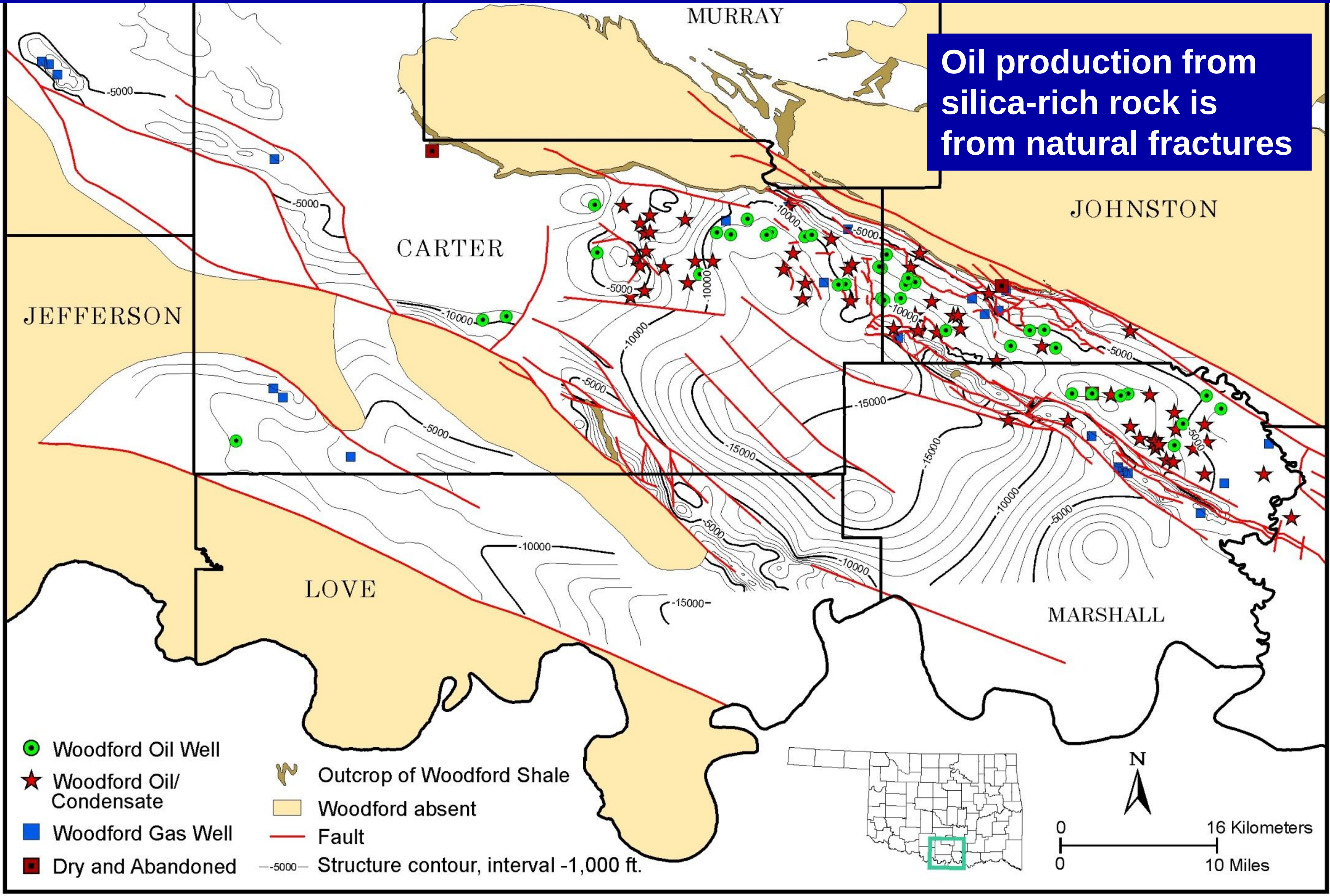
Other formations considered shale oil plays (mostly carbonates) are the Eagle Ford Shale (Late Cretaceous; Texas) and Niobrara Shale (Late Cretaceous; Rocky Mountains).

"The preferred rock type for a shale-oil play is a hybrid—that is, a formation with a good mix of non-shale lithologies, particularly carbonates"

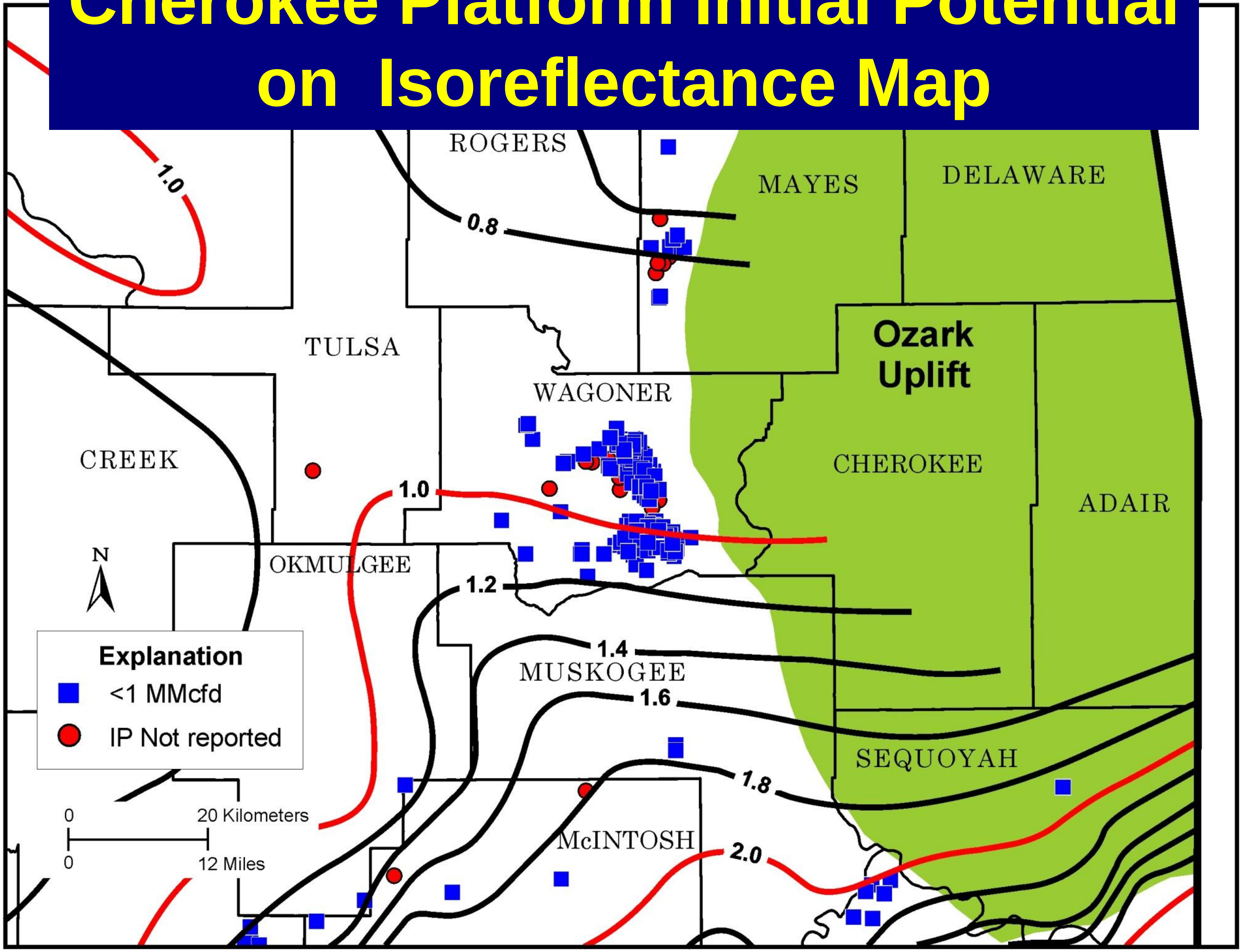
(Darbonne, 2011)

Woodford Production on Structure

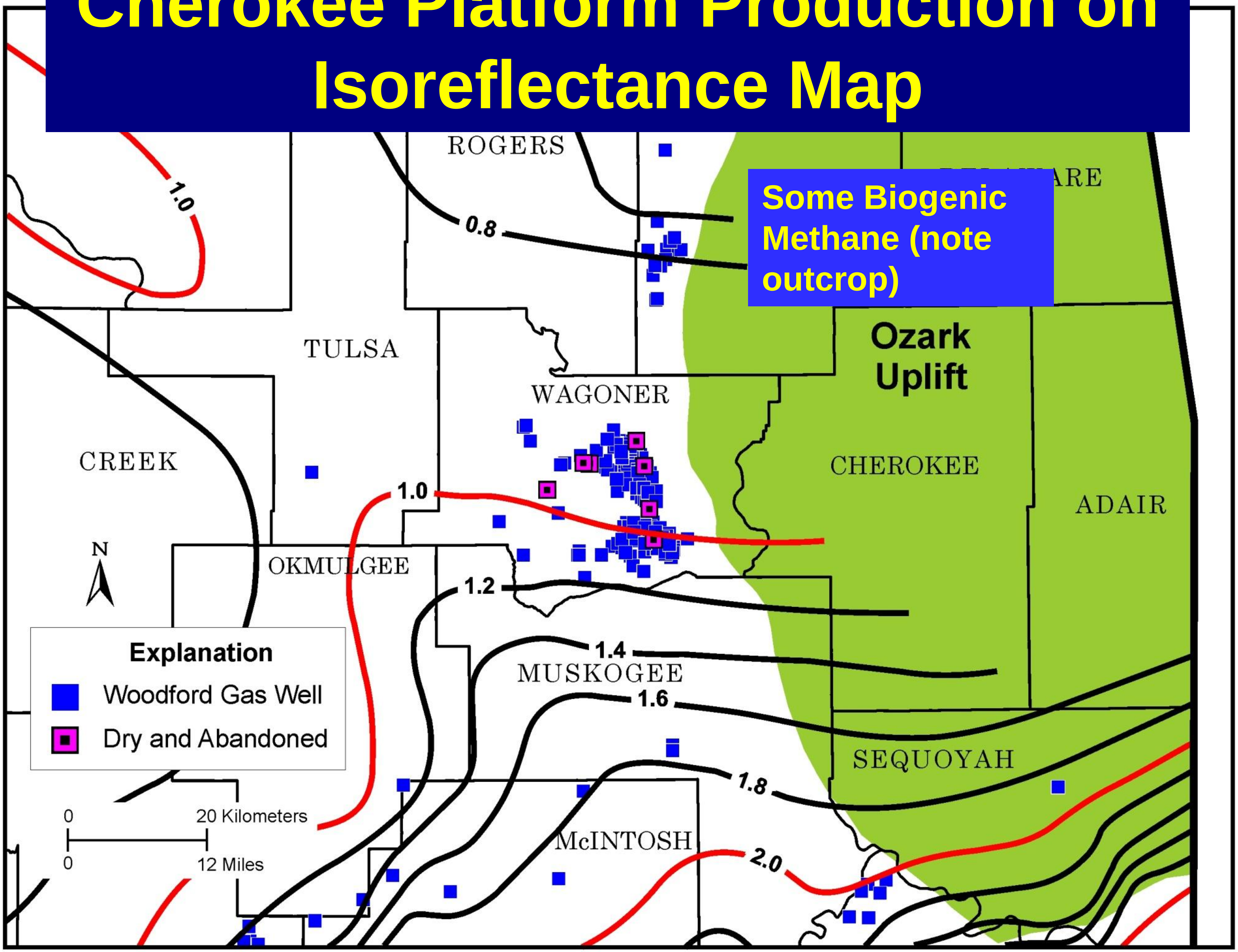
Oil production from silica-rich rock is from natural fractures



Cherokee Platform Initial Potential on Isoreflectance Map

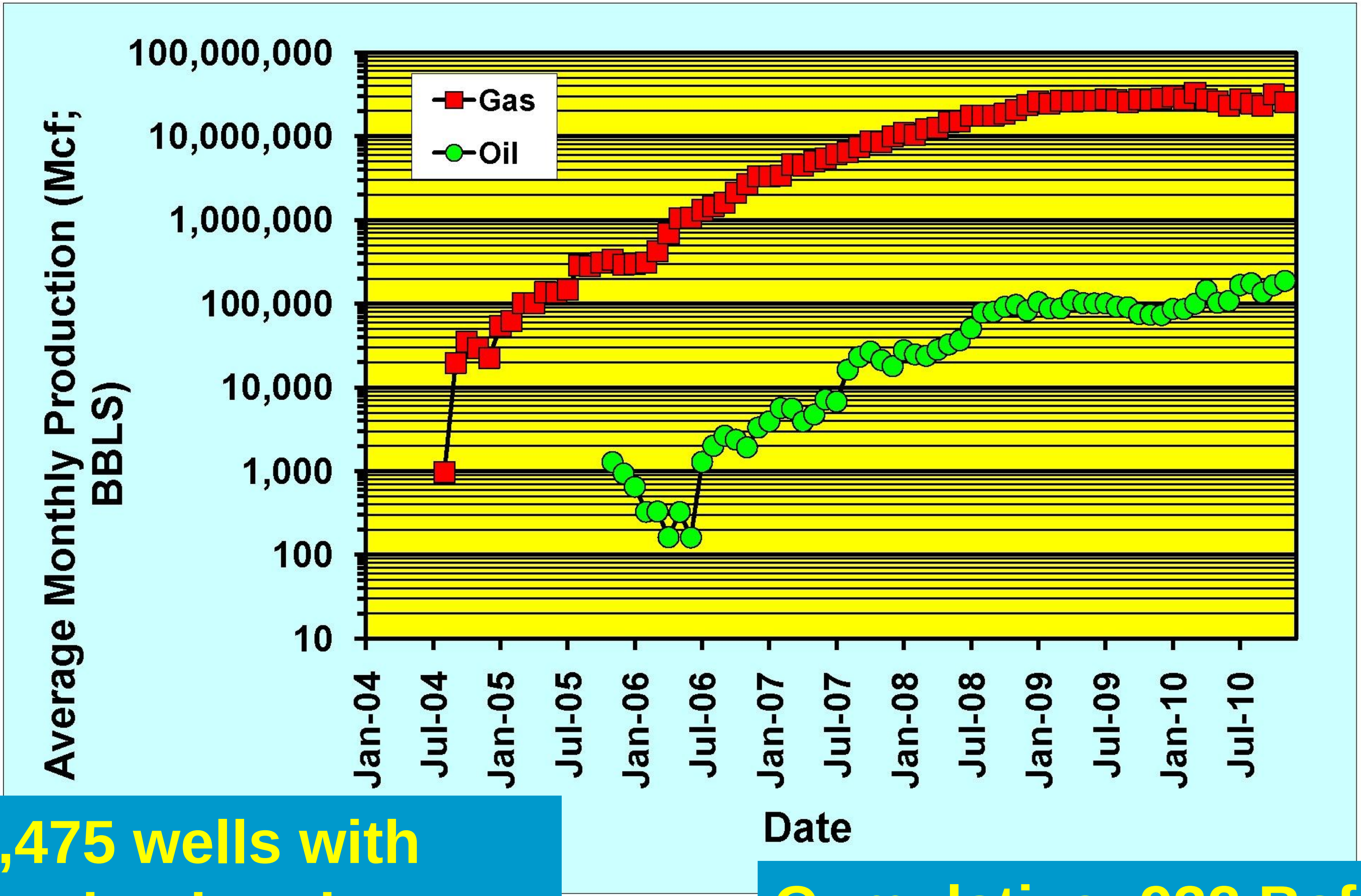


Cherokee Platform Production on Isoreflectance Map



Some Biogenic Methane (note outcrop)

Woodford-Only Production



1,475 wells with production data; excludes 55 OWWO

Cumulative: 932 Bcf, 3,701,330 Bo

Other useful petrographic thermal maturity indicators:

- Fluorescence color of telalginite
  [qualitative indicator in oil window]
  (green, greenish-yellow, yellow, orange, extinguished)
- Bitumen reflectance

"The primary mechanism of gas production from shales is the fracture network in the reservoir. Gas residing in the very tight matrix system is forced to flow into the fracture network, first through chemical desorption and then through diffusion, to travel to the matrix/fracture interface." (Biswas, 2011)

What is the potential for gas storage and diffusion within the organic network in shale?

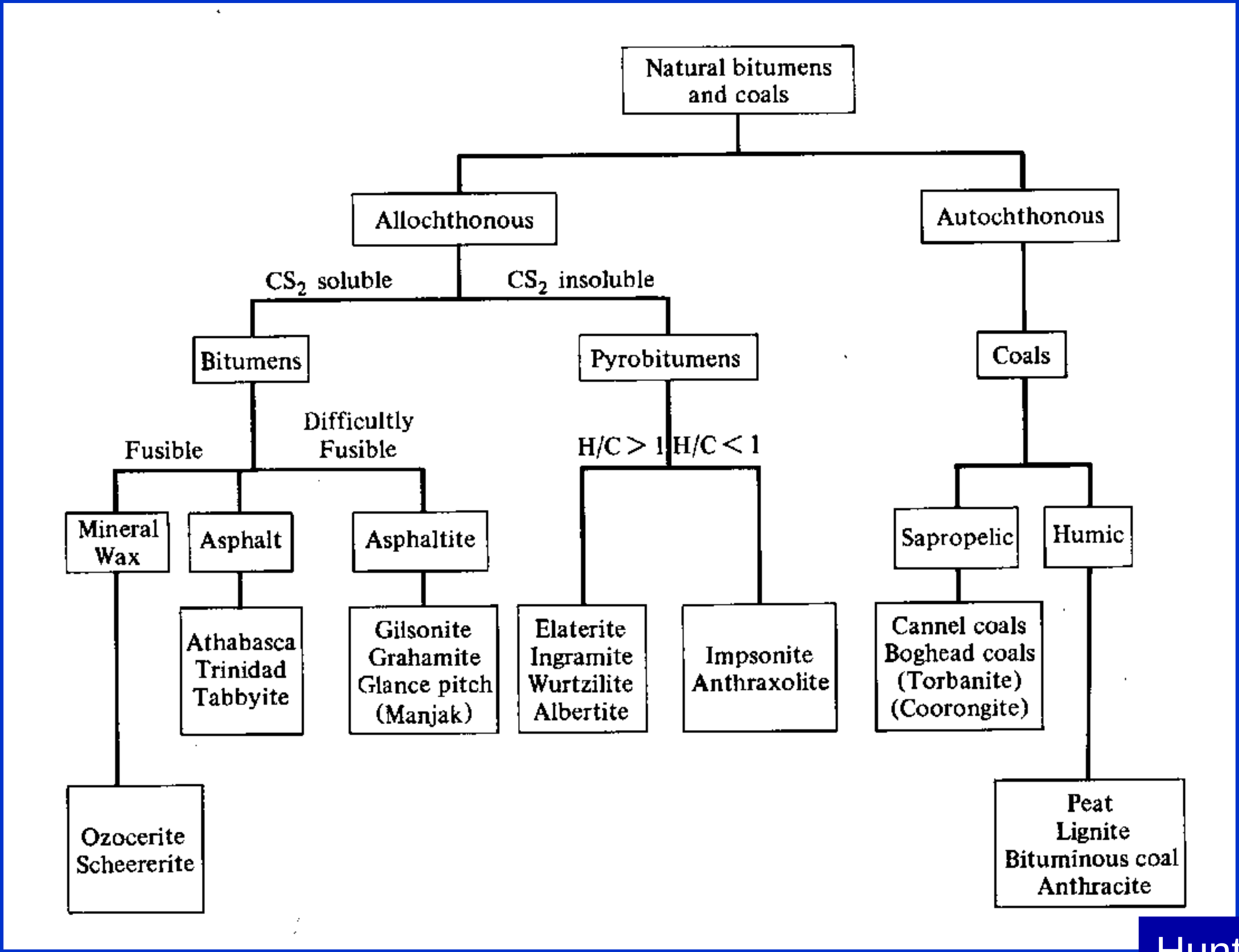
Importance of Bitumen to Gas-Shale Plays

- **Thermal Maturity Indicator**
- **Porous sites for gas storage and migration**

Bitumen is defined as organic matter that is soluble in organic solvents (e.g., carbon disulphide). There are many names for this type of organic matter:

Bitumen
Solid Bitumen
Migrabitumen
Solid Hydrocarbon
Asphaltite
Asphaltic Pyrobitumen

Generic Bitumen Classification



Hunt (1979)

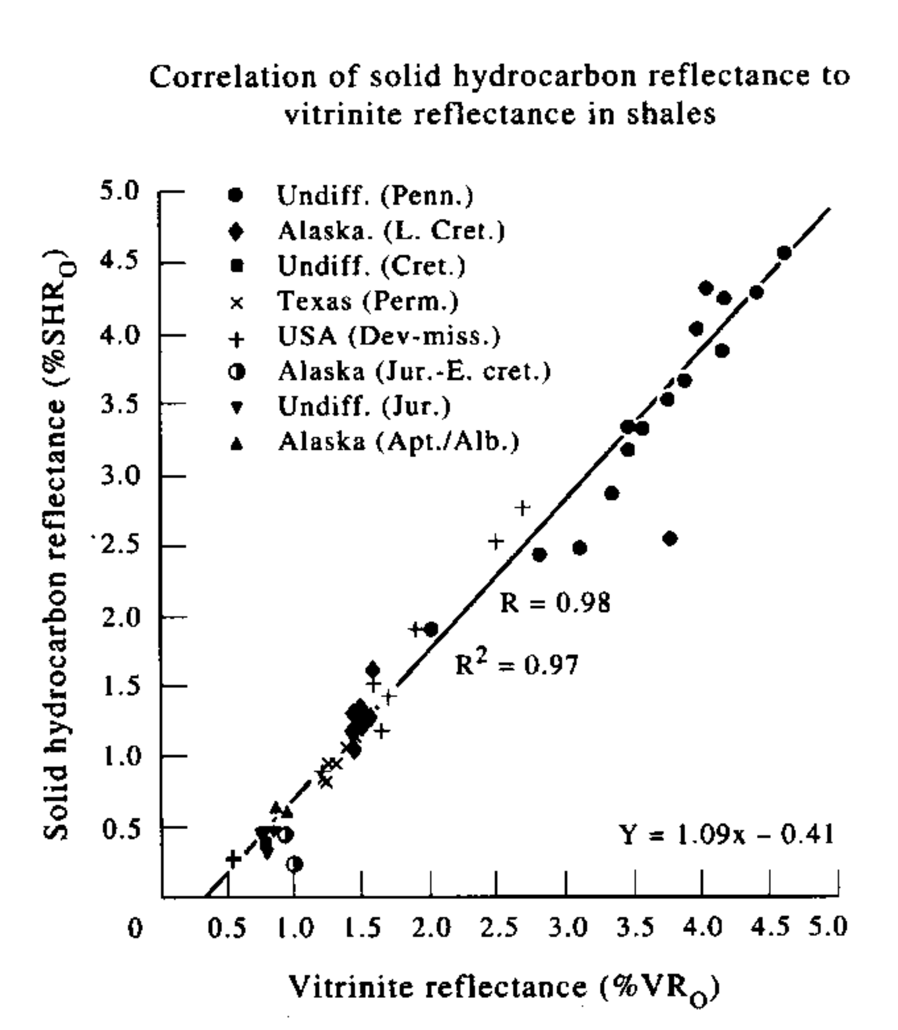
Genetic Bitumen Classification

- **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]
- **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.

[solid residue of primary oil migration]

Curiale (1986)

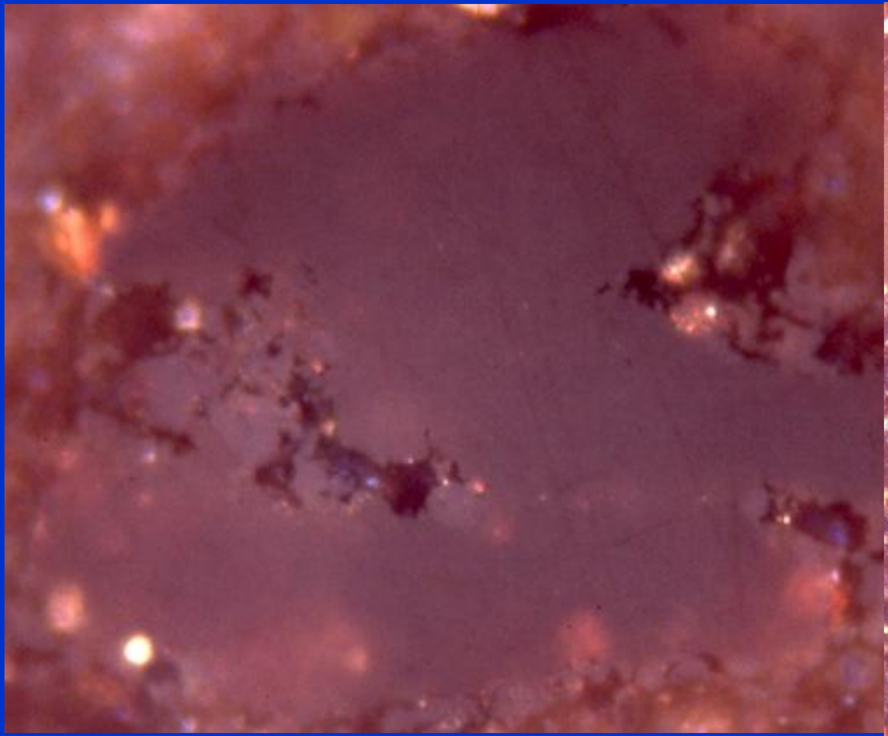
Use of pre-oil solid bitumen as thermal maturity indicator following "solid hydrocarbon" reflectance to vitrinite reflectance equivalent regression equation of Landis and Castaño (1994)



VRE = (BRo + 0.41)/1.09

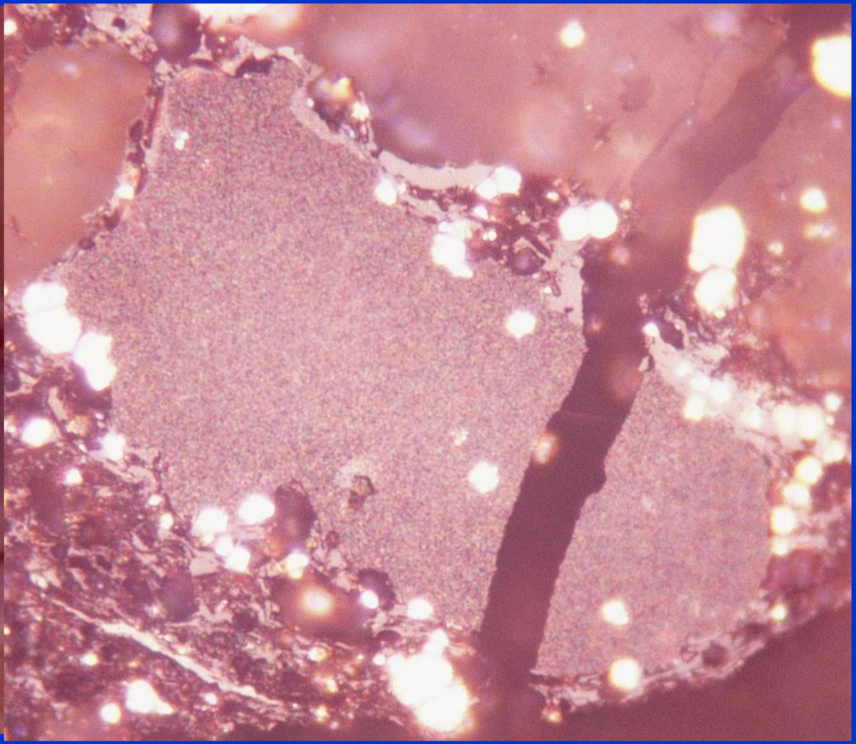
Two Common Pre-Oil Bitumen Optical Forms Based on Landis and Castaño (1994) [regression equation is based on homogenous form]

Homogenous form



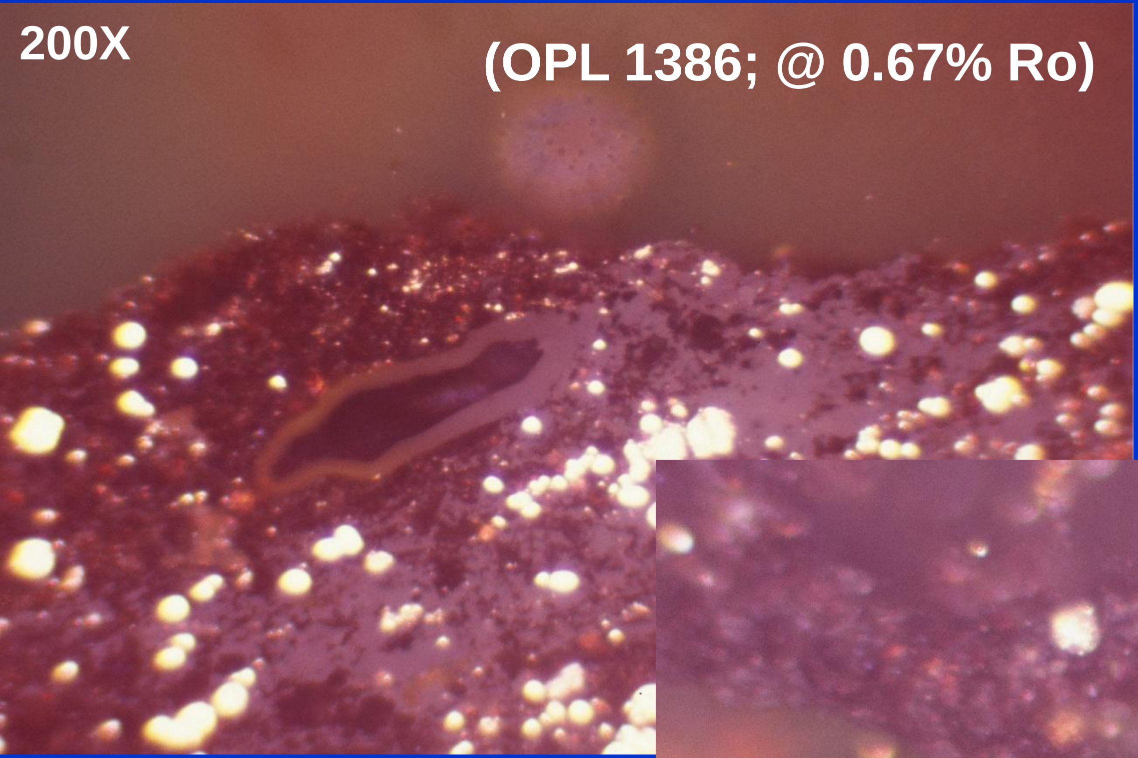
OPL 1333 500X

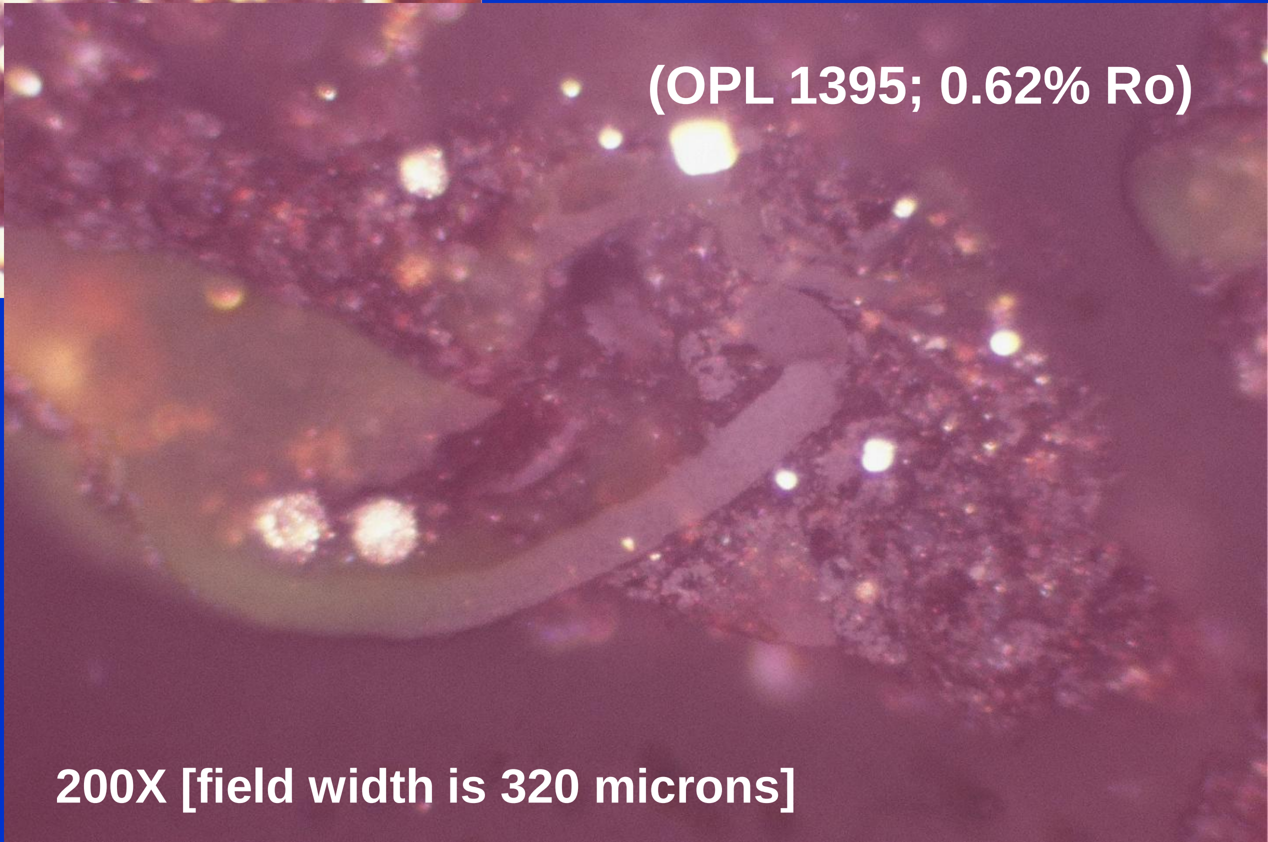
Granular form



OPL 1076 500X

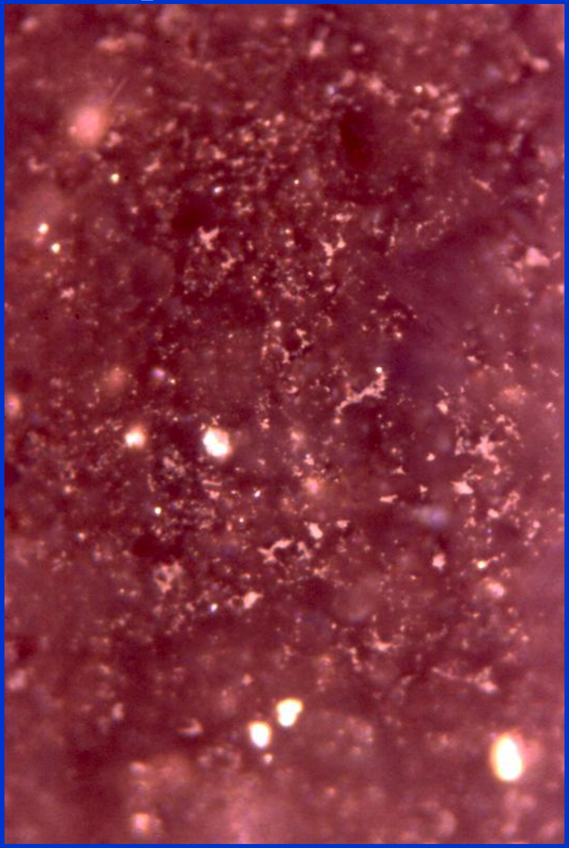
Formation of Pre-Oil Bitumen from Tasmanites





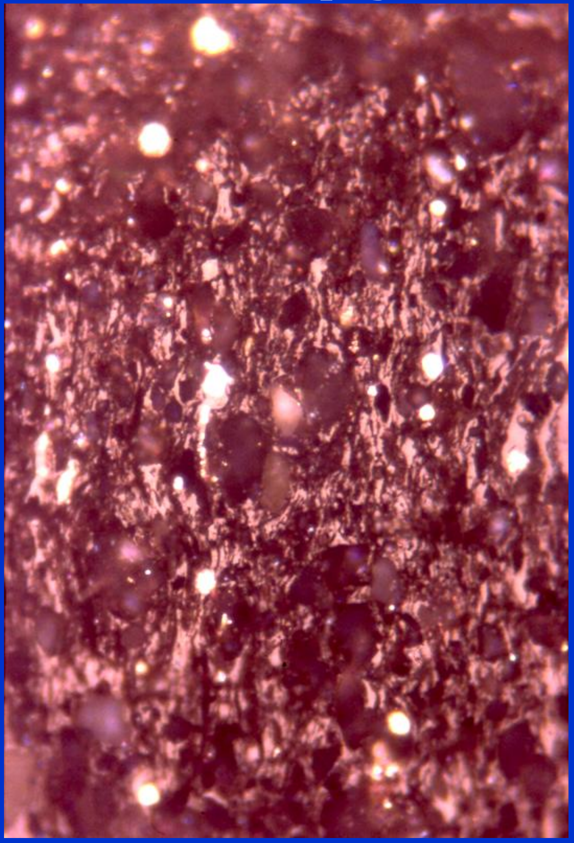
Proposed Post-Oil Bitumen Network Classification (@ 500X)

Speckled



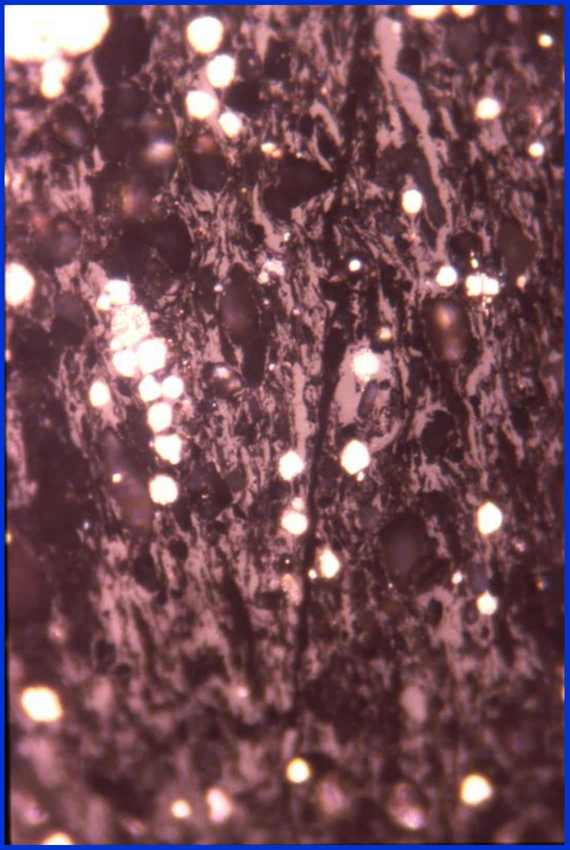
OPL 1368

Wispy



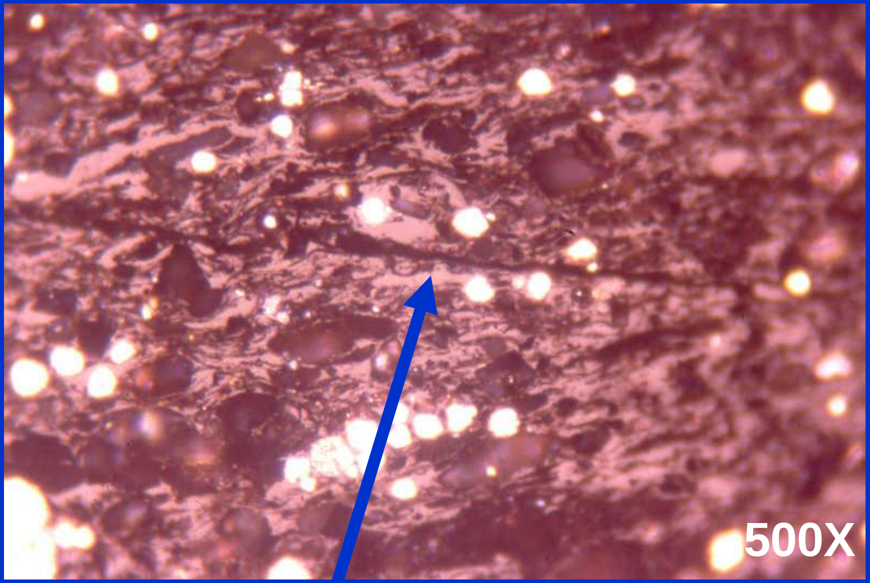
OPL 1372

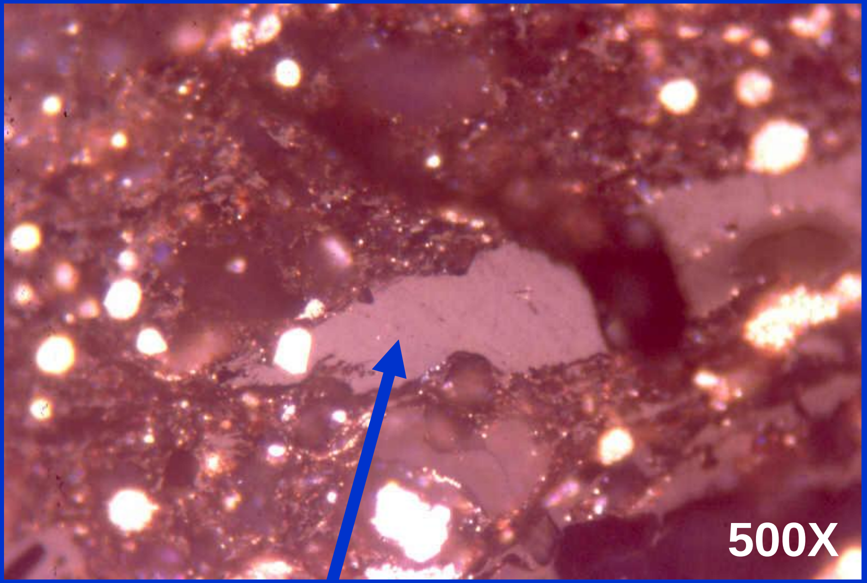
Connected



OPL 1366

Lowest thermal maturity containing post-oil bitumen network (0.85% VRo, n = 35)





Post-Oil Bitumen Connected Network

Vitrinite (0.90% Ro; sample OPL 1366)

[500X field width is 140 microns]

Nanopores associated with "organic matter" using ion milling and SEM (from Loucks and others, 2009)

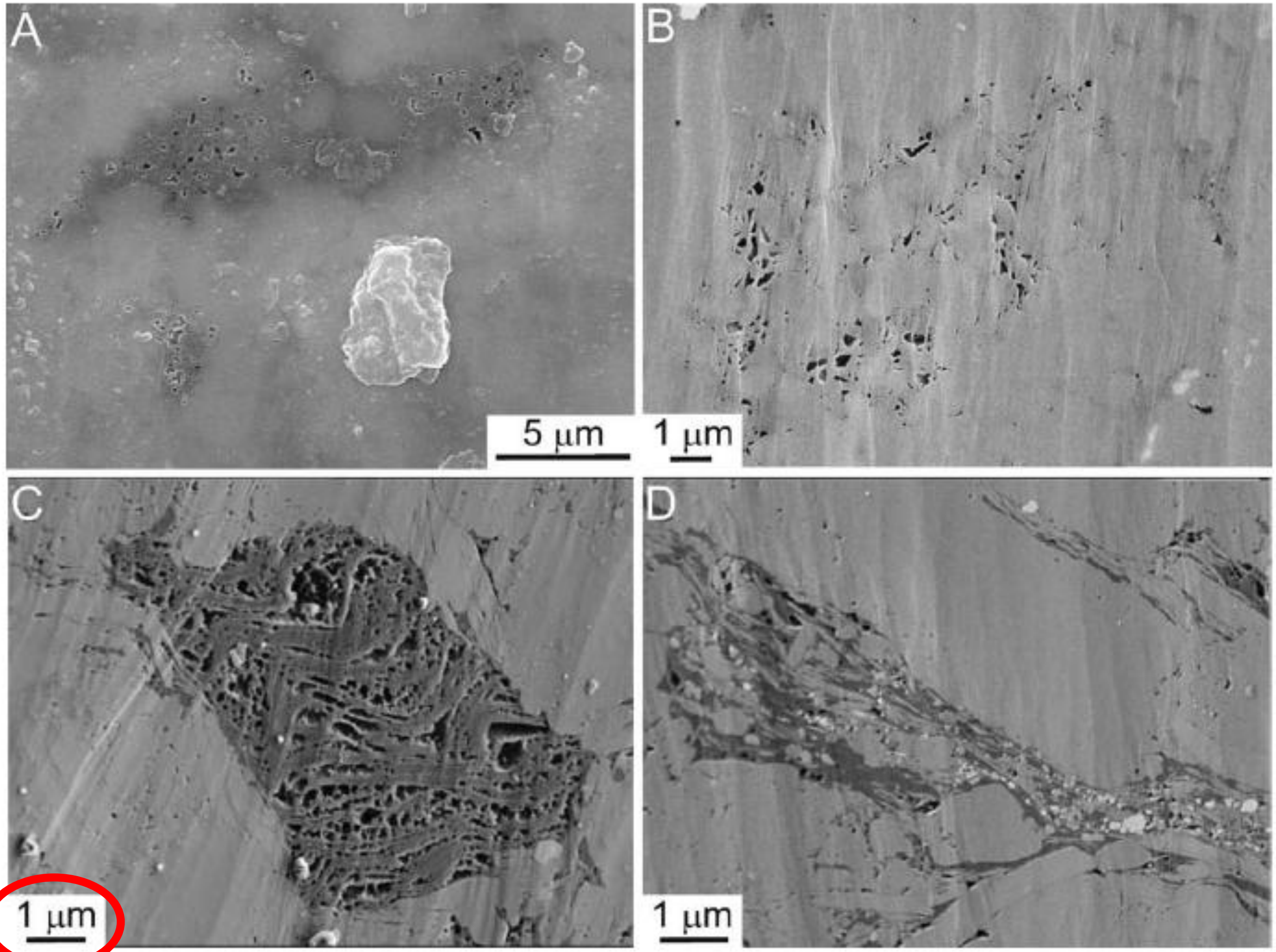


FIG. 5.—Nanopores associated with organic matter in the Barnett Shale. A) Elliptical to complexly rounded nanopores in an organic grain. Darker materials are organics. BSE image. Blakely #1, 2,167.4 m. B) Angular nanopores in a grain of organic matter. SE image. Blakely #1, 2,167.4 m. Accelerating voltage = 10 kV; working distance = 6 mm. C) Rectangular nanopores occurring in aligned convoluted structures. SE image. T.P. Sims #2, ~ 2,324 m. Accelerating voltage = 2 kV; working distance = 3 mm. D) Nanopores associated with disseminated organic matter. Carbon-rich grains are dark gray; nanopores are black. SE image. T.P. Sims #2, ~ 2,324 m. Accelerating voltage = 2 kV; working distance = 2 mm.

Study of Nanoporosity development by Organic Matter Types and Thermal Maturity using SEM backscatter electron imaging of ion milled samples

Working with Mark Curtis (OU) to sample from Known to Unknown

Sample Types:

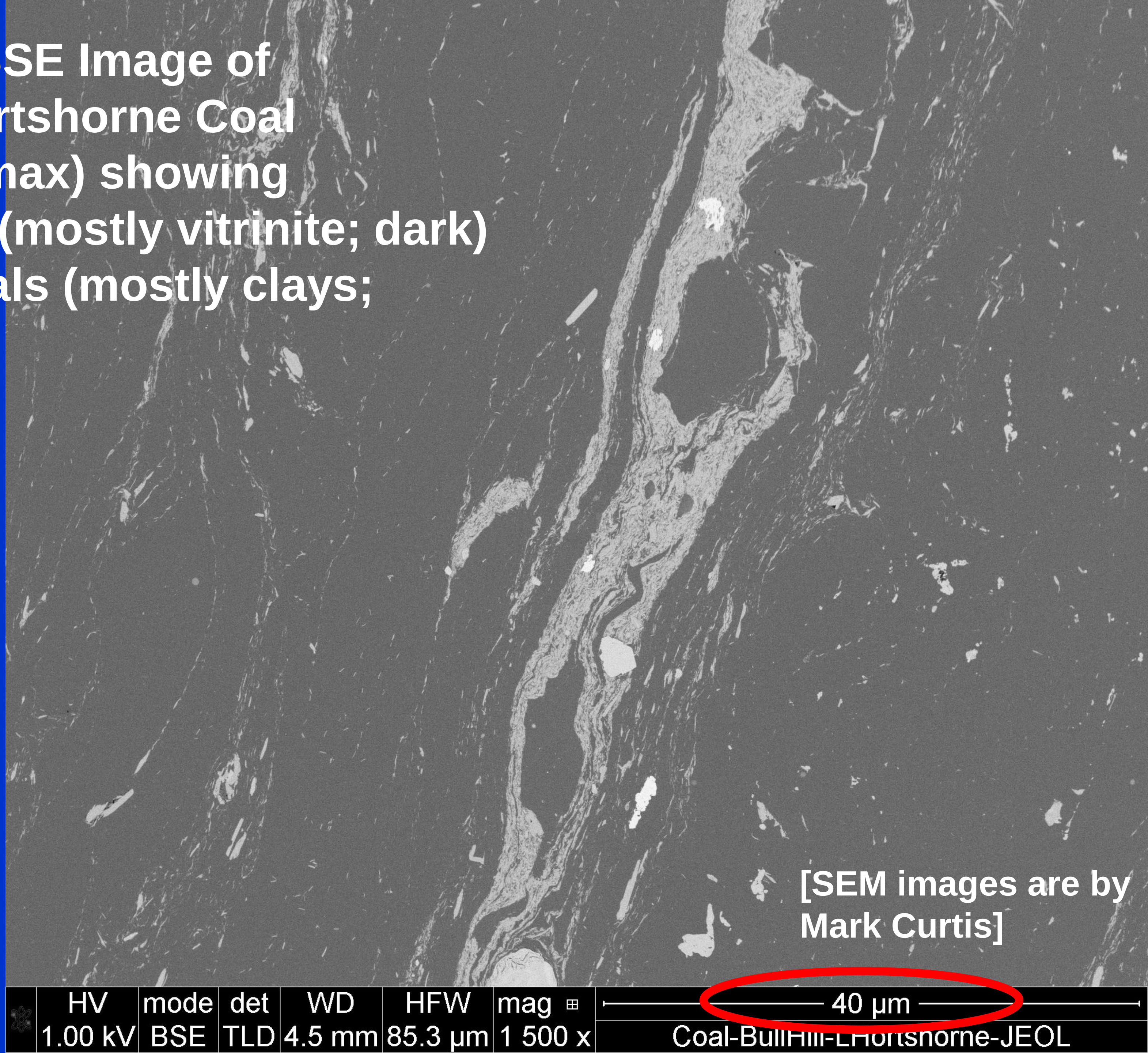
Solid Hydrocarbon vein deposits (grahamite and impsonite): study of post-oil bitumen

Coal (high volatile and medium volatile bituminous): study of maceral groups (vitrinite, liptinite, inertinite)

Woodford Shale:

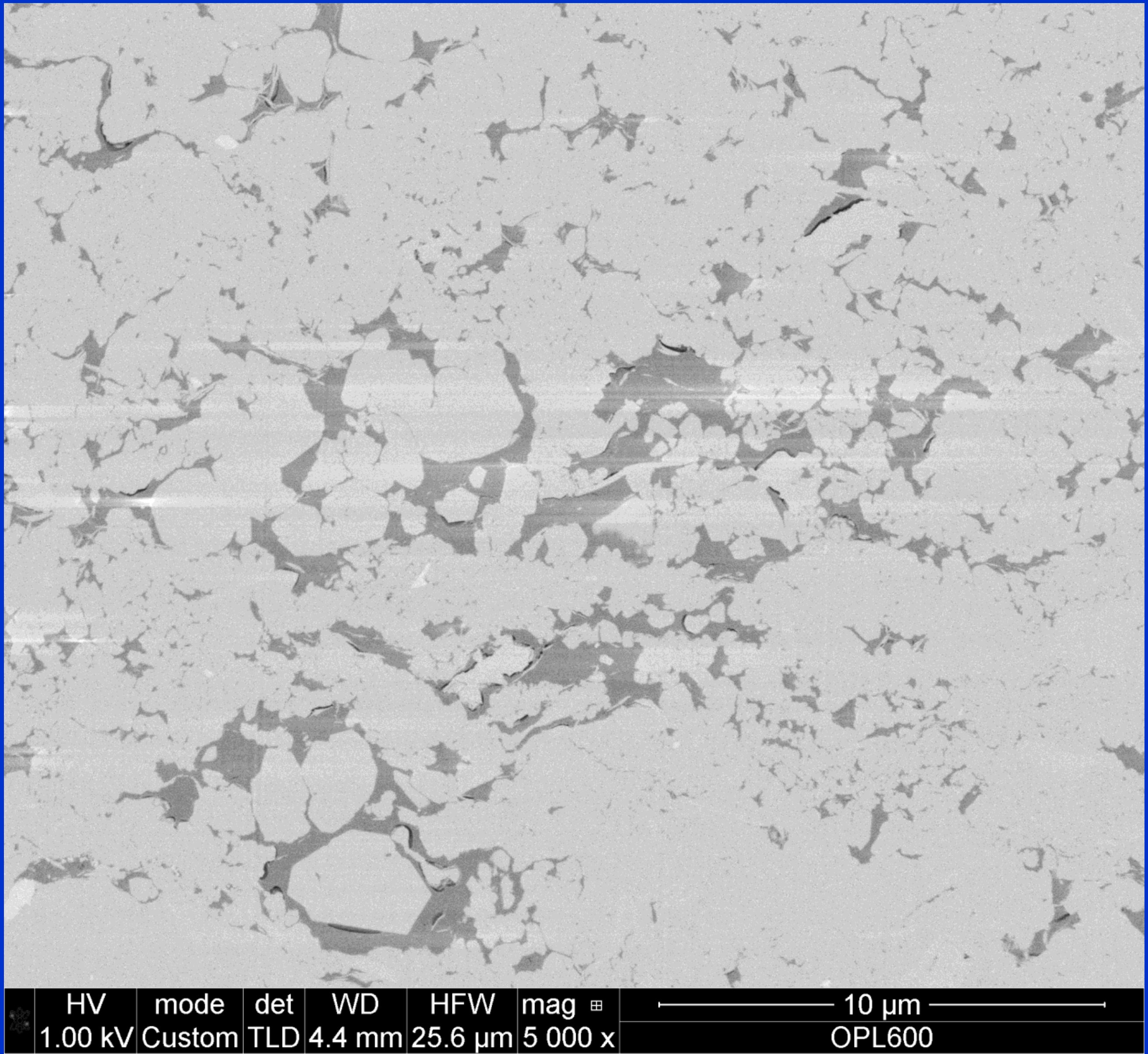
1. **low thermal maturity samples with amorphous organic matter, lamalginite, telalginite (<u>Tasmanites</u>), and pre-oil bitumen;**
2. **high thermal maturity samples with post-oil bitumen networks.**

2D SEM BSE Image of Lower Hartshorne Coal (1.28% Rmax) showing Organics (mostly vitrinite; dark) vs. Minerals (mostly clays; light)

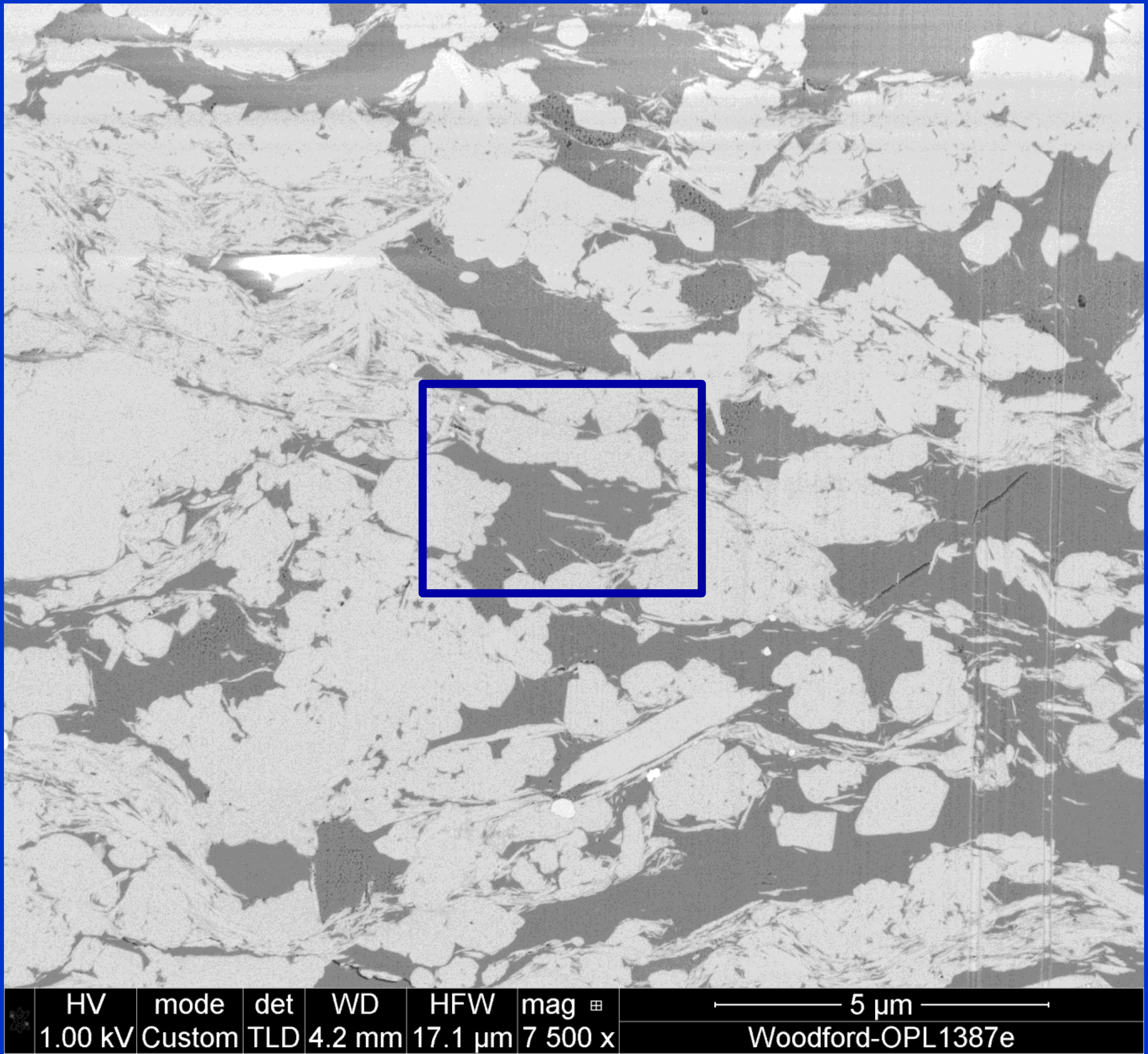


[SEM images are by Mark Curtis]

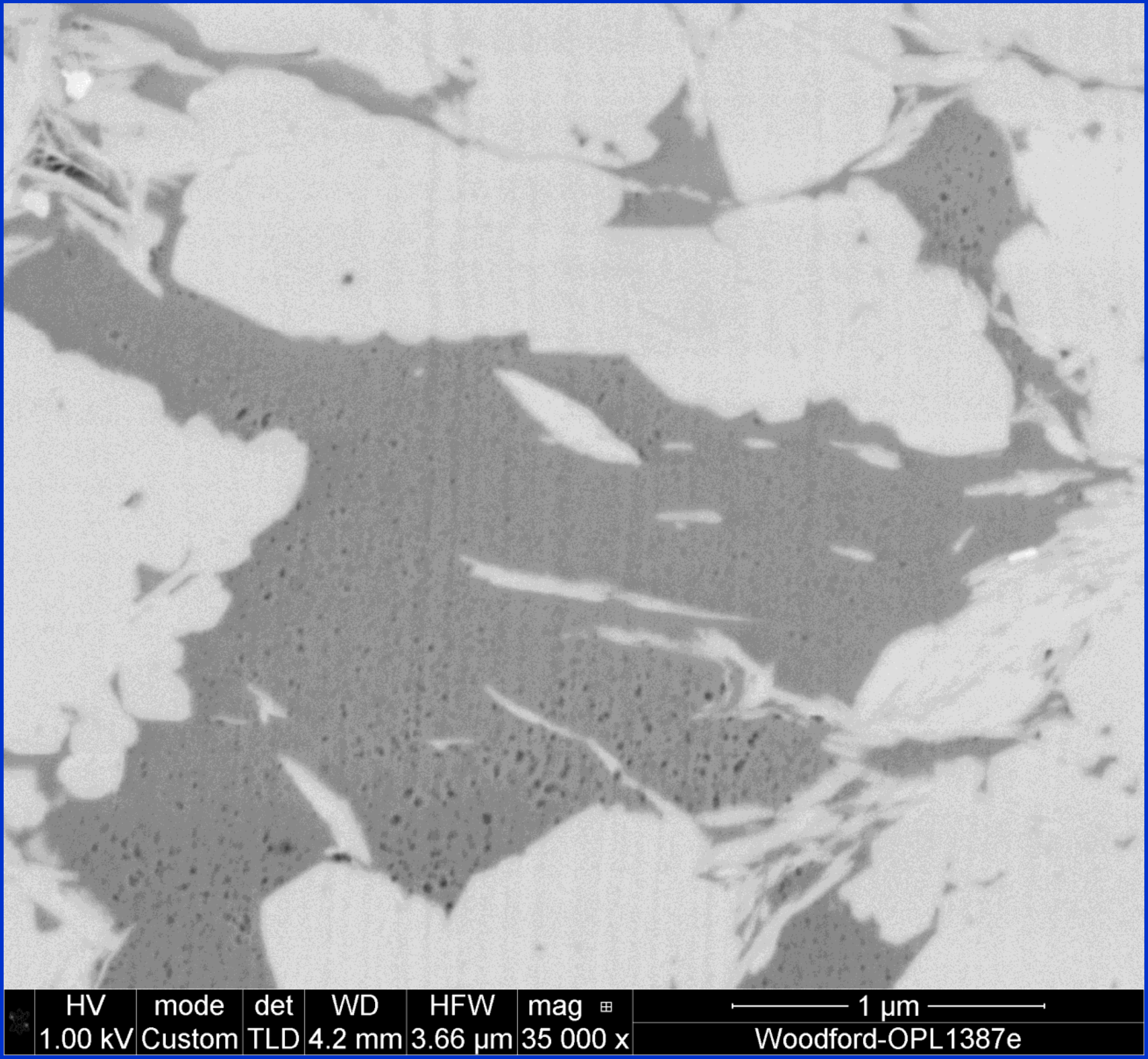
Focused Ion Beam (FIB) milling + SEM Backscattered Imaging: Low thermal maturity (0.56% Ro; OPL 600) Woodford Shale core containing amorphous organic matter, pre-oil bitumen, and Tasmanites



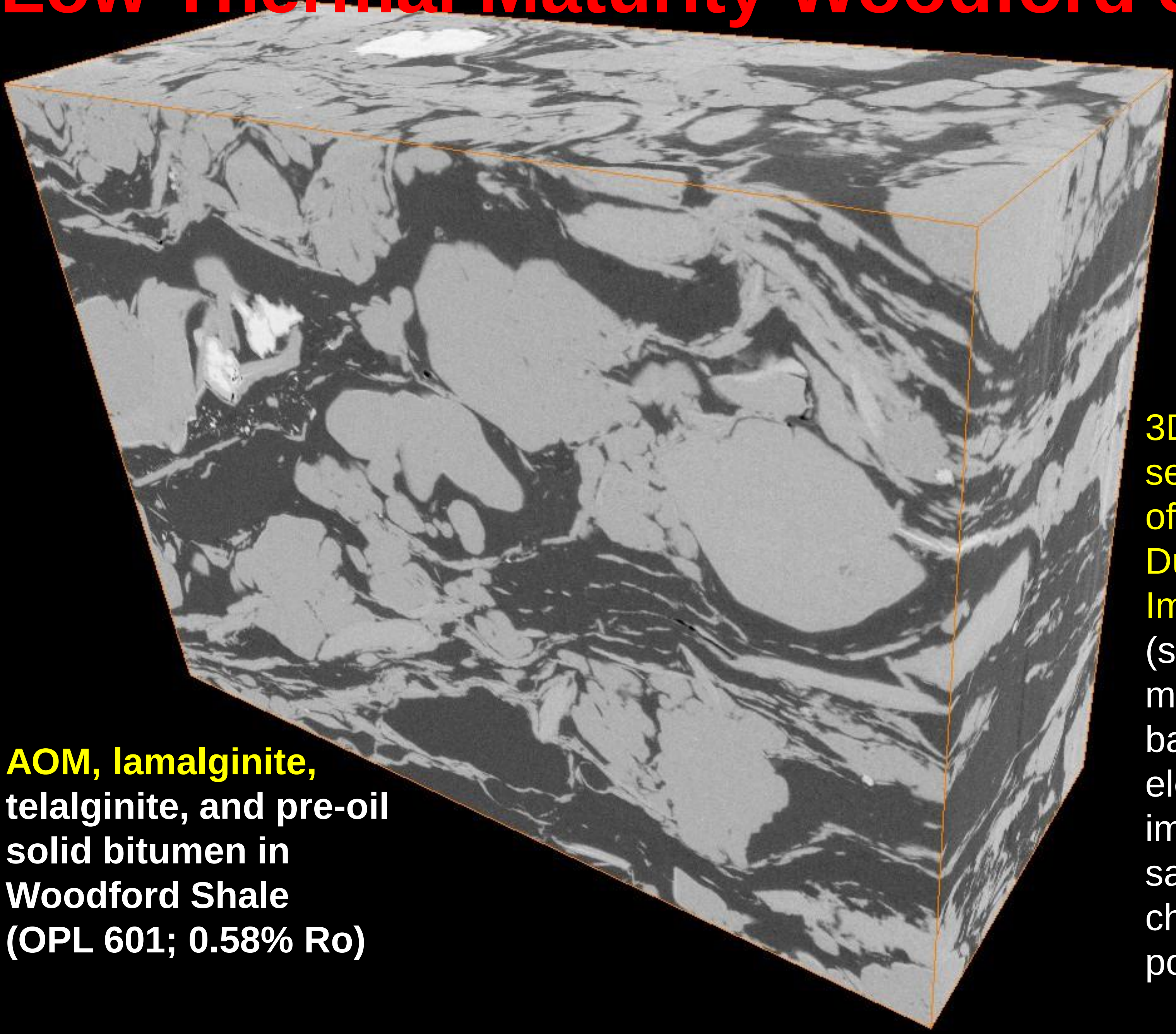
Higher thermal maturity (1.4% Ro; OPL 1387) Woodford Shale core containing wispy post-oil bitumen network @ 500X



Higher magnification of previous slide showing nanoporosity in wispy post-oil bitumen network



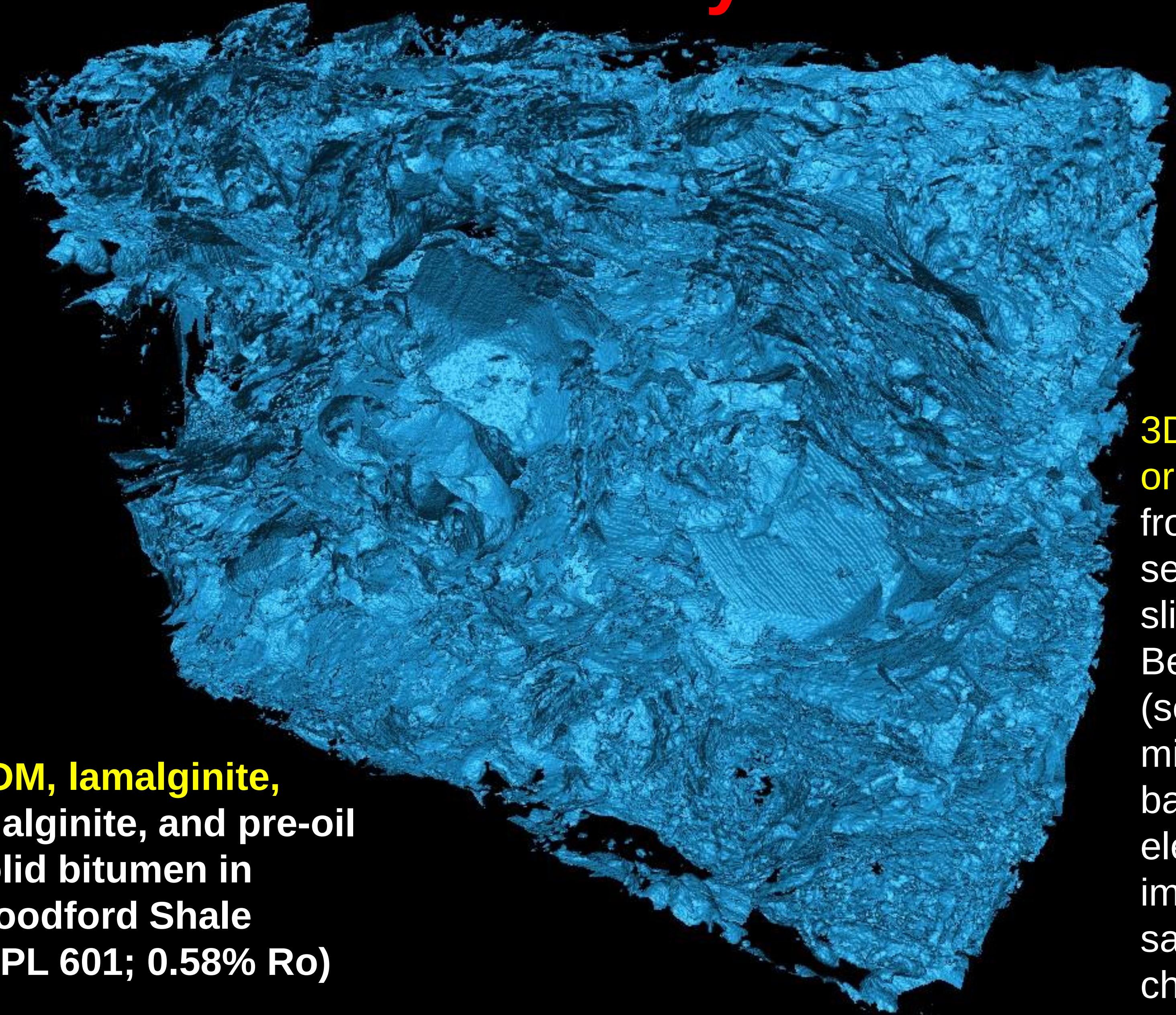
Low Thermal Maturity Woodford Shale



AOM, lamalginite, telalginite, and pre-oil solid bitumen in Woodford Shale (OPL 601; 0.58% Ro)

3D image from serial sectioning of 2D slices of Dual Beam Imaging (sequential ion-milling and backscatter electron imaging of a sample without changing its position)

Low Thermal Maturity Woodford Shale



AOM, lamalginite, telalginite, and pre-oil solid bitumen in Woodford Shale (OPL 601; 0.58% Ro)

3D image of organic matter from serial sectioning of 2D slices of Dual Beam Imaging (sequential ion-milling and backscatter electron imaging of a sample without changing its position)

SEM Backscatter image is favored to **ILLUSTRATE**:

- **Distribution** of organic matter (over a small area)
- **Abundance** of organic matter (especially amorphous organic matter and bitumen network)
- **Nanoporosity** in organic matter

Recognition of **ORGANIC MATTER TYPES (to date)** is favored using the light microscope (reflected white light, reflected fluorescent light, transmitted white light)