THE QUEST for "SWEET SPOTS" in an UNCONVENTIONAL OIL RESERVOIR

G.B. Asquith, TEXAS TECH

KEY FACTORS for ECONOMIC SHALE

[modified after: Rick Lewis (2013)]

RESERVOIR QUALITY

- **Hydrocarbons in Place [OOIP]**
- **Matrix Permeability [T2 CUT OFFS & K_{SDR}]**
- **Pore Pressure**

COMPLETION QUALITY

- **Hydraulic Fracture Surface Area [“Fracturability”]**
- **Hydraulic Fracture Conductivity**
- **Hydraulic Fracture Containment**

QUICK LOG SCAN EVALUATIONS

modified after: Lewis, 2009 w/ SCHLUMBERGER

Rt > 15 ohm-m [resistivity]

GR > 150API [gamma ray] not critical in carbonate-rich shales

ρb < 2.53g/cc [Φdls >11% Φdss>7%]

Φnls < 35% [Φnss<39%]

Φnls>35% [Φnss>39%] & Rt <=10ohm-m indicates Smectite which is BAD.

Pe < 4 barnes/electron [Quartz Pe = 1.81]

Neutron Porosity – Sonic Porosity Display [Φsonic > ΦNls]

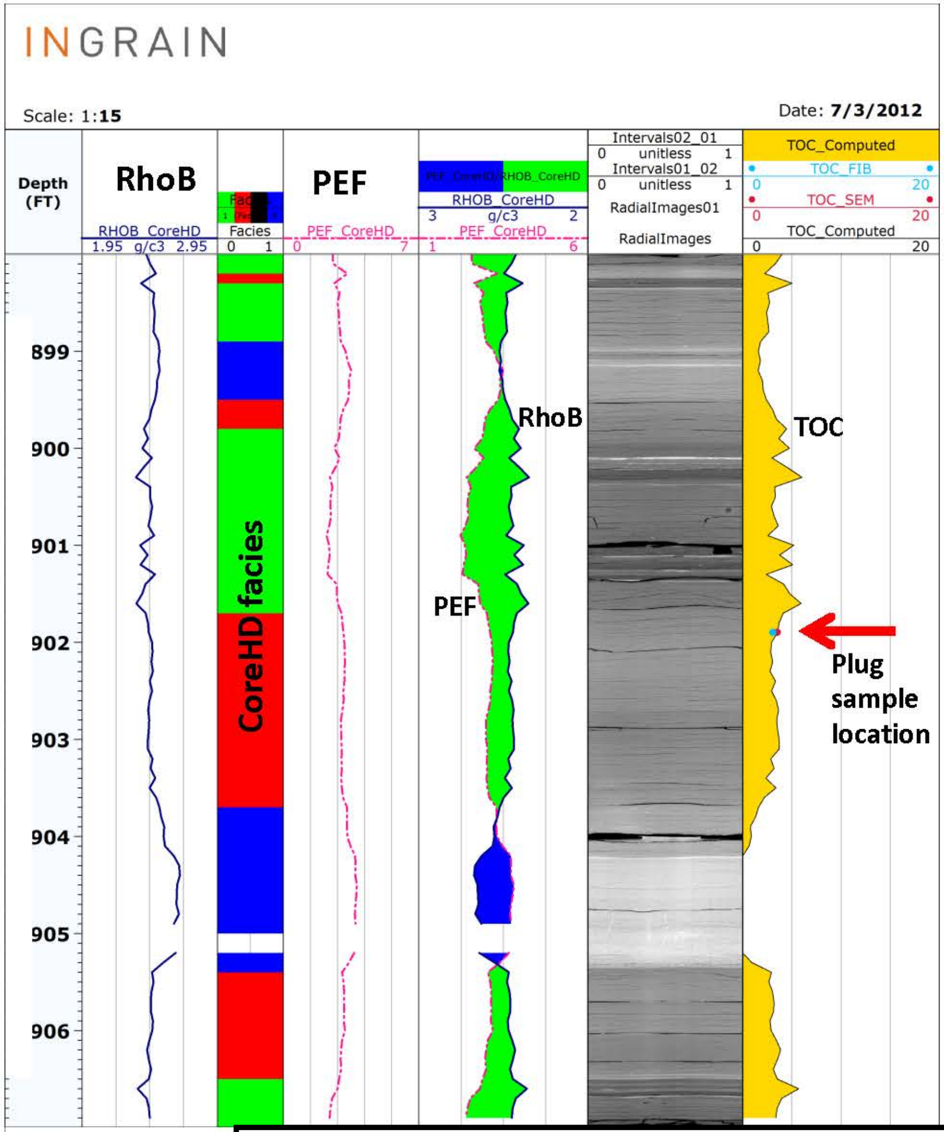
Pe versus RHOb Cross Plot ← **Walls & others, 2012**

Walls, J., B. Driskell, S.W. Sinclair, & J. Devito, (2012), Reservoir Characterization in the Eagle Ford Shale using Digital Rock Methods: WTGS 2012 Fall Symposium, Publ. No. 12-125.

- **Dual Energy (CT) whole core imaging for quick evaluation and sample selection for shale quality indication (“shale sweet spots”).**

- **High resolution (0.5mm) BULK DENSITY (RHOb) and PHOTOELECTRIC FACTOR (PEF).**

Whole bulk core density and photoelectric factor (PEF) for facies identification (Well SE) and sample selection

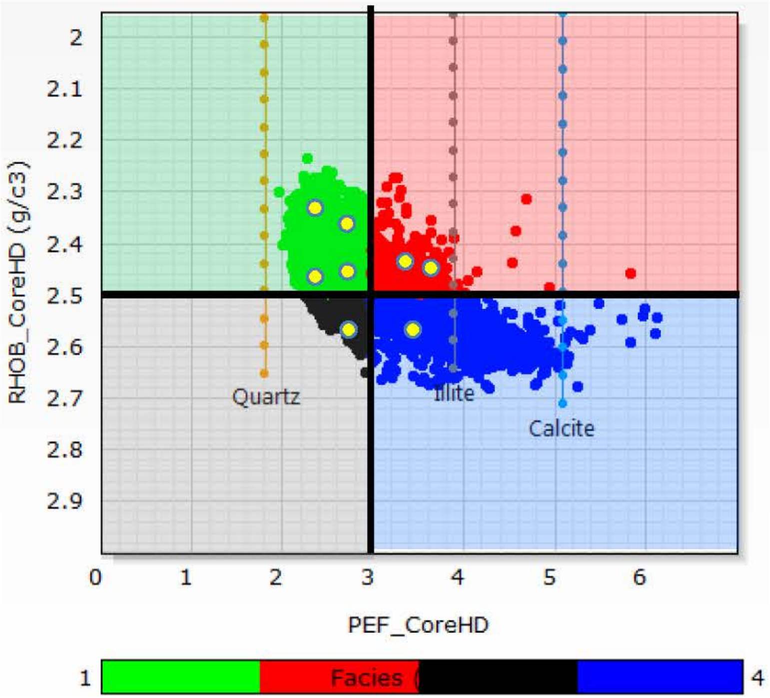


Green = Higher porosity and/or kerogen

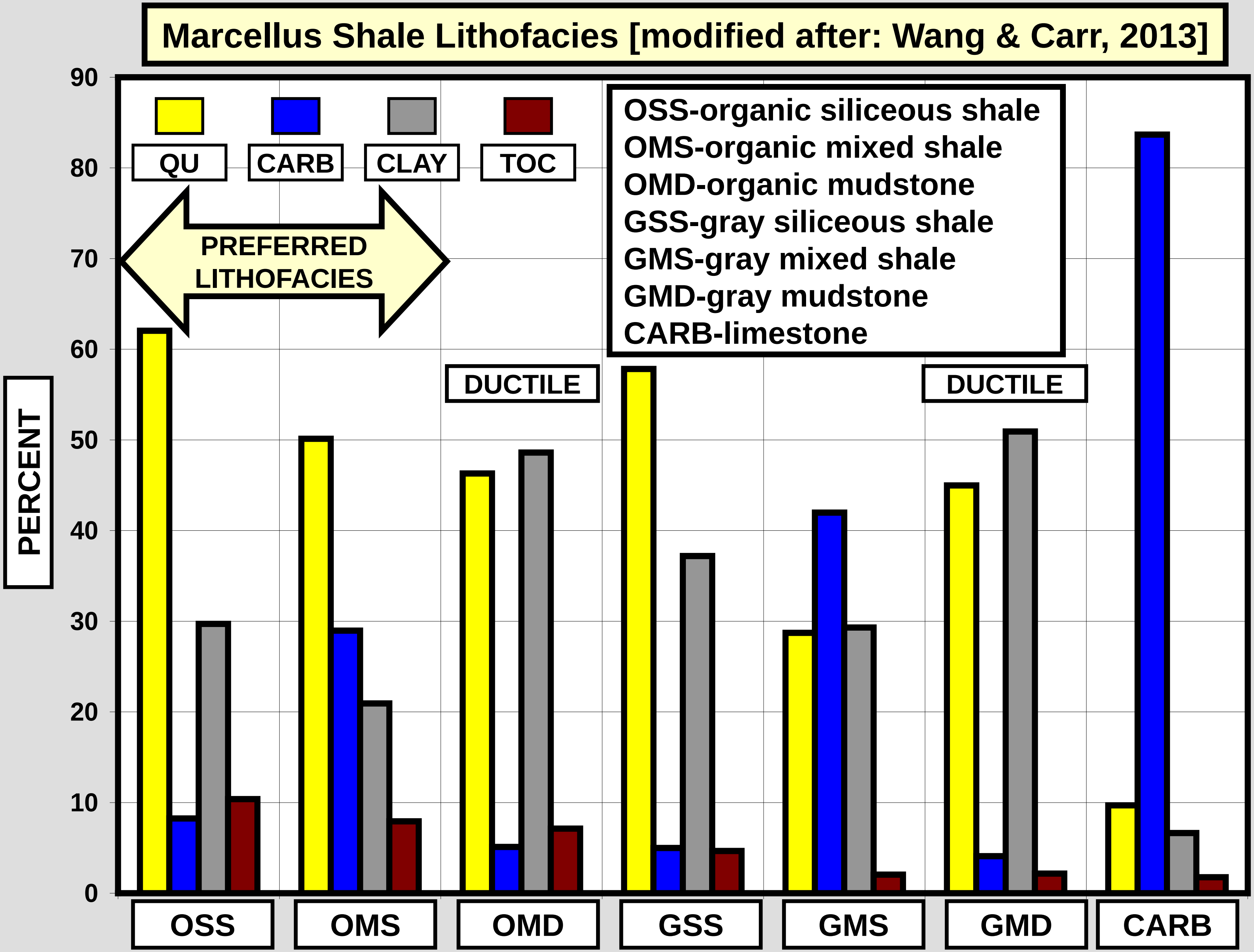
Red = Higher phi or kero; more calcite

Blue = Lower phi or kero, more calcite

Black = Lower phi or kero, less calcite

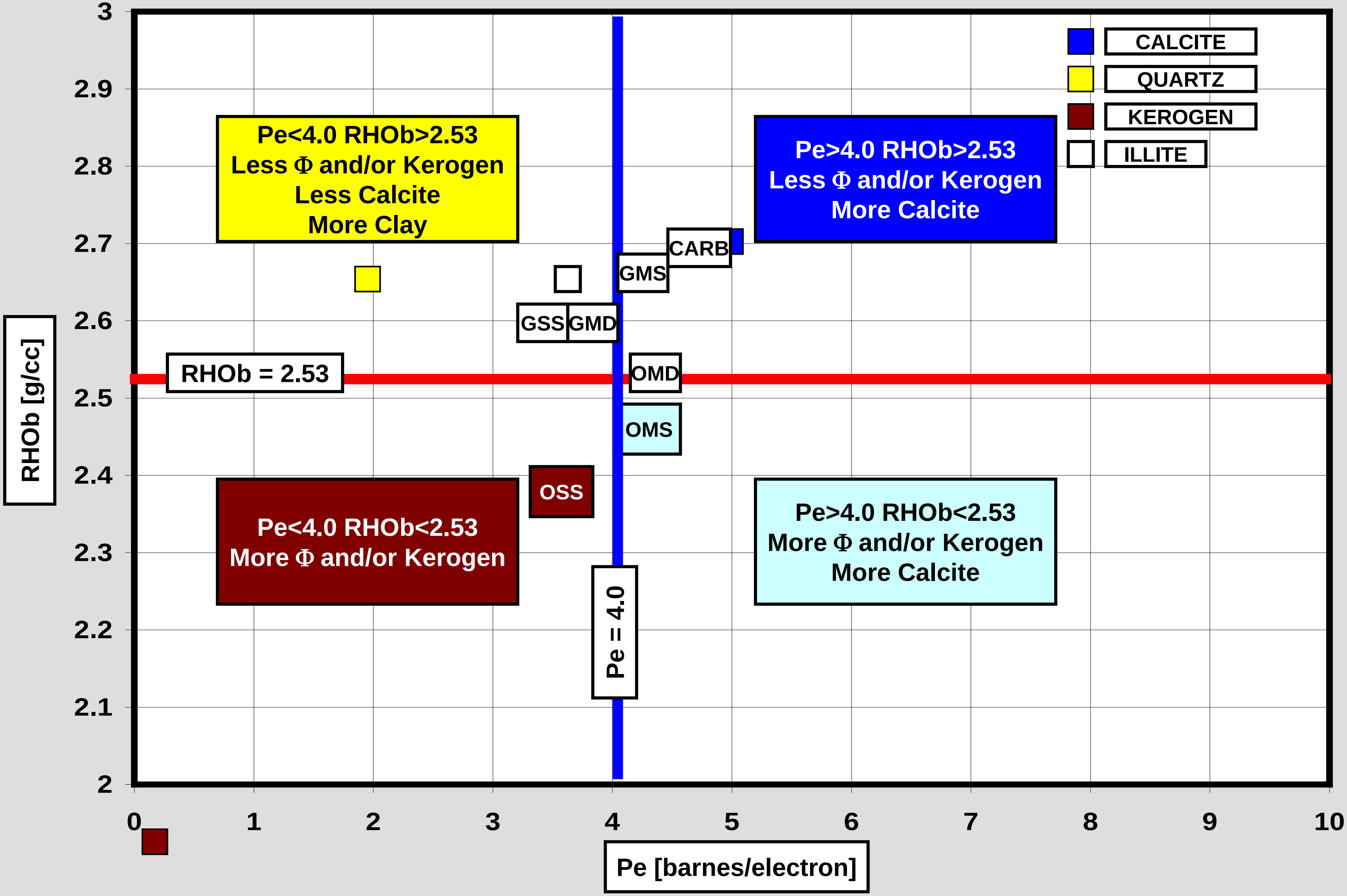


Modified After: Walls & others (2012) WTGS 2012 FALL SYMPOSIUM

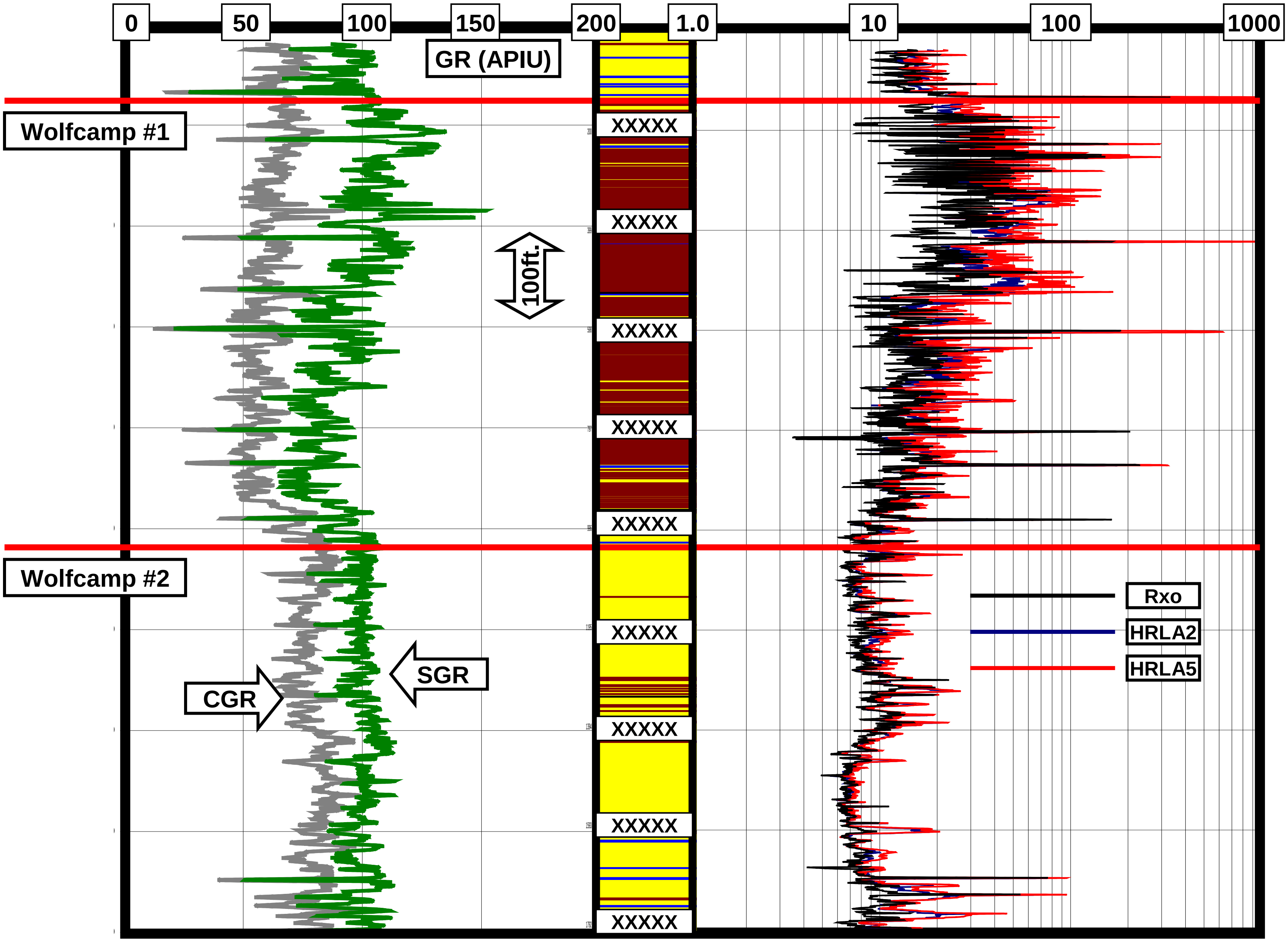


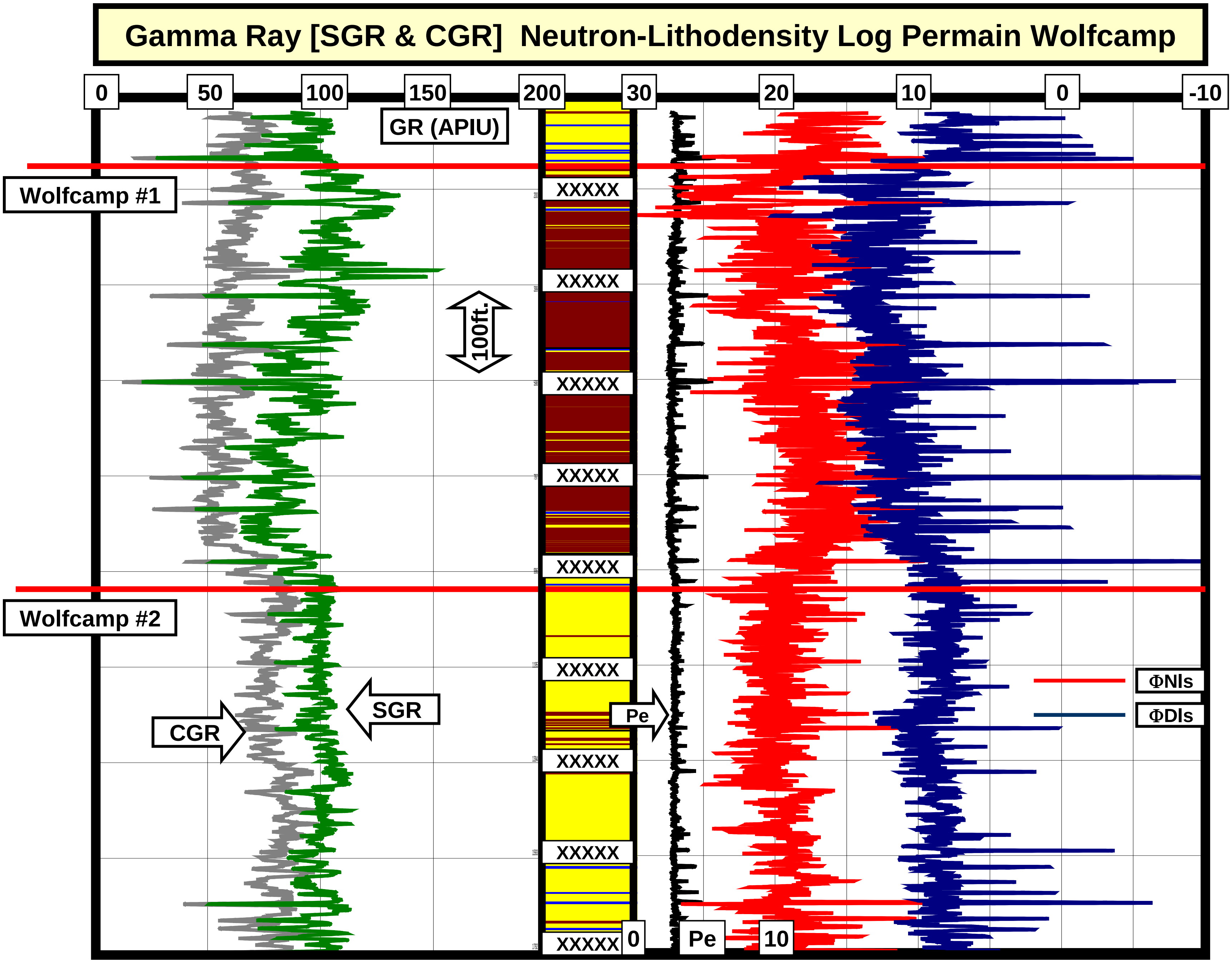
Marcellus Shale Lithofacies [modified after: Wang & Carr, 2013]
PERCENT
0
10
20
30
40
50
60
70
80
90
QU
CARB
CLAY
TOC
PREFERRED LITHOFACIES
OSS-organic siliceous shale
OMS-organic mixed shale
OMD-organic mudstone
GSS-gray siliceous shale
GMS-gray mixed shale
GMD-gray mudstone
CARB-limestone
DUCTILE
DUCTILE
OSS
OMS
OMD
GSS
GMS
GMD
CARB

Marcellus Shale Lithofacies [after: Wang & Carr, 2013]



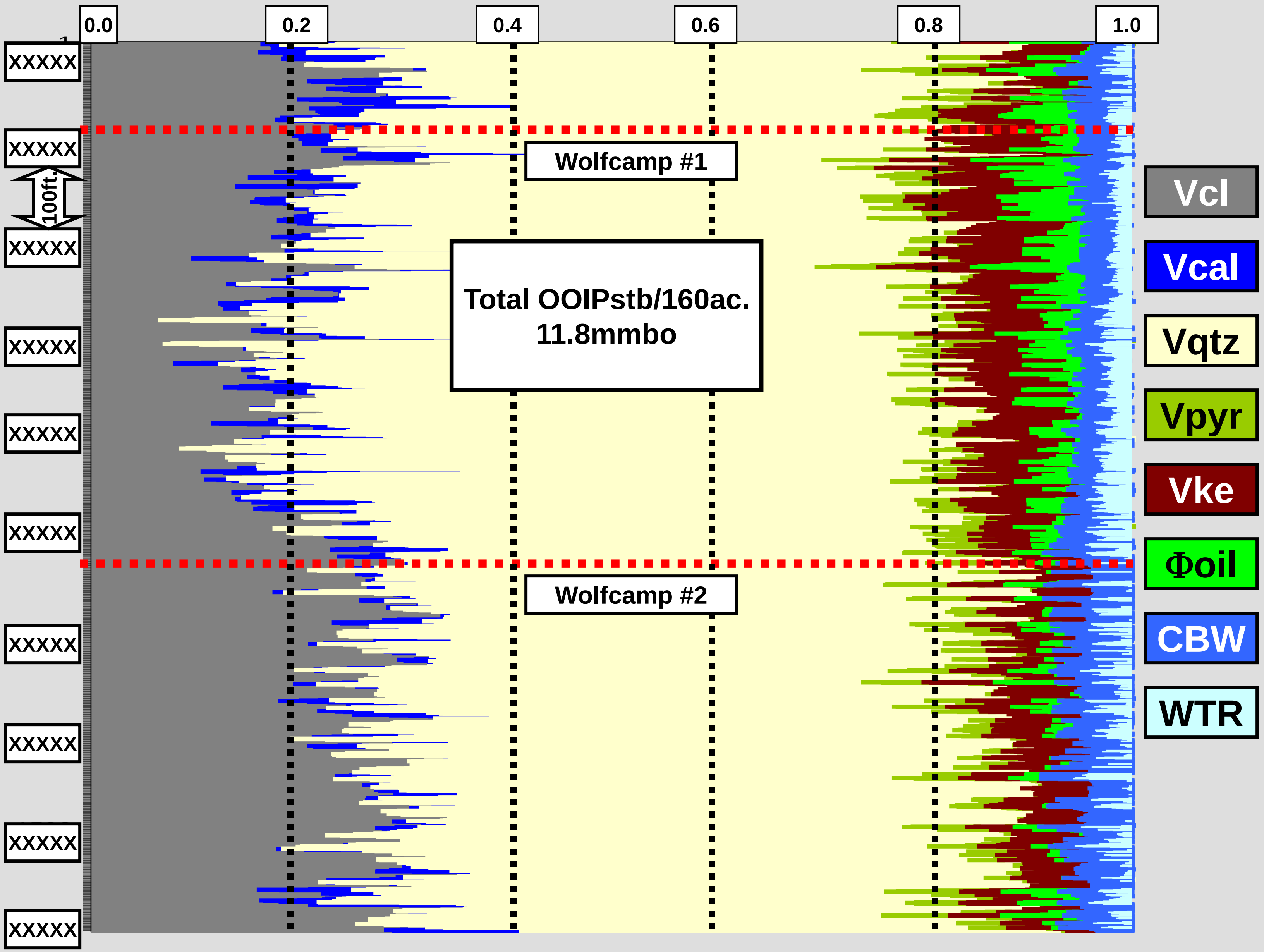
Gamma Ray [SGR & CGR] and Resistivity [HRLA] Permian Wolfcamp





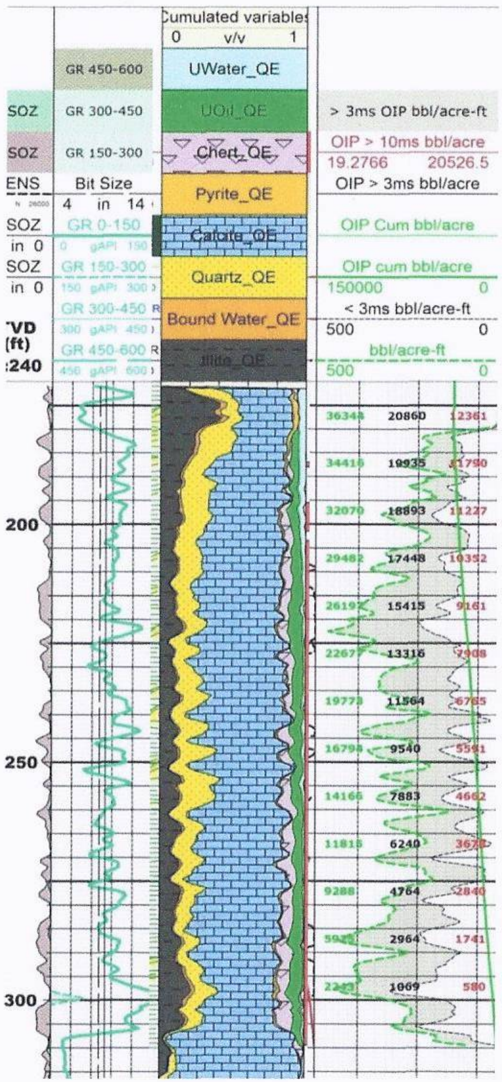
Gamma Ray [SGR & CGR] Neutron-Lithodensity Log Permain Wolfcamp
0
50
100
150
200
30
20
10
0
-10
GR (APIU)
Wolfcamp #1
XXXXX
100ft.
Wolfcamp #2
CGR
SGR
Pe
ΦNls
ΦDls
0
Pe
10

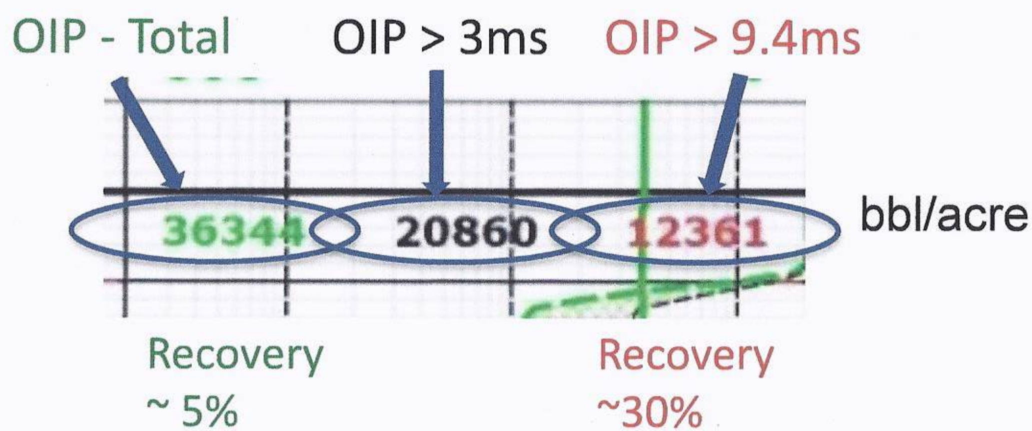
Lithology [ECS], Porosity and Saturation Permian Wolfcamp



Resource w/ T2 [ms] Cut-Offs Applied

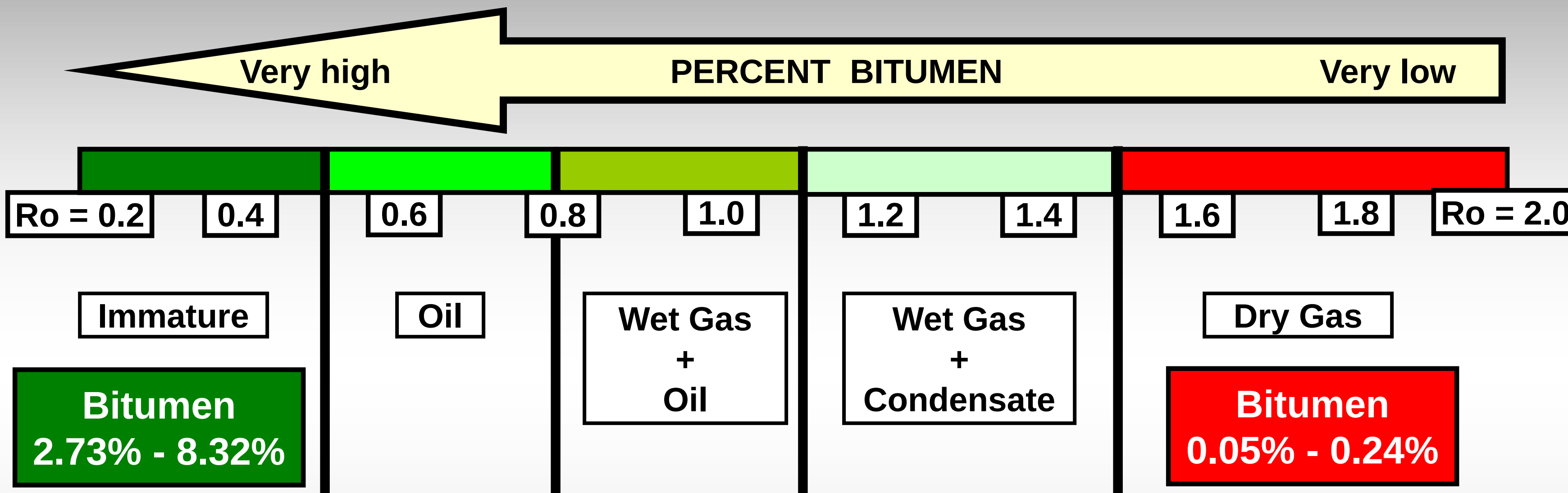
Modified After: Rylander, 2014 w/ SCHLUMBERGER





Comparing recovery efficiencies computed from the free hydrocarbon volume is a superior way of comparing the effectiveness of hydraulic fracture stimulations

Thermal Maturity [Ro] & Non-Producible Bitumen

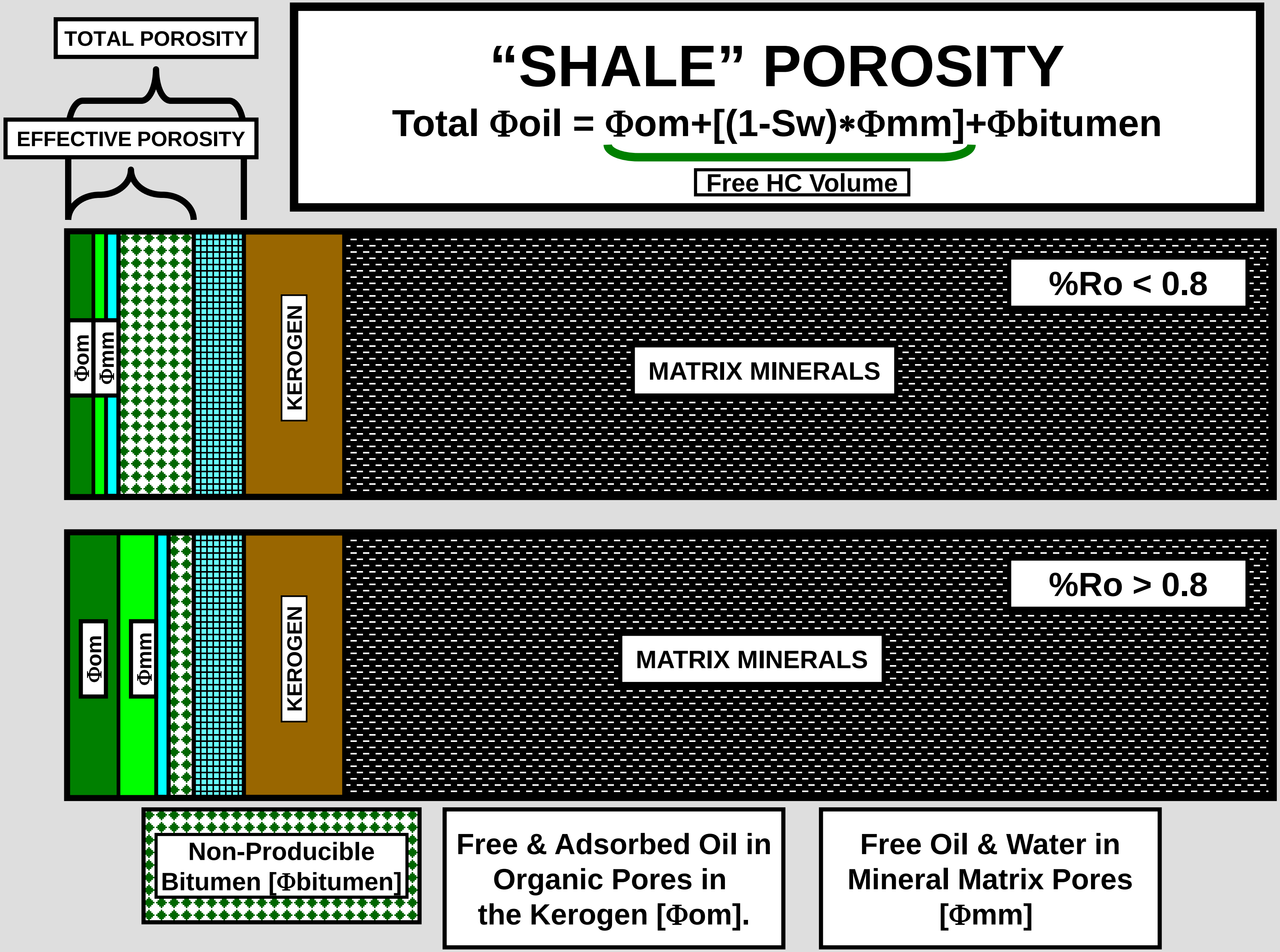


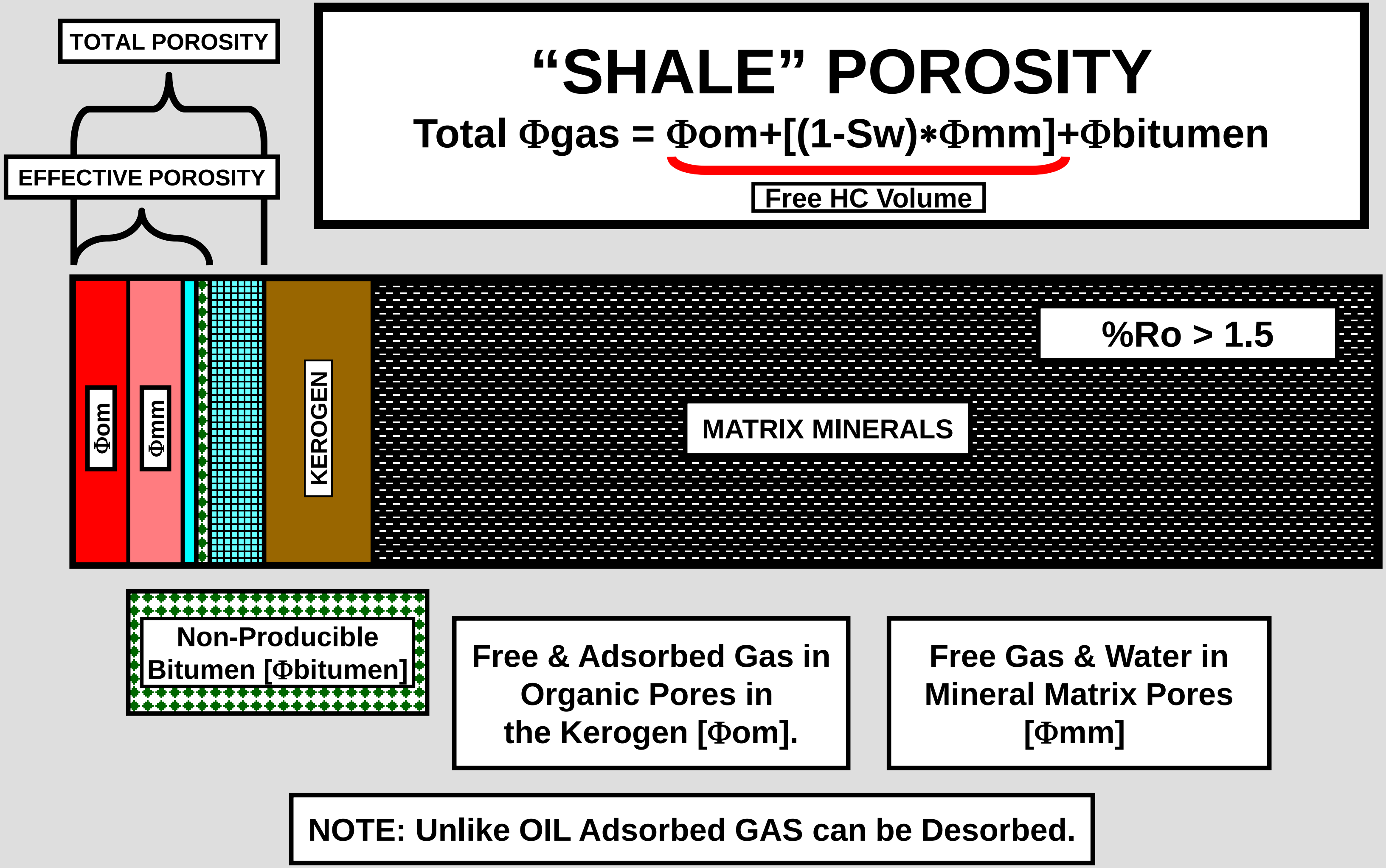
NOTE: As maturity increases the non-producible bitumen is converted to producible oil and gas. The problem is that the non-producible bitumen is calculated as producible HC in a standard log analysis [OOIPstb or OGIPscf].

% Bitumen from: Lewis (2013)

“SHALE” POROSITY

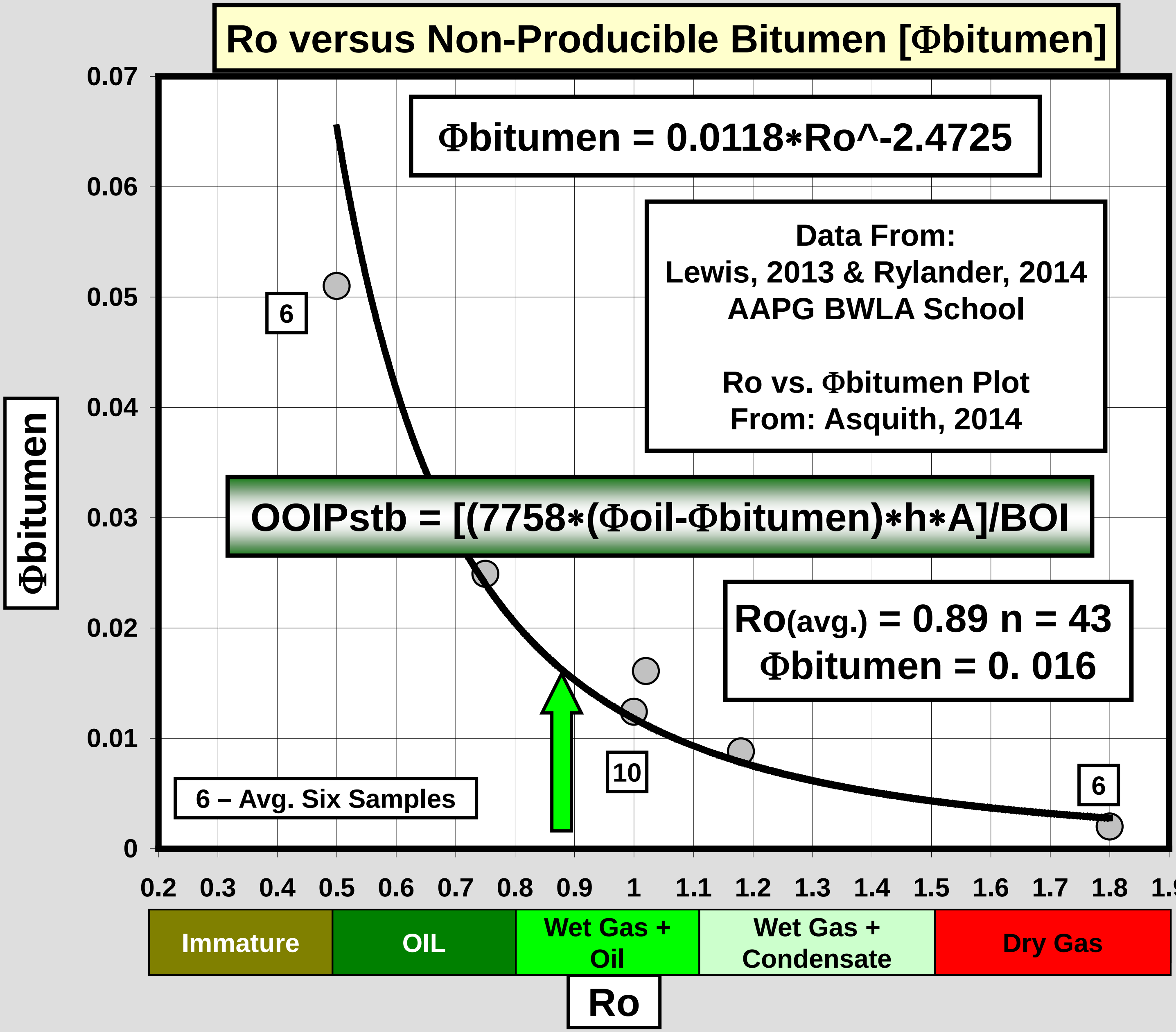
$$\text{Total } \Phi oil = \underbrace{\Phi om + [(1 - Sw) * \Phi mm]}_{\text{Free HC Volume}} + \Phi bitumen$$



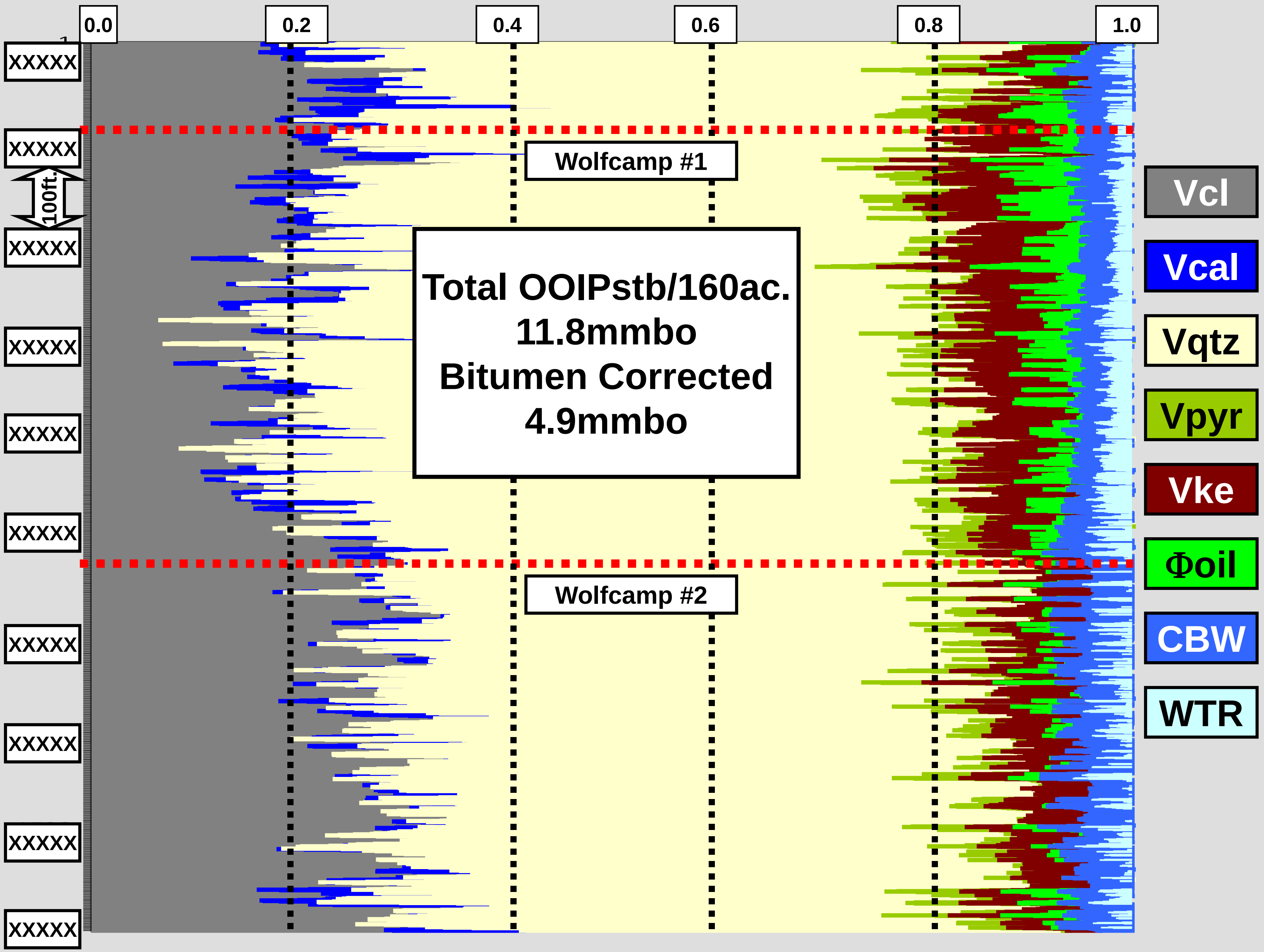

“SHALE” POROSITY
Total Φgas = Φom+[(1-Sw)∗Φmm]+Φbitumen
Free HC Volume
TOTAL POROSITY
EFFECTIVE POROSITY
Φom
Φmm
KEROGEN
MATRIX MINERALS
%Ro > 1.5
Non-Producible Bitumen [Φbitumen]
Free & Adsorbed Gas in Organic Pores in the Kerogen [Φom].
Free Gas & Water in Mineral Matrix Pores [Φmm]
NOTE: Unlike OIL Adsorbed GAS can be Desorbed.

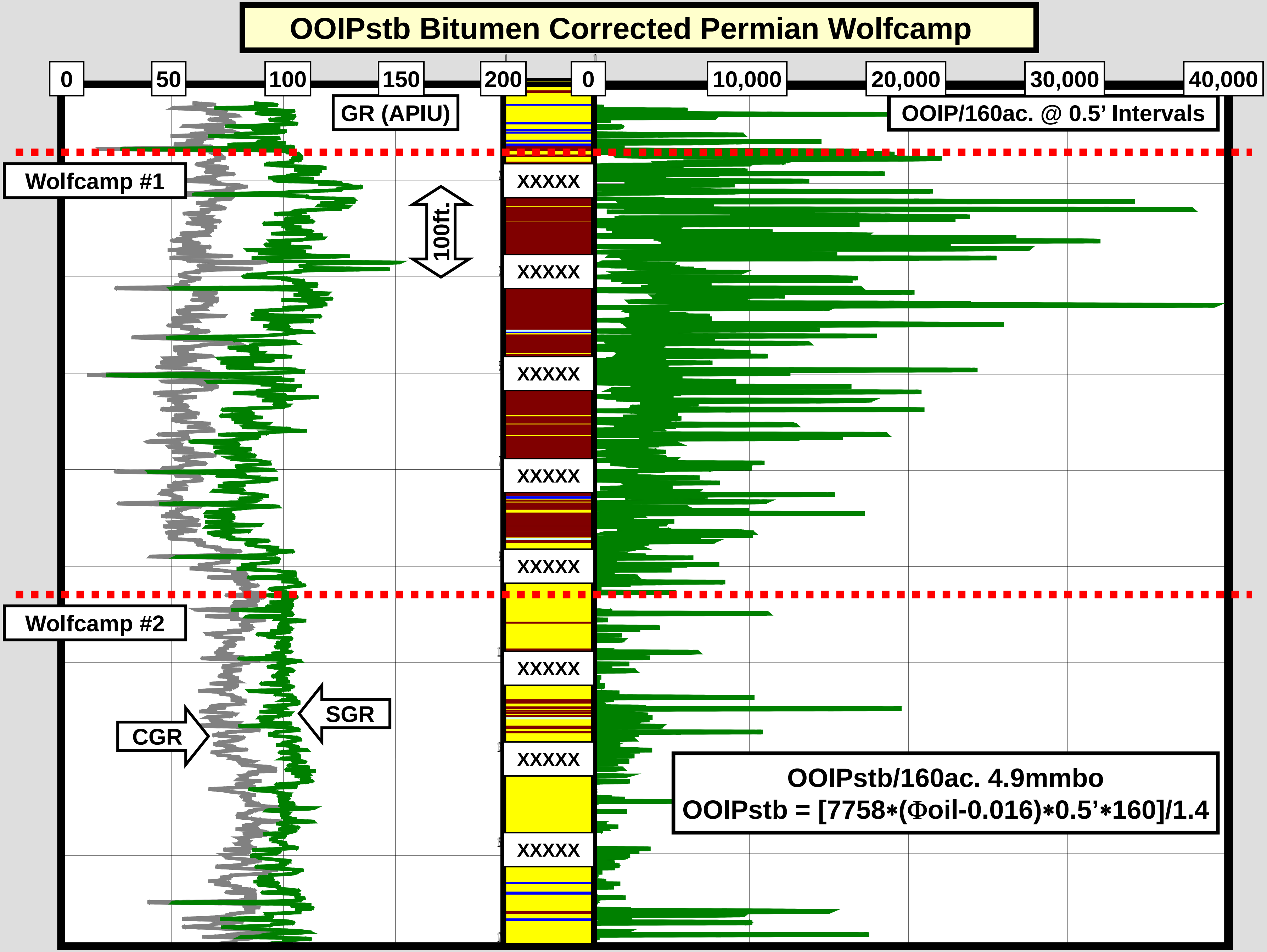
ELIMINATING BITUMEN

[%Ro versus Φbitumen]


Ro versus Non-Producible Bitumen [Φbitumen]
Φbitumen = 0.0118∗Ro^-2.4725
Data From:
Lewis, 2013 & Rylander, 2014
AAPG BWLA School
Ro vs. Φbitumen Plot
From: Asquith, 2014
OOIPstb = [(7758∗(Φoil-Φbitumen)∗h∗A]/BOI
Ro(avg.) = 0.89 n = 43
Φbitumen = 0. 016
6 – Avg. Six Samples
6
10
6
Φbitumen
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9
Immature
OIL
Wet Gas + Oil
Wet Gas + Condensate
Dry Gas
Ro

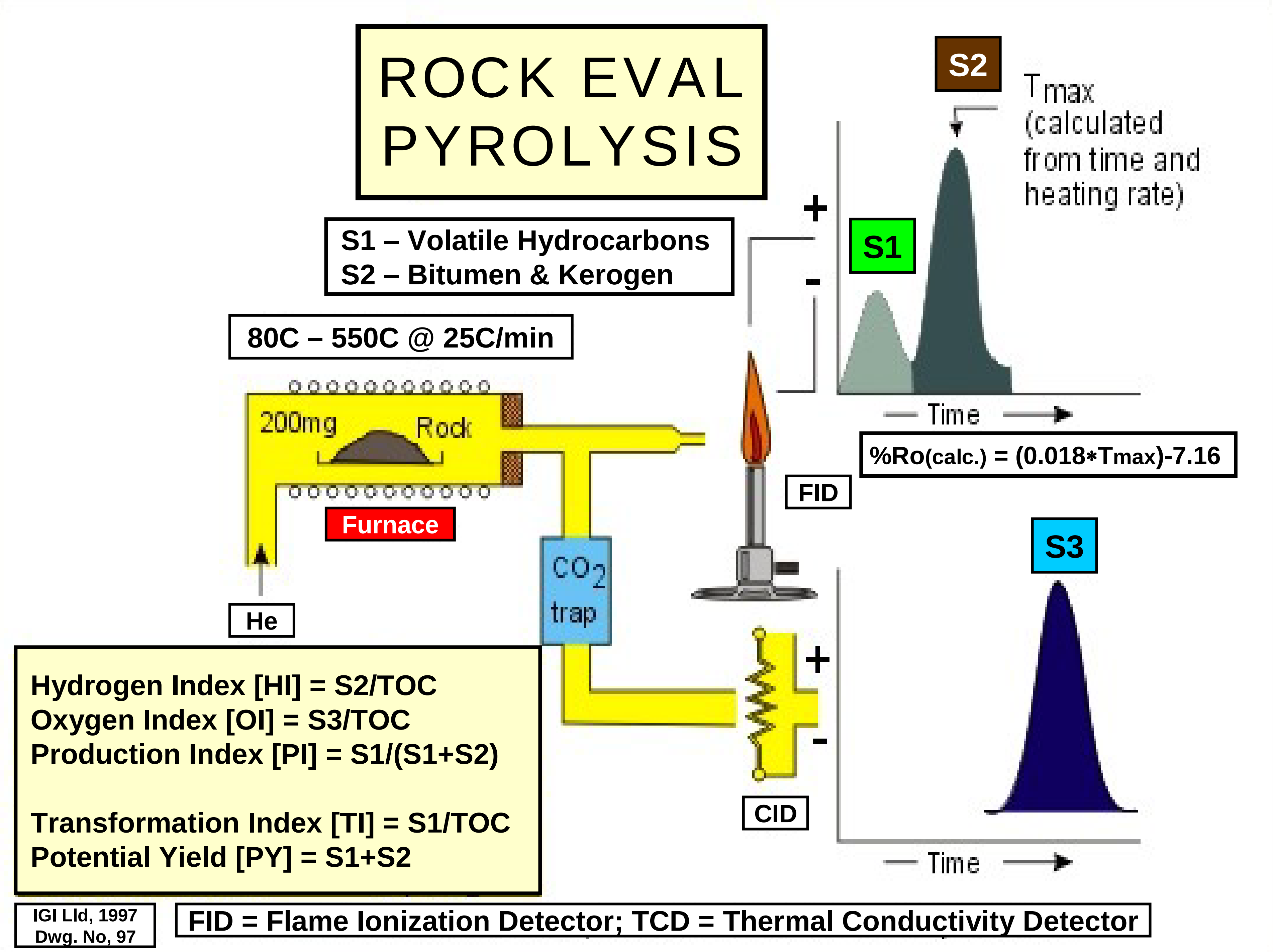
Lithology [ECS], Porosity and Saturation Permian Wolfcamp



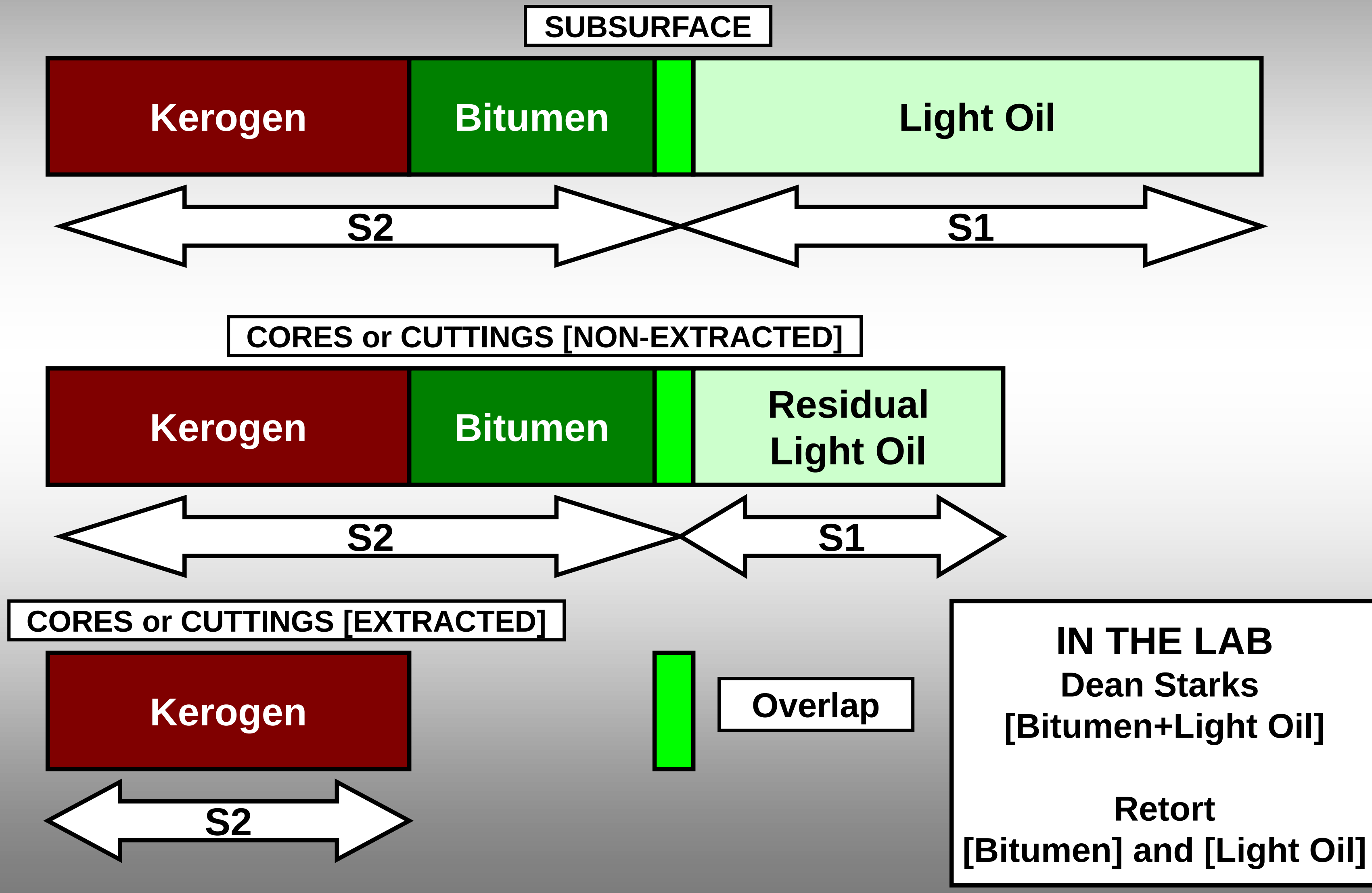


OOIPstb Bitumen Corrected Permian Wolfcamp
0
50
100
150
200
0
10,000
20,000
30,000
40,000
GR (APIU)
OOIP/160ac. @ 0.5' Intervals
Wolfcamp #1
100ft.
XXXXX
XXXXX
XXXXX
XXXXX
XXXXX
Wolfcamp #2
XXXXX
XXXXX
XXXXX
SGR
CGR
OOIPstb/160ac. 4.9mmbo
OOIPstb = [7758∗(Φoil-0.016)∗0.5'∗160]/1.4

ELIMINATING BITUMEN
[S1 from Rock EVAL PYROLYSIS]


ROCK EVAL PYROLYSIS
S1 – Volatile Hydrocarbons
S2 – Bitumen & Kerogen
80C – 550C @ 25C/min
200mg
Rock
Furnace
He
CO_2 trap
FID
CID
S1
S2
Tmax (calculated from time and heating rate)
+
-
Time
%Ro(calc.) = (0.018*Tmax)-7.16
S3
+
-
Time
Hydrogen Index [HI] = S2/TOC
Oxygen Index [OI] = S3/TOC
Production Index [PI] = S1/(S1+S2)
Transformation Index [TI] = S1/TOC
Potential Yield [PY] = S1+S2
IGI Lld, 1997
Dwg. No, 97
FID = Flame Ionization Detector; TCD = Thermal Conductivity Detector

TOTAL ORGANIC CARBON [TOC]



OOIP from PYROLYSIS S1 DATA

$$OOIP = \Sigma[(S1 * 21.89) * h * 160ac.]$$

$$OOIP = \Sigma[1241.34 * \rho b * S1 * (1/\rho oil) * h]$$

TOC(wt%) PERMIAN WOLFCAMP

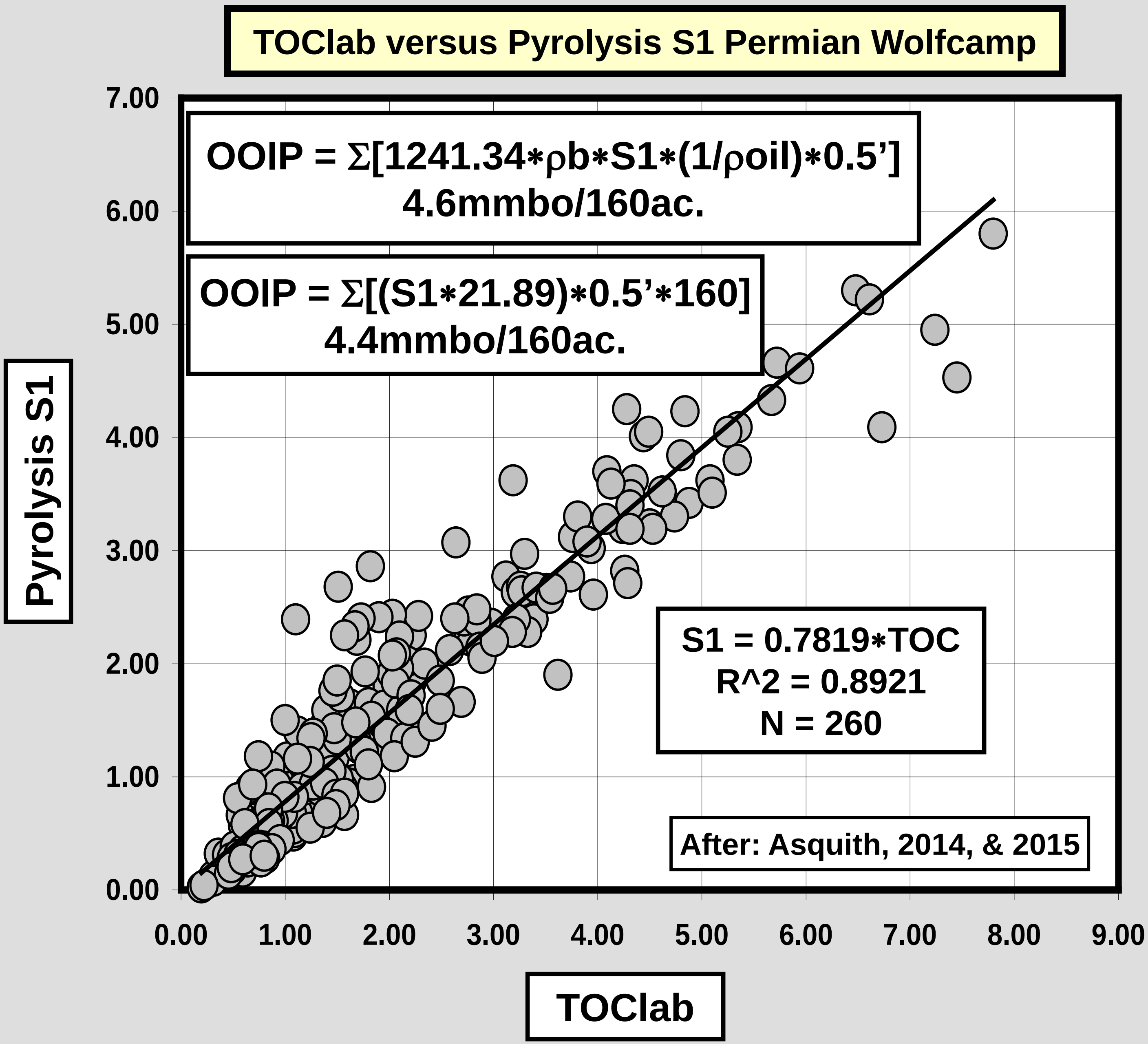
- **TOClab(wt%)**

0.2 – 7.8   avg. 2.2   N = 260

%Ro = 0.89

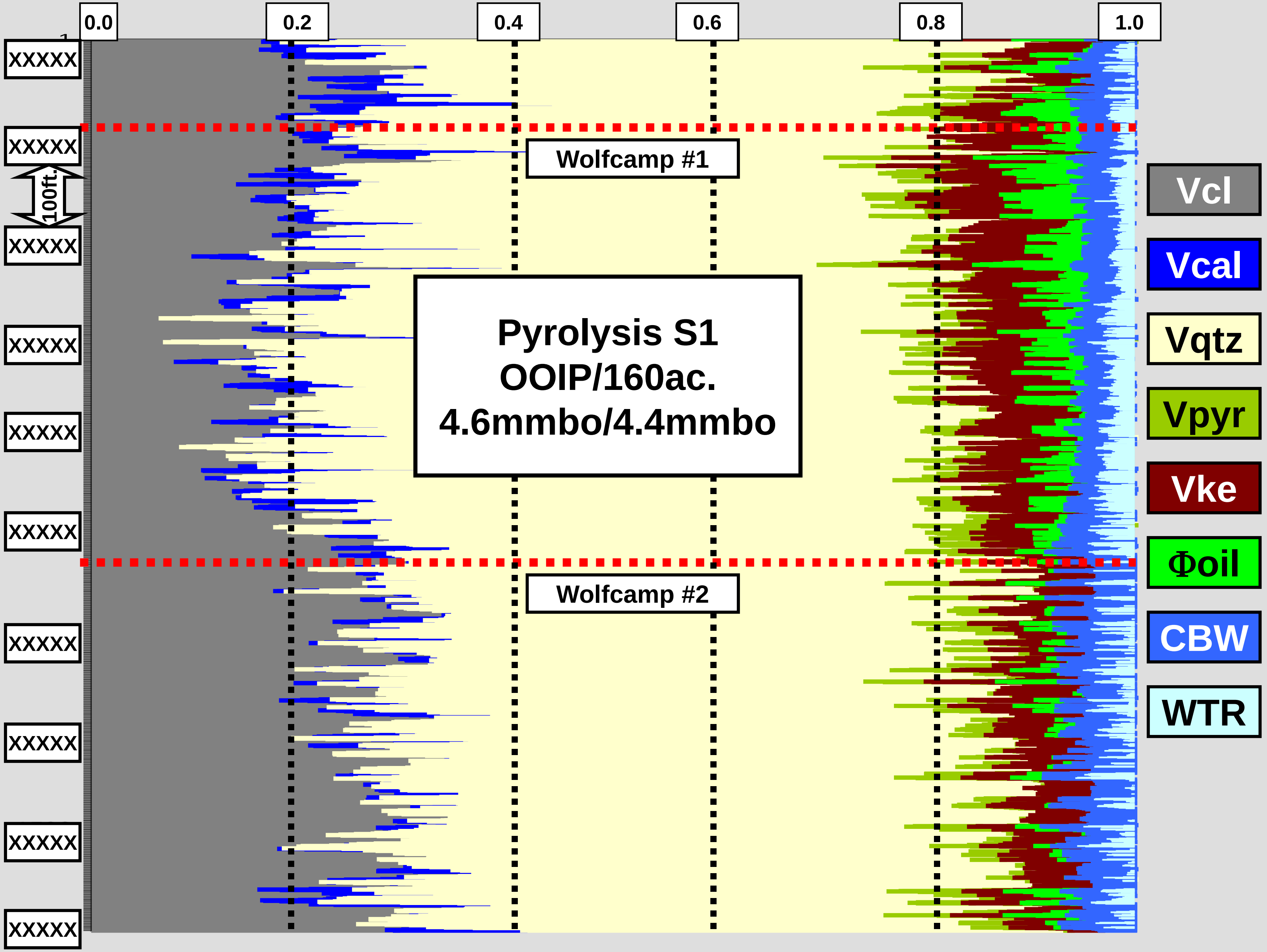
- **TOCschmoker(wt%)**

0.3 – 7.5   avg. 3.3   N = 1089



TOClab versus Pyrolysis S1 Permian Wolfcamp
OOIP = Σ[1241.34∗ρb∗S1∗(1/ρoil)∗0.5’]
4.6mmbo/160ac.
OOIP = Σ[(S1∗21.89)∗0.5’∗160]
4.4mmbo/160ac.
S1 = 0.7819∗TOC
R^2 = 0.8921
N = 260
After: Asquith, 2014, & 2015
Pyrolysis S1
TOClab
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00

Lithology [ECS], Porosity and Saturation Permian Wolfcamp

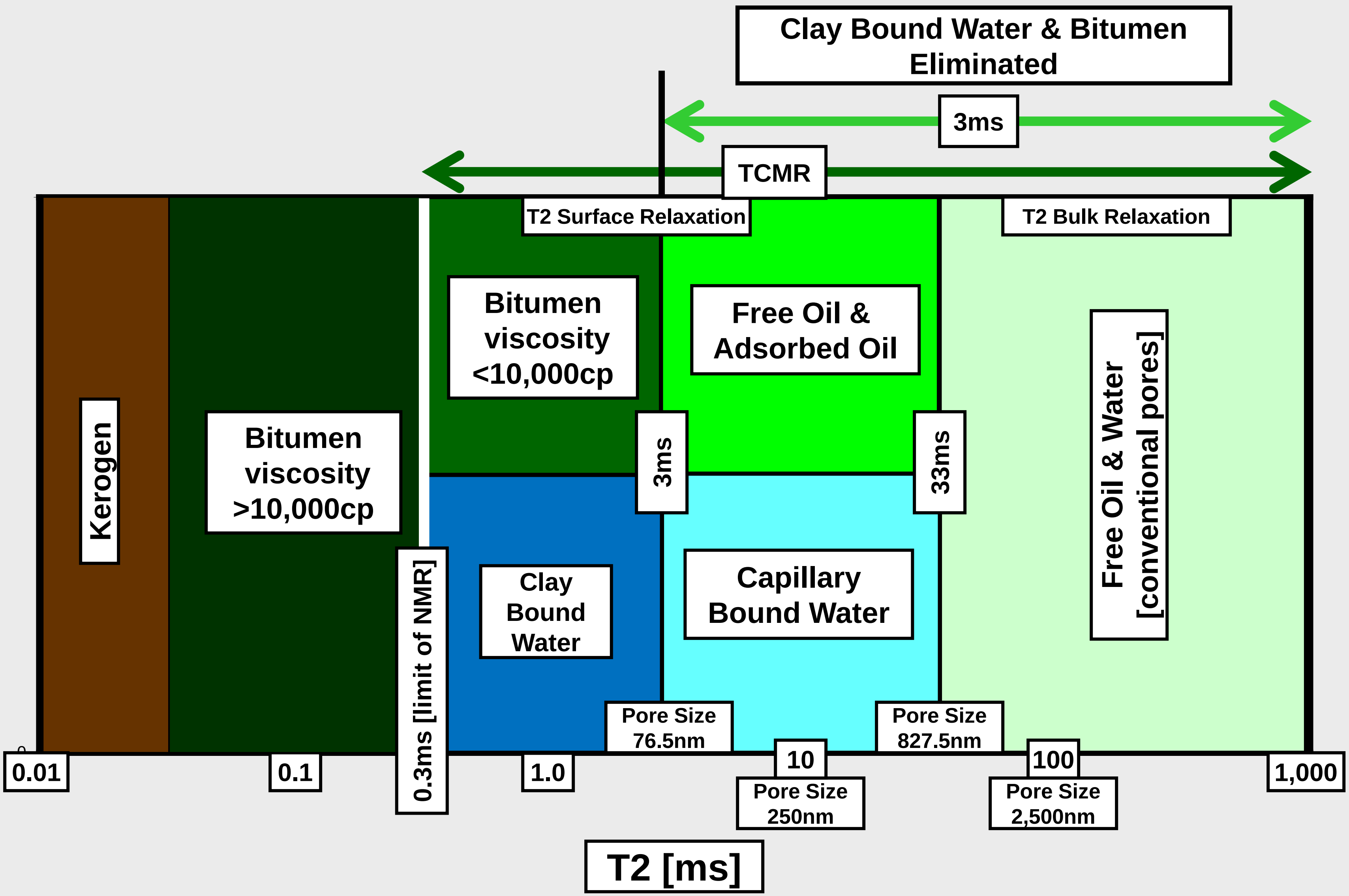


ELIMINATING BITUMEN and ADSORBED OIL

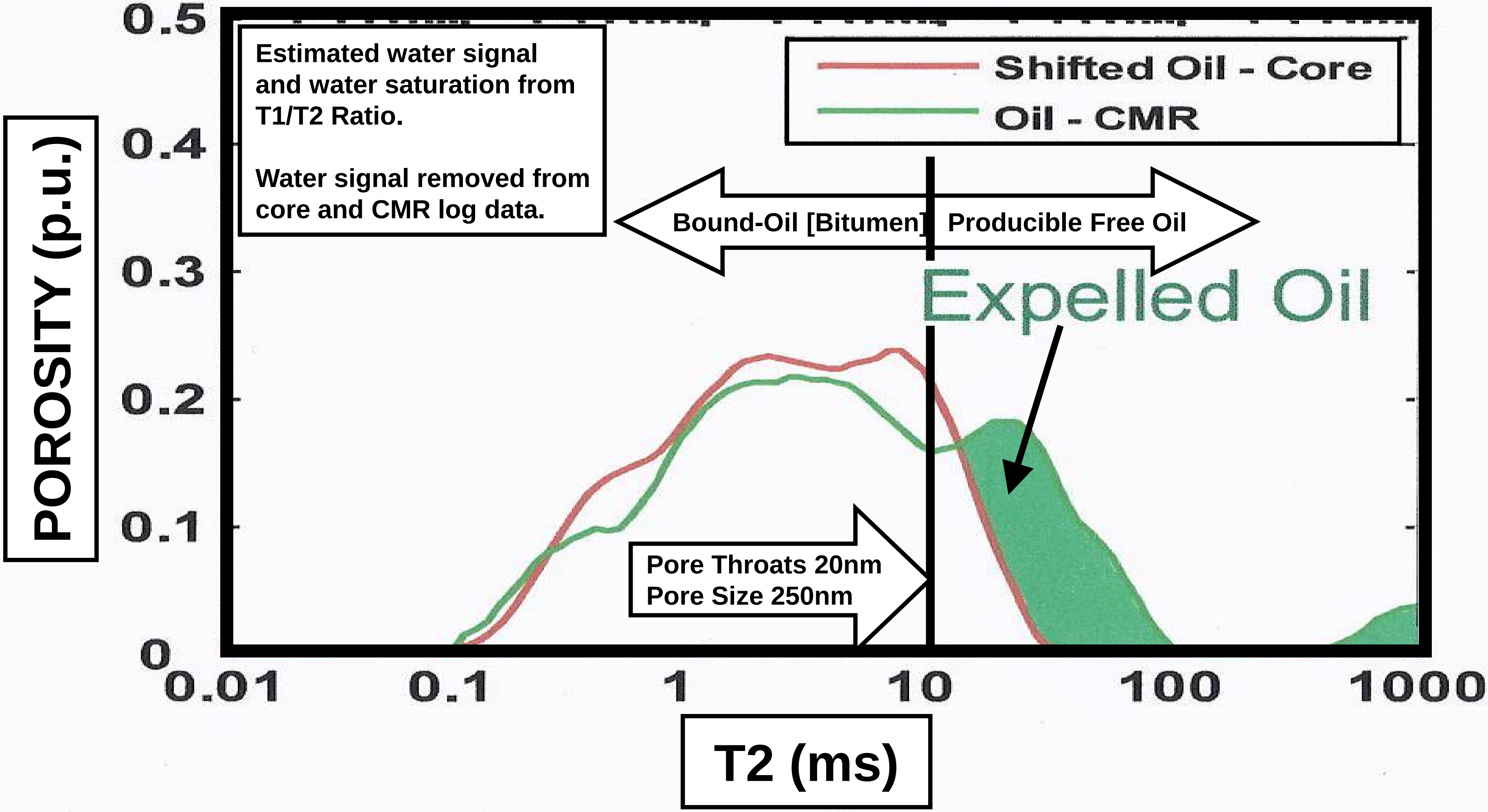
[CMR/NMR LOGS]

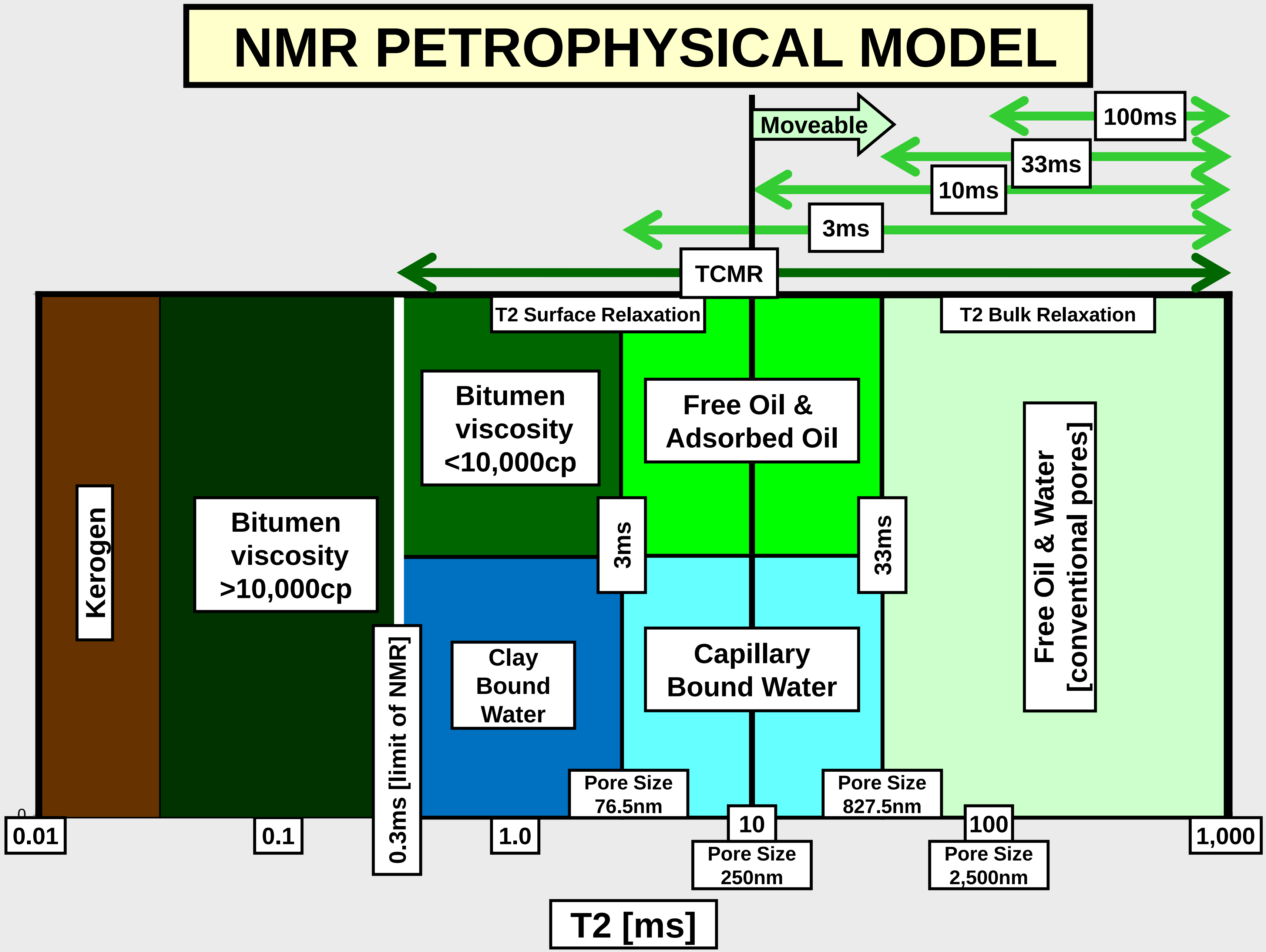

NOTE: ALL the very small kerogen pores contain only non-moveable adsorbed oil. PROBLEM: S1 includes Free and Adsorbed OIL.
Φmm
Φom
Kerogen
Φom
Free OIL
Adsorbed OIL
Water
1μm
Φom - Organoporosity & Φmm – Mineral Matrix Porosity

NMR PETROPHYSICAL MODEL



T2 DISTRIBUTIONS from CMR/NMR CORE and CMR/NMR LOG [Downhole]
[modified after: Rylander & others, 2013]



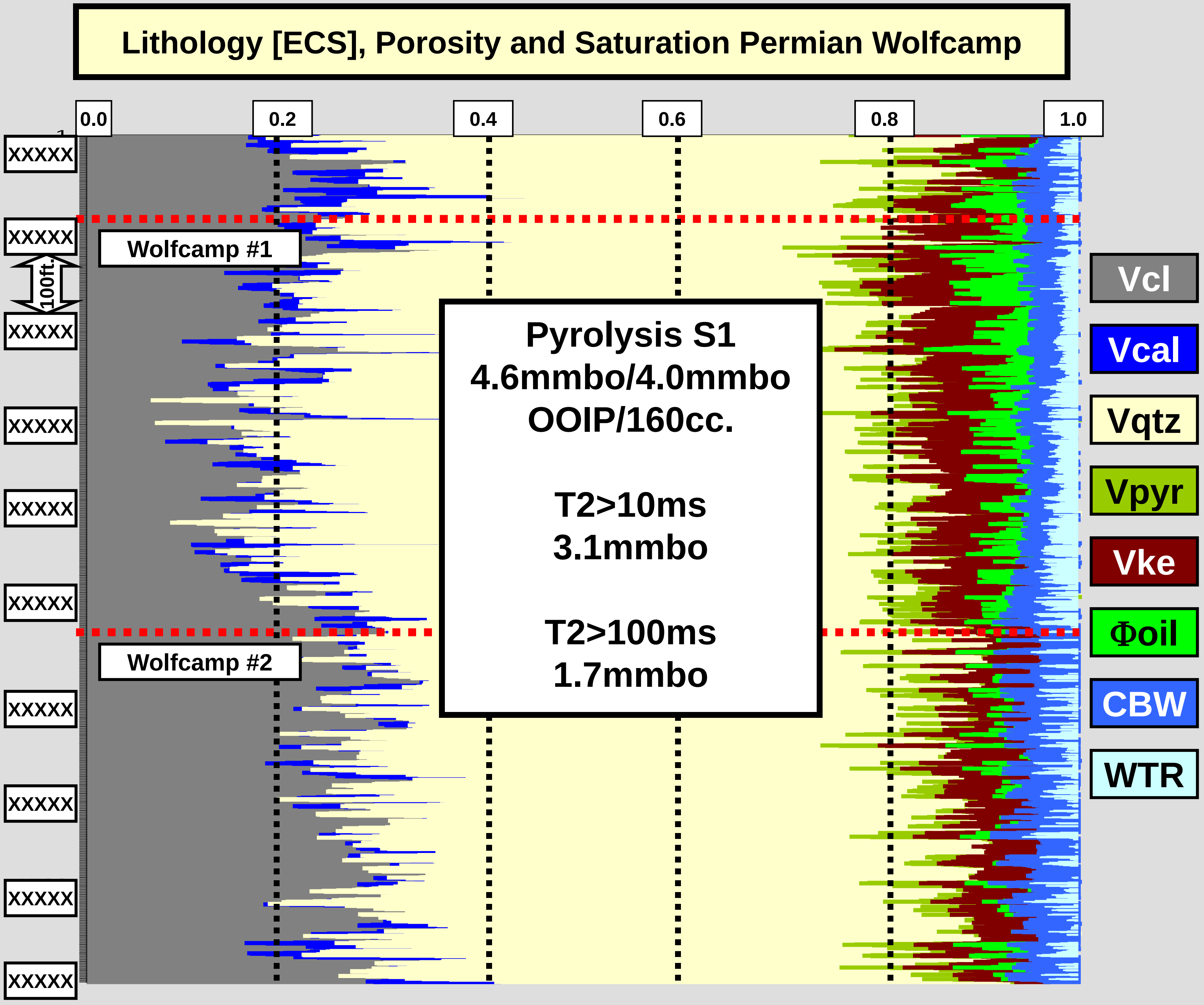

NMR PETROPHYSICAL MODEL
Moveable
100ms
33ms
10ms
3ms
TCMR
T2 Surface Relaxation
T2 Bulk Relaxation
Kerogen
Bitumen viscosity >10,000cp
Bitumen viscosity <10,000cp
Free Oil & Adsorbed Oil
Clay Bound Water
Capillary Bound Water
3ms
33ms
Free Oil & Water [conventional pores]
0.3ms [limit of NMR]
Pore Size 76.5nm
Pore Size 827.5nm
Pore Size 250nm
Pore Size 2,500nm
0.01
0.1
1.0
10
100
1,000
T2 [ms]

Petrophysical Characterization of the Pore Space in Permian Wolfcamp Rocks

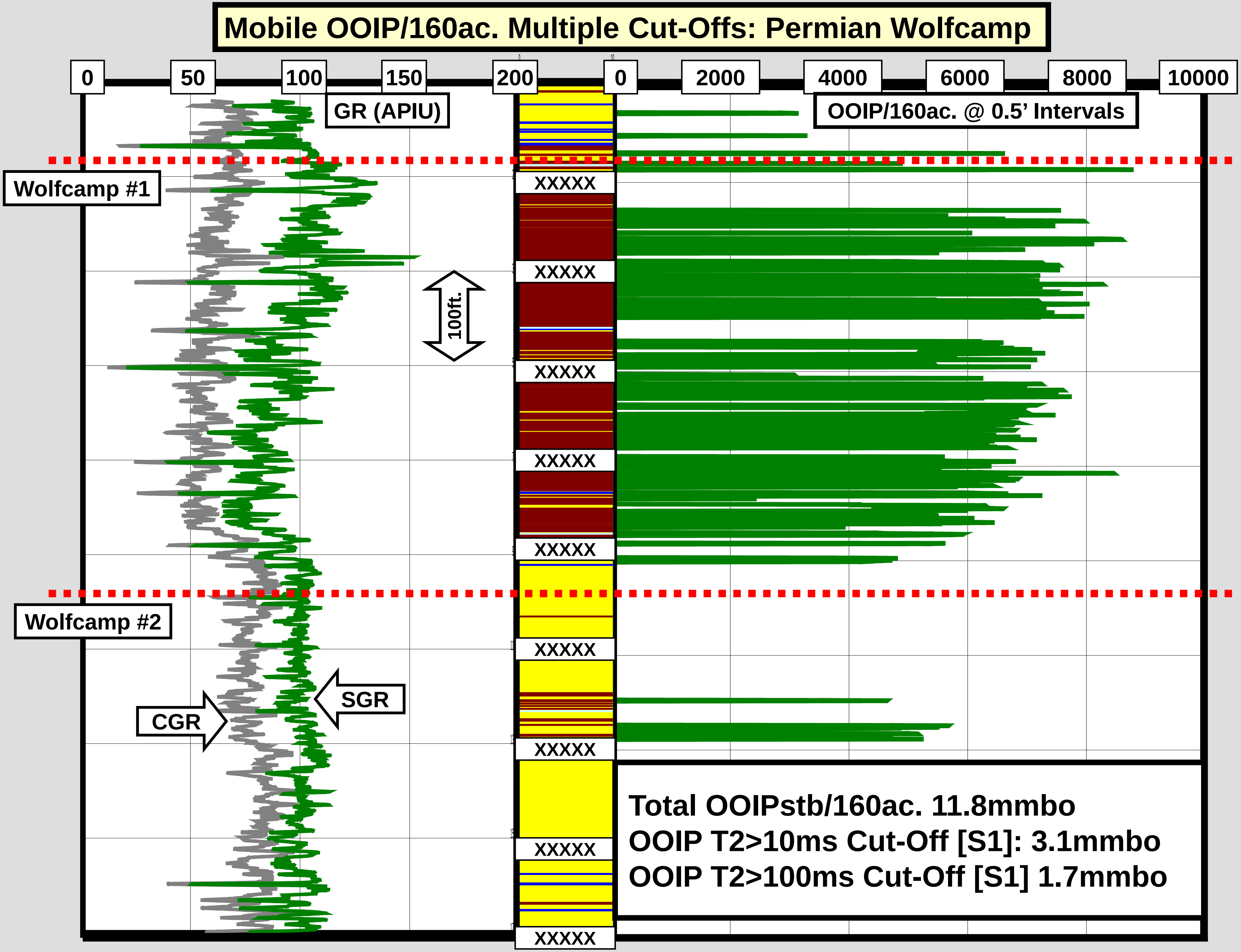
[Rafatian and Capsan, 2015]

PETROPHYSICS VOL. 56, No. 1, p. 45-55.

“the largest pore spaces and, by proxy, the largest continuous connected pore throats, have the largest impact on fluid flow”



Lithology [ECS], Porosity and Saturation Permian Wolfcamp
0.0
0.2
0.4
0.6
0.8
1.0
XXXXX
XXXXX
100ft.
XXXXX
XXXXX
XXXXX
XXXXX
XXXXX
XXXXX
XXXXX
XXXXX
Wolfcamp #1
Wolfcamp #2
Pyrolysis S1
4.6mmbo/4.0mmbo
OOIP/160cc.
T2>10ms
3.1mmbo
T2>100ms
1.7mmbo
Vcl
Vcal
Vqtz
Vpyr
Vke
Φoil
CBW
WTR


Mobile OOIP/160ac. Multiple Cut-Offs: Permian Wolfcamp
0
50
100
150
200
0
2000
4000
6000
8000
10000
GR (APIU)
OOIP/160ac. @ 0.5' Intervals
Wolfcamp #1
Wolfcamp #2
100ft.
XXXXX
CGR
SGR
Total OOIPstb/160ac. 11.8mmbo
OOIP T2>10ms Cut-Off [S1]: 3.1mmbo
OOIP T2>100ms Cut-Off [S1] 1.7mmbo

MATRIX PERMEABILITY

[KSDR PERMEABILITY]

K_{SDR} PERMEABILITY

After: Rick Lewis (2015) SCHLUMBERGER SEMINAR Midland, Texas

OIL

- **$K_{SDR} = [C * (\Phi cmr)^2 * (T2LOG)^2] * 10^6$**

K_{SDR} in nannodarcies

C = 0.35

Φcmr = Total CMR Porosity

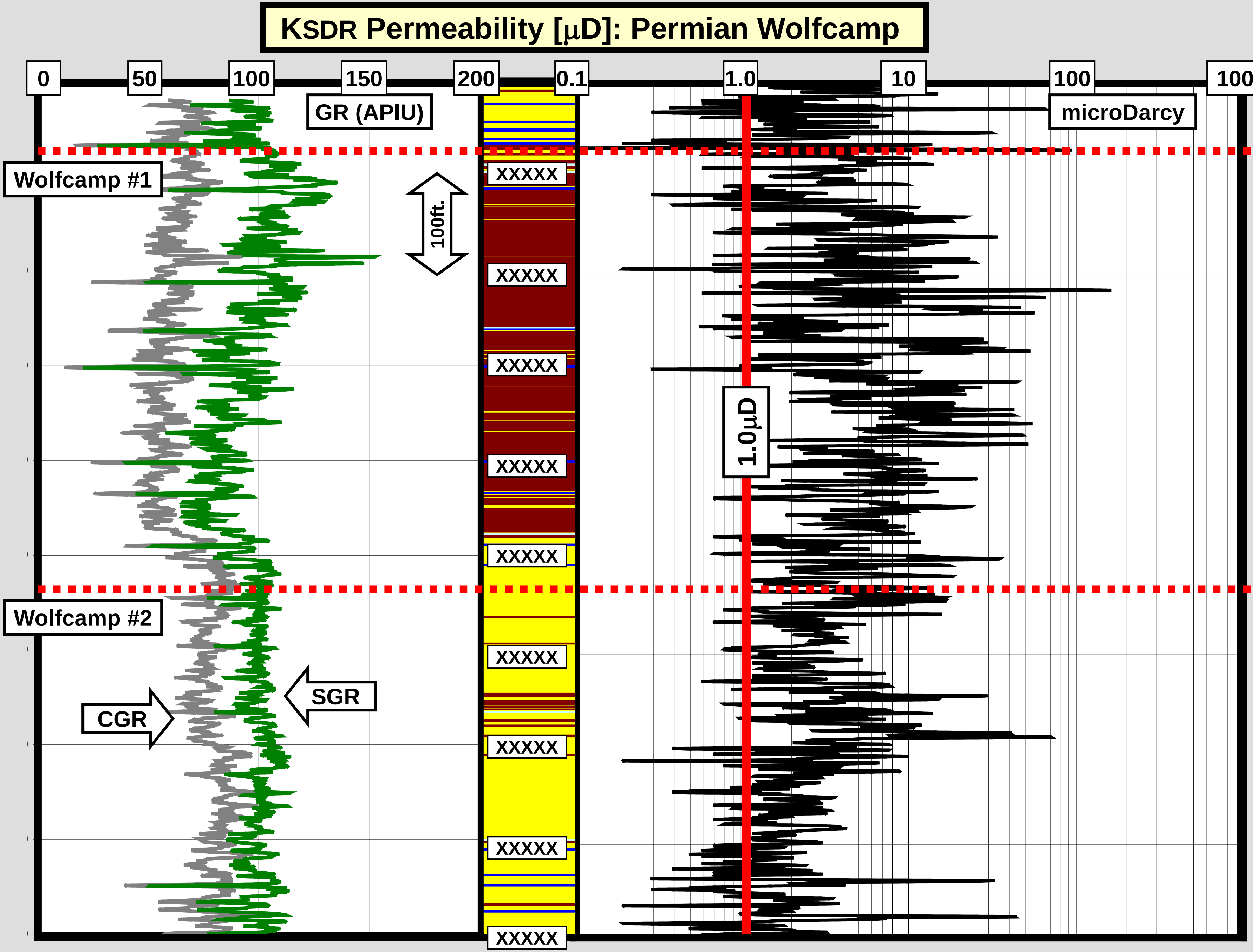
T2LOG = Logarithmic Mean T2 Distribution

K_{SDR} Permeability Cut-Off > 300nD

What Do We Look For (Shale-Associated Oil Production)?

- Higher absolute permeability than in gas shales [~1 microDarcy (1000nD) minimum and preferably much higher]. NanoDarcy-scale mudstone permeabilities are too low for economic oil production rates.

[modified after: Brown, 2015, SWAAPG]



KSDR Permeability [µD]: Permian Wolfcamp
0
50
100
150
200
0.1
1.0
10
100
100
GR (APIU)
microDarcy
Wolfcamp #1
Wolfcamp #2
100ft.
1.0µD
CGR
SGR
XXXXX
XXXXX
XXXXX
XXXXX
XXXXX
XXXXX
XXXXX
XXXXX
XXXXX

KEY FACTORS for ECONOMIC SHALE

[modified after: Rick Lewis (2013)]

RESERVOIR QUALITY

- **Hydrocarbons in Place [OOIP]**
- **Matrix Permeability [T2 CUT OFFS & K_{SDR}]**
- **Pore Pressure**

COMPLETION QUALITY

- **Hydraulic Fracture Surface Area [“Fracturability”]**
- **Hydraulic Fracture Conductivity**
- **Hydraulic Fracture Containment**

GEOMECHANICS
&
FRACTURABILITY

Poisson’s Ratio [μ] & Young’s Modulus [E]

- **Poisson’s Ratio [μ]**

$\mu = [(0.5*r^2)-1]/(r^2-1)$ r = ITTs/ITTc

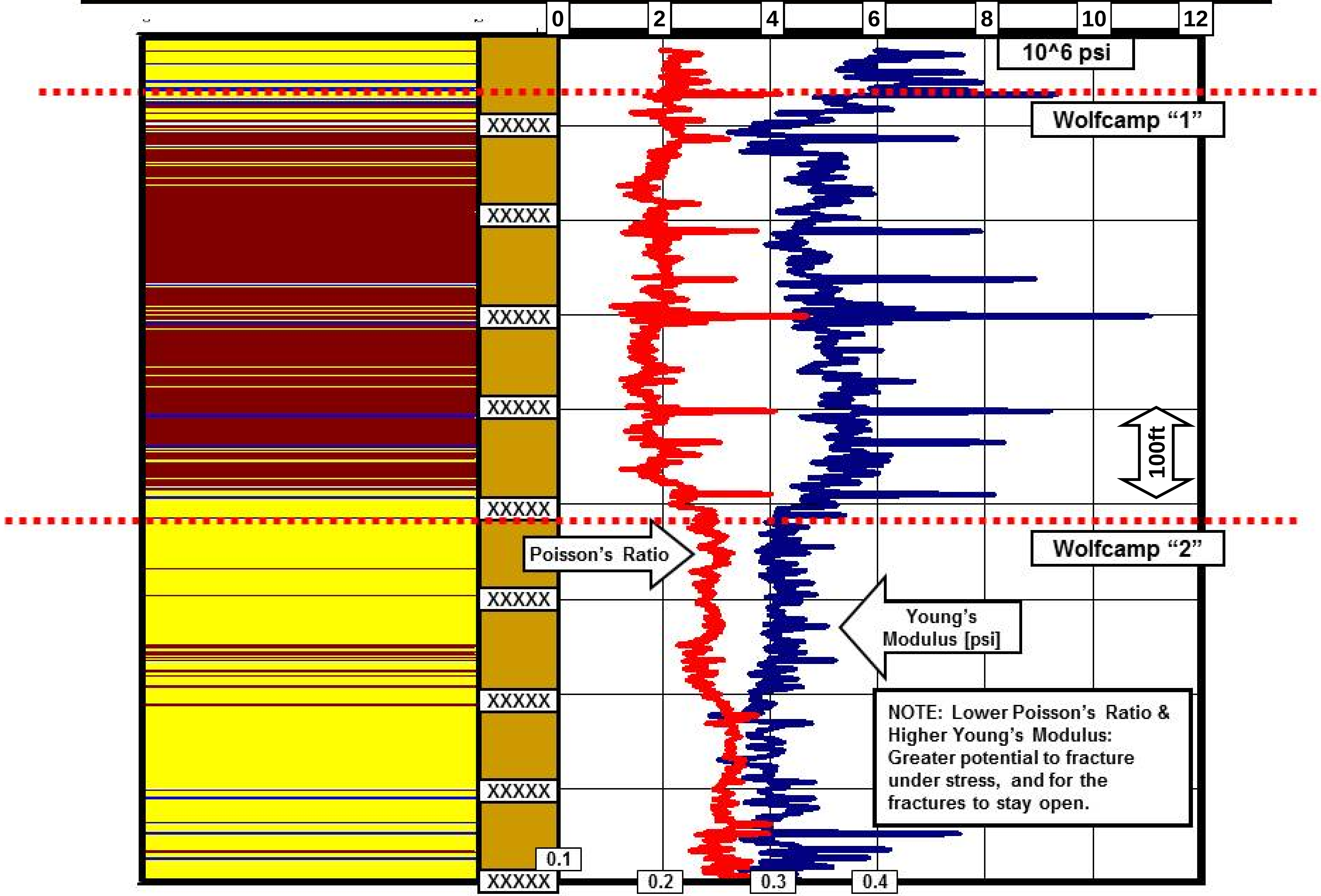
“Fracturability” the likelihood of formation failure under stress.

- **Young’s Modulus [E]**

$E = \{2*[(\rho b/ITTs^2)*1.34*10^{10}]\}*(1+\mu)$

The ability to maintain a fracture.

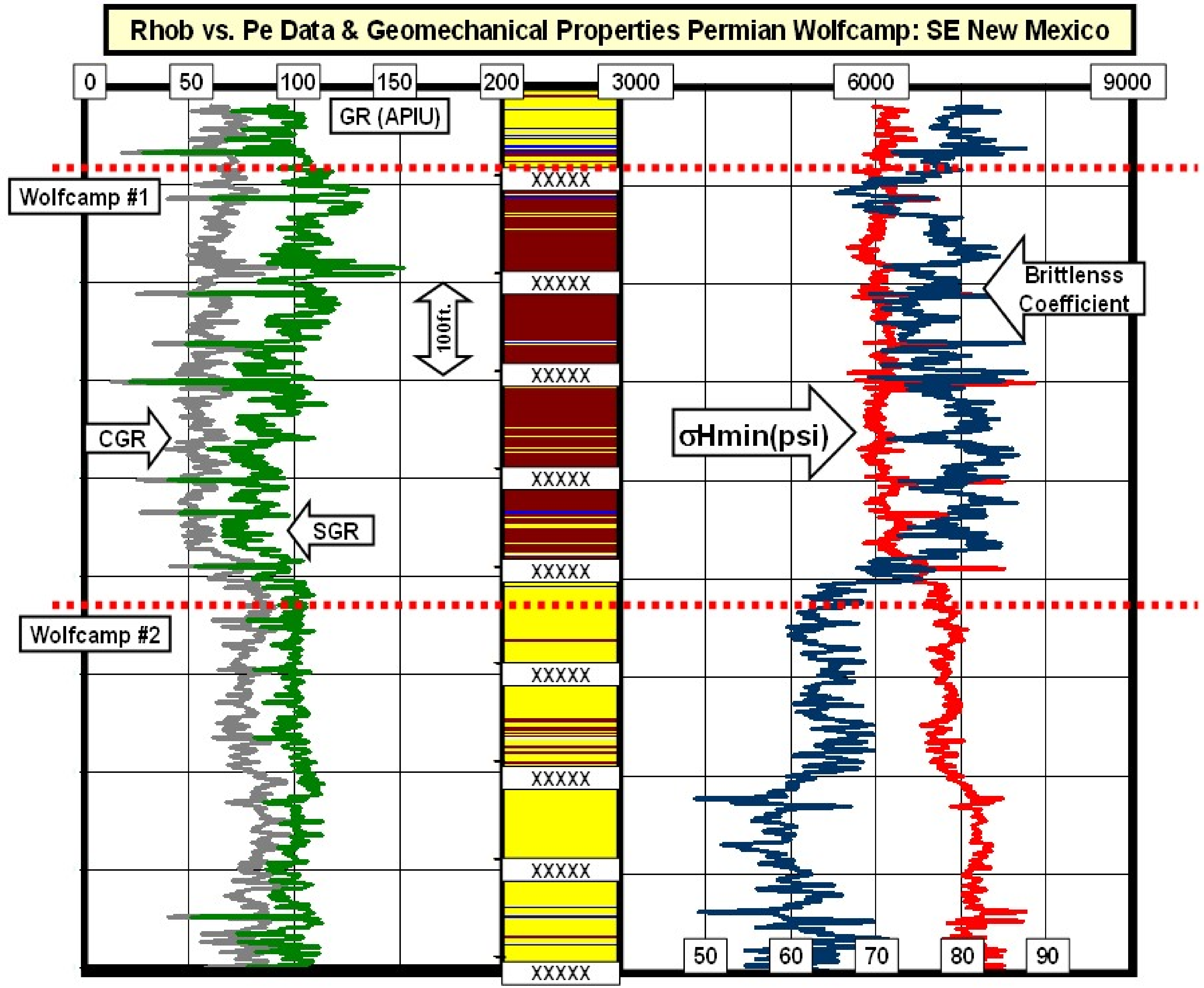
Pe & RHOb Data, Poisson's Ratio, & Young's Modulus: Permian Wolfcamp Shale



Minimum Closure Stress (σHmin) & Brittleness Coefficient

$$\sigma Hmin = [\mu/(1-\mu)] * [\sigma v - X * Pp)] + (X * Pp)$$

$$\text{Brittleness Coefficient} = 50 * \{[(E-1)/7] + [(0.4-\mu)/0.25]\}$$


Rhob vs. Pe Data & Geomechanical Properties Permian Wolfcamp: SE New Mexico
0
50
100
150
200
3000
6000
9000
GR (APIU)
Wolfcamp #1
XXXXX
100ft.
Brittlenss Coefficient
CGR
σHmin(psi)
SGR
Wolfcamp #2
50
60
70
80
90

CONCLUSIONS

- The application of T2 Cut-Offs to OOIPstb plus Pyrolysis S1 Data can be used to define the distribution of the larger pores with free hydrocarbons which have the greatest impact on fluid flow.

- When OOIPstb determine from S1 data and T2 cut-offs is combined with RHOb and Pe cut-offs the unconventional reservoir's "SWEET SPOT" with lower Poisson's Ratio and higher Youngs Modulus can be delineated.