Source Rock Evaluation from Well Logs – Four Decades of Technical Tipping Points*

Quinn R. Passey[1]

Search and Discovery Article #60056 (2019)**
Posted September 30, 2019

*Adapted from oral presentation given at 2019 AAPG Hedberg Conference, The Evolution of Petroleum Systems Analysis, Houston, Texas, March 4-6, 2019
**Datapages © 2019 Serial rights given by author. For all other rights contact author directly. DOI:10.1306/60056Passey2019

[1]Retired (Passey.quinn@gmail.com)

Abstract

The evaluation of geologic formations and their fluids has evolved from the 1920's when downhole resistivity logs were first pioneered by the Schlumberger brothers. In 1942, Gus Archie conducted laboratory experiments on various sandstones and determined that the resistivity of a rock depends on the water saturation, water salinity, porosity, and a factor (tortuosity) related to how the pores are connected. After World War II, new nuclear-based technology began to be incorporated in downhole well-logging tools, and the natural gamma-ray, gamma-gamma density tool, neutron porosity, and Photoelectric (PE) logs became part of the arsenal of downhole measurements, along with a variety of acoustic-based sonic logs. Initially, combinations of these logging instruments were used to differentiate and quantify lithology, mineralogy, porosity, and fluid type (oil, gas, water).

In the 1950's-1960's, scientists applied the natural gamma-ray well log to explore for uranium in Appalachian Devonian-age organic-rich rocks. In the late 1960's, research scientists (Waxman and Smits), determined that additional electrical conductivity due to the presence of dispersed and/or laminated clay required corrections to the earlier Archie equation. Various combinations of well-logging technologies were applied to source rocks during the 1970's-80's and it was recognized that source rock maturity was related to resistivity log response in the Bakken formation (Meissner), and that the organic matter had anomalously low density and slow velocity (long transit time). Early studies in the Bakken and Mowry shales indicated that well logs could easily identify potential source rock intervals.

In the 1980's, the research organizations of several major oil companies developed and published a variety of techniques to evaluate organic richness based on a combination of sonic/resistivity or density/resistivity well-log crossplots. Also, in the late 1980's, new logging tools evolved for the direct determination of carbon.

In 1989-90, the ΔlogR technique (Passey et al., 1990) was published after details of the previously internal proprietary approach began leaking out into industry; this approach utilized previous approaches but also incorporated source rock maturity as an additional factor in determining organic richness (or TOC – total organic carbon) from well logs; moreover, in addition to commonly used crossplot methods, the ΔlogR

approach utilized a well-log overlay technique that allowed for “normalizing” log responses to address variable porosity, lithology, and fluid salinity (all of which were previously problematic to determine in organic-rich mudstones). The well-log overlay plots allowed for the determination of the stratigraphic distribution of TOC, and demonstrated the role of sequence stratigraphy on source rock occurrence (Creaney and Passey, 1993) - a key input to today’s placement of horizontal wells in unconventional reservoirs.

A major tipping point in the evaluation of organic richness came about with the onset of the shale-gas and later shale-oil unconventional reservoirs, started by the Barnett Shale work in central Texas in the 1990’s-2000’s. The expansion to explore dozens of “source-rock” formations as reservoirs worldwide provided abundant fresh mudstone cores, development of new core analysis techniques, and the application and revision of well-log evaluation techniques.

Among the key recent learnings included are: (1) utilization of ion-milled samples which allowed for recognition of nano-meter scale pores in the organic matter (Loucks and Reed, 2014), (2) identification of different habits for kerogen and bitumen, (3) ability to make accurate nano-Darcy permeability measurements on core plugs (Sinha et al., 2013), (4) recognition of the presence of early graphite at very high thermal maturities (Vro>2) (Walters et al., 2012) resulting in additional electrical conductivity paths and, often, extremely low resistivity values, and (5) modification of previous well-log interpretation methods (Passey et al., 2010). Work continues on determining the presence of organic porosity and its role in the production of shale-oil reservoirs such as the Eagleford, Bakken, Marcellus, and others. Currently, the knowledge of source rocks and their ultimate transformation to unconventional reservoirs is high; with this knowledge we are able to work with our engineering teams to optimize the production of hydrocarbons for the future.

References Cited

Creaney, S., and Q.R. Passey, 1993, Recurring patterns of total organic carbon and source rock quality within a sequence stratigraphic framework: AAPG Bulletin, v. 77/3, p. 386-401.

Loucks, R.G., and R.M. Reed, 2014, Scanning-electron-microscope petrographic evidence for distinguishing organic-matter pores associated with depositional organic matter versus migrated organic matter in mudrocks: GCAGS Journal, v. 3, p. 51-60.

Luffel, D.L., C.W. Hopkings, and P.D. Schettler Jr., 1993, Matrix permeability measurement of gas productive shales: SPE 26633.

Meissner, F.F., 1978, Petroleum geology of the Bakken Formation, Williston Basin, North Dakota and Montana: Montana Geological Society, The Economic geology of the Williston Basin, p. 207-227.

Passey, Q.R., S. Creaney, J.B. Kulla, F.J. Moretti, and J.D. Stroud, 1990, A practical model for organic richness from porosity and resistivity logs: AAPG Bulletin, v. 74/12, p. 1777-1794.

Passey, Q.R., K.M. Bohacs, W.L. Esch, R. Klimentidis, and S. Sinha, 2010, From Oil-Prone Source Rock to Gas-Producing Shale Reservoir – Geologic and Petrophysical Characterization of Unconventional Shale-Gas Reservoirs: SPE 131350, presented at the CPS/SPE International Oil & Gas Conference and Exhibition in China, Beijing, China, 8-10 June 2010.

Spears, R.W., D. Dudus, A. Foulds, Q. Passey, S. Sinha, and W.L. Esch, 2011, Shale gas core analysis: strategies for normalizing between laboratories and a clear need for standard materials: 52nd Annual SPWLA Logging Symposium Transactions, Paper A, 11 p.

Sinha, S., E.M. Braun, M.D. Determan, et al., 2013, Steady-State Permeability Measurements on Intact Shale Samples at Reservoir Conditions - Effect of Stress, Temperature, Pressure, and Type of Gas: SPE Middle East Oil and Gas Show and Conference, Manama, Bahrain, March10-13. SPE-164263-MS. https://doi.org/10.2118/164263-MS.

Tissot, B.P., and D.H. Welte, 1984, Petroleum Formation and Occurrence: Springer-Verlag, Berlin, Germany, 699 p.

Walters, C.C., P.G. Lillis, and K.E. Peters, 2012, Molecular indicators of geothermal history, *in* N.B. Harris and K.E. Peters, eds., Analyzing the thermal history of sedimentary basins: Methods and case studies: SEPM Special Publication, v. 103, p. 17-28.

Source Rock Evaluation from Well Logs – Four Decades of Technical Tipping Points

Quinn R. Passey

Based on information in the following primary references:

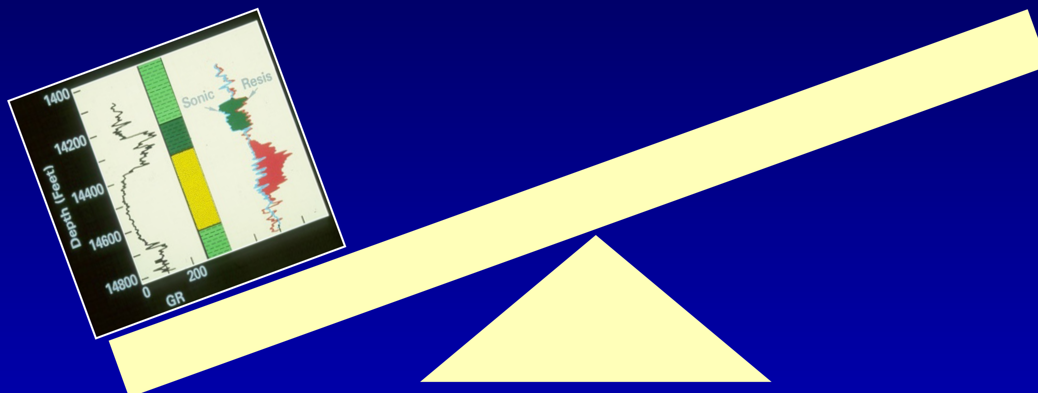
Passey, Q.R., S. Creaney, J.B. Kulla, F.J. Moretti, J.D Stroud (1990) A practical Model for Organic Richness from Porosity and Resistivity Logs, AAPG Bulletin Volume 74, Number 12 (December 1990), Page 1777 – 1794.

Creaney, S., and Passey, Q. R., (1993) Recurring Patterns of Total Organic Carbon and Source Rock Quality within a Sequence Stratigraphic Framework, AAPG Bulletin, Volume 77, Number 3 (March 1993), page 386-401.

Passey, Q.R., Bohacs, K.M., Esch, W. L., Klimentidis, R., and Sinha, S. (2010) From Oil-Prone Source Rock to Gas-Producing Shale Reservoir – Geologic and Petrophysical Characterization of Unconventional Shale-Gas Reservoirs, SPE 131350, presented at the CPS/SPE International Oil & Gas Conference and Exhibition in China, Beijing, China, 8-10 June 2010.

Tipping Points

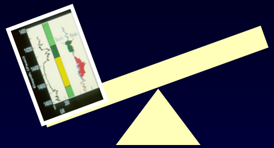
The Tipping Point (1984-85)



The critical point in a situation, process, or system beyond which a significant and often unstoppable effect or change takes place.

https://www.merriam-webster.com/dictionary/tipping%20point

Archie Equation (1942)



$$S_w{}^{n} = \frac{R_w}{(\Phi^m \times R_t)}$$

where:

S_w = water saturation of the uninvaded zone

n = saturation exponent, which varies from 1.8 to 4.0 but normally is 2.0

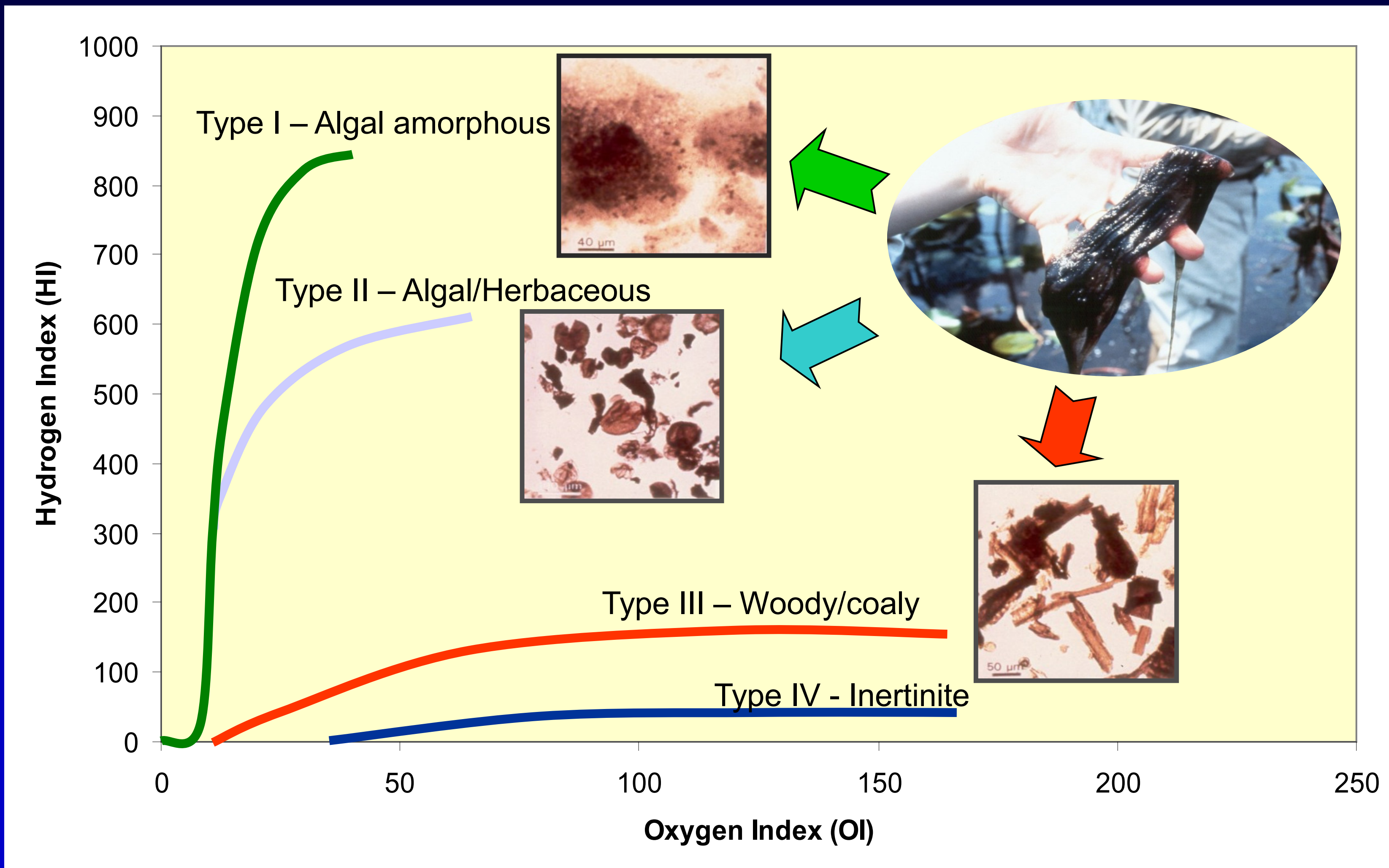
R_w = formation water resistivity at formation temperature

Φ = porosity

m = cementation exponent, which varies from 1.7 to 3.0 but normally is 2.0

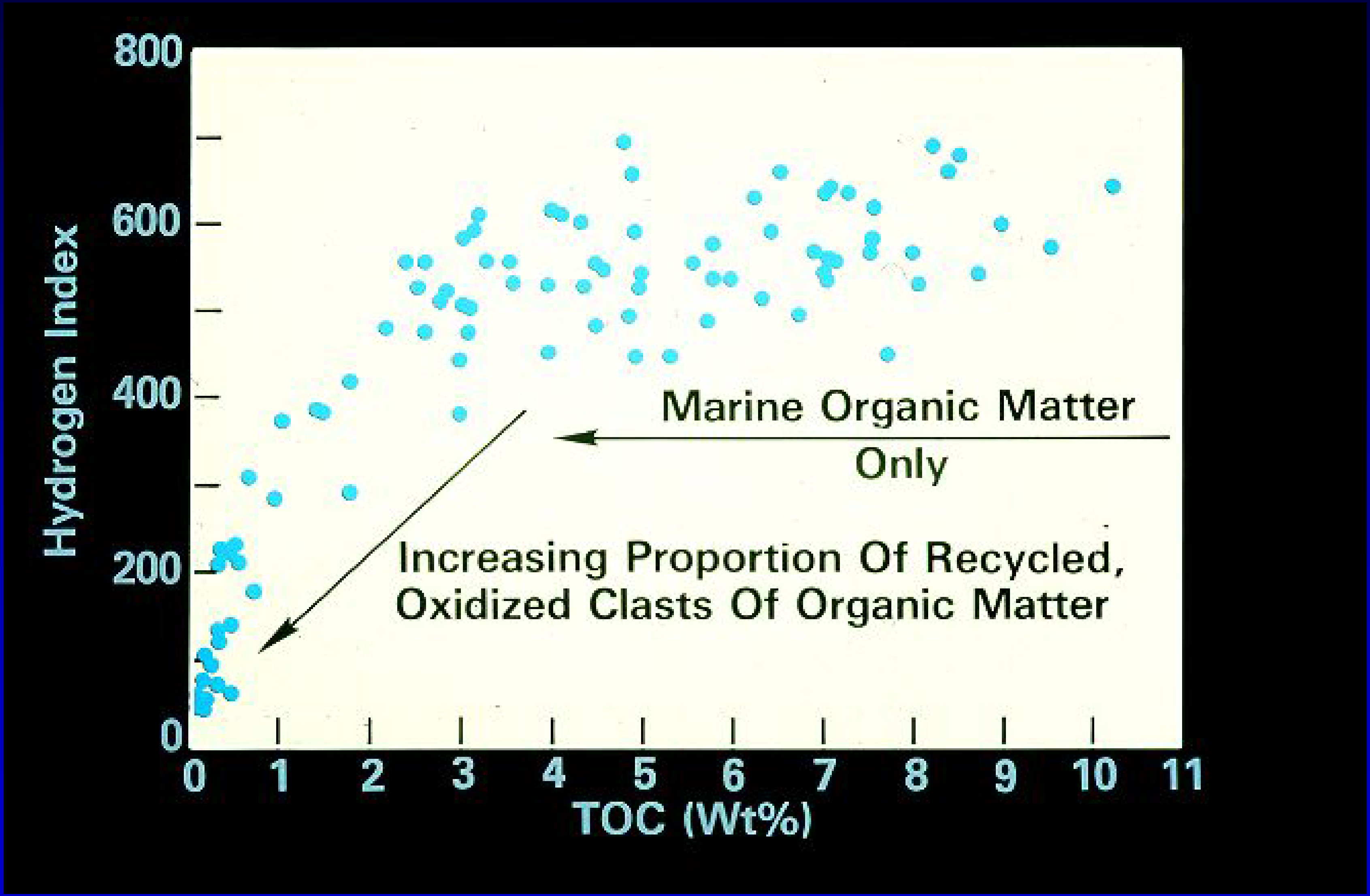
R_t = true resistivity of the formation, corrected for invasion, borehole, thin bed, and other effects

Organic Matter Type & Pyrolysis



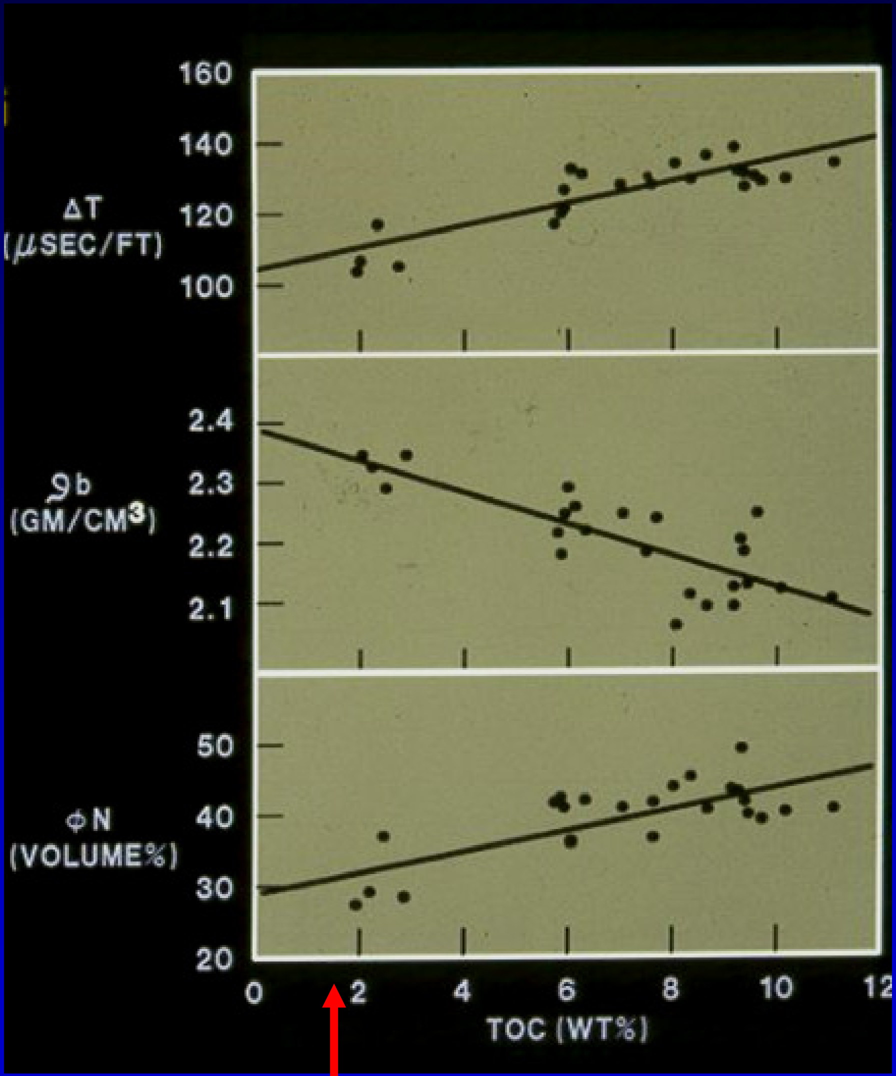
(After Tissot and Welte, 1984)

TOC vs OMT (Hydrogen Index) – Duverney Shale



(After Creaney & Passey, 1993)

Porosity Log and TOC Response



Common threshold for ‘source potential’ is TOC > 1.5 wt%

Porosity log response in organic-rich rocks:

Sonic Log –

- Transit time (ΔT) increases in organic-rich rocks.
- Log is commonly run, correctable for common borehole problems and is available for most vintage wells.

Density Log –

- Bulk density (ρ_b) decreases in organic-rich rocks.
- Log is common but is a ‘pad’ tool and therefore has ‘issues’ in rugose boreholes.

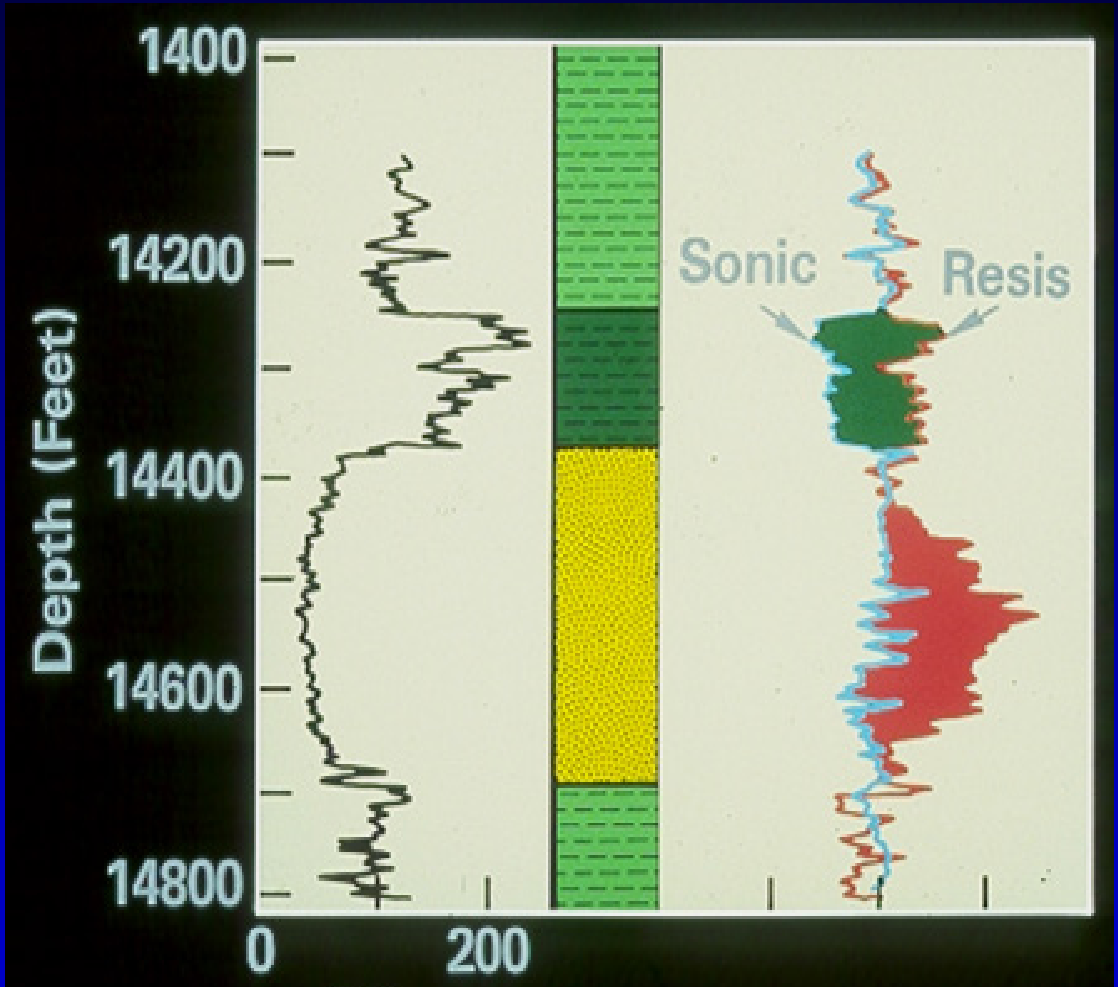
Neutron Log –

- Neutron porosity (ϕ_N) increases in organic-rich rocks
- Commonly run today but less so on older wells.

Bottom Line: All porosity logs respond to organic matter as if it were additional porosity. We tend to use the sonic log since it is most commonly available and less sensitive to borehole condition

(After Passey et al., 1990)

Log Response in Organic-rich Rocks



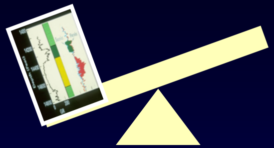
Example is Kimmeridge Clay, North Sea

Well logs can be used to estimate the following properties:

- **Source Thickness**
- **Source Richness**
- **Stratigraphic location of source**
- **Maturity – immature vs mature+**
- **Inferences on source type based on geologic context**

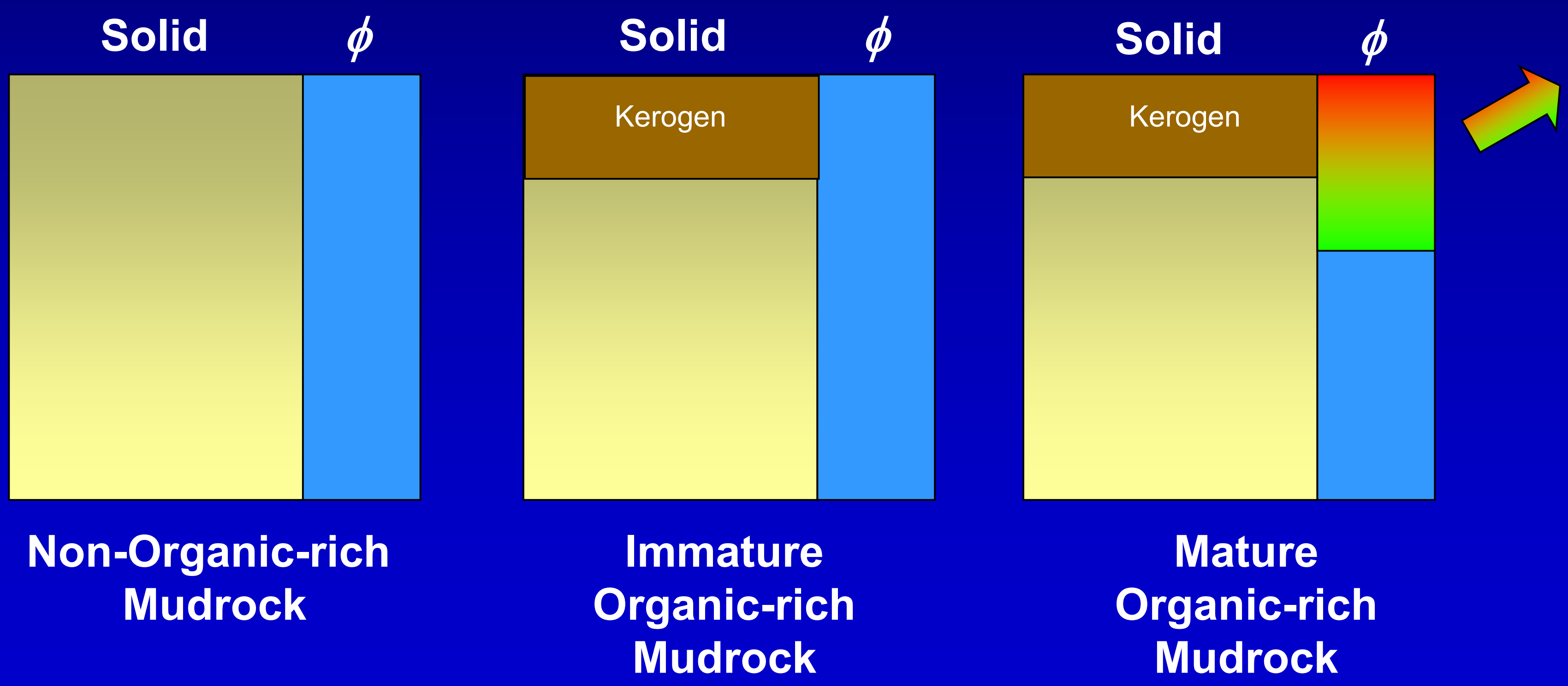
(After Passey et al., 1990)

Porosity and Matrix in Organic-rich Rocks

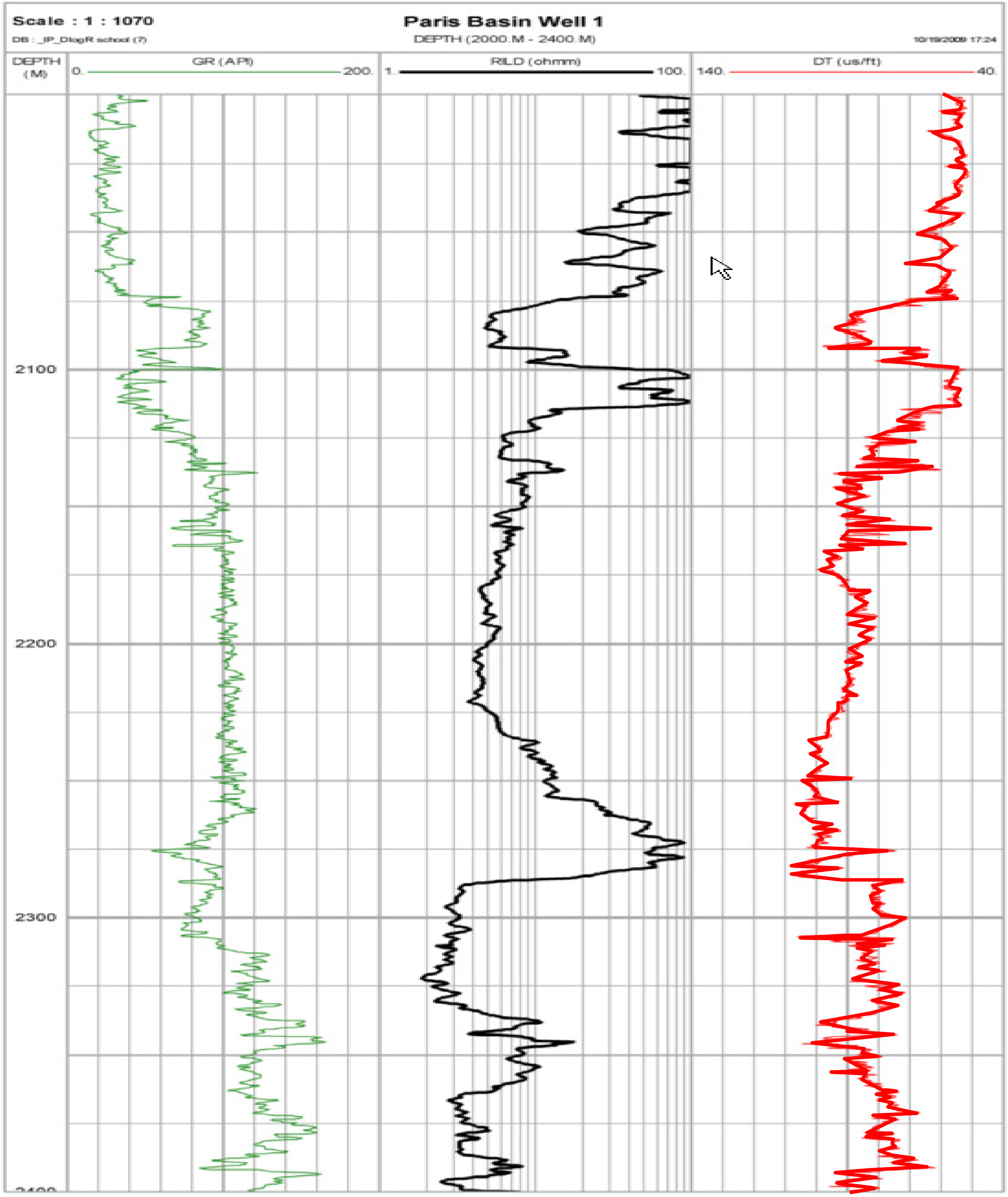


Basic Physics:

- Shales and mudrocks are solid matrix (clay sized particulates) and pore water
- Organic-rich mudrocks additionally contain solid organic matter
- When mature, organic-rich mudrocks will generate HC's which enter porosity with the water and are eventually expelled



(After Passey et al., 1990)



What Do We Know?

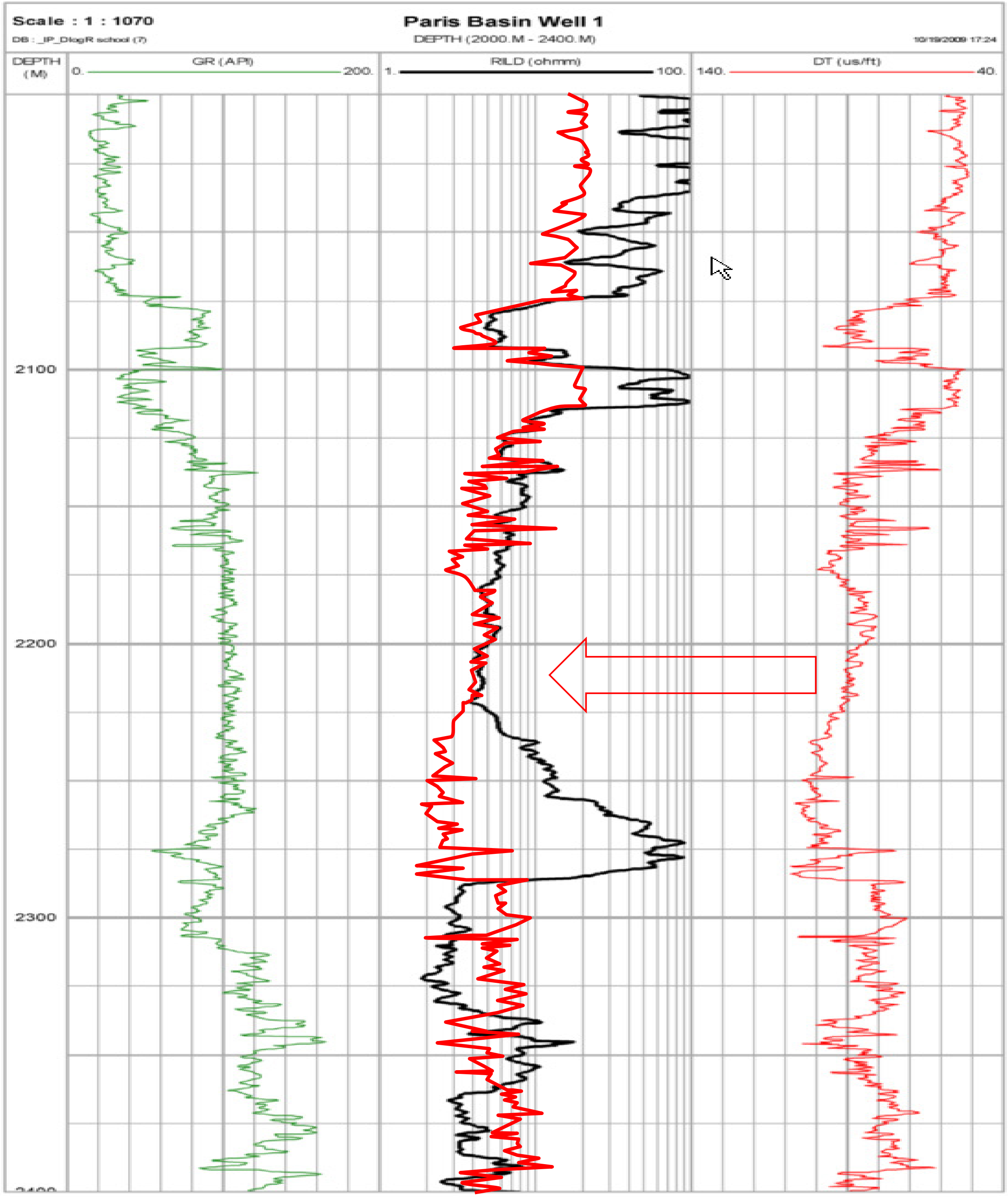
Don't Know

$$S_w{}^n = \frac{R_w}{(\Phi^m \times R_t)}$$

Do Know

(After Passey et al., 1990)

What Do We Know?



Don't Know

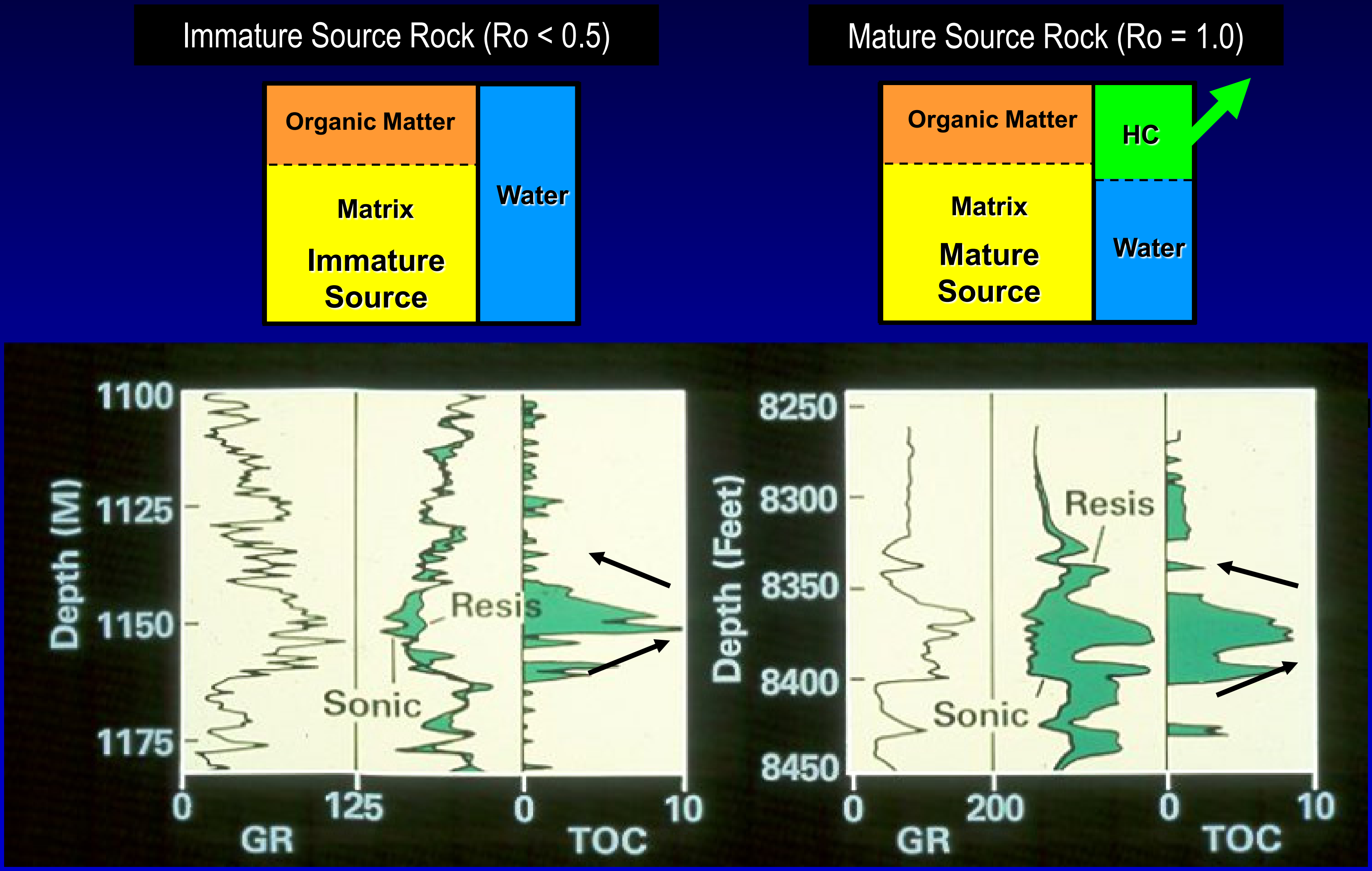
$$S_w^{\,n} = \frac{R_w}{(\Phi^m \times R_t)}$$

Do Know

"Baselining" covers a multitude of unknowns

(After Passey et al., 1990)

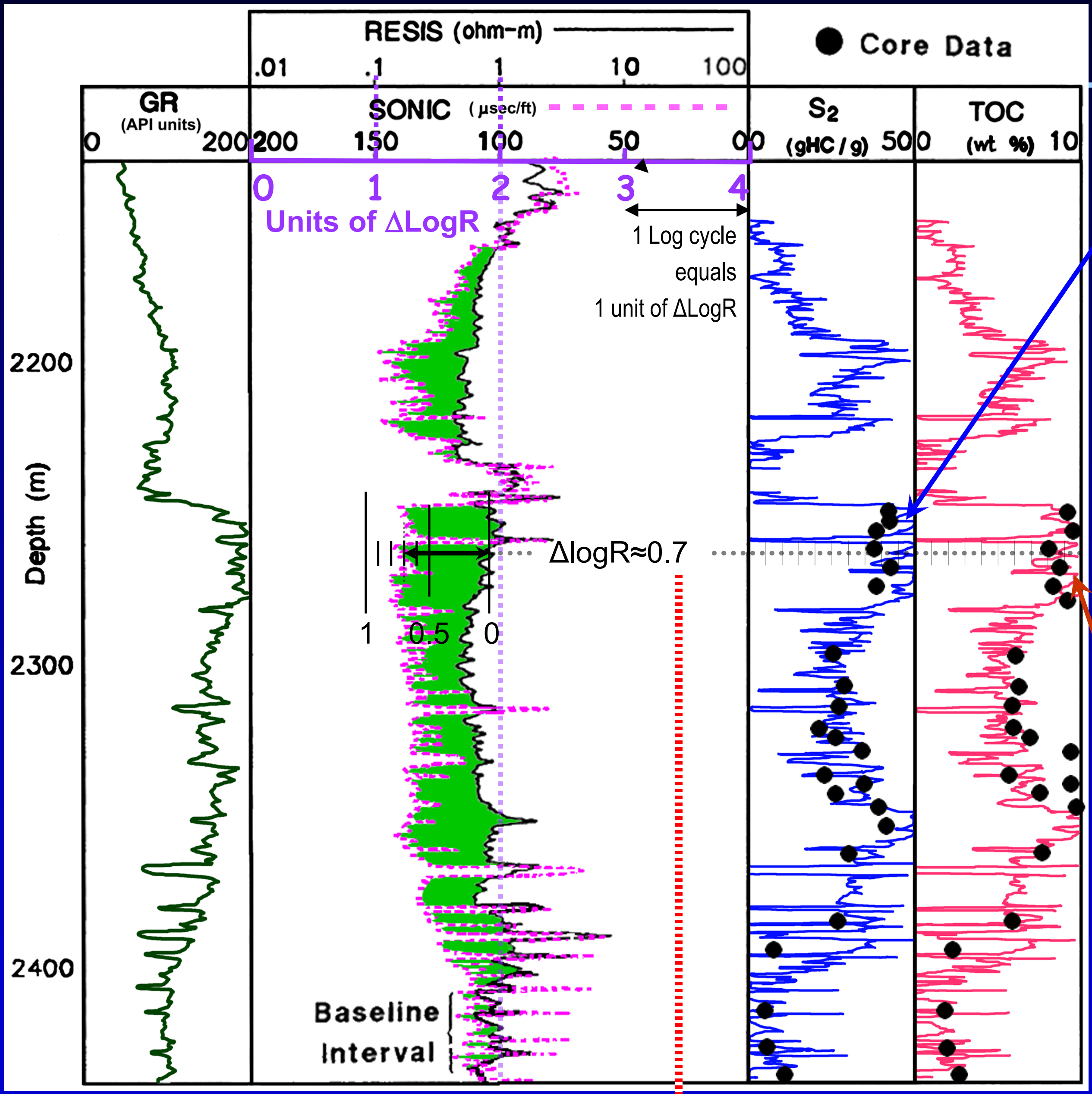
Maturity Effect on Log Response in Organic-rich Intervals

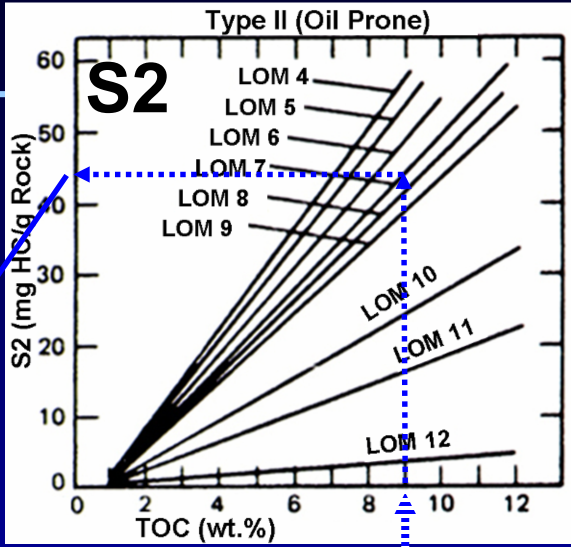


(After Passey et al., 1990; see also Meissner, 1978)

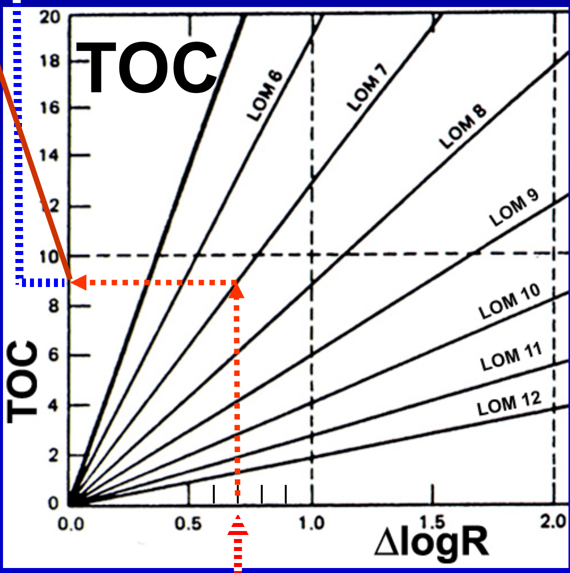
ΔlogR to TOC Calculation

(After Passey et al., 1990)



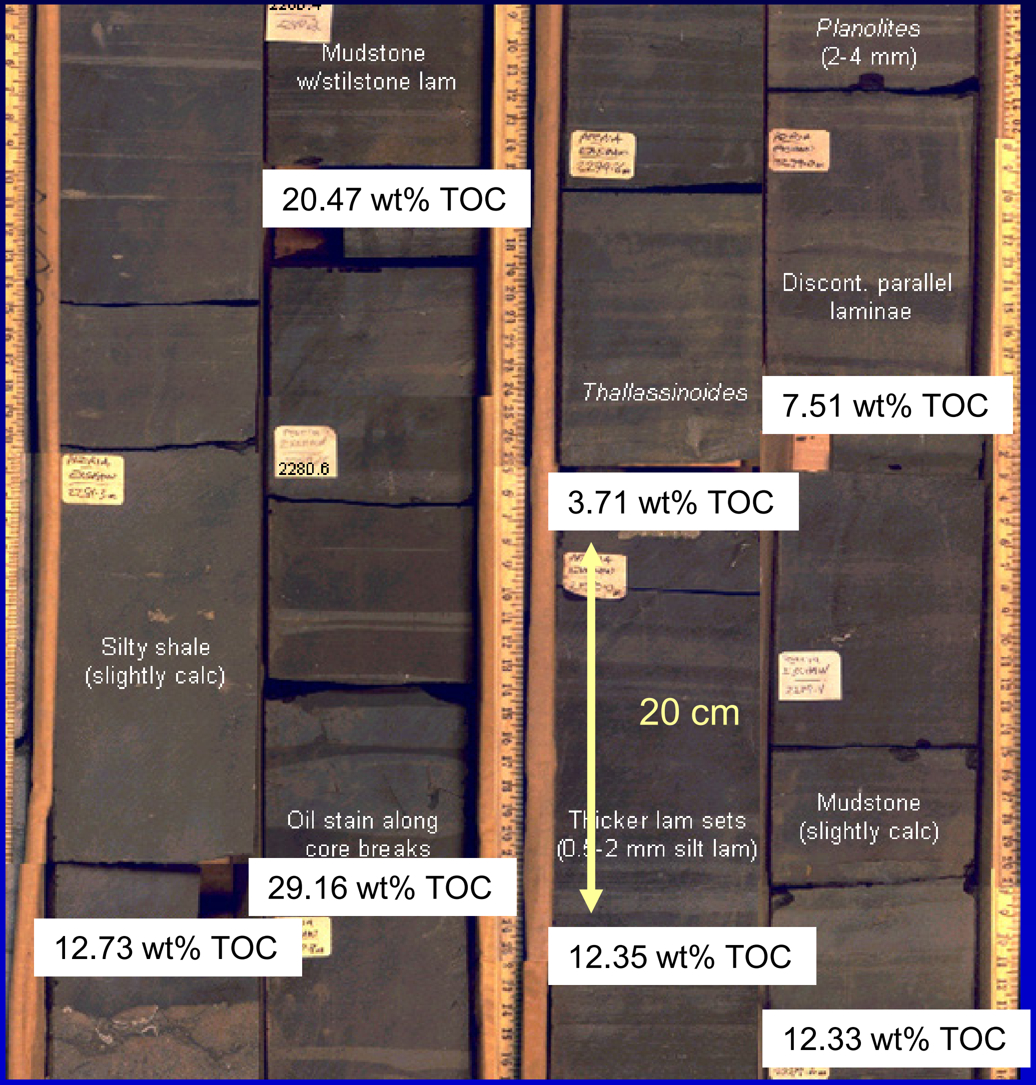


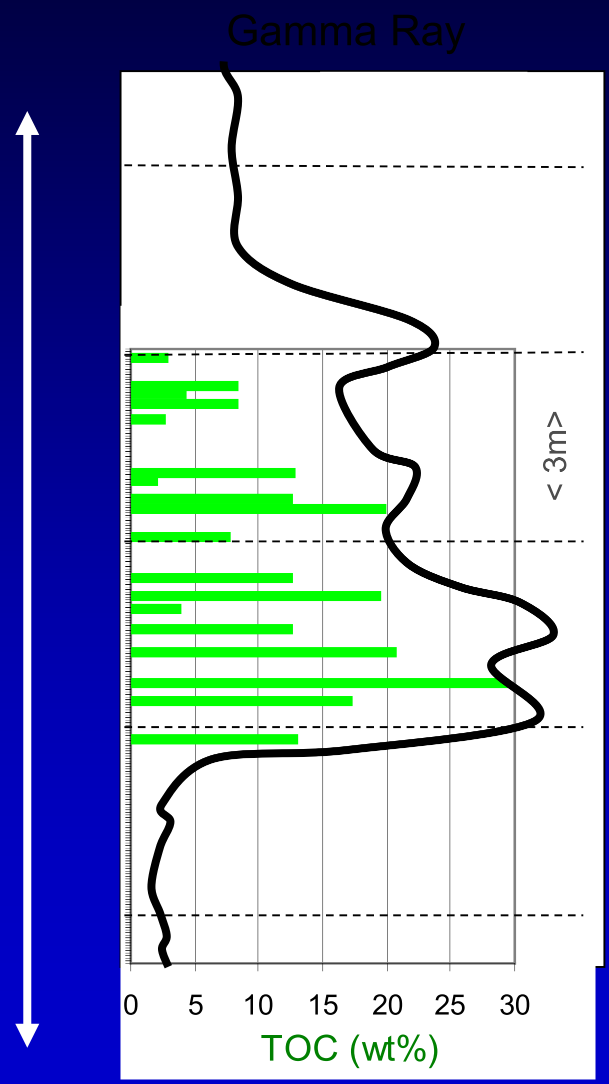
(LOM = 7, Type II)



Vertical Variability Scale of cm to meters

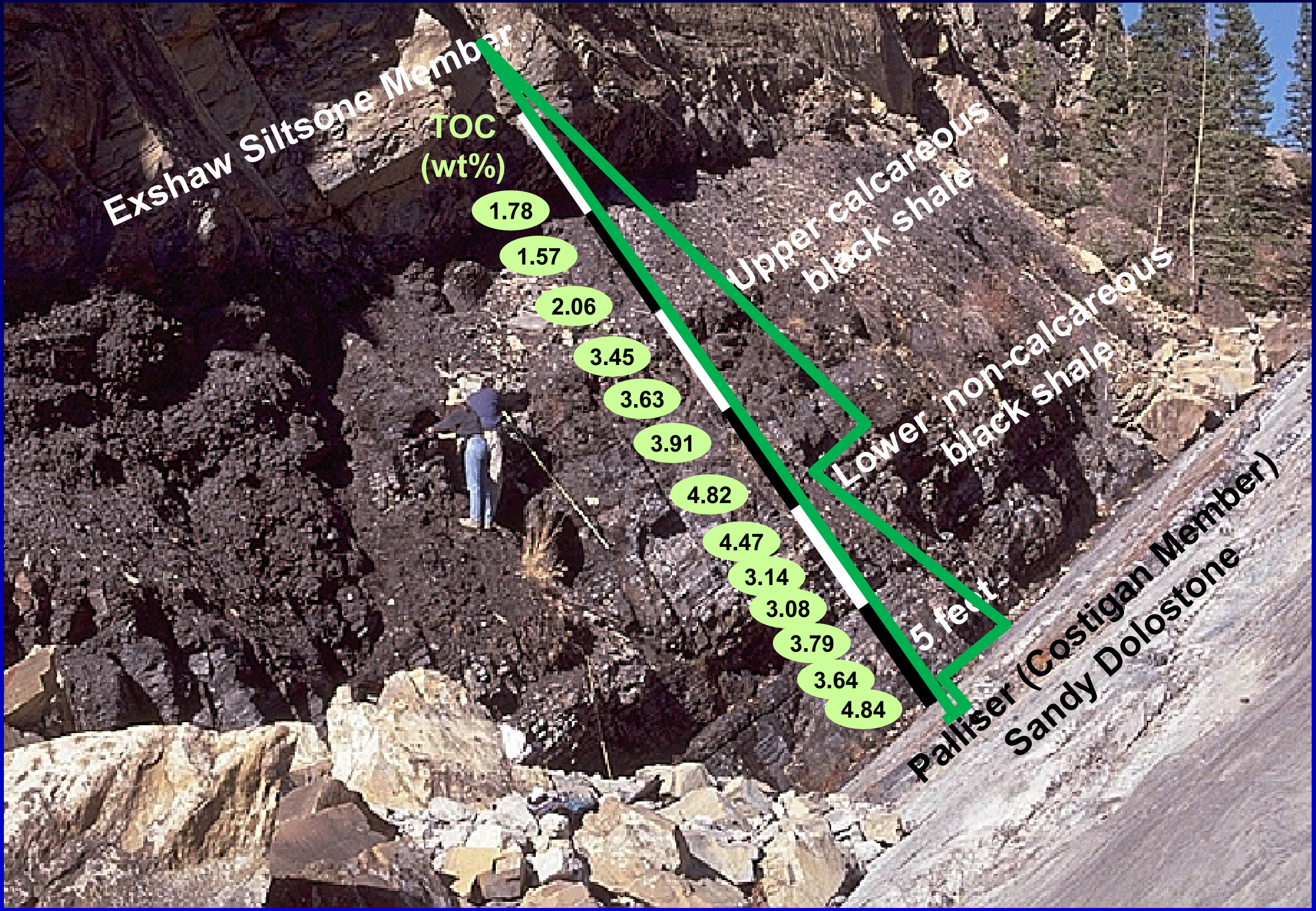
Exshaw Formation





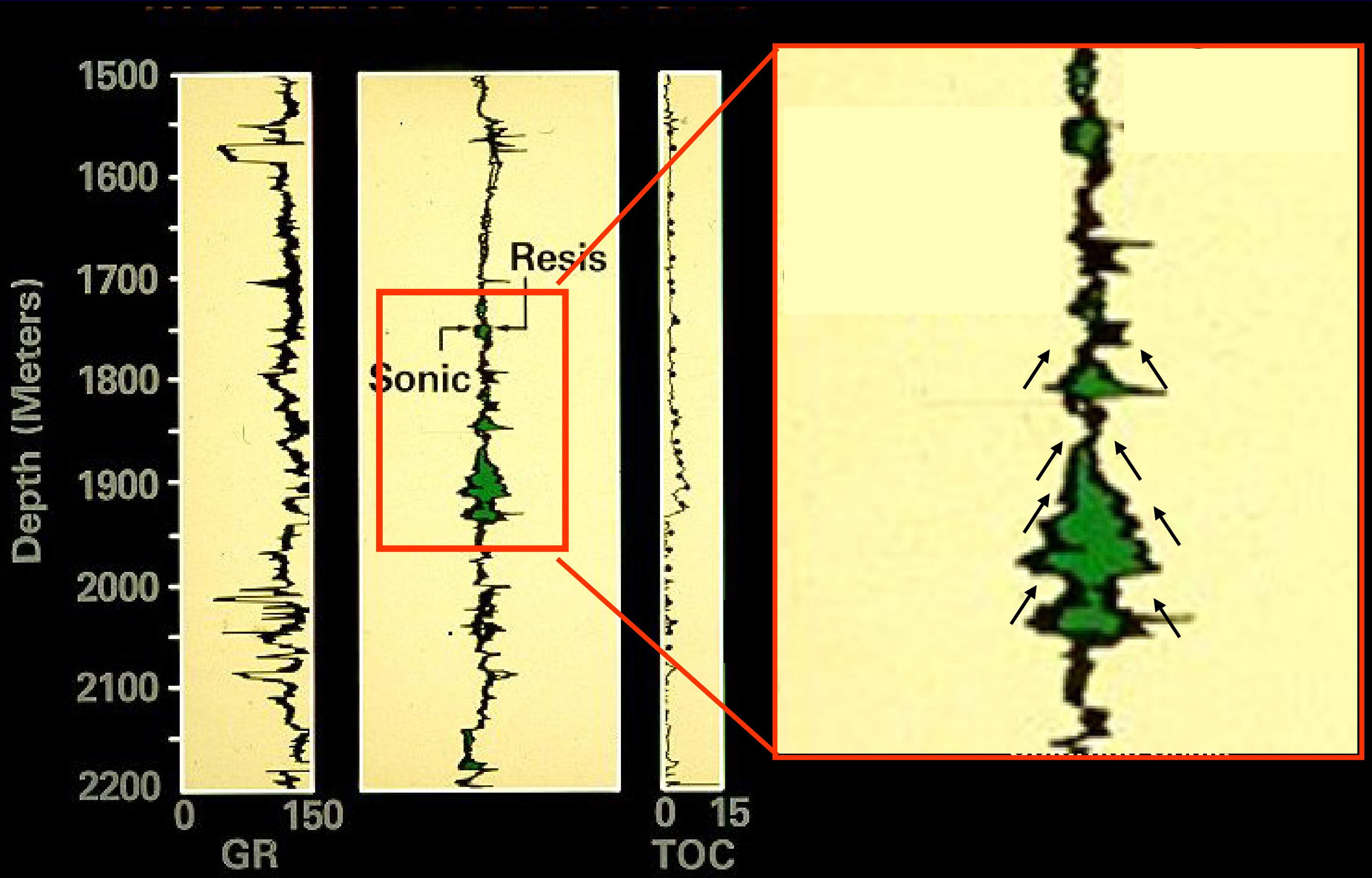
(Passey et al., 2010)

TOC Stacking at Parasequence Scale
Exshaw Formation, Alberta



(After Passey et al., 2010)

Vertical Variation in TOC from Well Logs
Colorado Shale, Alberta



(After Creaney & Passey, 1993)

Key Moments in the Field –
What are the ΔlogR Triangles?

Niobrara Limestone
Cretaceous
Near Canon City, Colorado

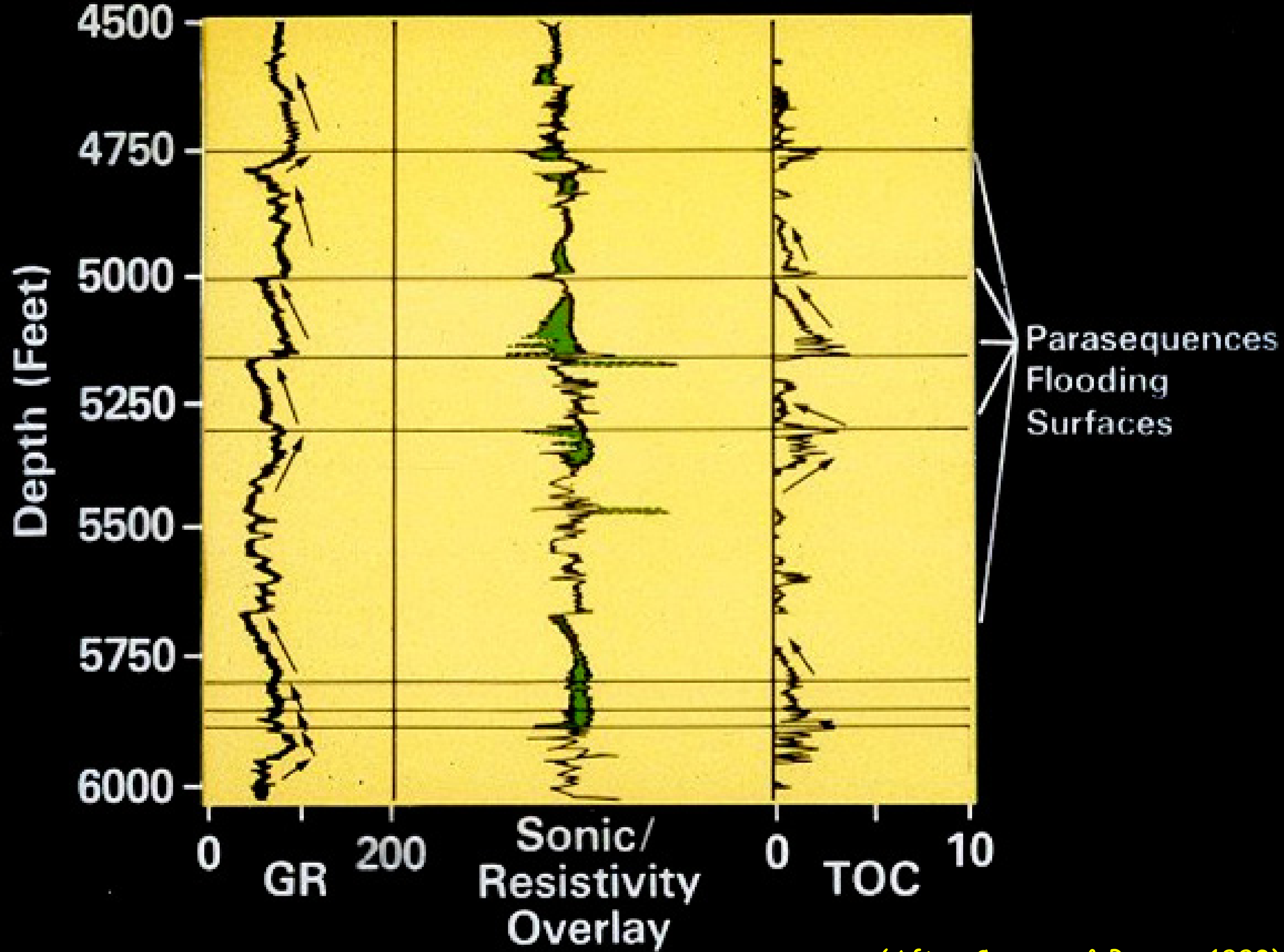
Earl Kaufmann

Peter Vail

Kevin Bohacs

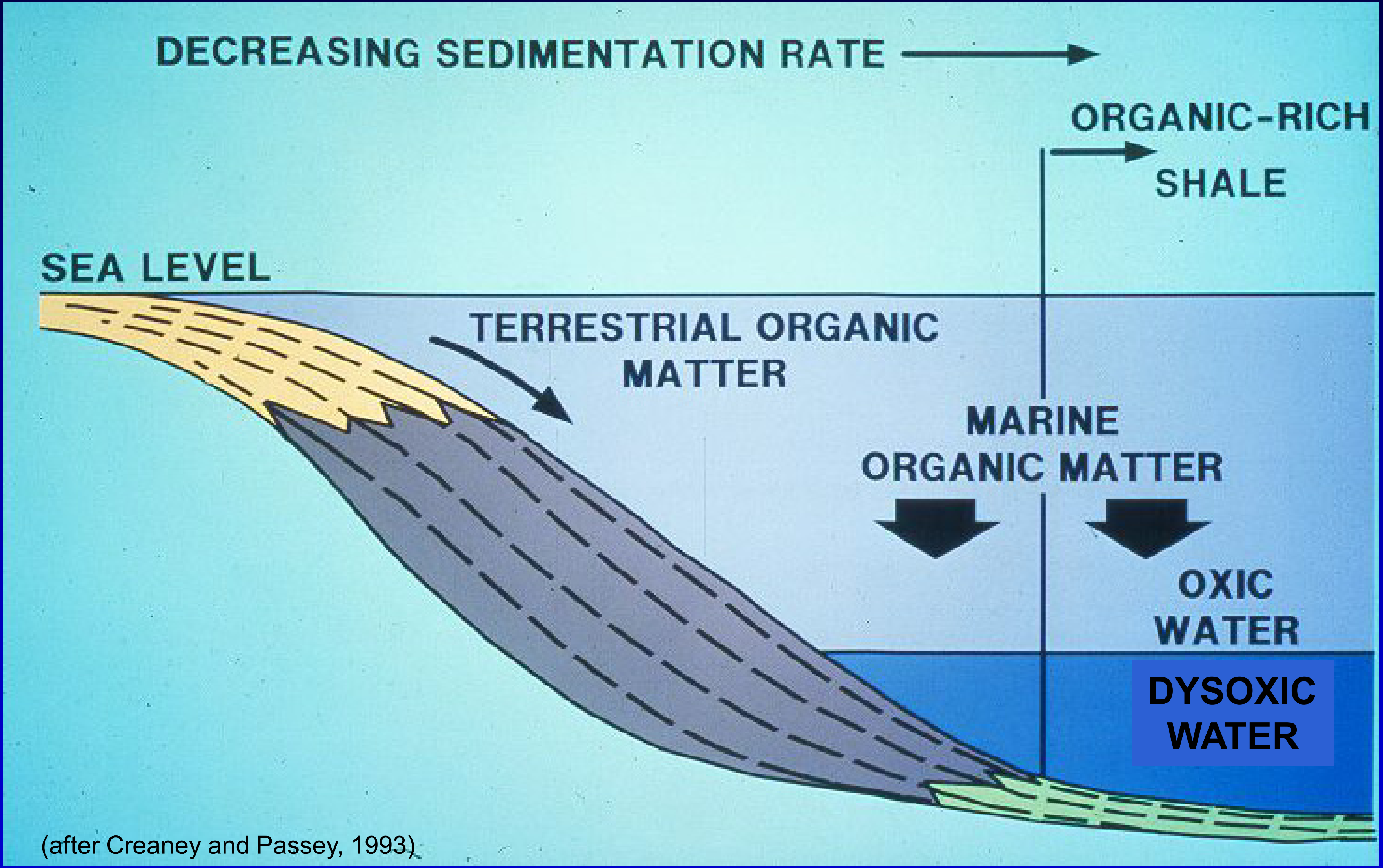
July 20-26, 1985

Stacking Patterns of TOC in Marine Shales

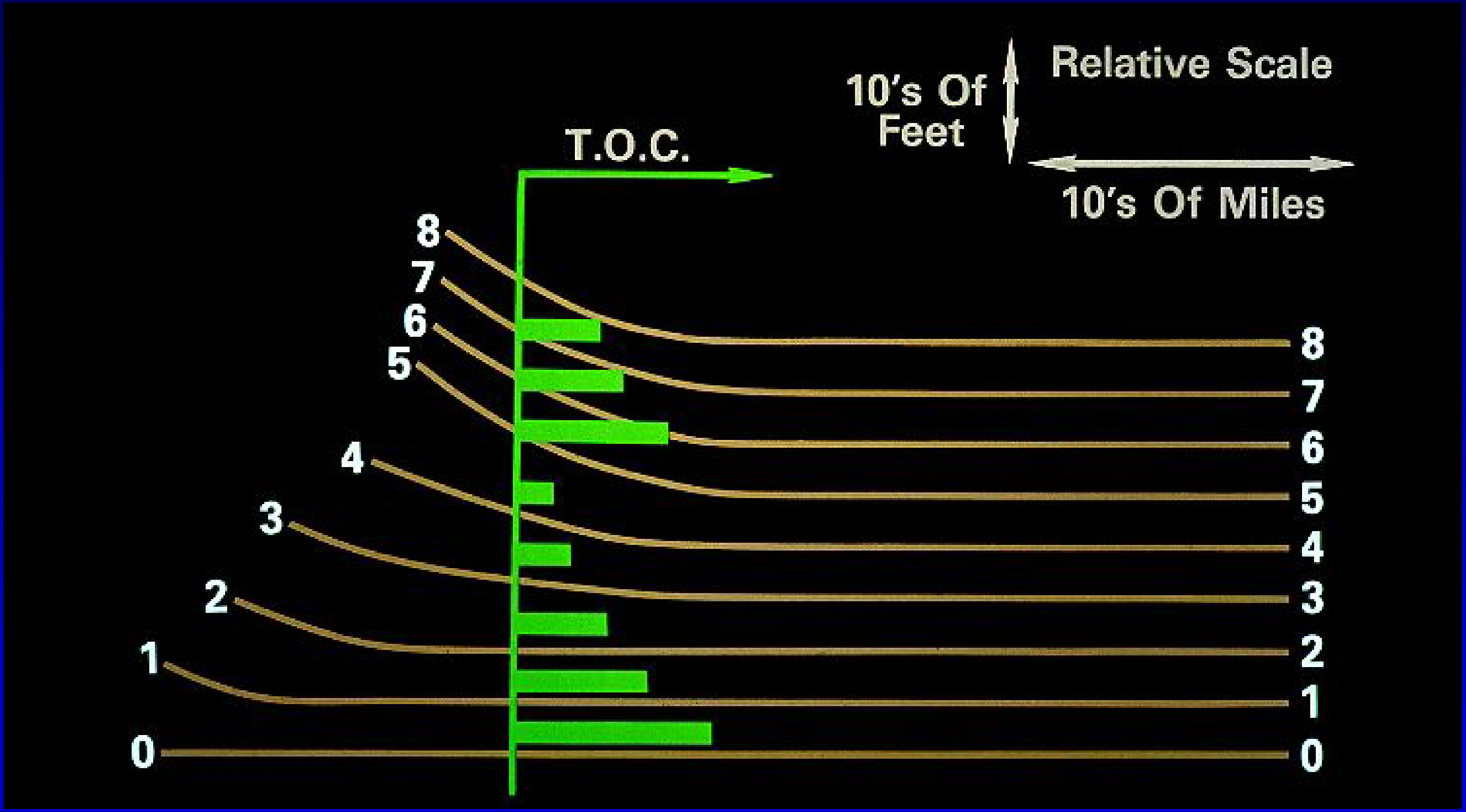


(After Creaney & Passey, 1993)

Simple Model for Marine Organic Enrichment via Sediment Dilution

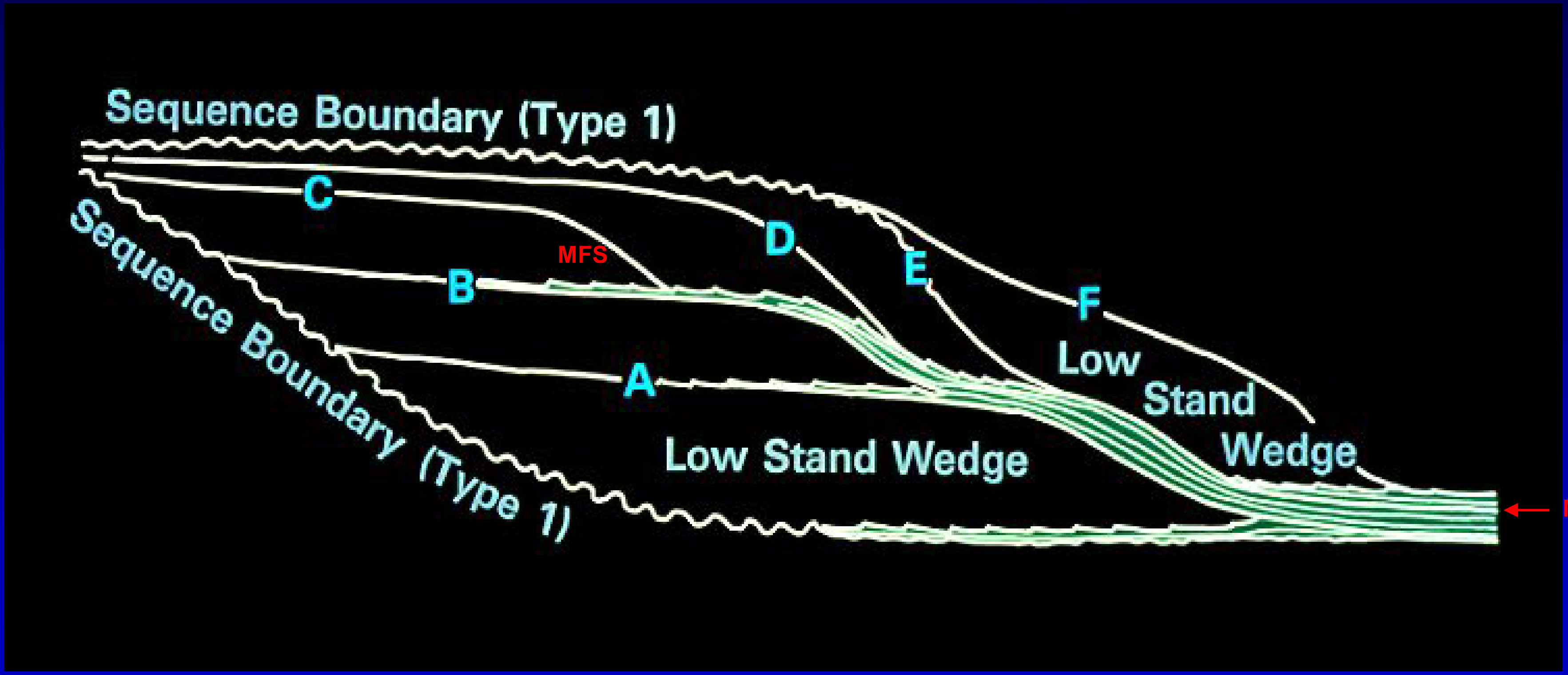


Stacked TOC Triangles (2 Parasequences)



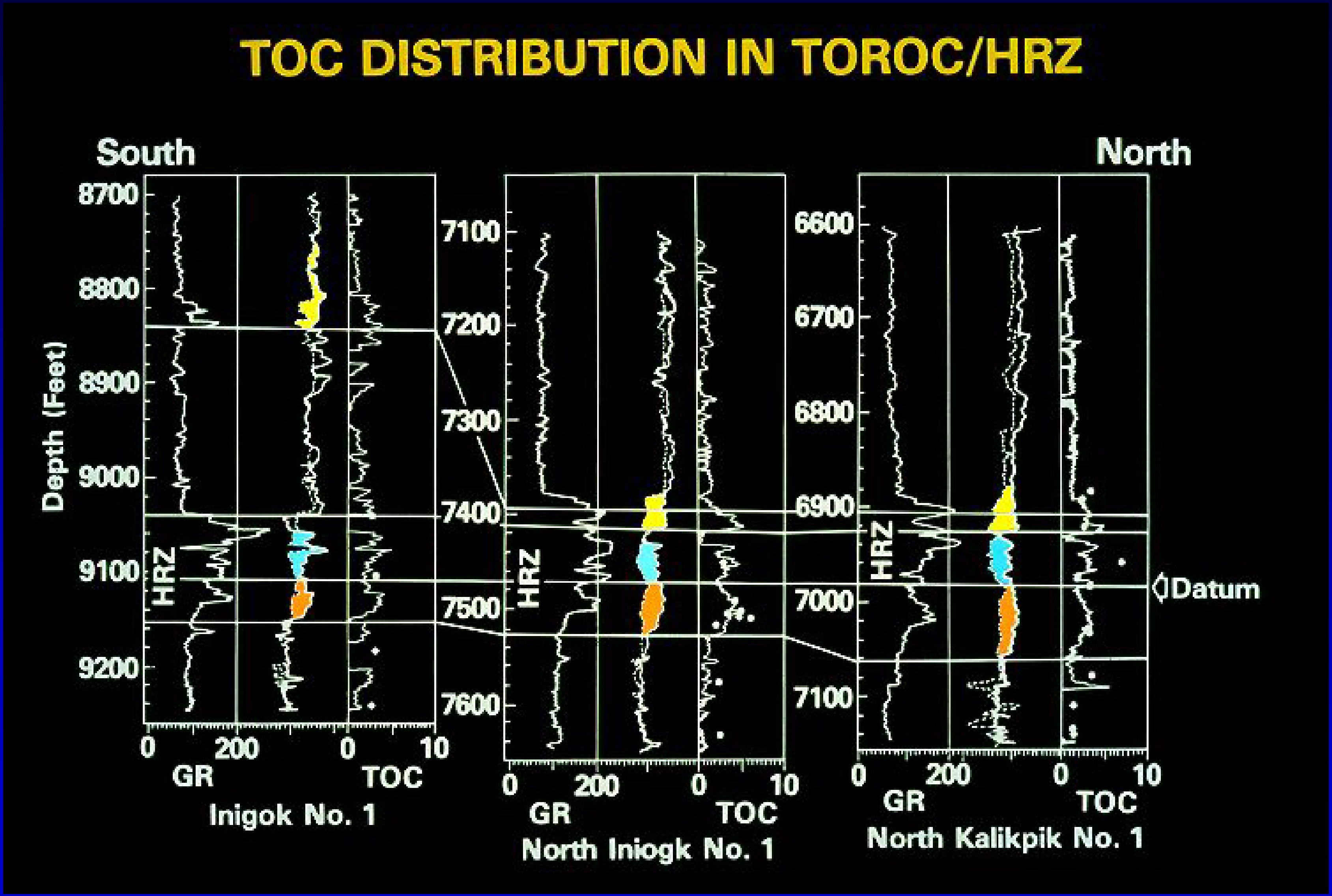
(After Creaney & Passey, 1993)

Distribution and Amalgamation of TOC-Rich Intervals



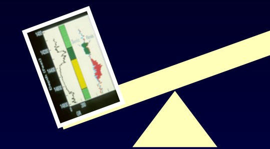
(After Creaney & Passey, 1993)

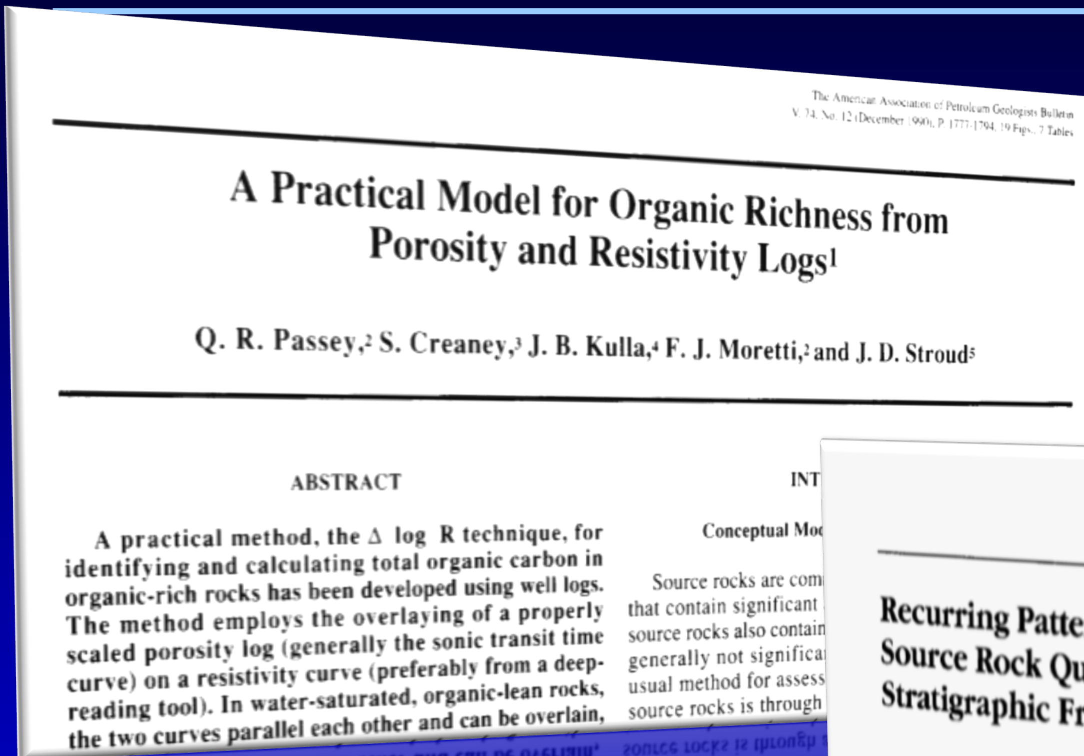
Log Response Inigok to N. Inigok, Alaska



(After Creaney & Passey, 1993)

From Trade Secret to External Publication





The American Association of Petroleum Geologists Bulletin
V. 74, No. 12 (December 1990), P. 1777-1794, 19 Figs., 7 Tables

A Practical Model for Organic Richness from Porosity and Resistivity Logs[1]

Q. R. Passey,[2] S. Creaney,[3] J. B. Kulla,[4] F. J. Moretti,[2] and J. D. Stroud[5]

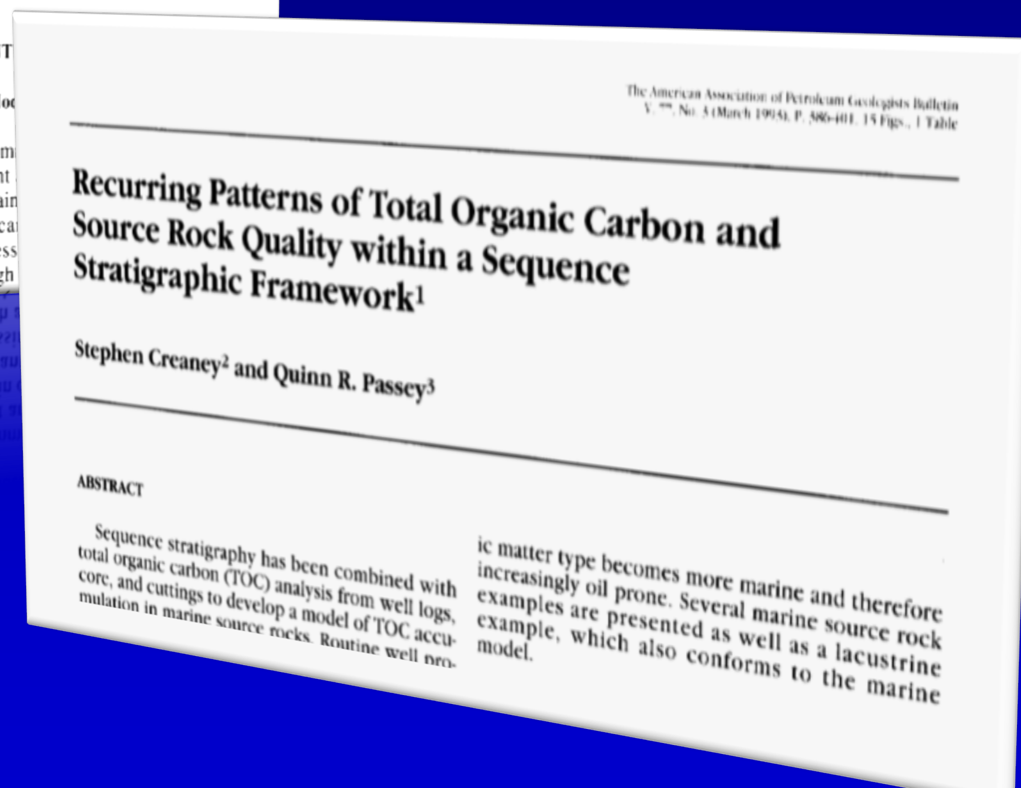
ABSTRACT

A practical method, the Δ log R technique, for identifying and calculating total organic carbon in organic-rich rocks has been developed using well logs. The method employs the overlaying of a properly scaled porosity log (generally the sonic transit time curve) on a resistivity curve (preferably from a deep-reading tool). In water-saturated, organic-lean rocks, the two curves parallel each other and can be overlain,

INT

Conceptual Mod

Source rocks are com
that contain significant
source rocks also contain
generally not significa
usual method for assess
source rocks is through



The American Association of Petroleum Geologists Bulletin
V. 77, No. 3 (March 1993), P. 386-401, 15 Figs., 1 Table

Recurring Patterns of Total Organic Carbon and Source Rock Quality within a Sequence Stratigraphic Framework[1]

Stephen Creaney[2] and Quinn R. Passey[3]

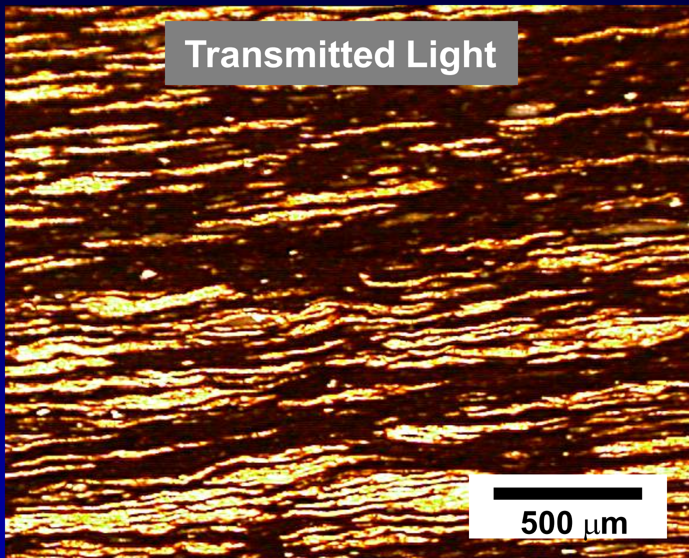
ABSTRACT

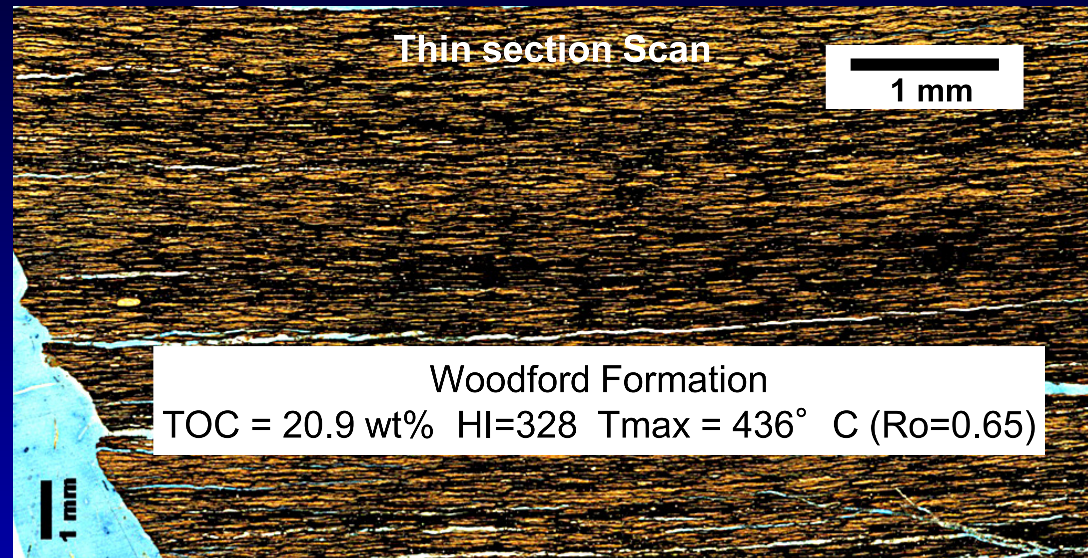
Sequence stratigraphy has been combined with total organic carbon (TOC) analysis from well logs, core, and cuttings to develop a model of TOC accumulation in marine source rocks. Routine well pro-

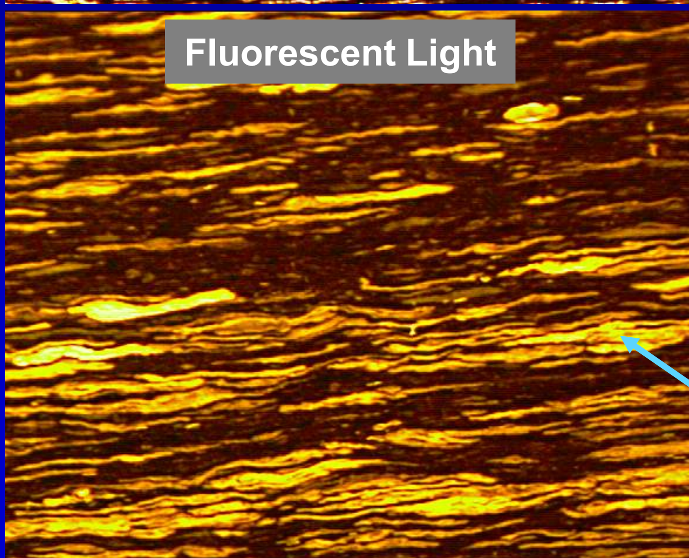
ic matter type becomes more marine and therefore increasingly oil prone. Several marine source rock examples are presented as well as a lacustrine example, which also conforms to the marine model.

Low Magnification Petrographic Thin Section

20 wt% TOC → 40 vol% Kerogen - Woodford Shale

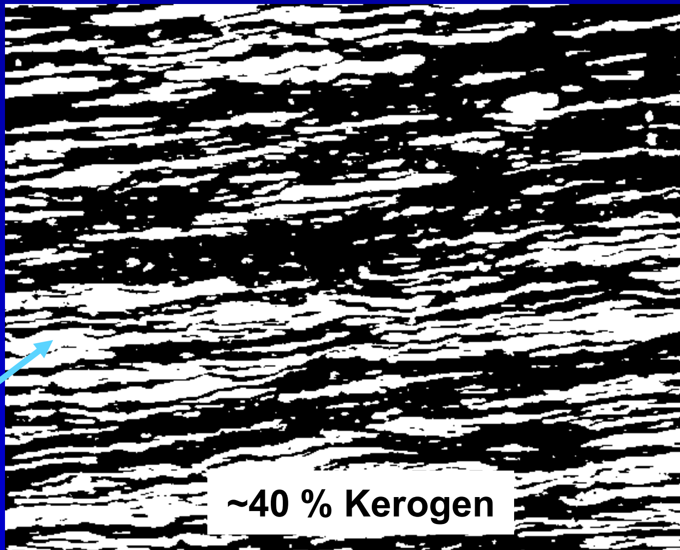






Apply threshold

Fluorescing kerogen (Tasmanites cysts of marine algae)

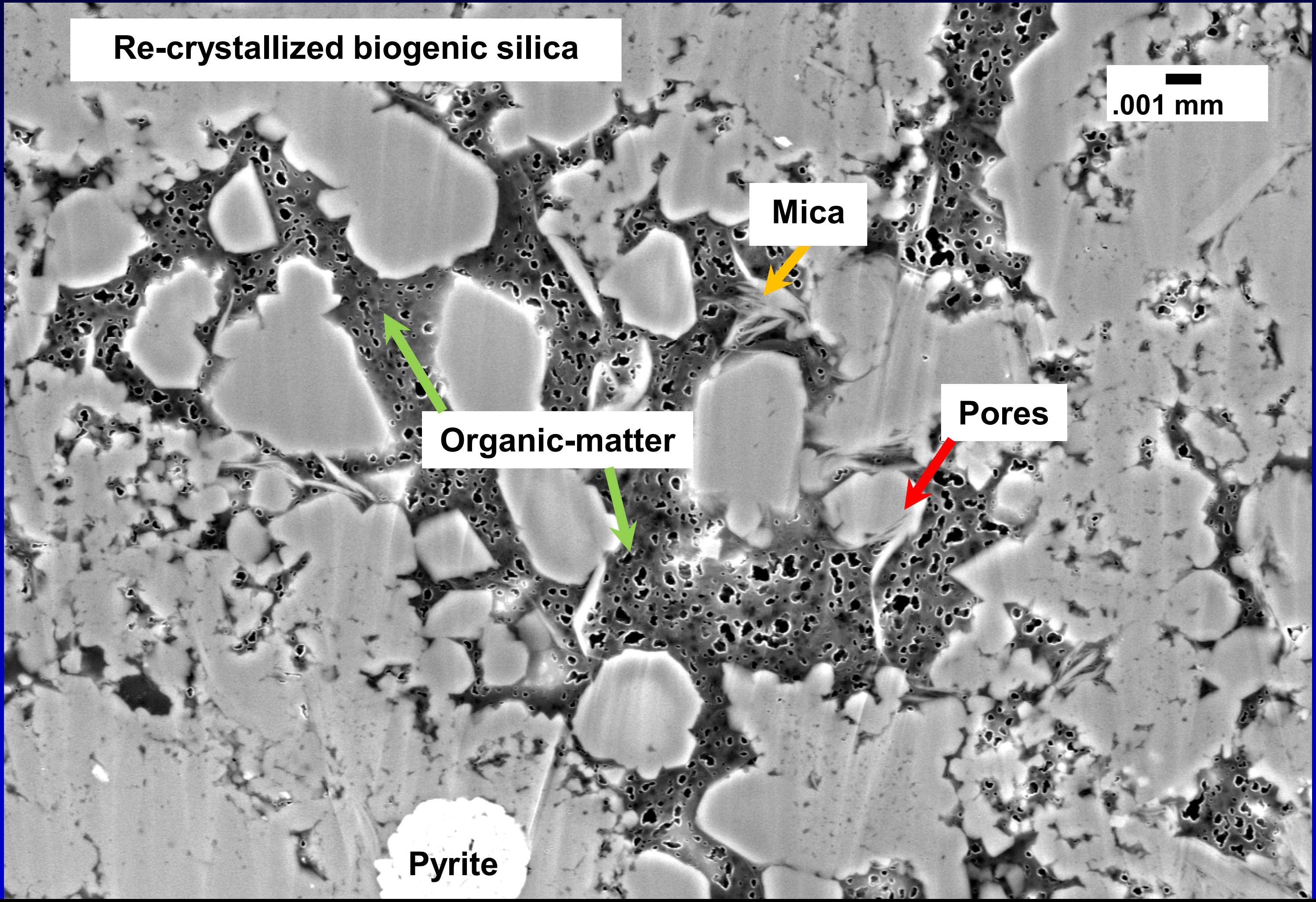


(After Passey et al., 2010)

Ion-milled Polished Section

Barnett Shale, Texas

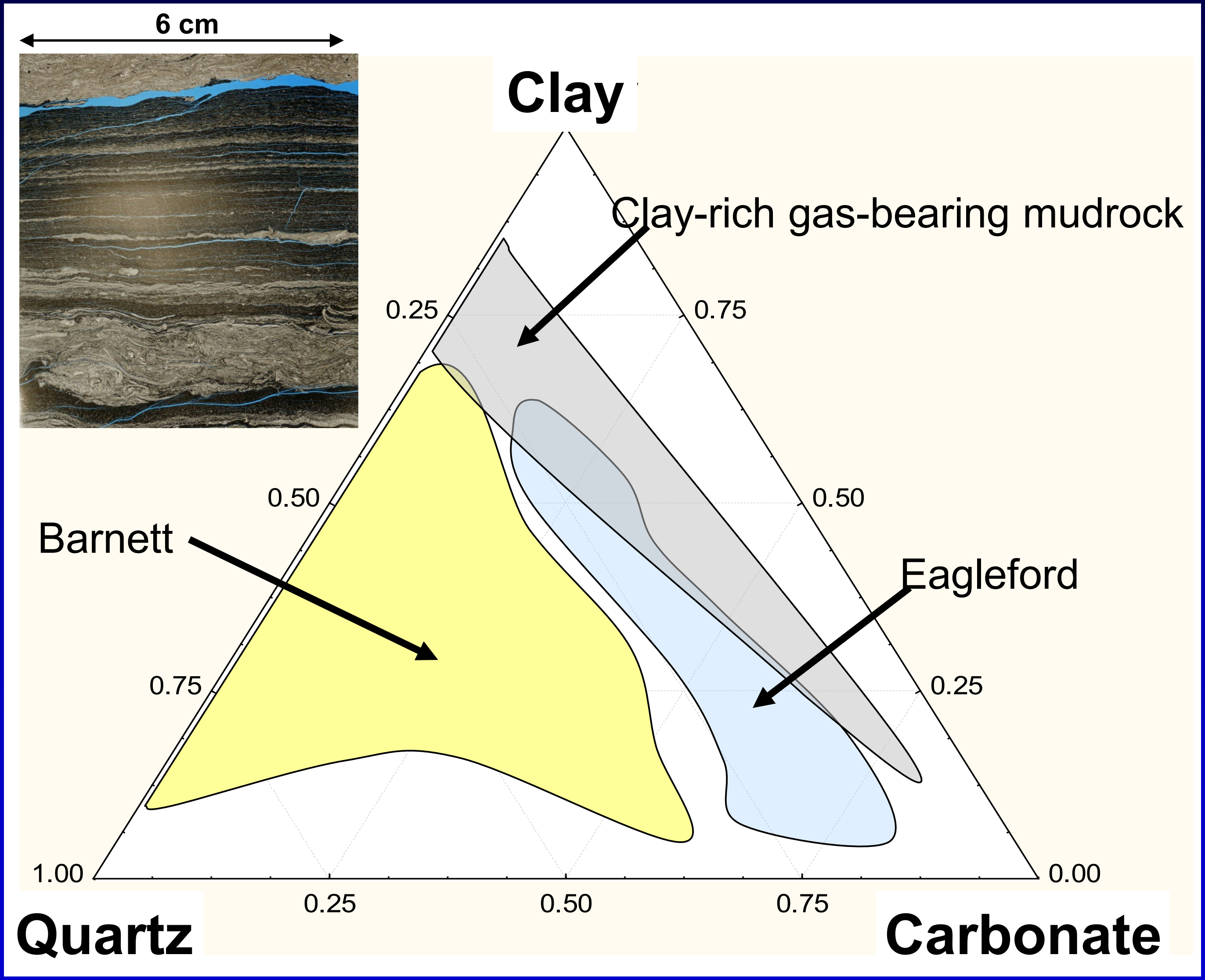
(Loucks & Reed April 2007)

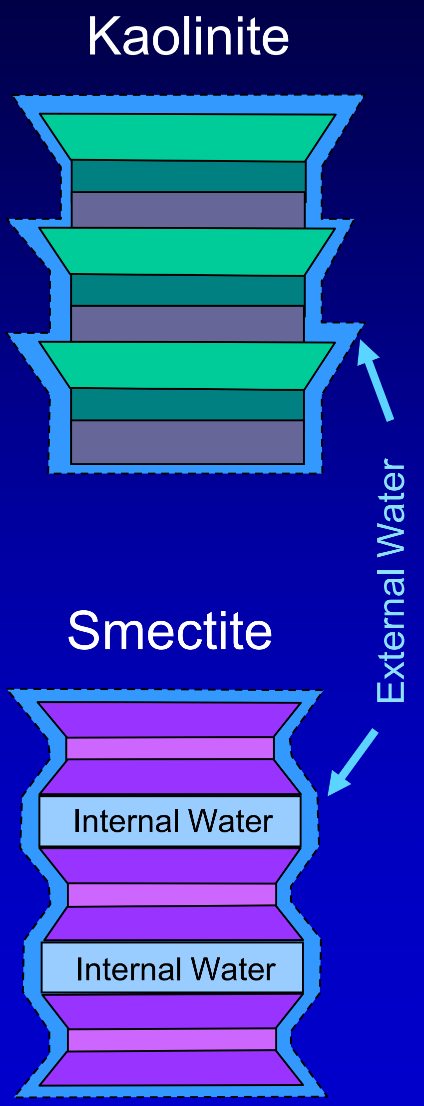


Porosity in Organic Matter >> Porosity in Recrystalized Silica Matrix

(After Passey et al., 2010)

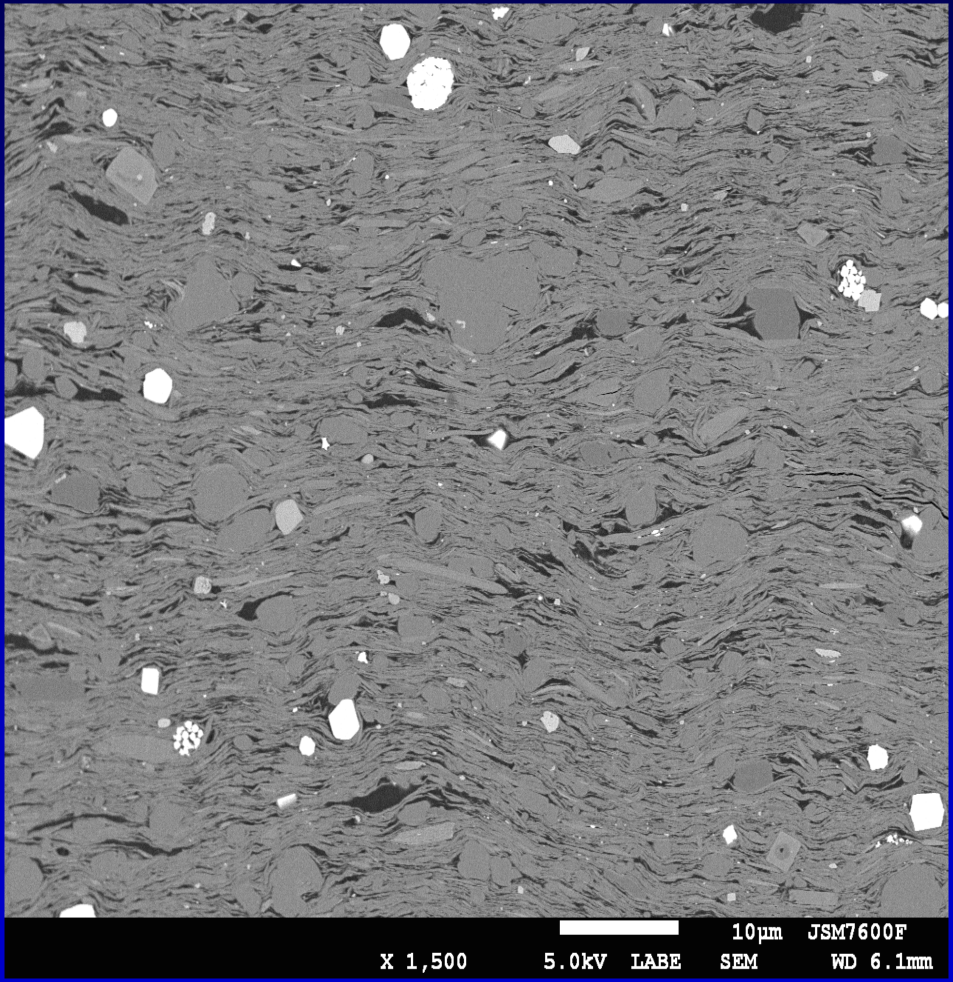
Variation in Lithology for Shale Gas Formations

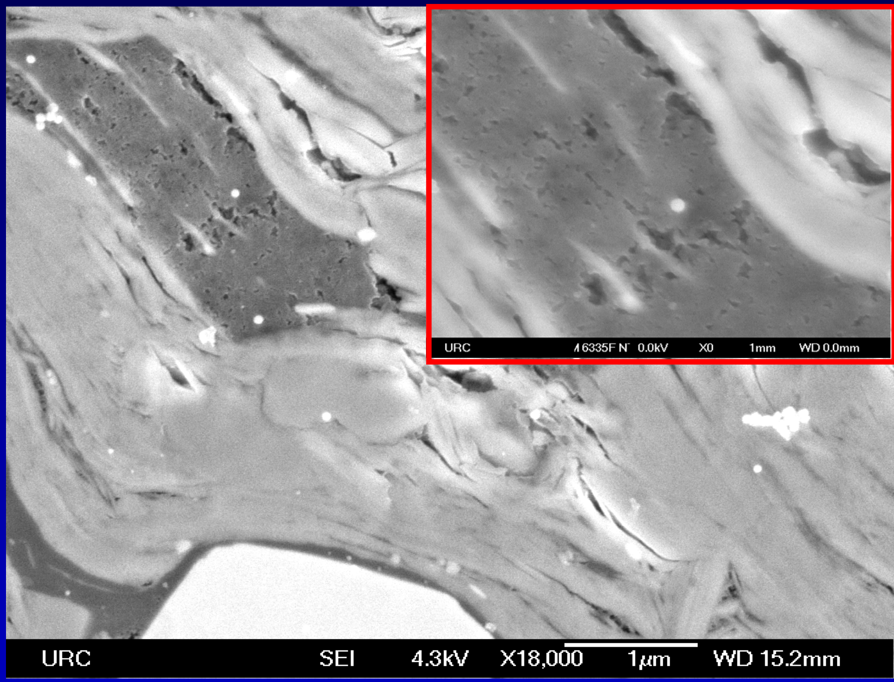




(After Passey et al., 2010)

Ion-milled Image of a Clay-rich Unconventional Reservoir





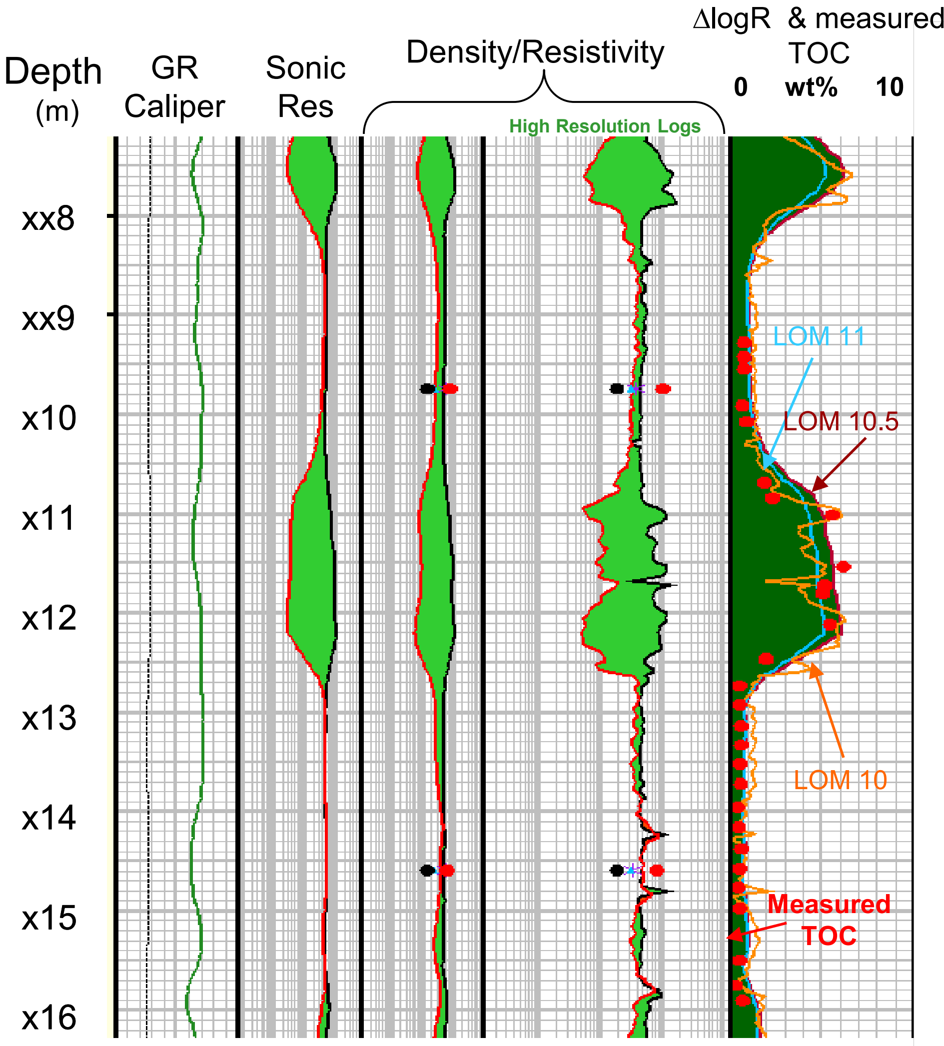
TOC =5.6 wt%

Ro =2.2

$\phi_t \cong$ 15 p.u. (~ 8 p.u. water)

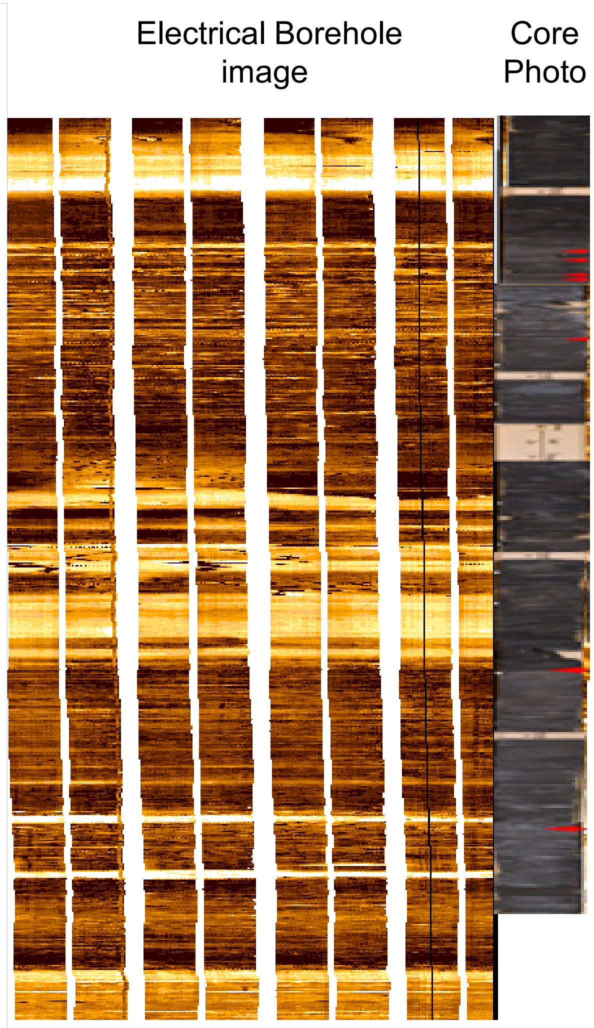
(After Passey et al., 2010)

TOC from Well Log and Borehole Image Log Response – Clay-rich Shale Gas Play



Low Resistivity → Water Filled

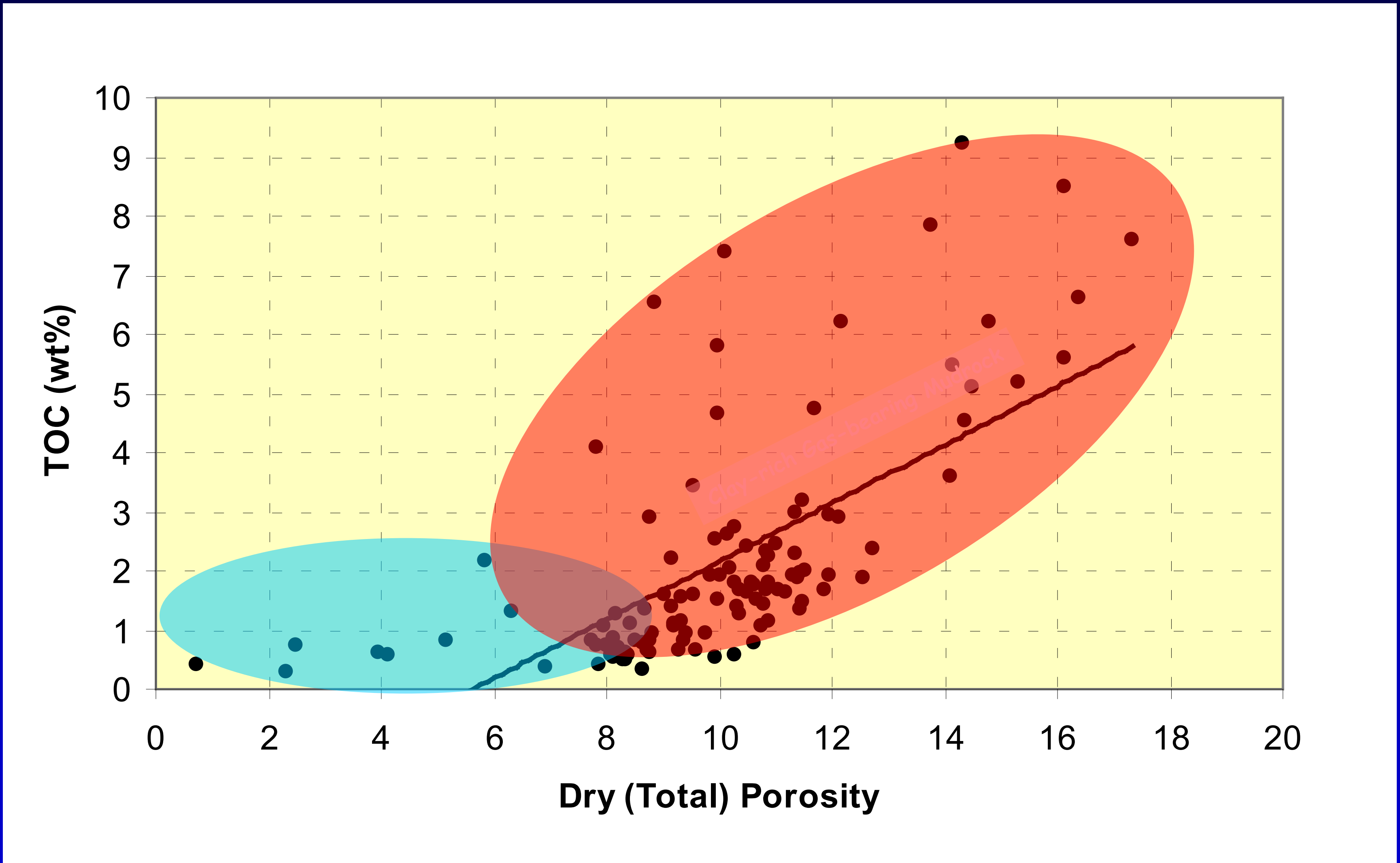
High Resistivity → Hydrocarbons



(After Passey et al., 2010)

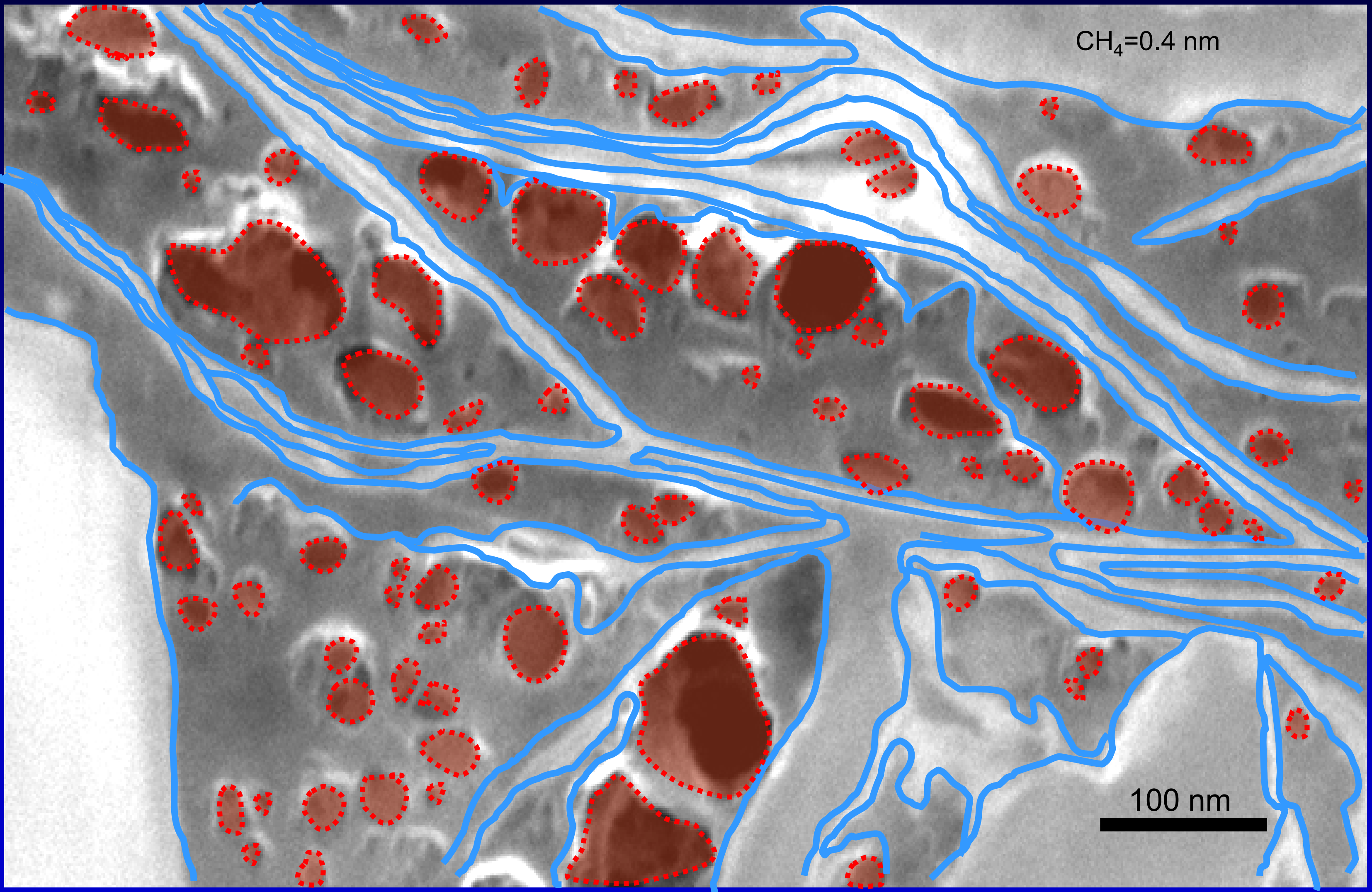
So, where are the hydrocarbons stored??

TOC versus Total Porosity in Gas-bearing Clay-rich Mudstone



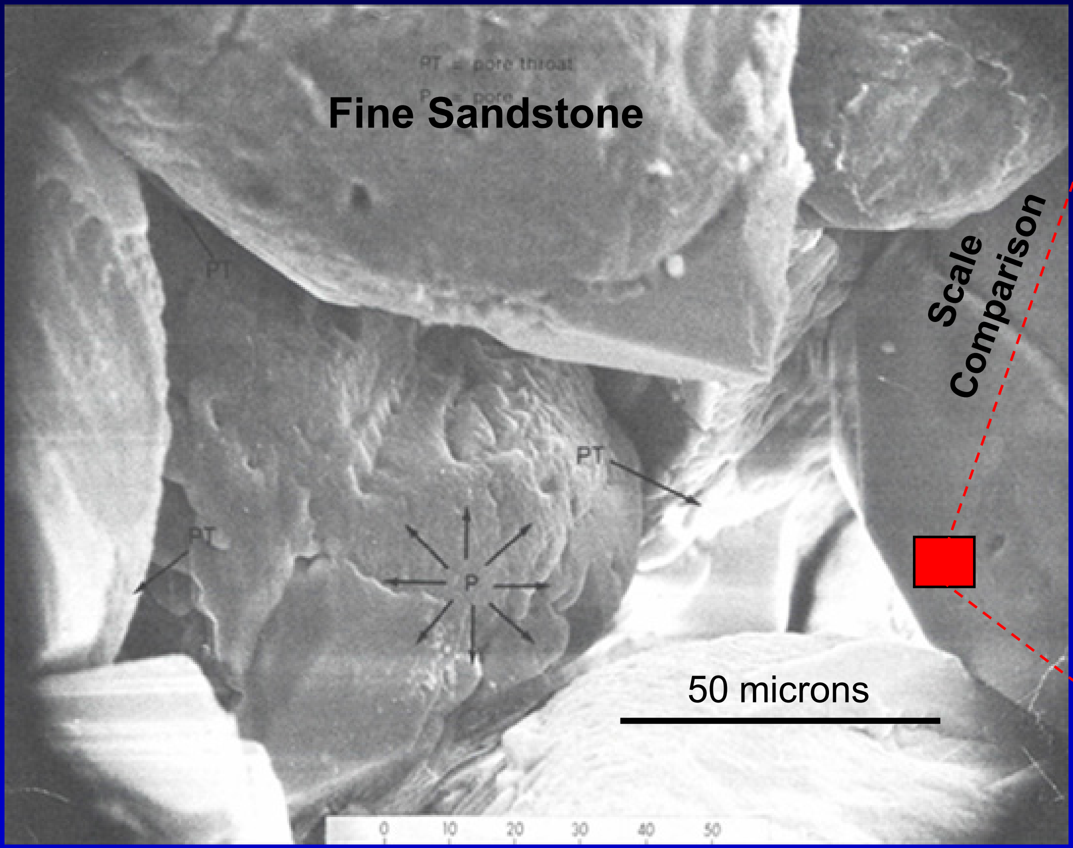
(After Passey et al., 2010)

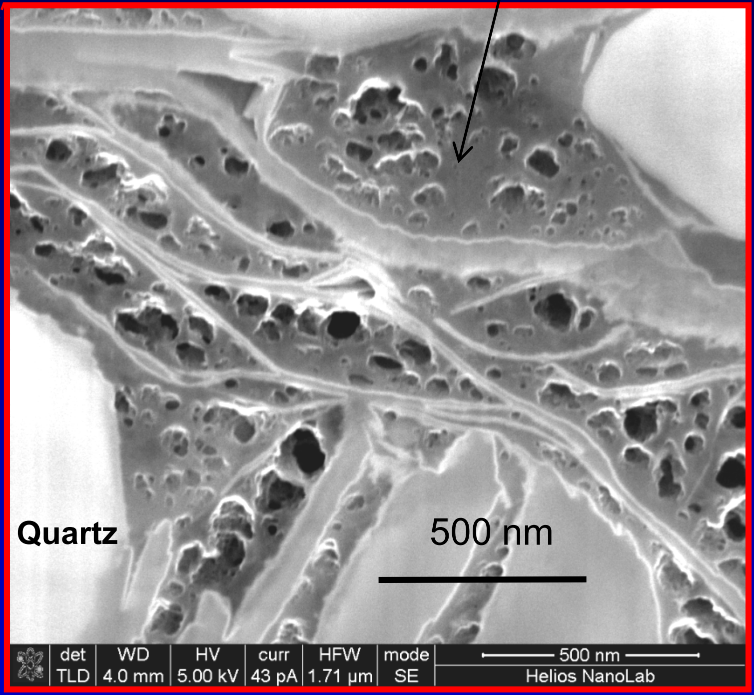
Hypothetical Distribution of Gas and Water



(After Passey et al., 2010)

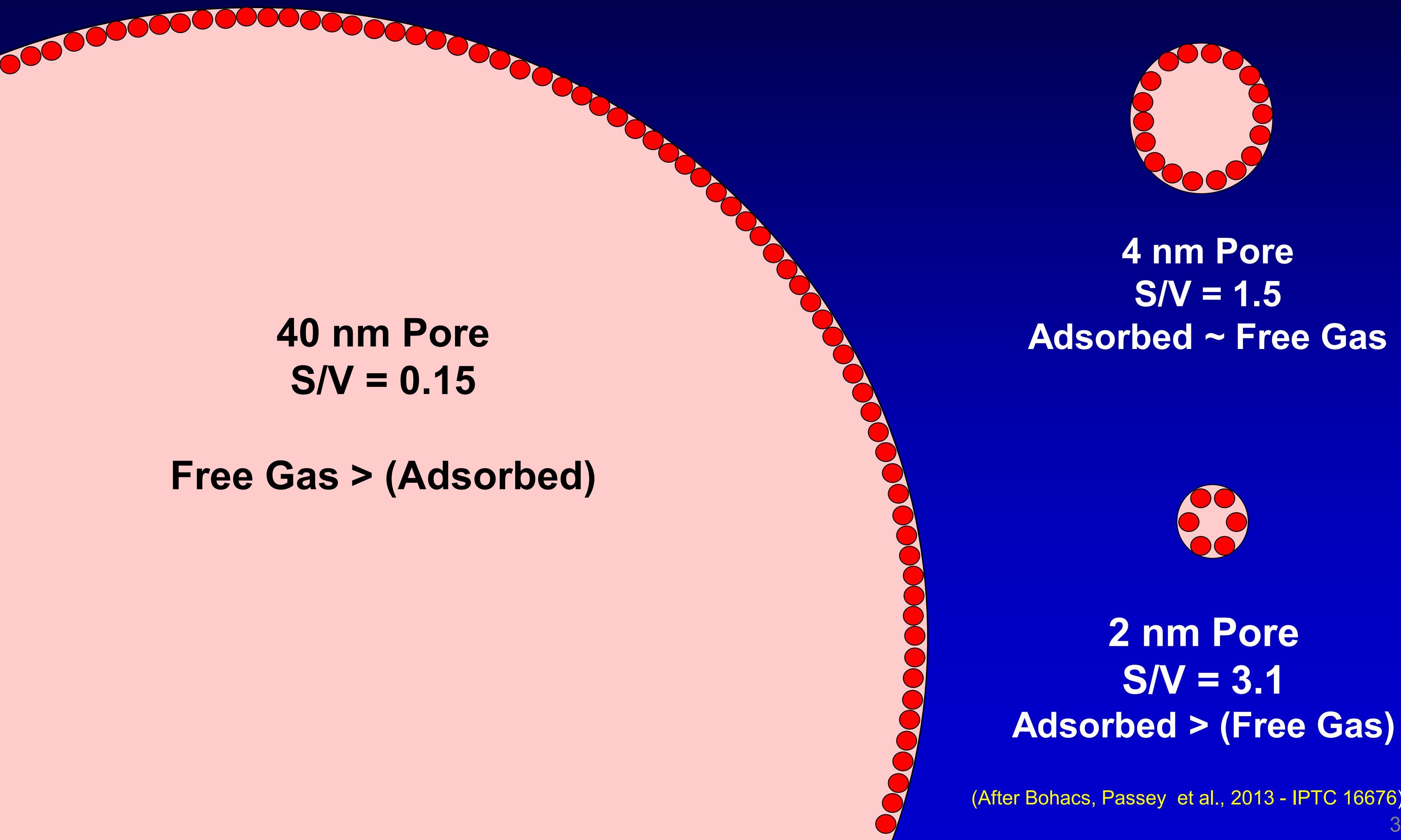
Pore Size Comparison – Fine Sandstone Pores versus Organic-matter Pores





(Passey, et al., 2010)

Adsorbed Gas Fraction Higher in Small Pores (Surface to Volume)



(After Bohacs, Passey et al., 2013 - IPTC 16676)

TOC wt% ≠ TOC vol%
Implications for Hydrocarbon Storage

For a "Typical" Shale Gas the current TOC = 5 wt%

5 wt% TOC

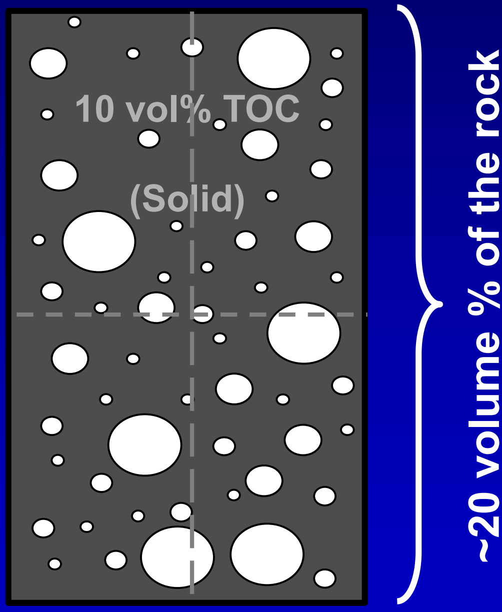
(Solid)

Because the grain density of organic matter is ~½ that of rock minerals, the vol% TOC is ~2 times the wt% TOC

10 vol% TOC

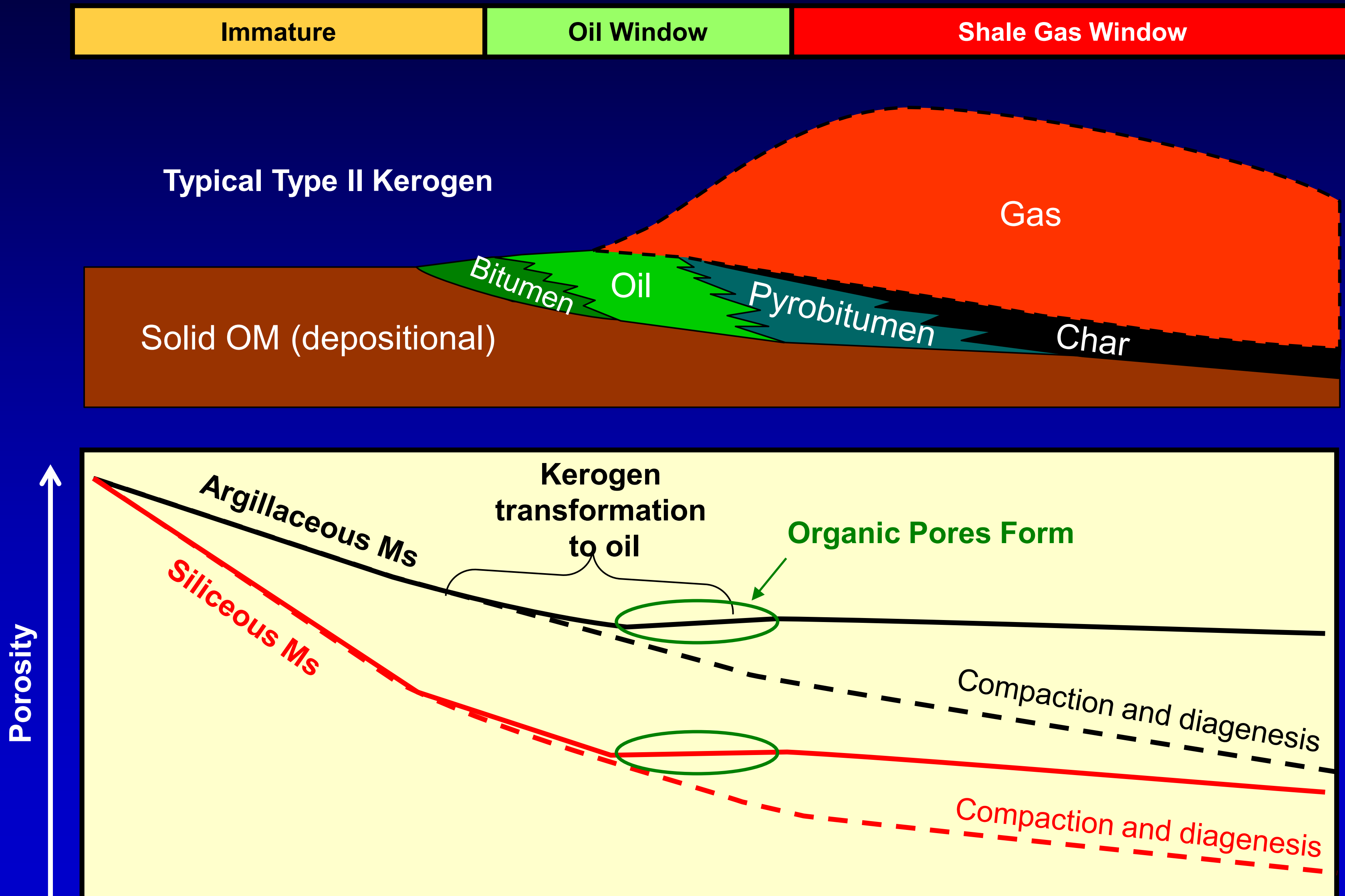
(Solid)

If 50 vol% of the <u>original</u> organic matter volume is now pores, the volume impacted by the current 5 wt% TOC is approximately 20 vol% of the rock.



(After Passey, et al., 2010)

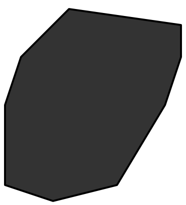
Porosity Evolution in Unconventional Reservoirs



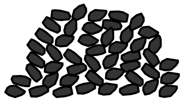
(After Passey et al., 2010)

GRI or crushed-rock method

- Original GRI (Gas Research Institute) method developed for very tight rocks ; 0.002 – 0.45 nanoDarcy*
- Shale reservoirs of commercial interest have permeability in ~ 10 – 3000 nanoDarcy range



As-received sample

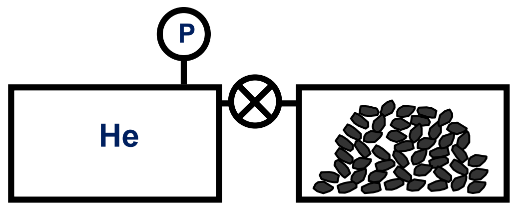


Crush to 20/35 mesh size

Maintain fluid content

15-30 grams

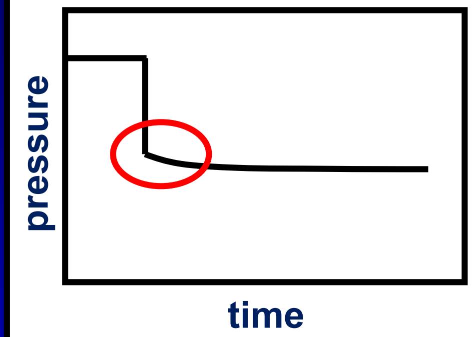
Estimate bulk volume from as-received bulk density



Helium expansion measurement

Typically used for grain volume

Reaches equilibrium slowly as gas enters chips



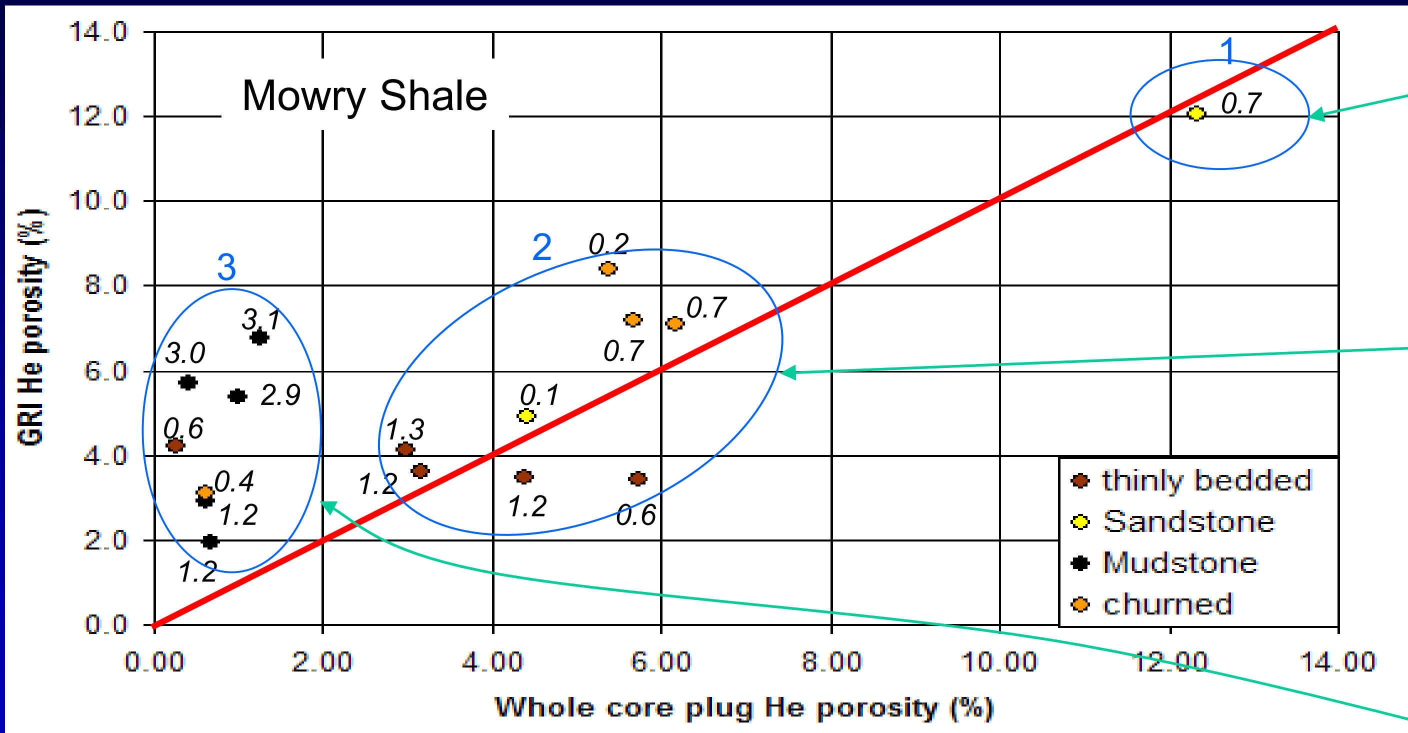
Data range used for permeability interpretation*:

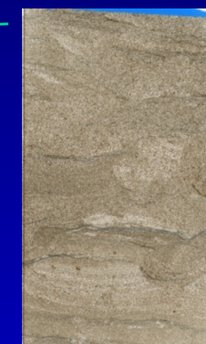
101-100 psi

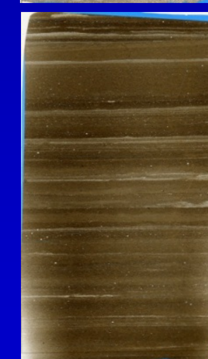
0-15 min

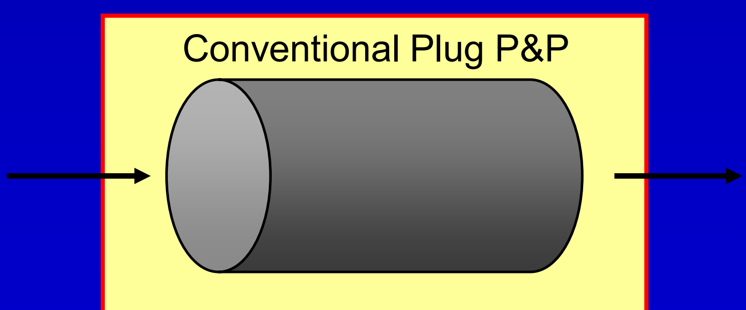
* Luffel et al. (1993) SPE 26633
"Matrix Permeability Measurement of Gas Productive Shales"

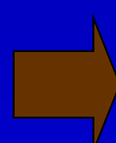
GRI Crushed Rock vs Plug Porosity

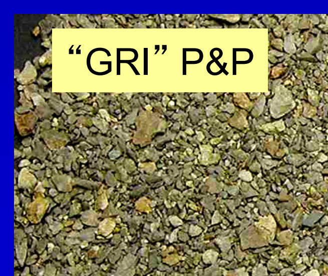








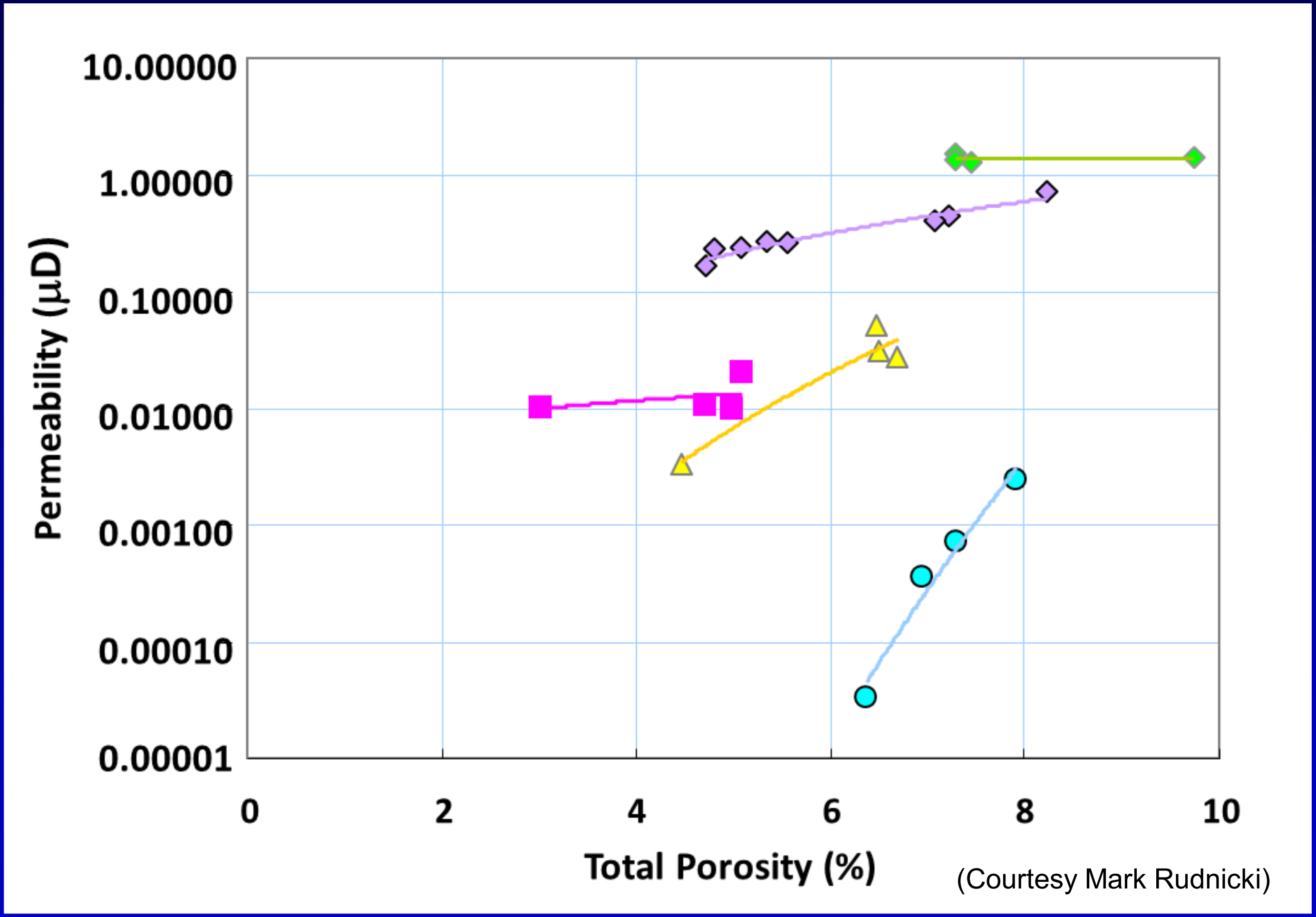




(Courtesy Rene Jonk reported in Spears et al, 2011)

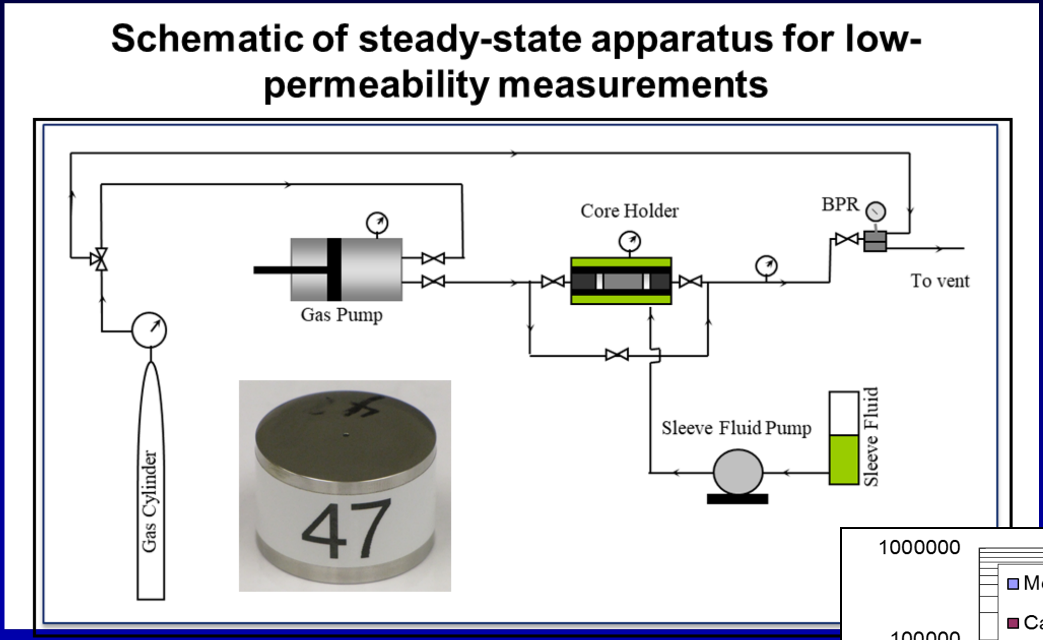
Limitations of GRI/crushed-rock method

Inconsistent Permeability results reported by 5 labs using similar techniques*



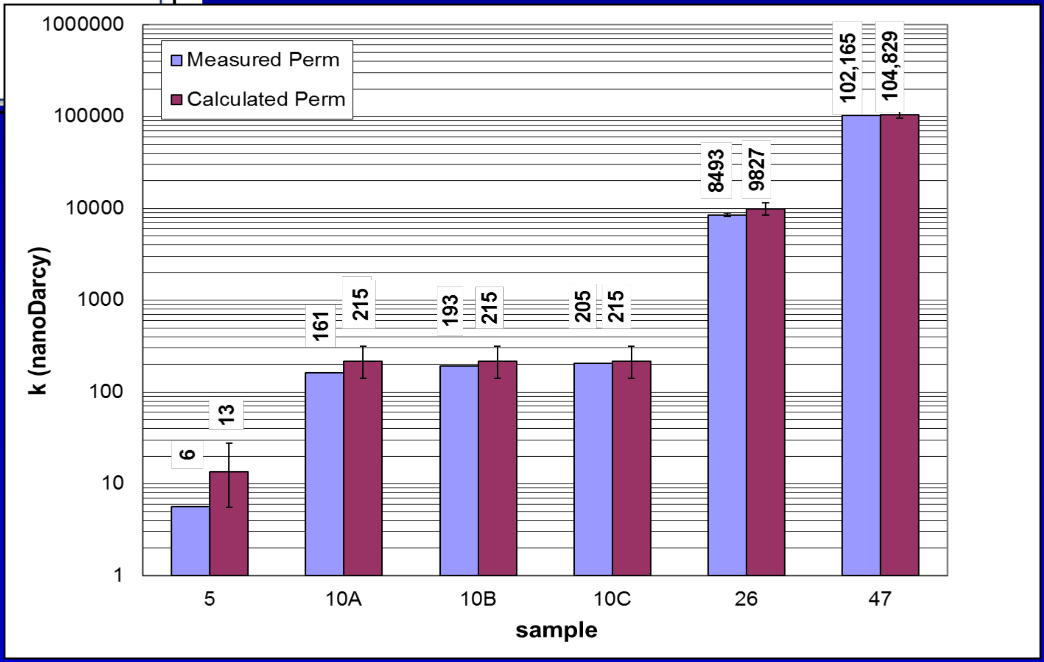
* From Spears et al., 2011 "Shale Gas Core Analysis: Strategies for Normalizing Between Laboratories and a Clear Need for Standard Materials", SPWLA 52nd Annual Symposium, Colorado Springs, May 2011

Steady-state NanoDarcy Plug Measurements and Calibration Standards



Excellent agreement between measurements and permeability calculated from first principles

(After Sinha, Braun et al., 2012, SPE 152257 and SPE 164263)



Key Tipping Points for Source Rock Evaluation from Well Logs