SPE DISTINGUISHED LECTURER

Science of kerogen: Engineering applications for shale E&P

Paul Craddock
Schlumberger-Doll Research, Cambridge, MA

Society of Petroleum Engineers
Distinguished Lecturer Program
www.spe.org/dl

Trade Compliance & Control

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June 2021

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Kerogen: reservoir science to application

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INTRODUCTION

What is kerogen?
Why is it important?

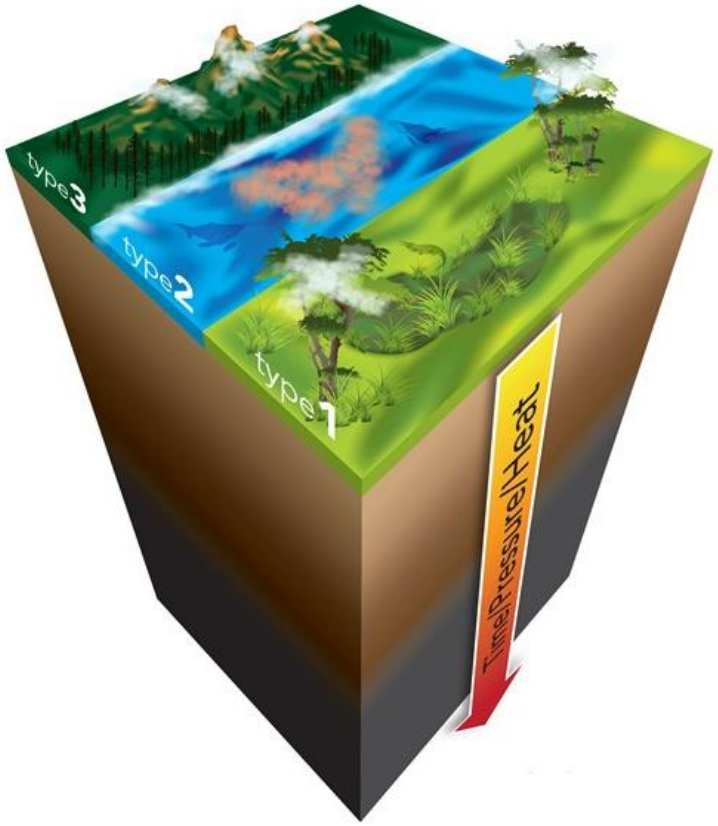
SCIENCE

Chemical insights → Petrophysical properties
Microstructural insights → Kerogen-pore interactions

APPLICATION

Reservoir characterization
Reservoir storage, transport, production

Kerogen: what is it?

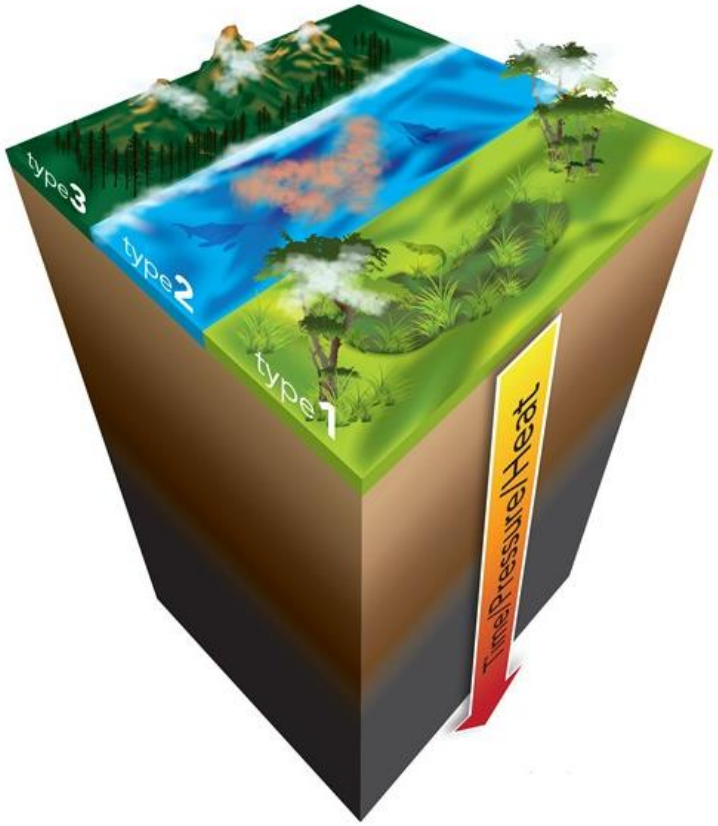


Solid, black powder in sedimentary rocks (coal-like)

From degradation & burial of fossil plants/algae

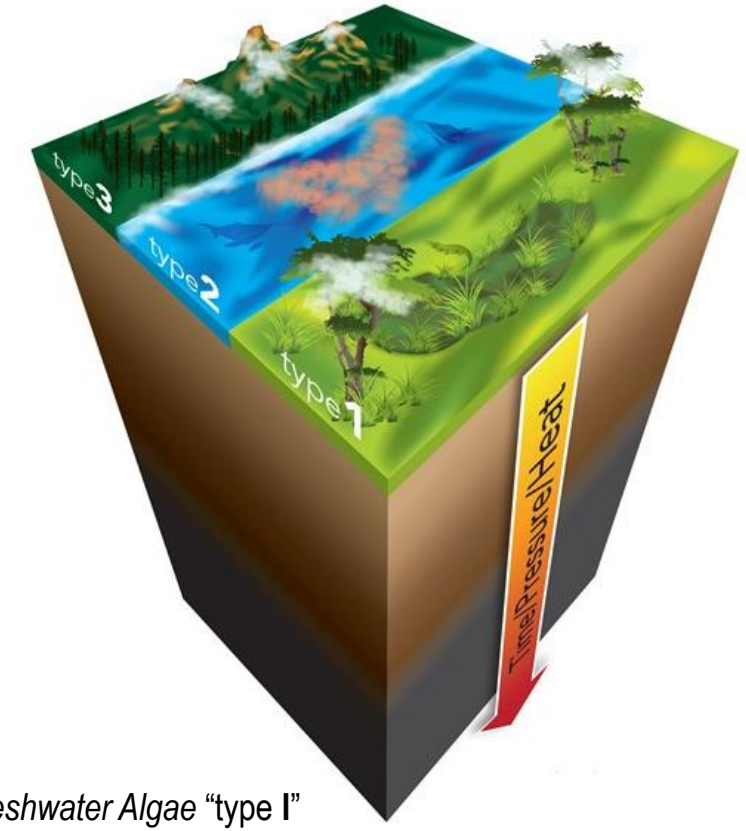
Organic matter source of oil & gas

Kerogen: “*type*”



- *Freshwater Algae* “type **I**”
- *Marine plankton* “type **II**”
- *Coastal land plants* “type **III**”

Kerogen: “*thermal maturity*”



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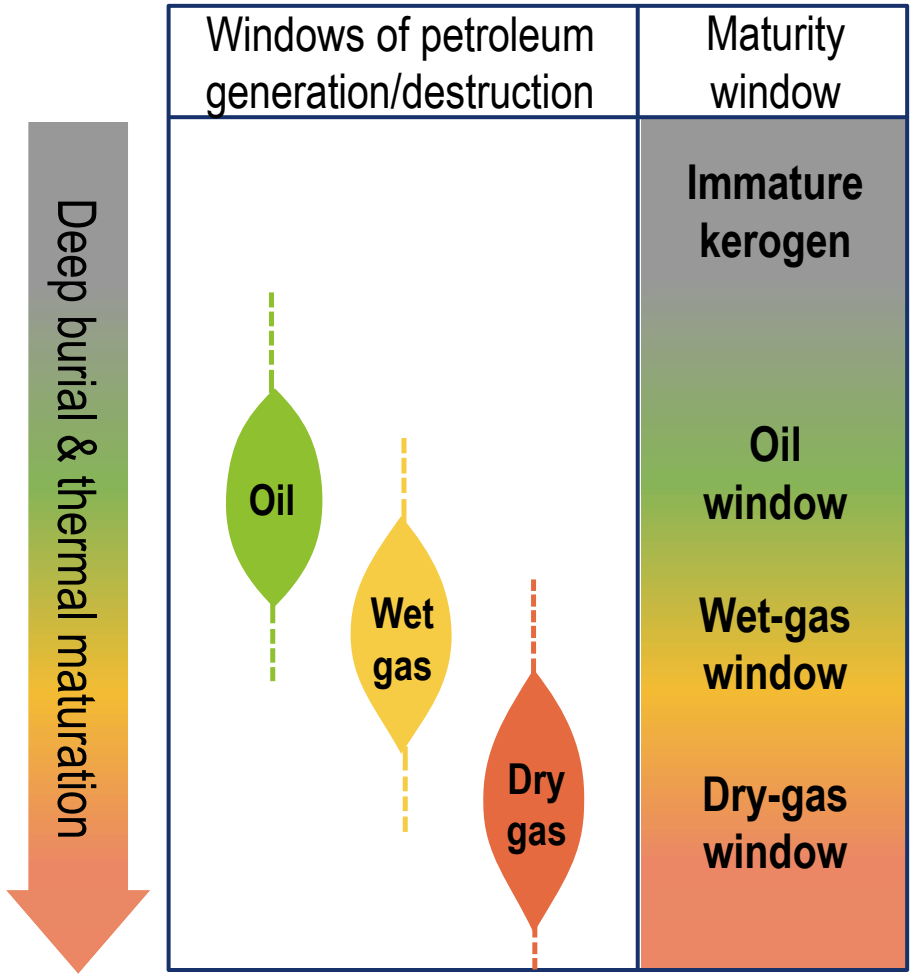
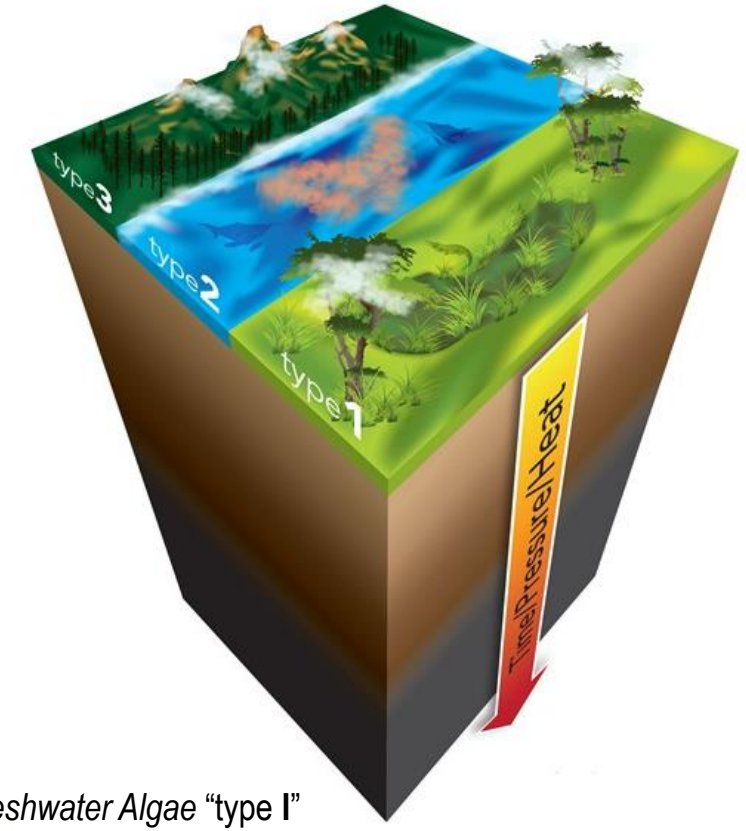


Less “cooking”

More “cooking”

Dow, 1977, J. Geo. Expl.; Hartkopf et al., 2016, Int. J. Coal Geol.

Kerogen: “*thermal maturity*”



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Marine plankton “type **II**”
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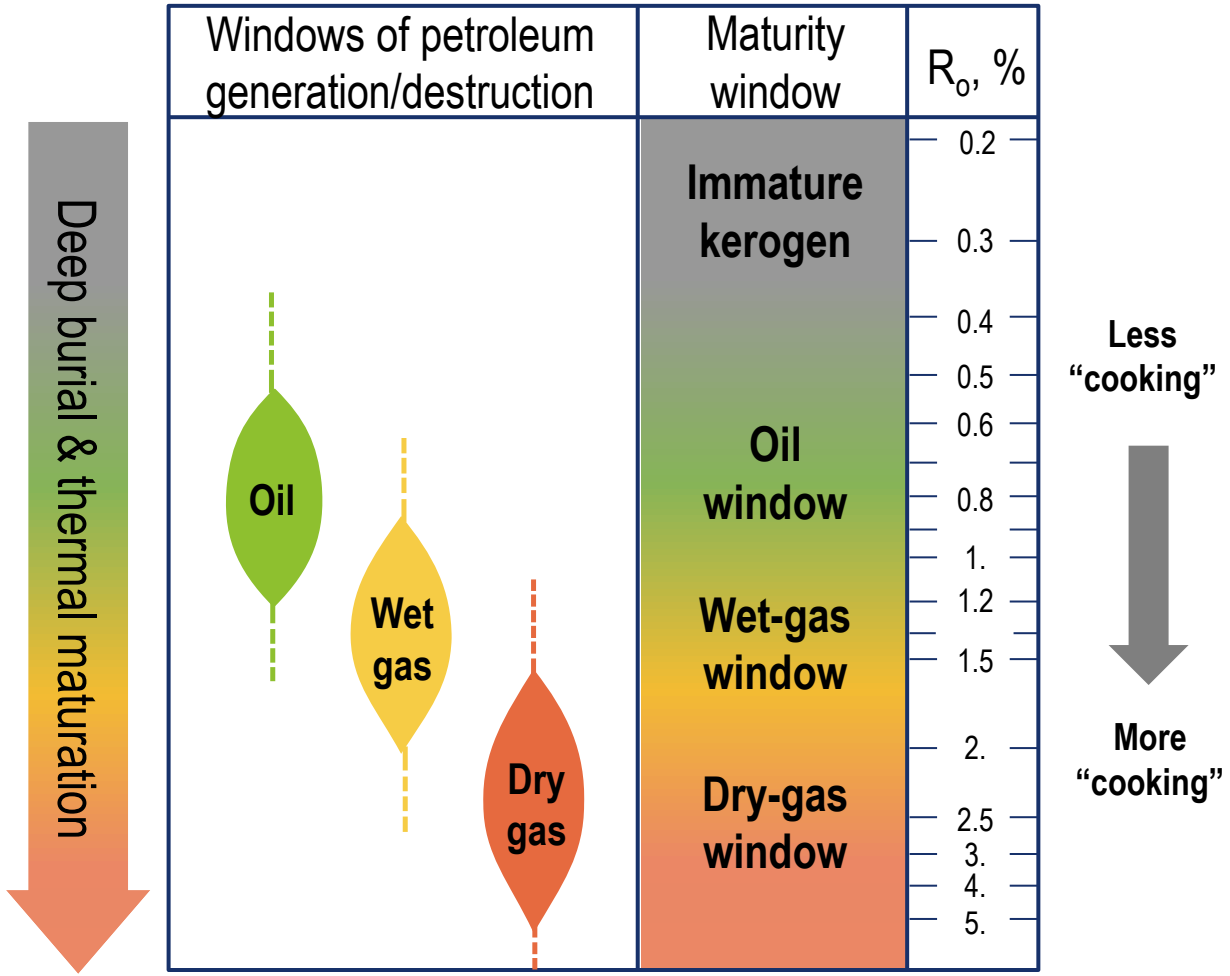
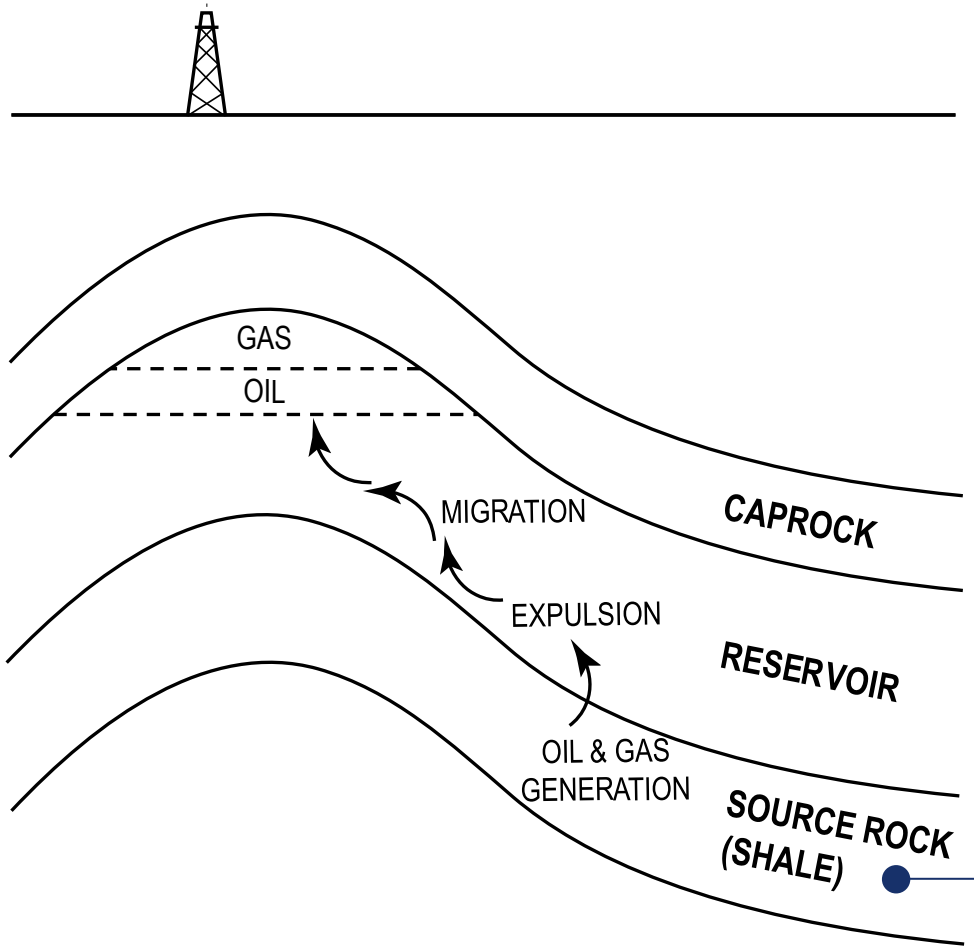


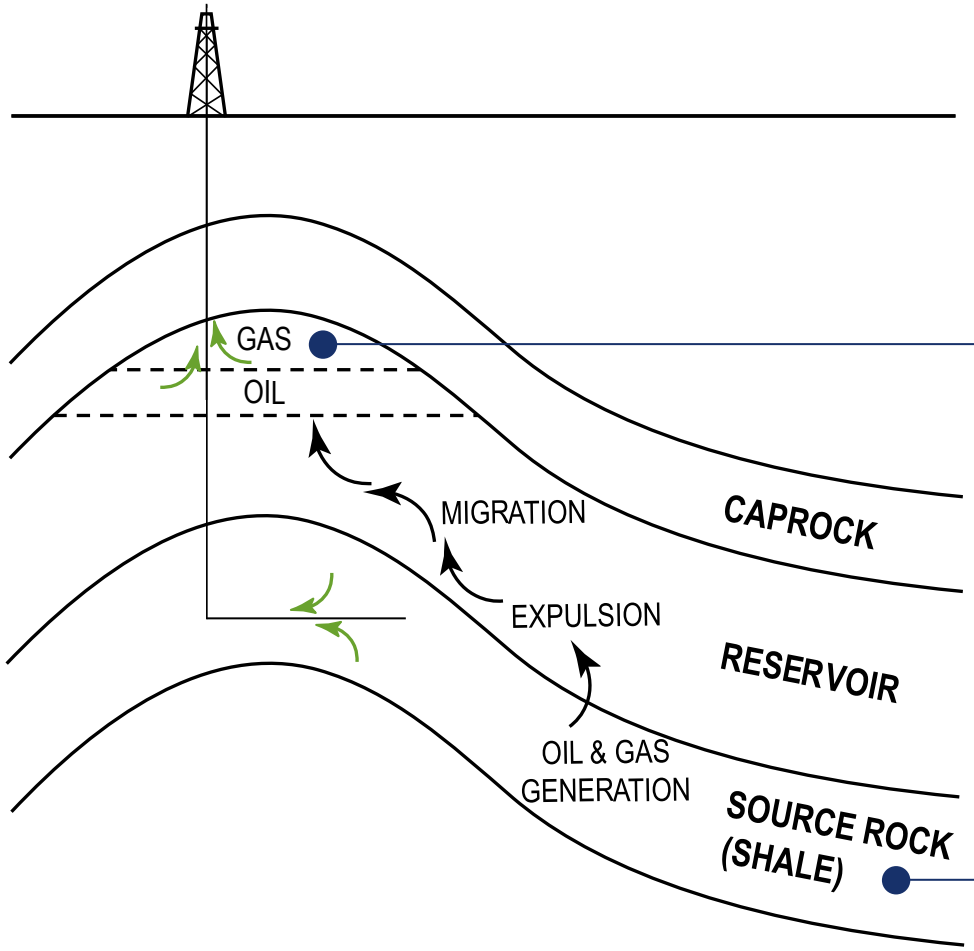
Dow, 1977, J. Geo. Expl.; Hartkopf et al., 2016, Int. J. Coal Geol.

Kerogen: why is it important?



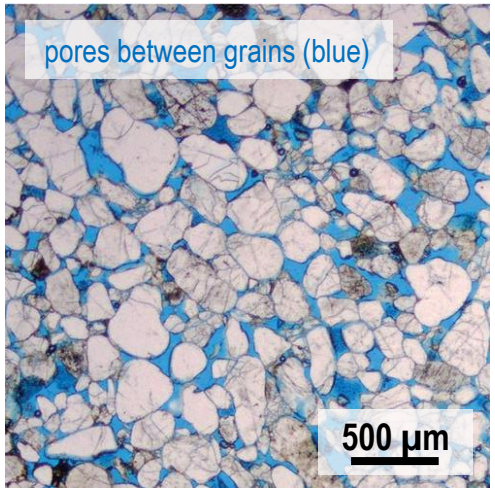
Oil & gas ***generation*** controlled by kerogen

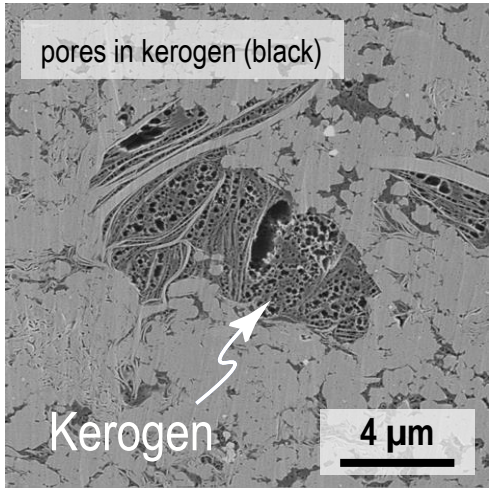
Kerogen: why is it important?



Oil & gas ***storage & transport*** controlled by minerals

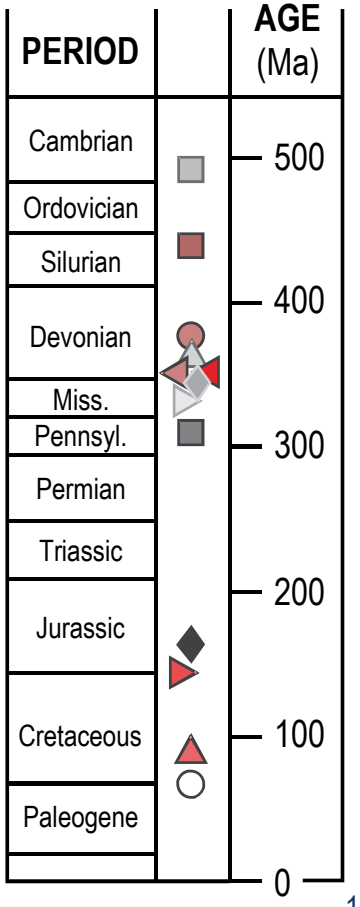
Oil & gas ***storage & transport*** controlled by kerogen?





Kerogen: how to study it?

→ Diversity → location, age, thermal maturity



Kerogen: how to study it?

Shale core or cuttings

Crush to powder

Solvents to remove soluble organics

Non-oxidizing acids to remove inorganic minerals

Kerogen isolate

Analyze using novel and diverse techniques

Kerogen: reservoir science to application

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Microstructural insights → Kerogen-pore interactions

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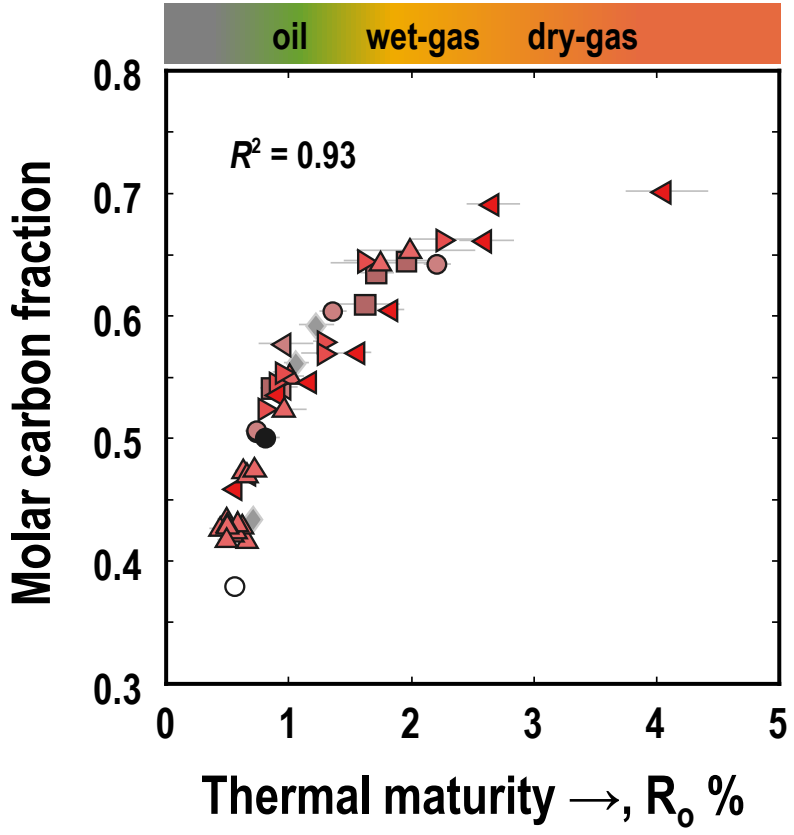
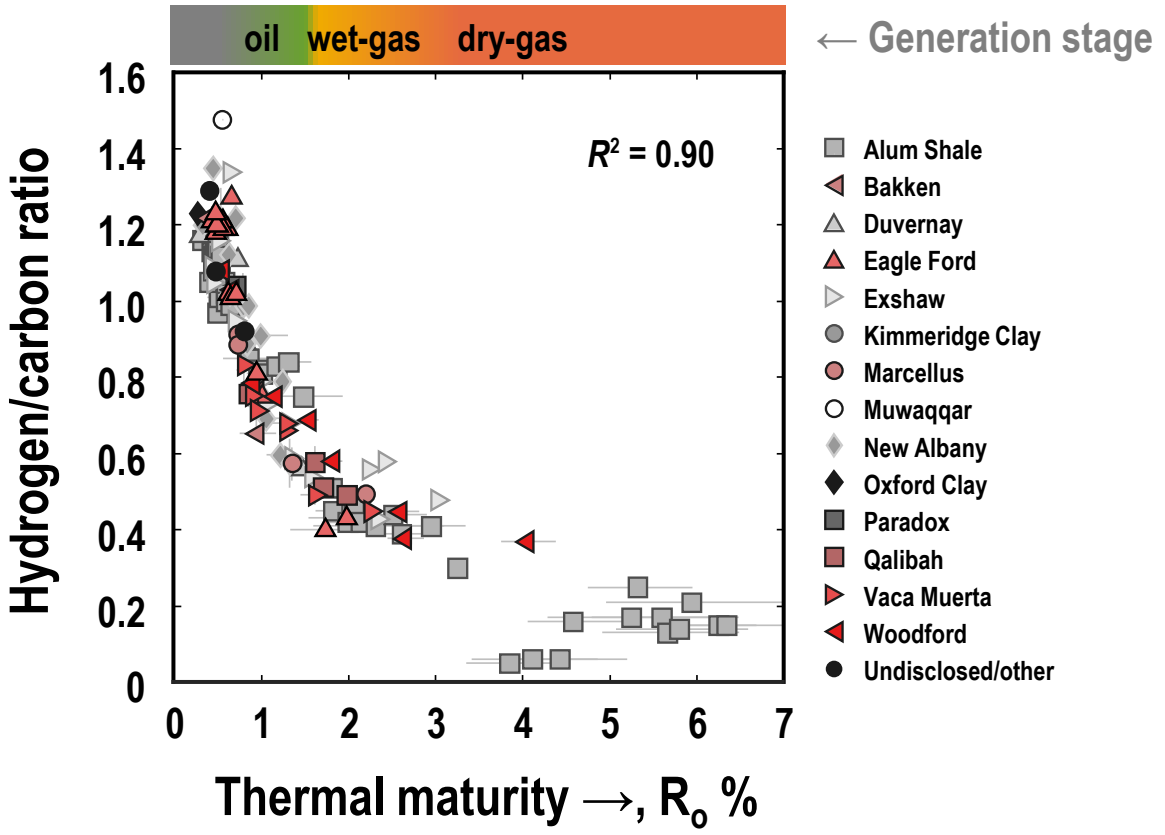
Reservoir storage, transport, production

Kerogen: chemical abundances

→ Large spread → As big as between oil and gas → Controlled by thermal maturation

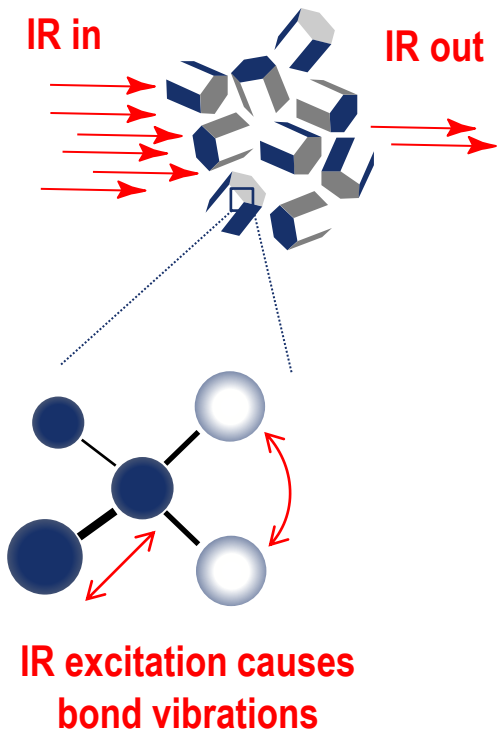


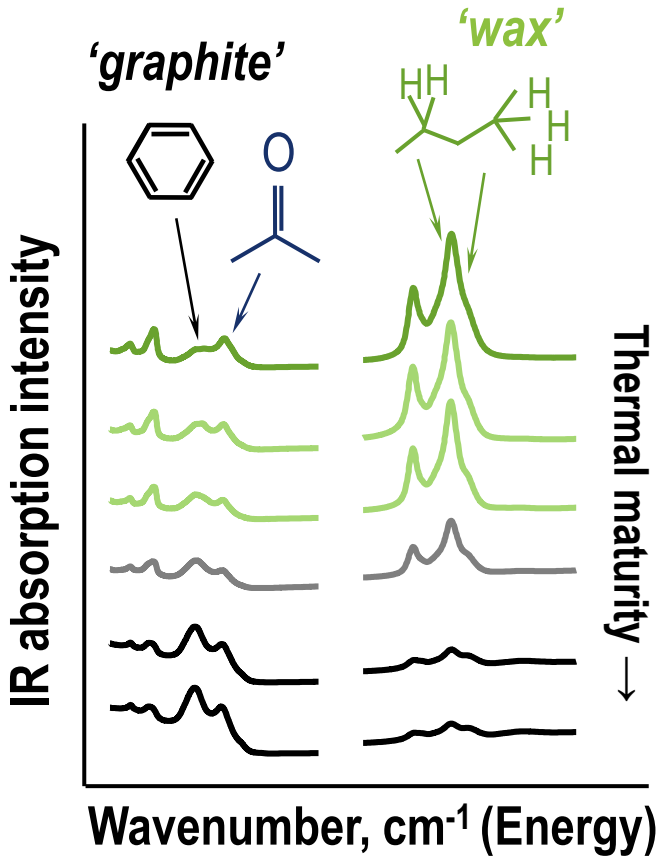


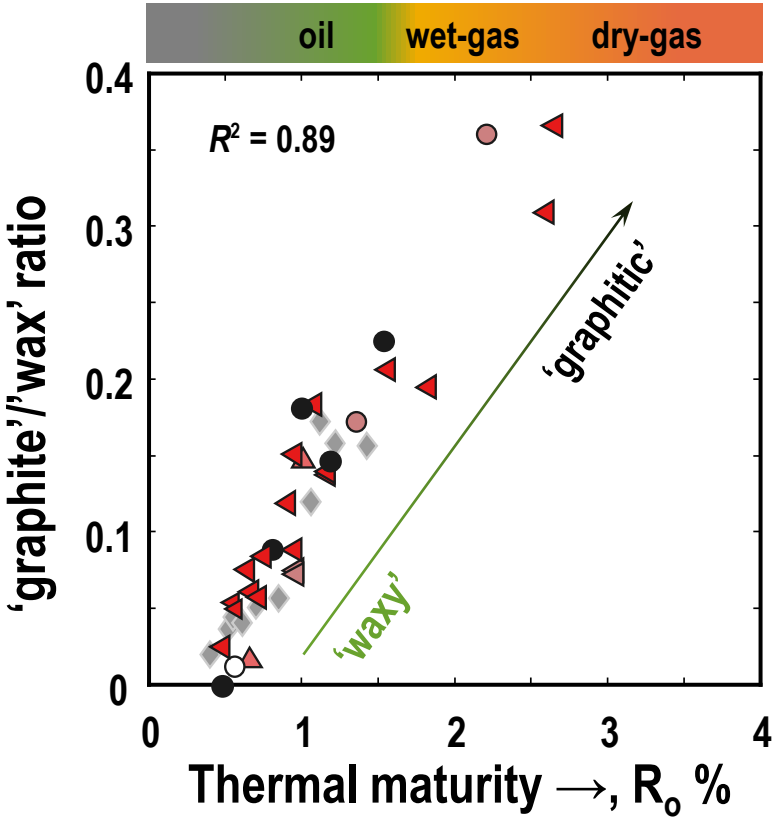
e.g., Buchardt & Lewan, 1990, AAPG; Lis et al., 2005, Org. Geochem; Kelemen et al., 2007, Energy Fuels; Cheshire et al., 2017, Int. J. Coal Geol; Craddock et al., 2019 Org. Geochem, French et al., 2020, MPG

Kerogen: chemical structures

→ *Solid state spectroscopies* → e.g., infrared, nuclear magnetic resonance, Raman, X-ray

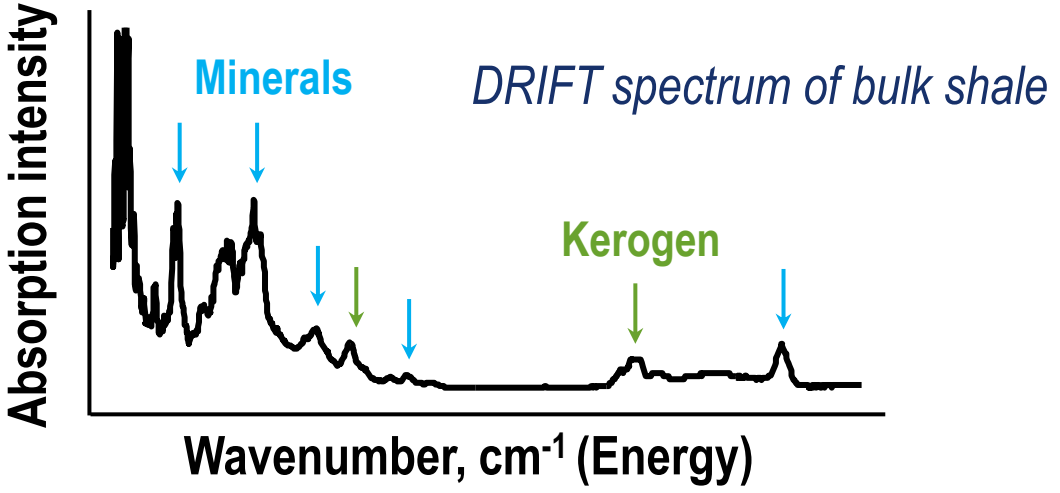






e.g. Lin & Ritz, 1993, Org. Geochem.; Ibarra et al., 1996, Org. Geochem.; Lis et al., 2005, Org. Geochem.; Craddock et al., 2018, Energy Fuels

App 1: Diffuse reflectance IR spectroscopy



Measurement of rock characteristics:

→ Mineral type & concentrations

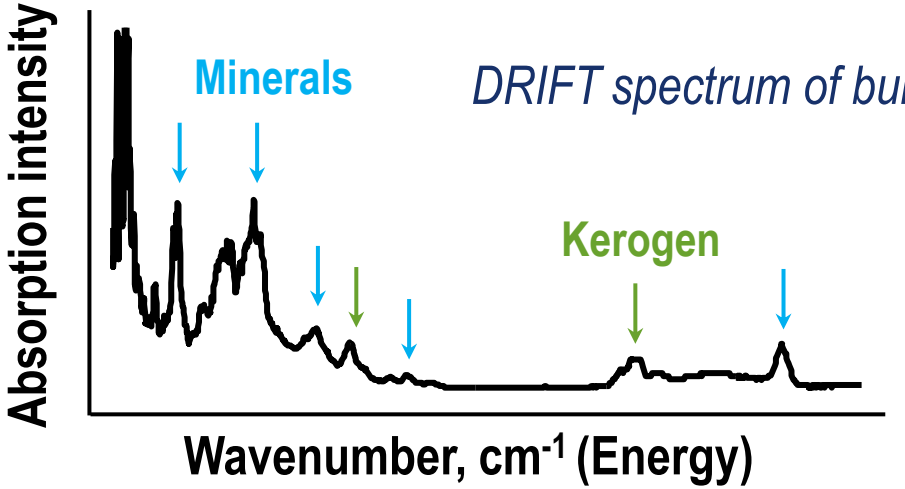
→ Kerogen concentration

→ Kerogen chemistry/properties

→ Kerogen thermal maturity

e.g., Christy et al., 1991, Org. Geochem; Charsky & Herron, 2012; Herron et al., 2014, SPWLA; Craddock et al., 2017, Org. Geochem.; Craddock et al., 2018, Petrophysics

App 1: Diffuse reflectance IR spectroscopy



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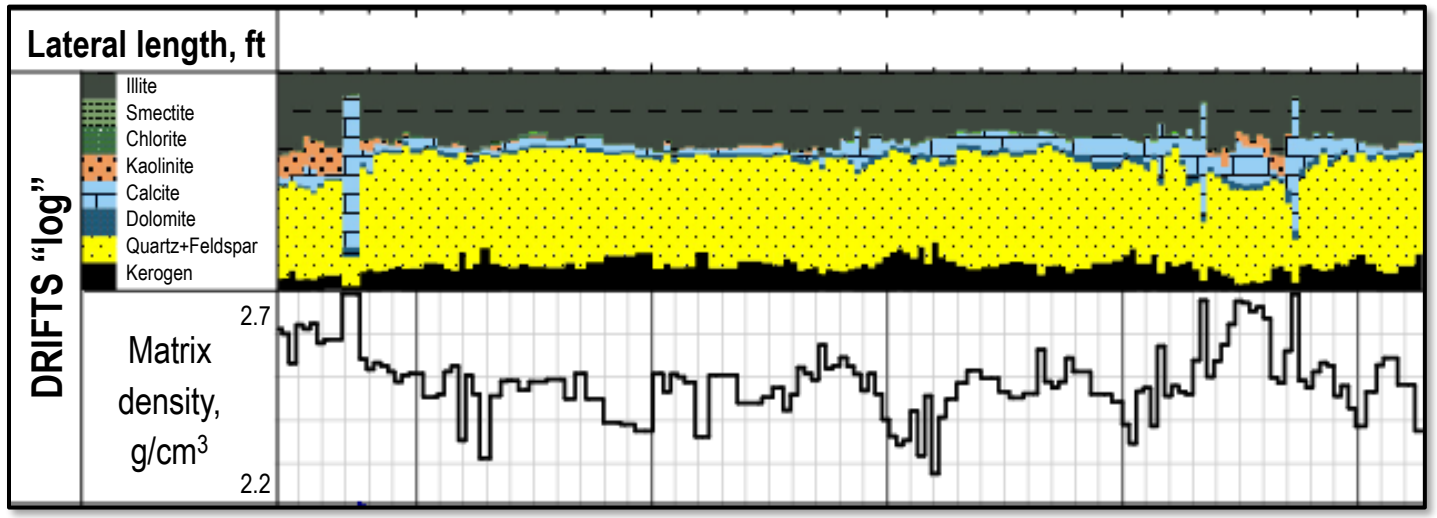


Real-time rock characterization:

→ Horizontal well cuttings, any mud type

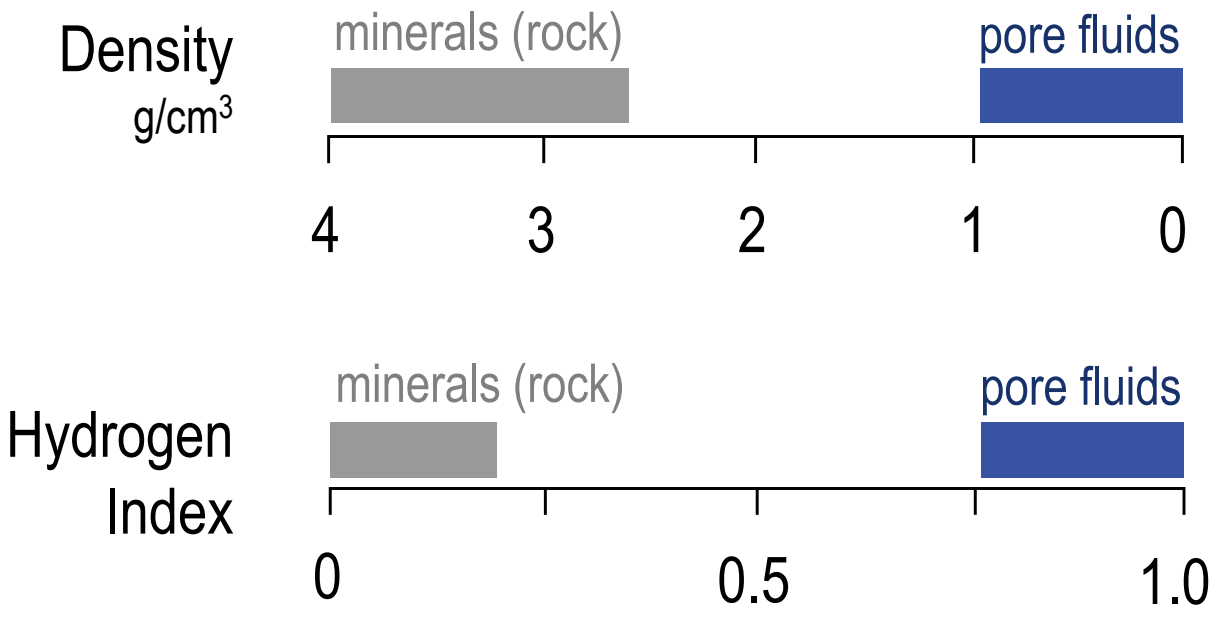
→ Integrated with logging measurements

e.g., Christy et al., 1991, Org. Geochem; Charsky & Herron, 2012; Herron et al., 2014, SPWLA; Craddock et al., 2017, Org. Geochem.; Craddock et al., 2018, Petrophysics

Kerogen: petrophysical properties

→ Porosity → key reservoir property → density & neutron (hydrogen index) logs

→ Use large difference between rock and pore properties



e.g., Guidry et al, 1995, API; Okiongbo et al., 2005, Energy & Fuels; Cheshire et al, 2017, Int. J. Coal Geol.; Craddock et al., 2018, Petrophysics; Craddock et al., 2019, Org. Geochem.

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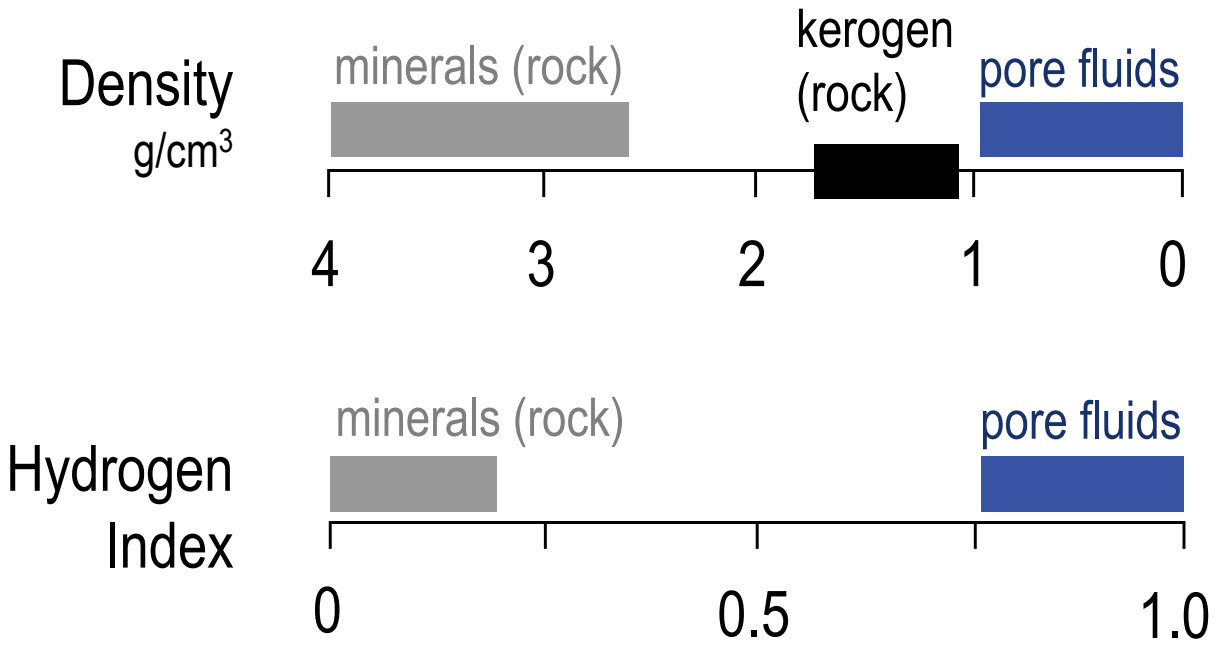

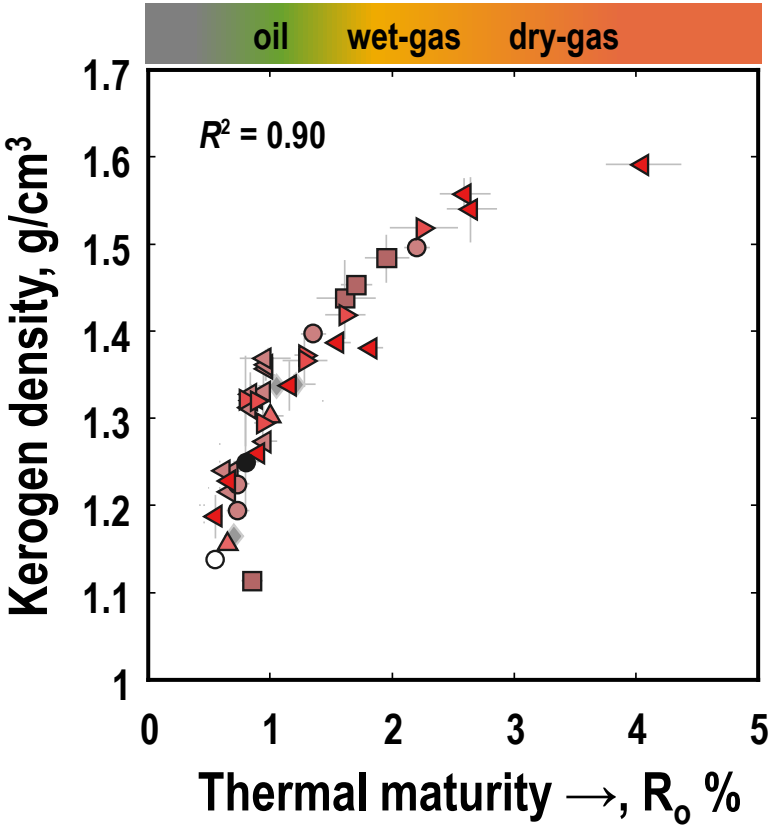

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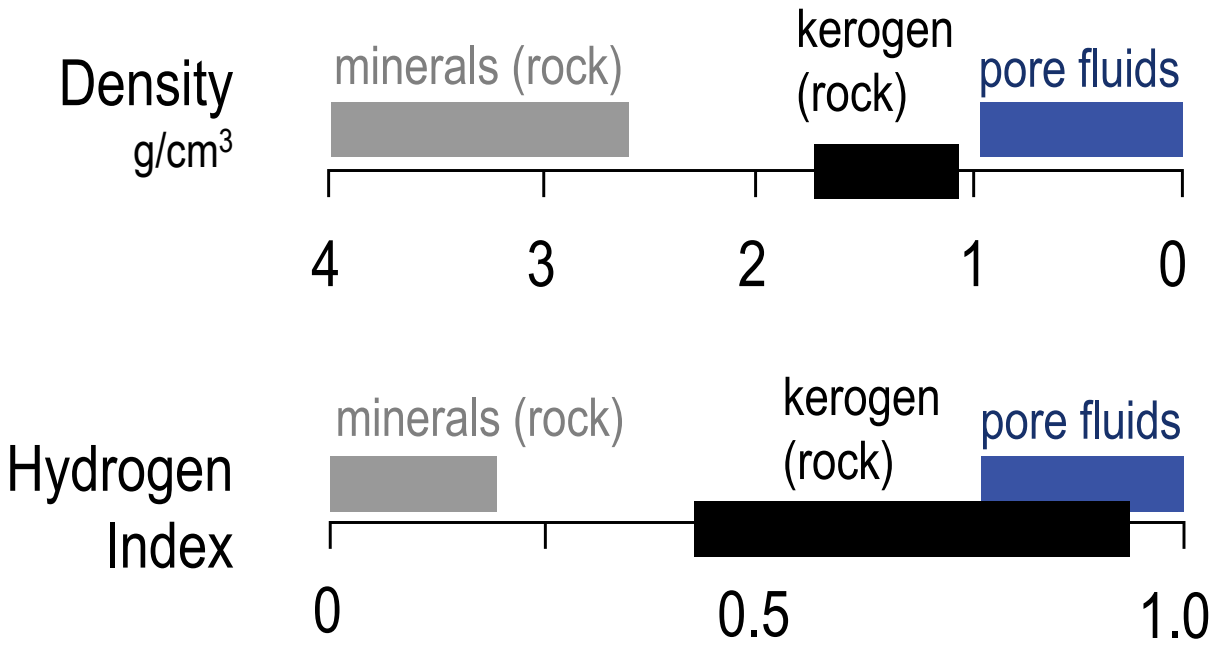

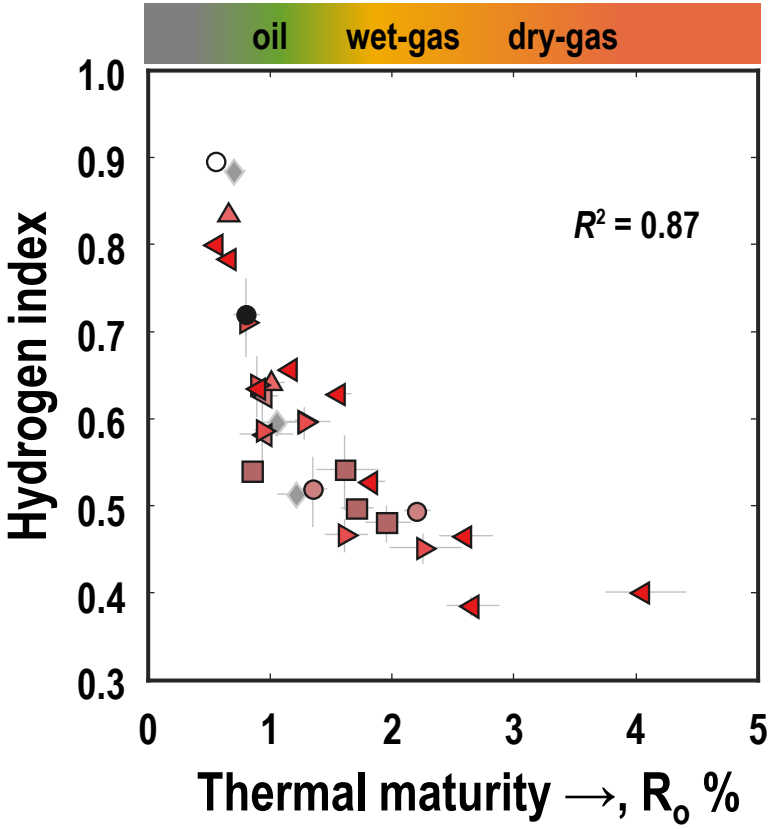

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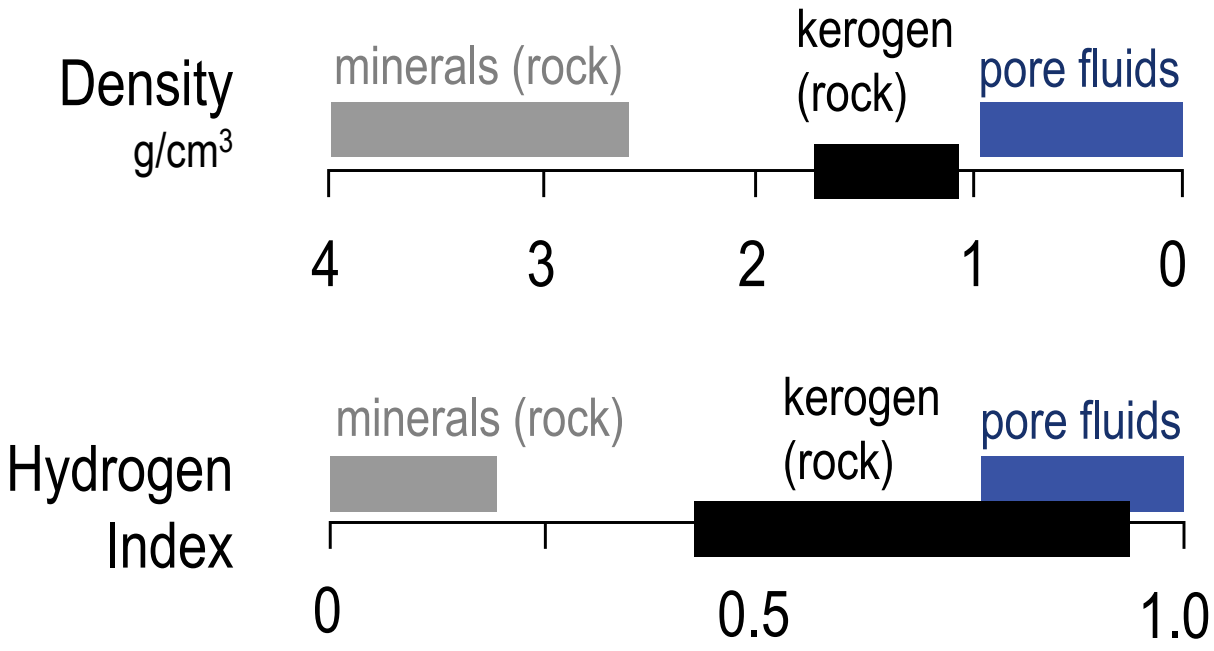
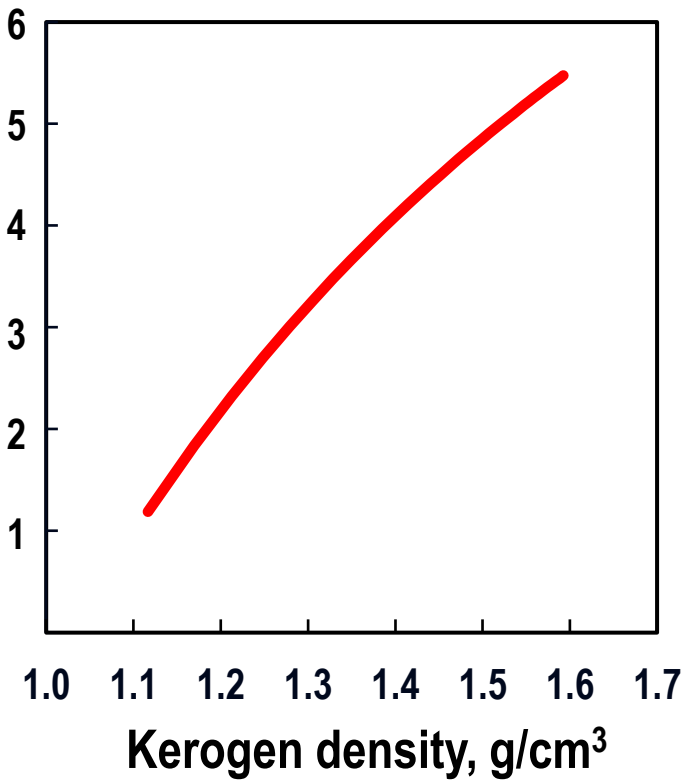
Kerogen: petrophysical properties

→ Kerogen (matrix) properties determine shale evaluations

→ Kerogen properties are variable and rarely known





e.g., Craddock et al., 2020 Petrophysics

App 2: TMALI THERMAL MATURITY-ADJUSTED LOG INTERPRETATION

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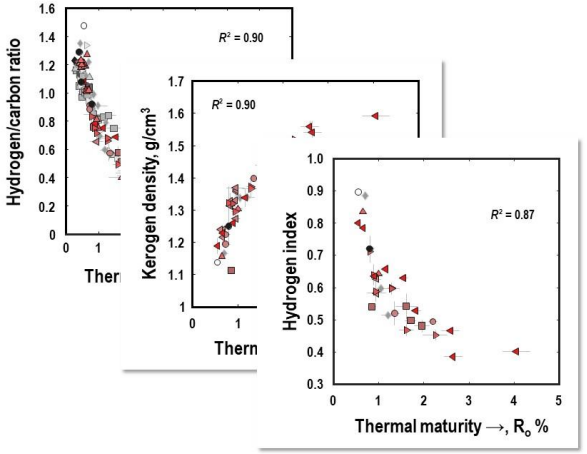
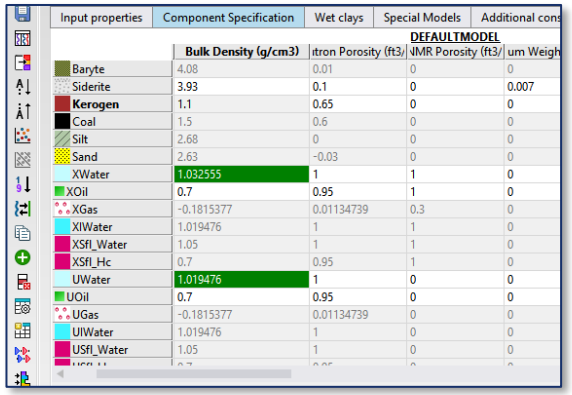
Input:
Thermal maturity

R_o

TMALI property correlations
(type II kerogen)



Output:
Type II kerogen endpoints



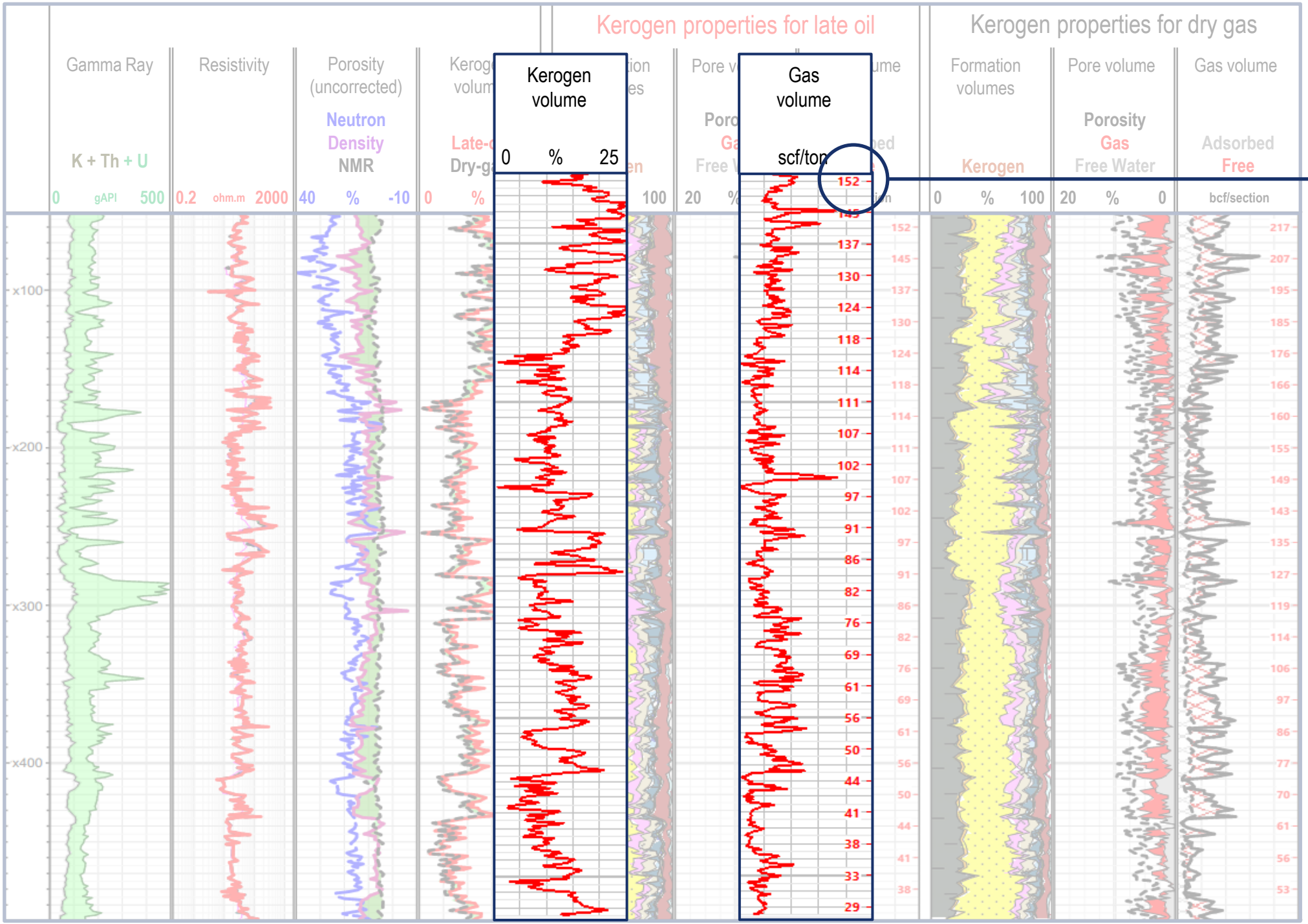
Input properties | Component Specification | Wet clays | Special Models | Additional cons

DEFAULTMODEL

	Bulk Density (g/cm3)	itron Porosity (ft3/	NMR Porosity (ft3/	um Weigh
Baryte	4.08	0.01	0	0
Siderite	3.93	0.1	0	0.007
Kerogen	1.1	0.65	0	0
Coal	1.5	0.6	0	0
Silt	2.68	0	0	0
Sand	2.63	-0.03	0	0
XWater	1.032555	1	1	0
XOil	0.7	0.95	1	0
XGas	-0.1815377	0.01134739	0.3	0
XIWater	1.019476	1	1	0
XSfl_Water	1.05	1	1	0
XSfl_Hc	0.7	0.95	1	0
UWater	1.019476	1	0	0
UOil	0.7	0.95	0	0
UGas	-0.1815377	0.01134739	0	0
UIWater	1.019476	1	0	0
USfl_Water	1.05	1	0	0

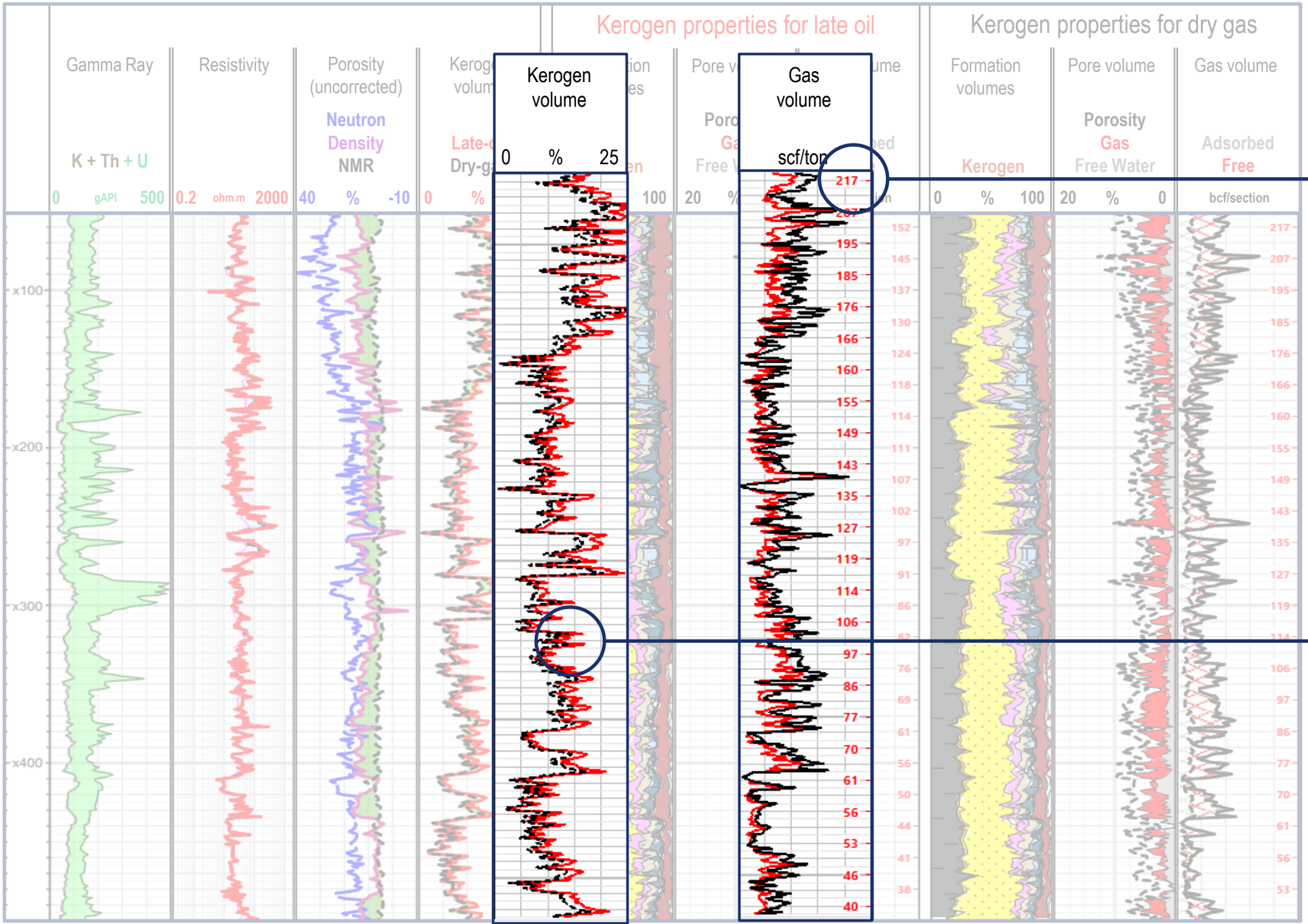
- Grain Density
- Electron Density
- Log Density
- Photoelectric Factor
- Formation Volumetric Factor
- Carbon Mole Fraction
- Hydrogen Mole Fraction
- H/C Mole Fraction Ratio
- Carbon Weight Fraction
- Hydrogen Weight Fraction
- Conversion Factor (TOC-to-TOM)
- Hydrogen Index
- Thermal Neutron Porosity
- Epithermal Neutron Porosity
- Sigma
- Fast Neutron Cross Section

Craddock et al., 2020 Petrophysics



Gas-in-place:

152 bcf/section



Gas-in-place:

217 bcf/section

ΔGIP: 40%

Δ$: 100M

Kerogen volume decreases

Gas volume increases

Kerogen: reservoir science to application

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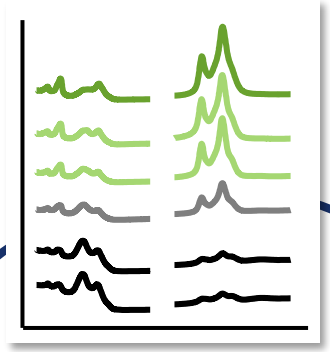
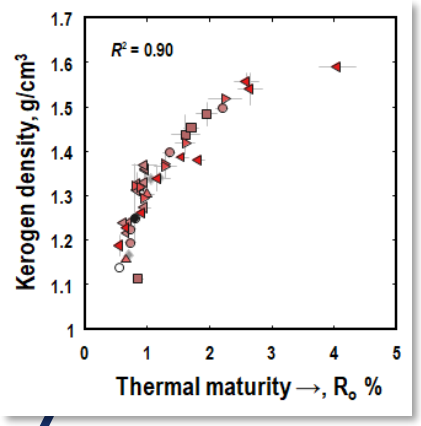
SCIENCE

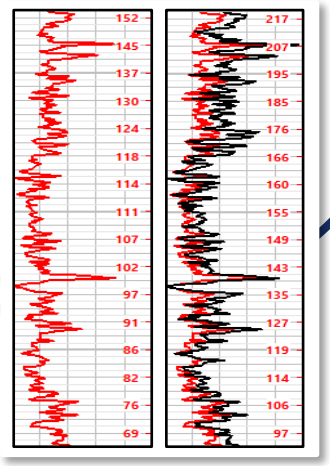


Chemical insights



Petrophysical log responses

APPLICATION



Reservoir characterization

Kerogen: reservoir science to application

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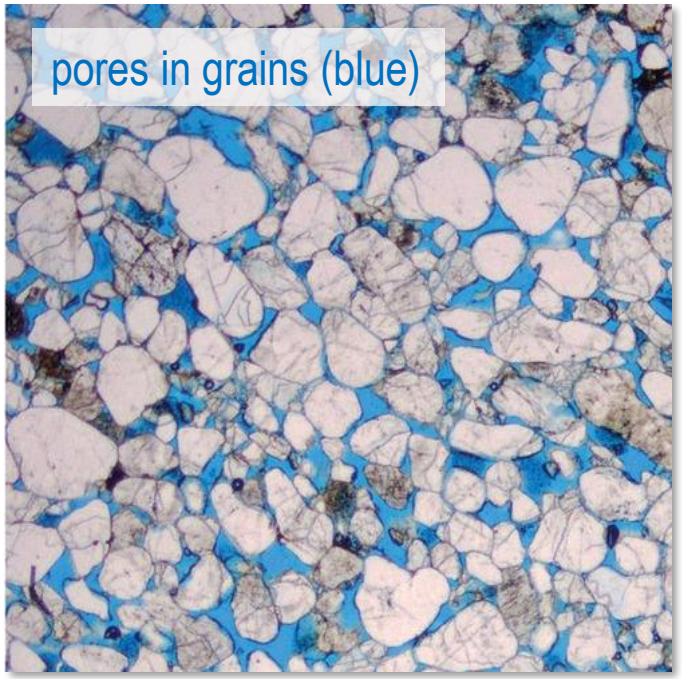
Reservoir storage, transport, production

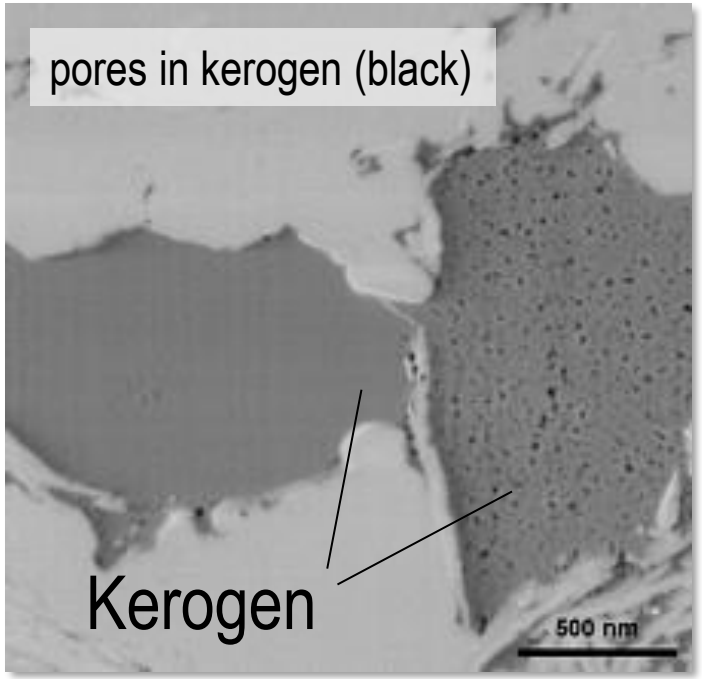
Kerogen: high-resolution imaging

Conventional sandstone
(Photomicrography)



0.5 mm

Unconventional shale
(Scanning Electron Microscopy)



0.0005 mm

→ Porosity can be all in organics!

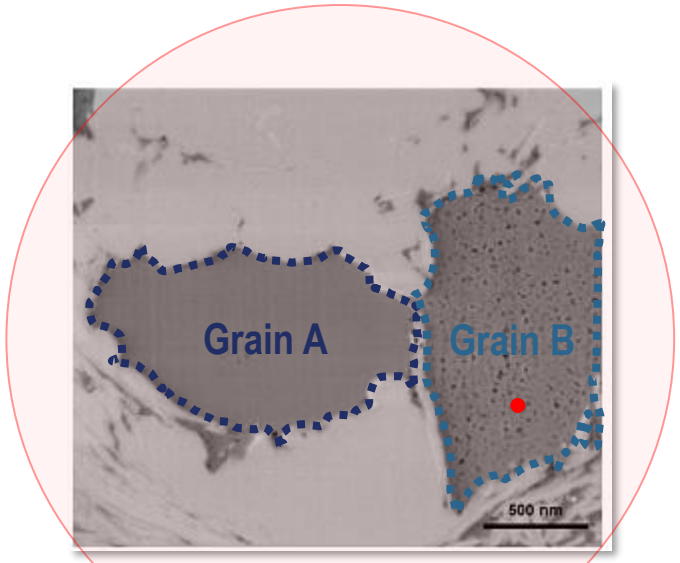
→ Physical differences at grain scale!

→ Other differences at grain scale?

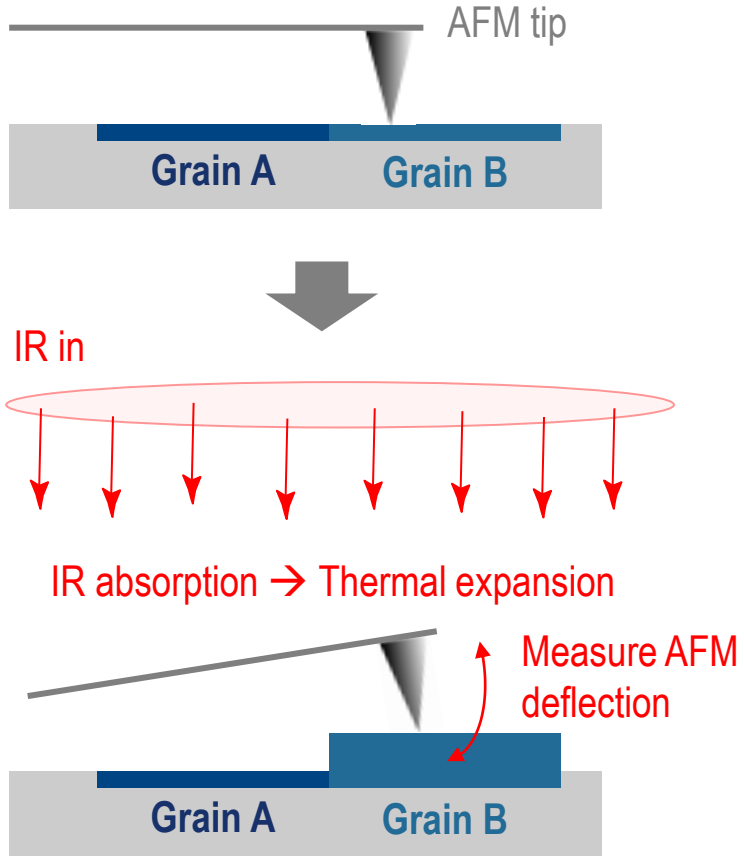
e.g., Loucks et al., 2009, J. Sed. Res.; Curtis et al., 2012, Int. J. Coal Geol., Loucks et al., 2014, GCAGS J.; Zuluaga , 2017, Geol. Soc. Spec. Publ.

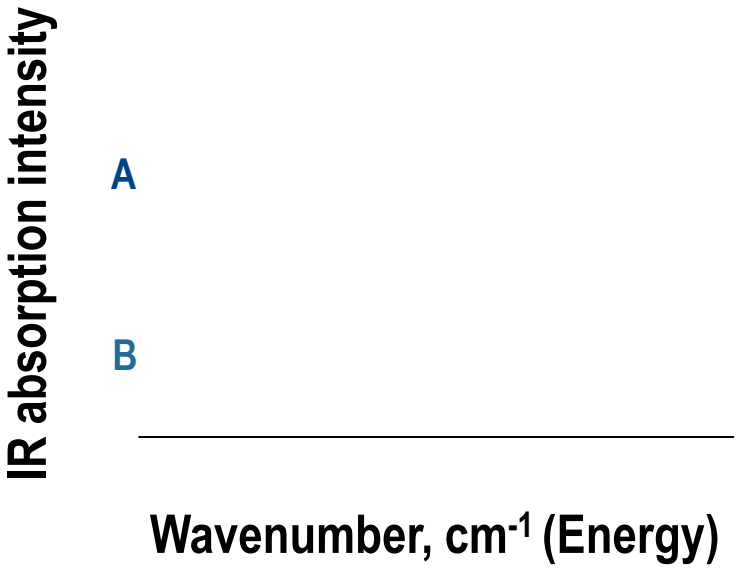
Kerogen: ‘nano-IR’

→ Atomic force microscopy (AFM) + IR spectroscopy → ‘nano-IR’



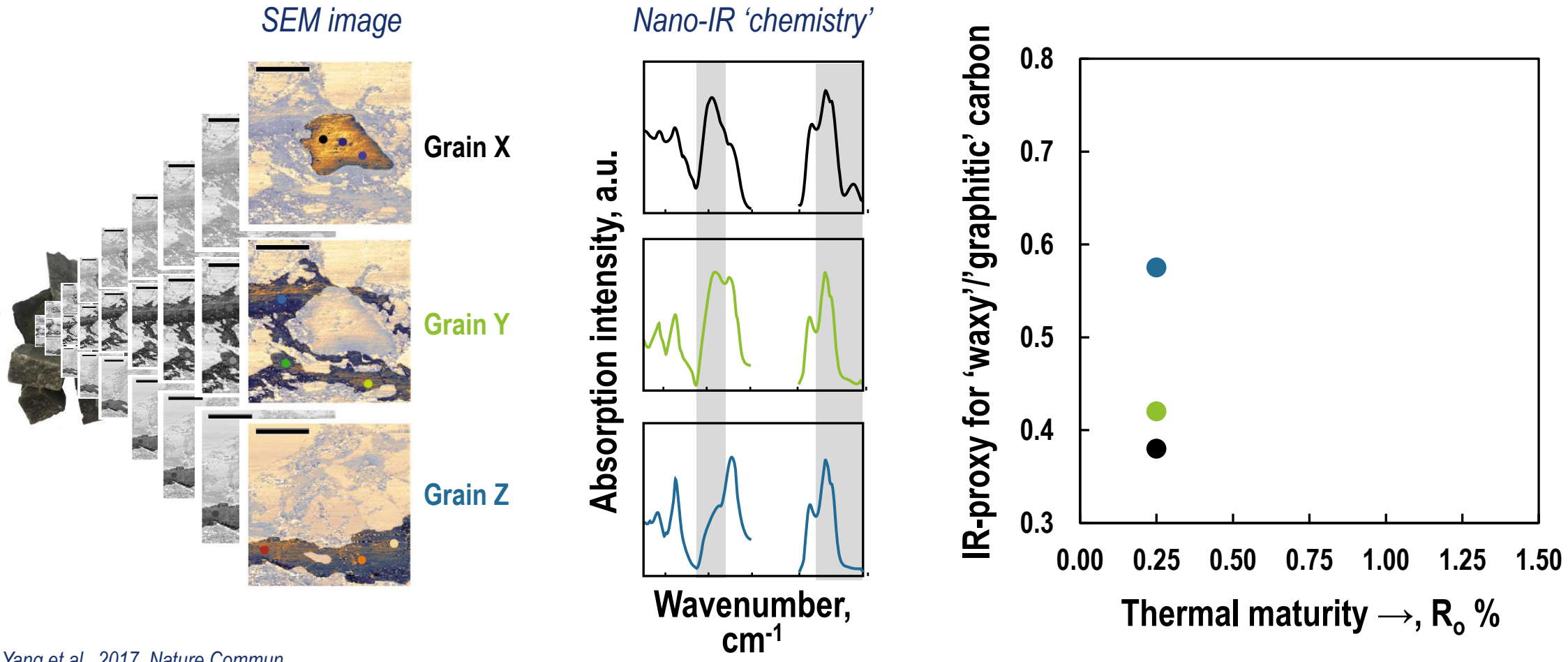
Size of AFM tip much smaller than individual grains!
Smallest size of IR ‘spot’ bigger than individual grains!





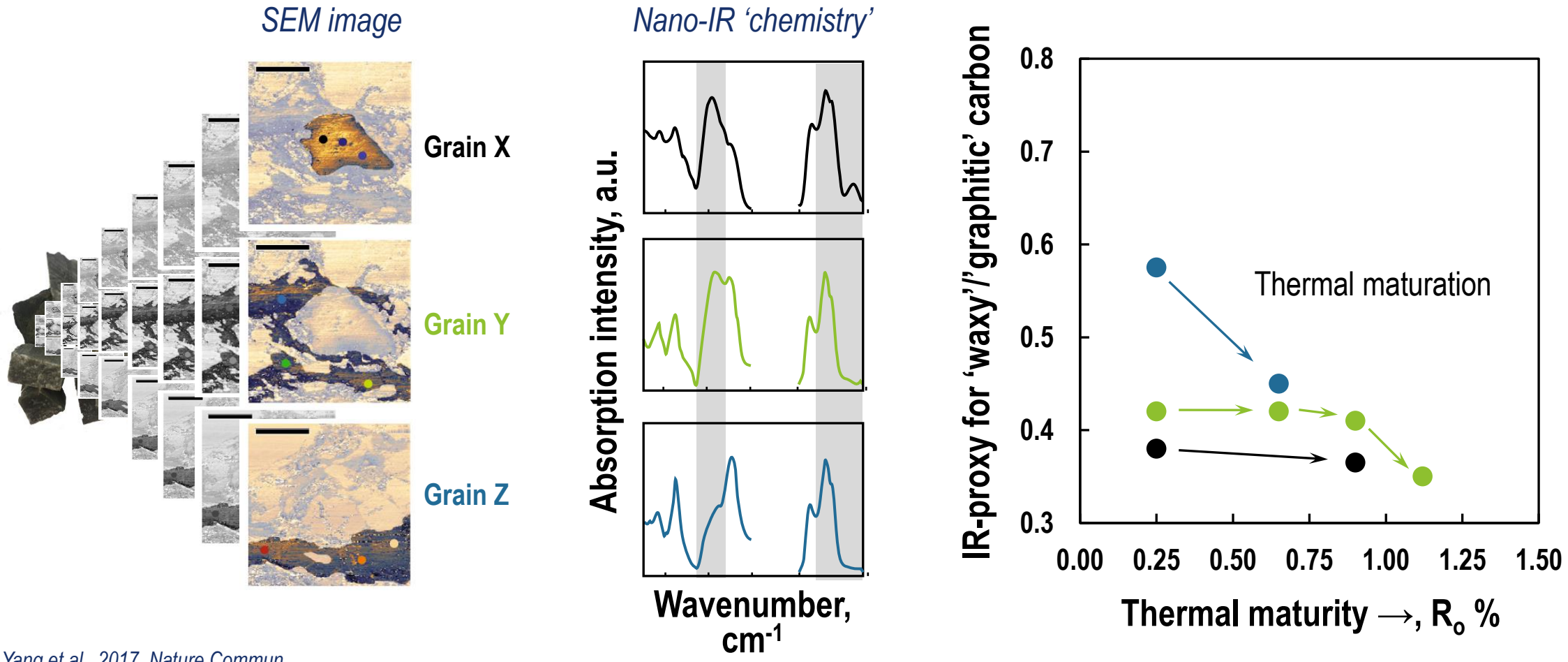
Yang et al., 2017, Nature Commun.

Kerogen: ‘nano-IR’ chemical mapping



Yang et al., 2017, Nature Commun.

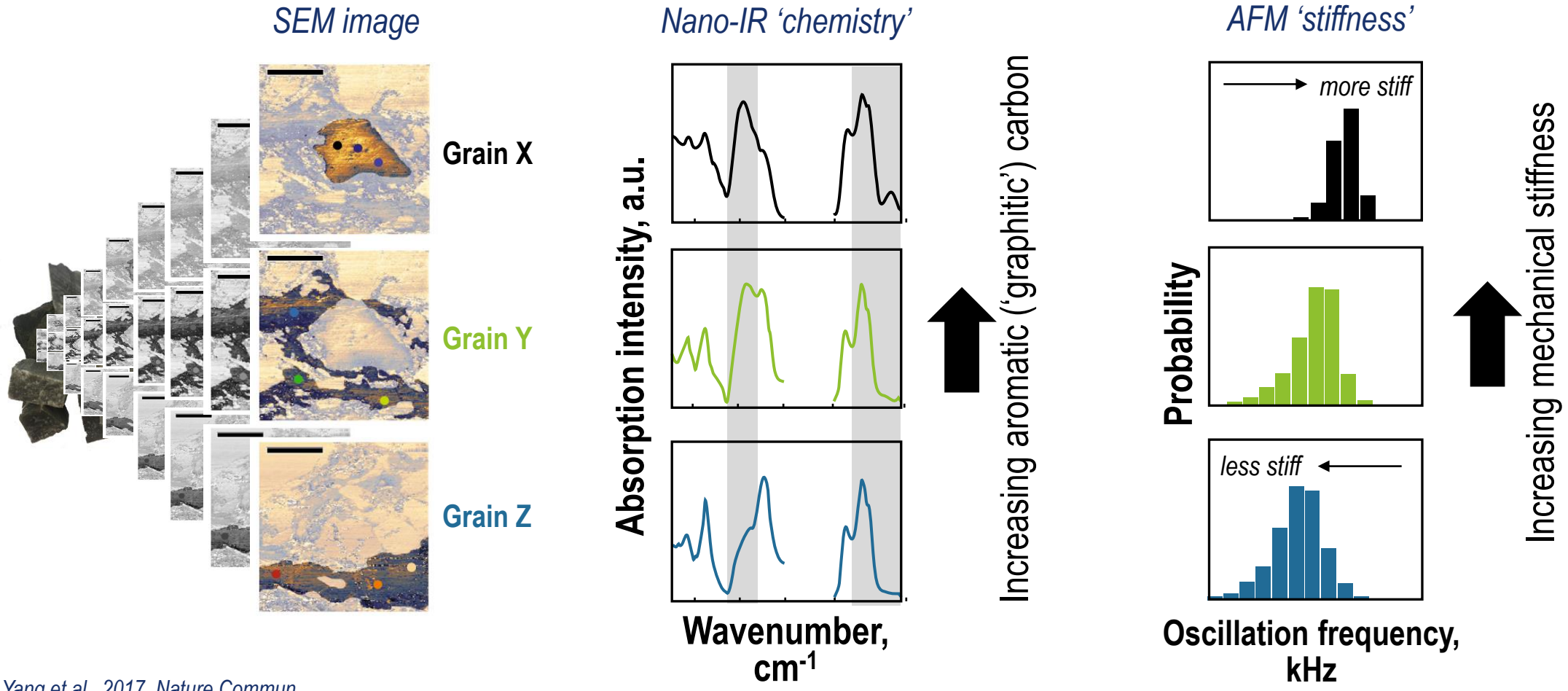
Kerogen: ‘nano-IR’ chemical mapping



Yang et al., 2017, Nature Commun.

Kerogen: ‘nano-IR’ mechanical mapping

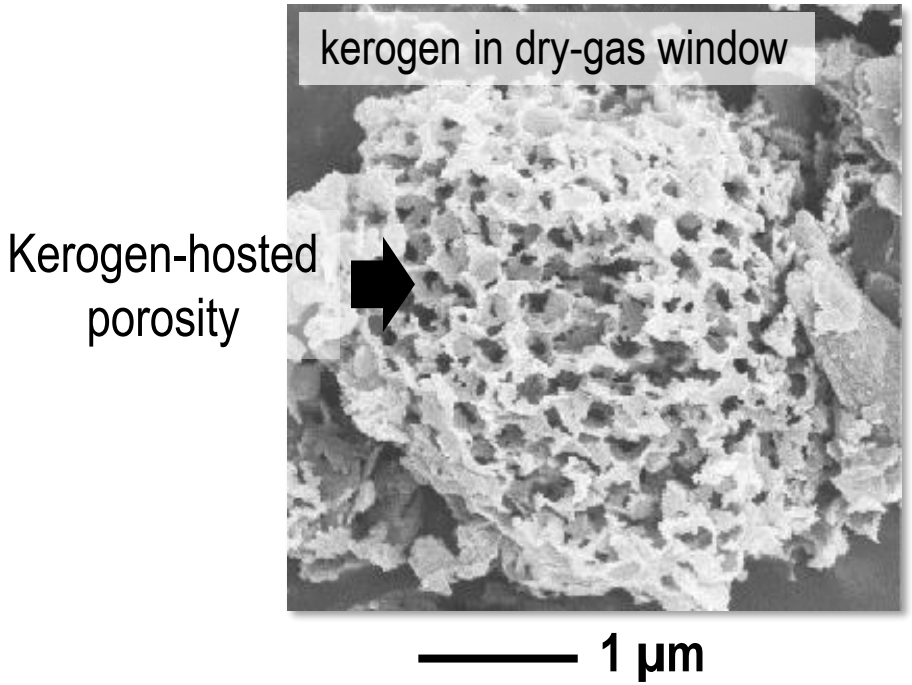
→ Chemical & Mechanical properties → correlated at molecular scale

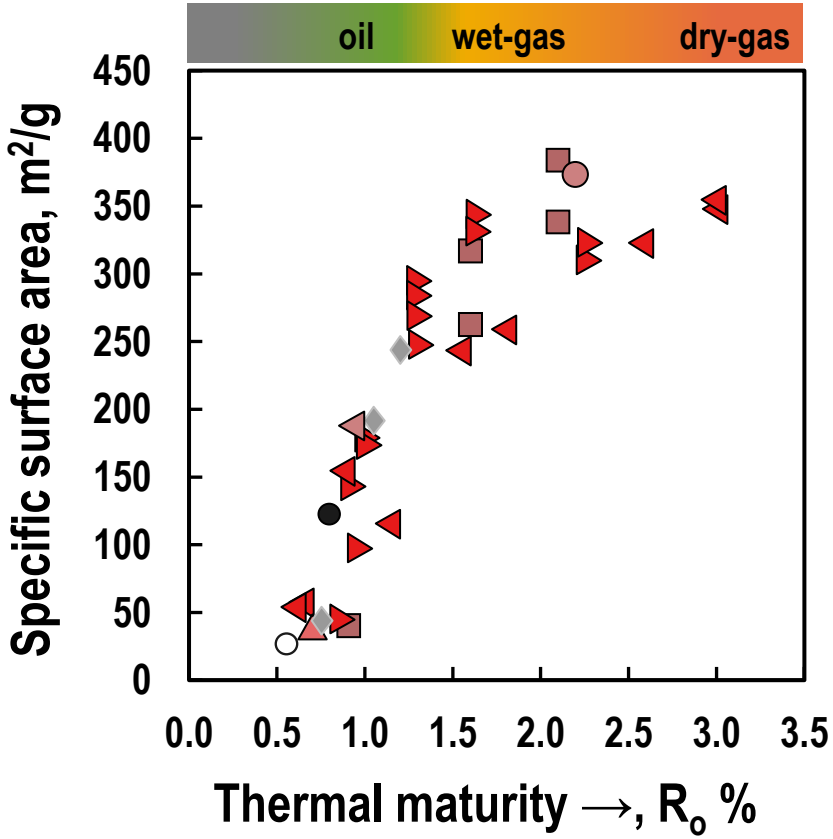


Yang et al., 2017, Nature Commun.

Kerogen: pore-structure quantification

→ Kerogen surface area → generated by thermal maturity → high → surface interactions

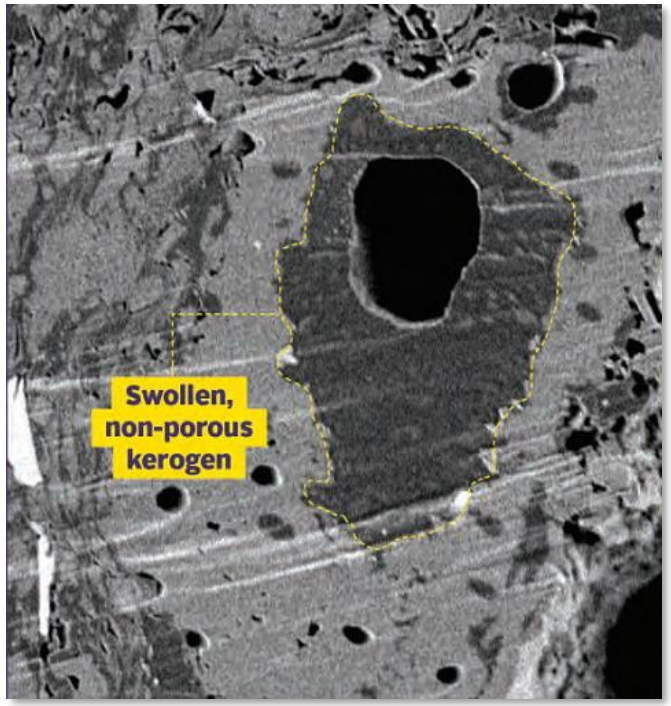




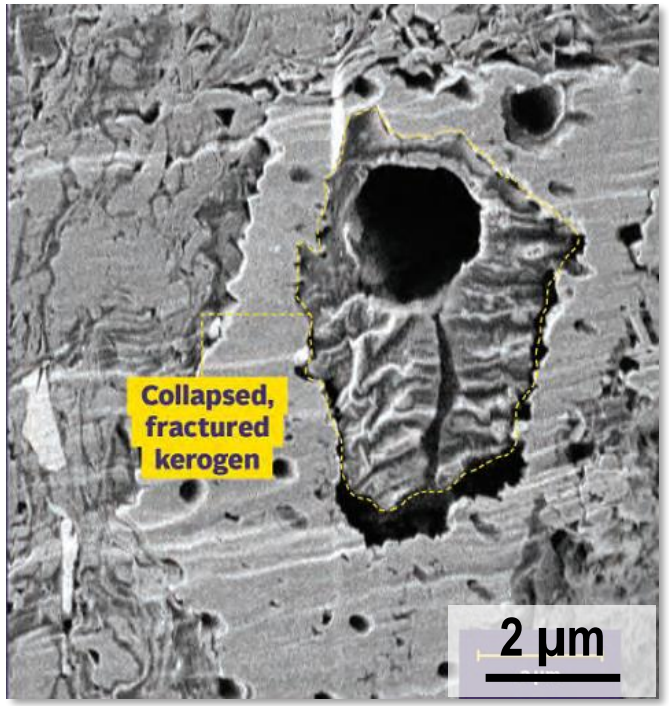
Valenza et al., 2013, Geology; Suleimenova et al., 2014, Fuel; Cheshire et al., 2017, Int. J. Coal Geol; Craddock et al., 2018, Energy Fuels

Kerogen: pore ‘swelling’

Kerogen, *before* liquids extraction



Kerogen, *after* liquids extraction



→ Kerogen acts like a ‘sponge’

→ Adsorbs hydrocarbon gases

→ Swells with hydrocarbon liquids

→ Swelling blocks pores

→ Inhibits production

Reeder et al., 2016, Petrophysics

App 3: RPI RESERVOIR PRODUCIBILITY INDEX

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Conventional reservoirs

Total Organic Carbon = Oil + Gas

TOC ↑ ✓

vs.

Unconventional tight-oil

Total Organic Carbon = Oil + Bitumen + Kerogen

TOC ↑ ????

✓ Oil (producible liquid)

✗ Kerogen (swells)

✗ Bitumen (non-producible liquid)

⇩

→ RPI ∝ Oil/TOC

→ RPI ↑ Production ↑

→ '**Sweet spots**' in Tight Oil

Reeder et al., 2016, Petrophysics; Kausik et al., 2015, URTeC

App 3: RPI RESERVOIR PRODUCIBILITY INDEX

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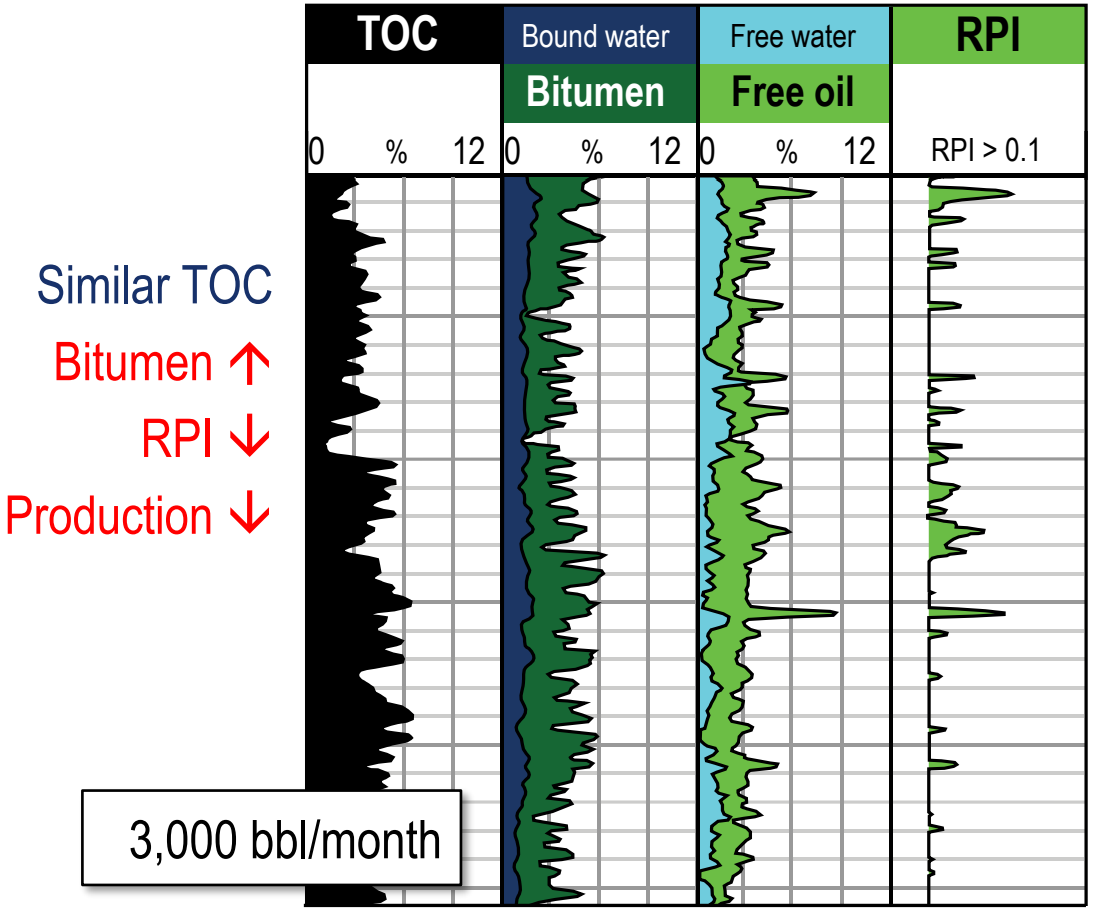
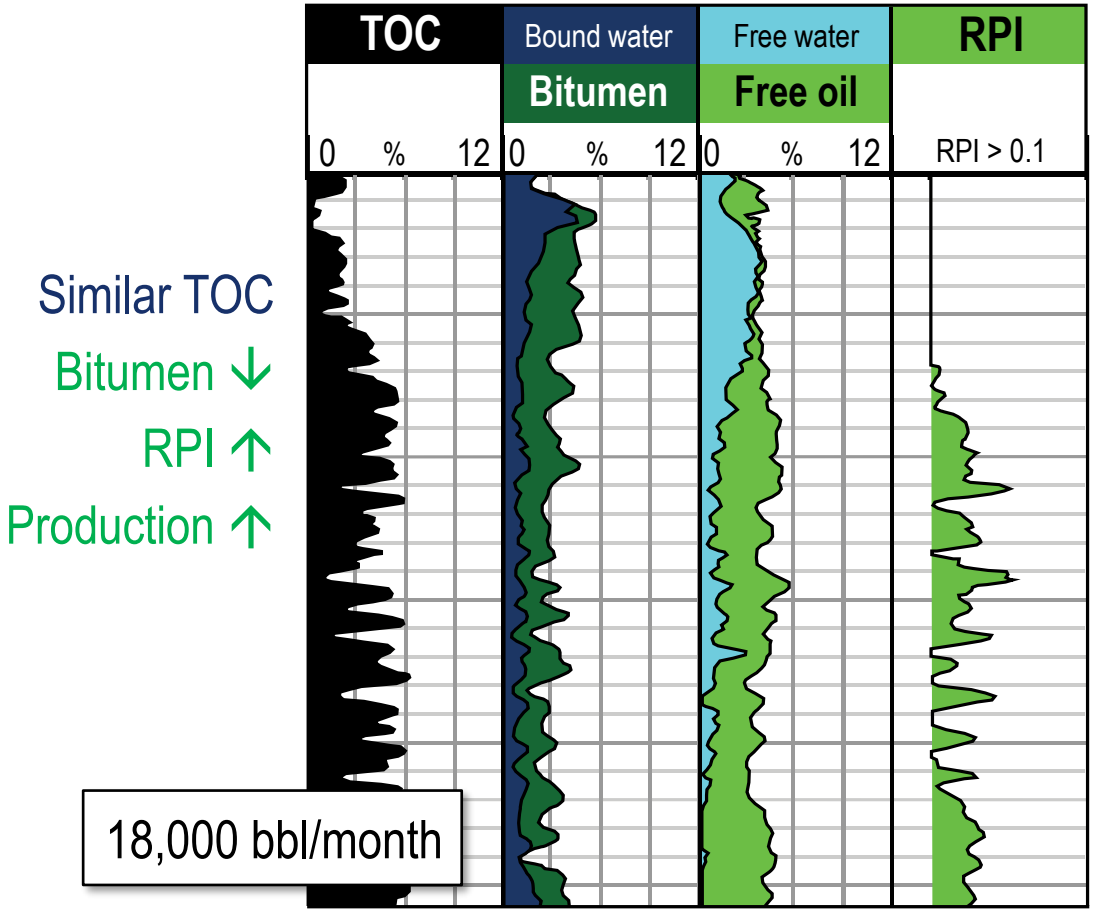
Eagle Ford, early-oil window



Eagle Ford, peak/late-oil window



Reeder et al., 2016, Petrophysics; Kausik et al., 2015, URTeC

App 4: EOR for Tight Oil?

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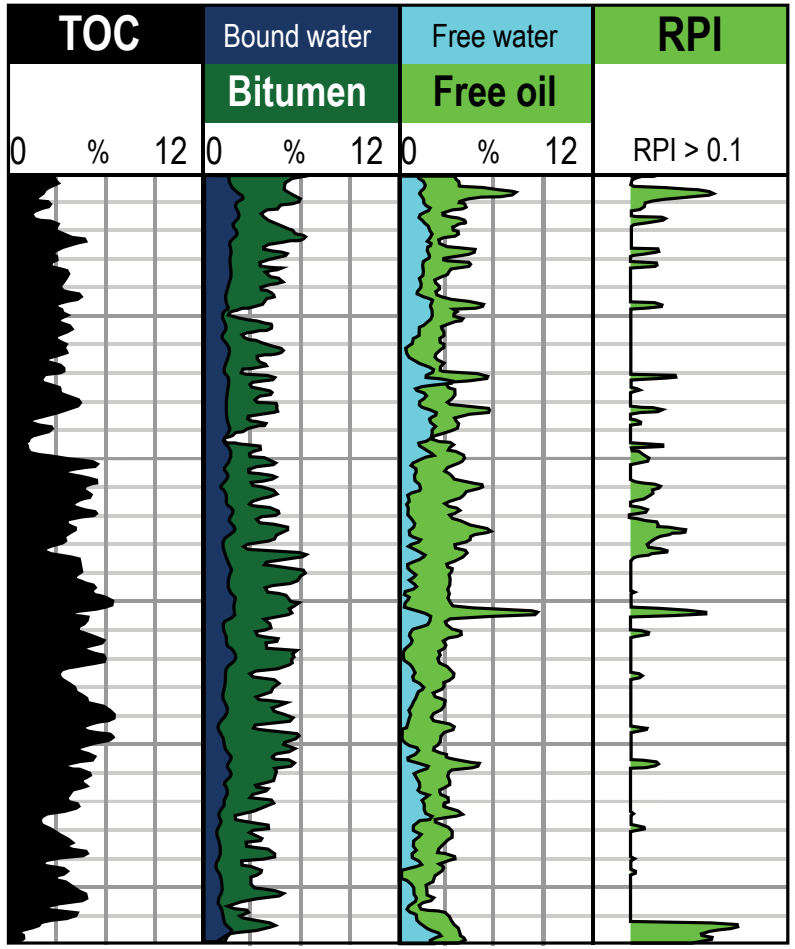
→ Source-rock bitumen is common in oil window

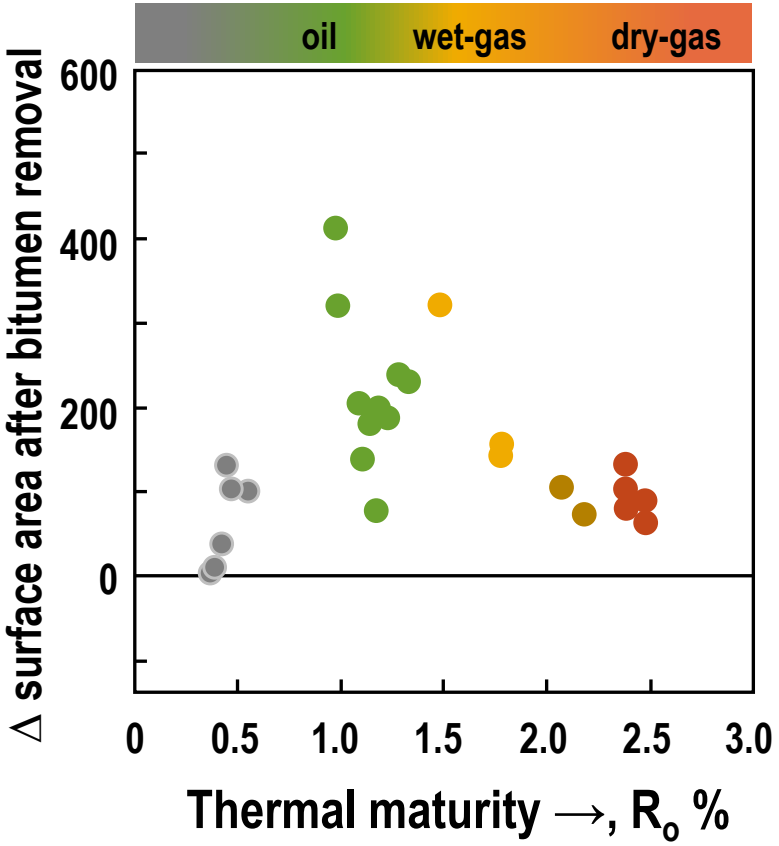
→ (Important to know R_o)

→ Dissolve bitumen w/ solvent

→ Increase pore connectivity

→ Pump 'green' solvent downhole for initial stimulation or workover?





Valenza et al, 2013, Geology

Summary: SPE DL Tour of kerogen

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Science to build knowledge of kerogen…

Chemical/molecular properties

Petrophysical properties

Microstructure

Diversity and heterogeneity

Evolution during thermal maturation

Develop applications to improve…

Surface reservoir evaluation

Downhole reservoir evaluation

'Sweet spot' (target) identification

Production strategies in shale

Selected readings

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