Overview of Unconventional Reservoirs

Kevin M. Bohacs

ExxonMobil Upstream Research (retired)

KMBohacs GEOconsulting

KMBohacs
GEOconsulting

Learning Objectives

By the end of our discussion, you should be able to describe:

- **Essential components of effective reservoirs**
- **Differences between conventional and unconventional reservoirs**
- **Where, when, and why unconventional reservoirs occur**
- **Potential research opportunities**
  - **Heisenberg Uncertainty Principle for mudstones**

General Thoughts

- ☞ Continuous spectrum of properties
- ☞ Many combinations can work
- ☞ It's all about ratios/trade-offs
- ☞ 'Rules' of 4:
  - » Pore types
  - » Porosity systems
  - » Reservoir classes
  - » Ms reservoir families

- ☞ This is just a snapshot, your actual mileage may vary, plenty of room for discussion and research...

Unconventional Resources: General Definitions

Unconventional Hydrocarbon Accumulations are:

- » **Normally generated HCs in…**
- » **Reservoirs with atypical reservoir/fluid properties:**
  - **Widespread, diffuse** ***(a/k/a "continuous-type" deposits)***
  - **Thin stratigraphic intervals** ***(10s m)***
  - **Generally not significantly affected by hydrodynamic influences**
  - ***Many are HC source rocks at high thermal maturity***
- » **Although present on a regional scale, changes in intrinsic properties often result in more localized "sweet spots" based on resource-density, productivity, or commerciality criteria.**
- » **Such accumulations require specialized assessment methods and extraction technology which differ from "conventional" (traditional) resources.**

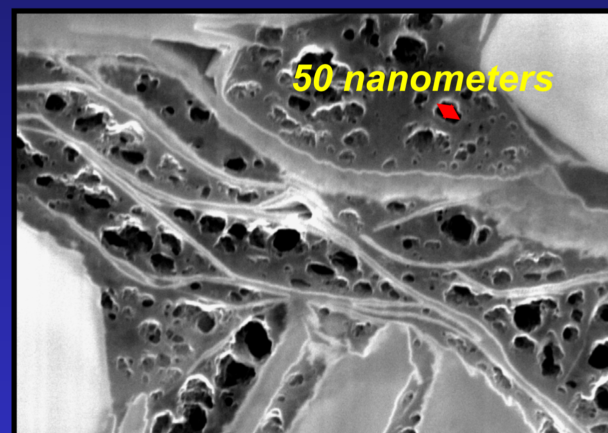
Unconventional Resources

Broad range of non-traditional reservoirs &/or HC's…

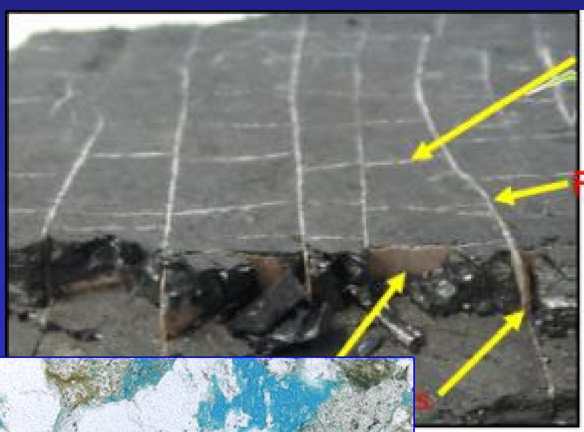
- Some tight Ss & CO_3 reservoirs
- Tight Oil/Shale Oil
- Shale Gas
- Chalks
- Coalbed methane
- Heavy oil *(< 20° API)*
- Oil Sands

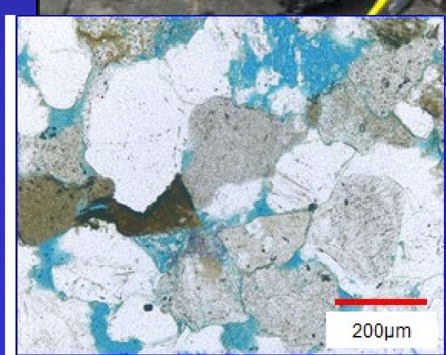
Heavy Oil

Shale Gas/Oil



Coal Bed Methane





Tight Gas Ss

Oil Sand

Outline

- Essential attributes of effective reservoirs
- ☞ Differences between conventional and unconventional reservoirs
- ☞ Where, when, and why unconventional reservoirs occur
- ☞ Research Opportunities

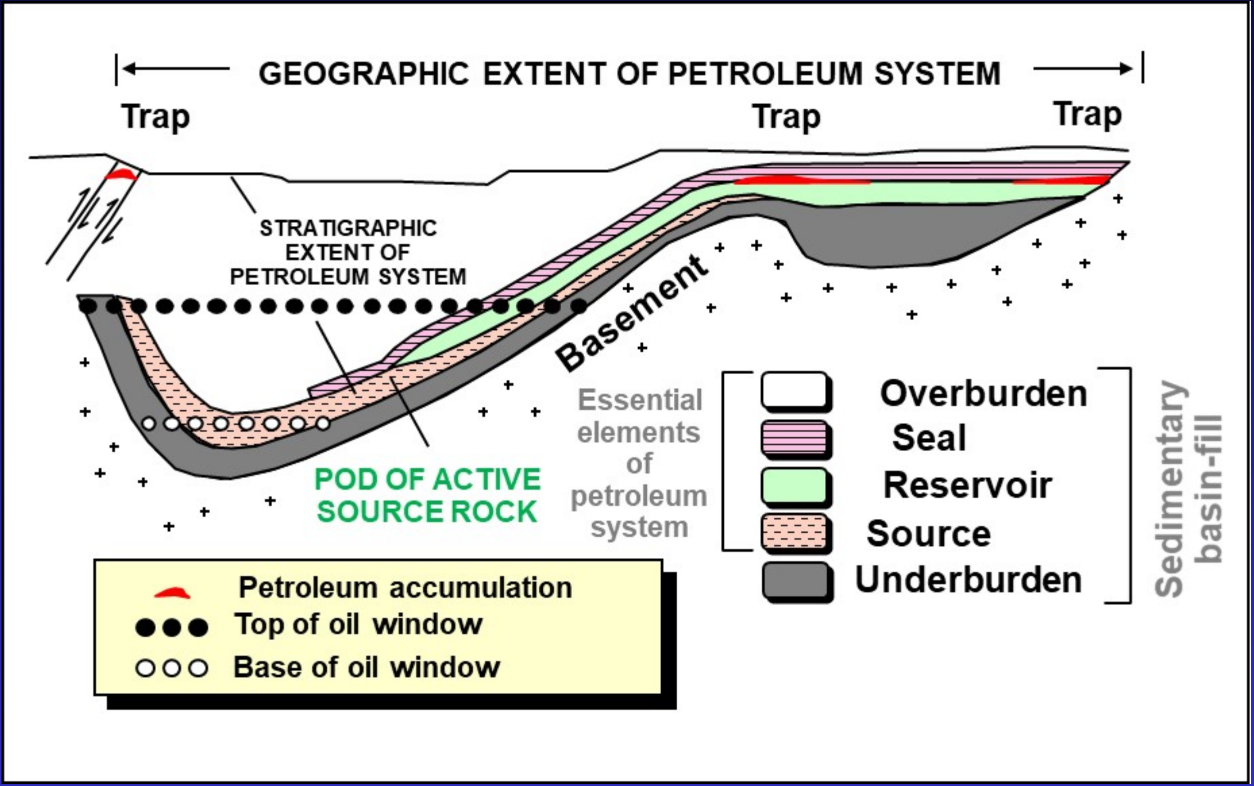
Where Does Oil Come From ?

Reservoirs in HC Systems Context

Source:
- ☞ Organic C *(TOC)*
- ☞ Hydrogen *(HI)*

Maturity:
- ☞ Thermal stress *(R_o)*

Migration:
- ☞ Carrier beds *(Φ, k)*



Reservoir:
- ☞ Porous *(Φ)*
- ☞ Permeable *(k)*

Seal:
- ☞ Low Perm.
- ☞ Ductility

(after Magoon, 1998)

Essential attributes of effective reservoirs

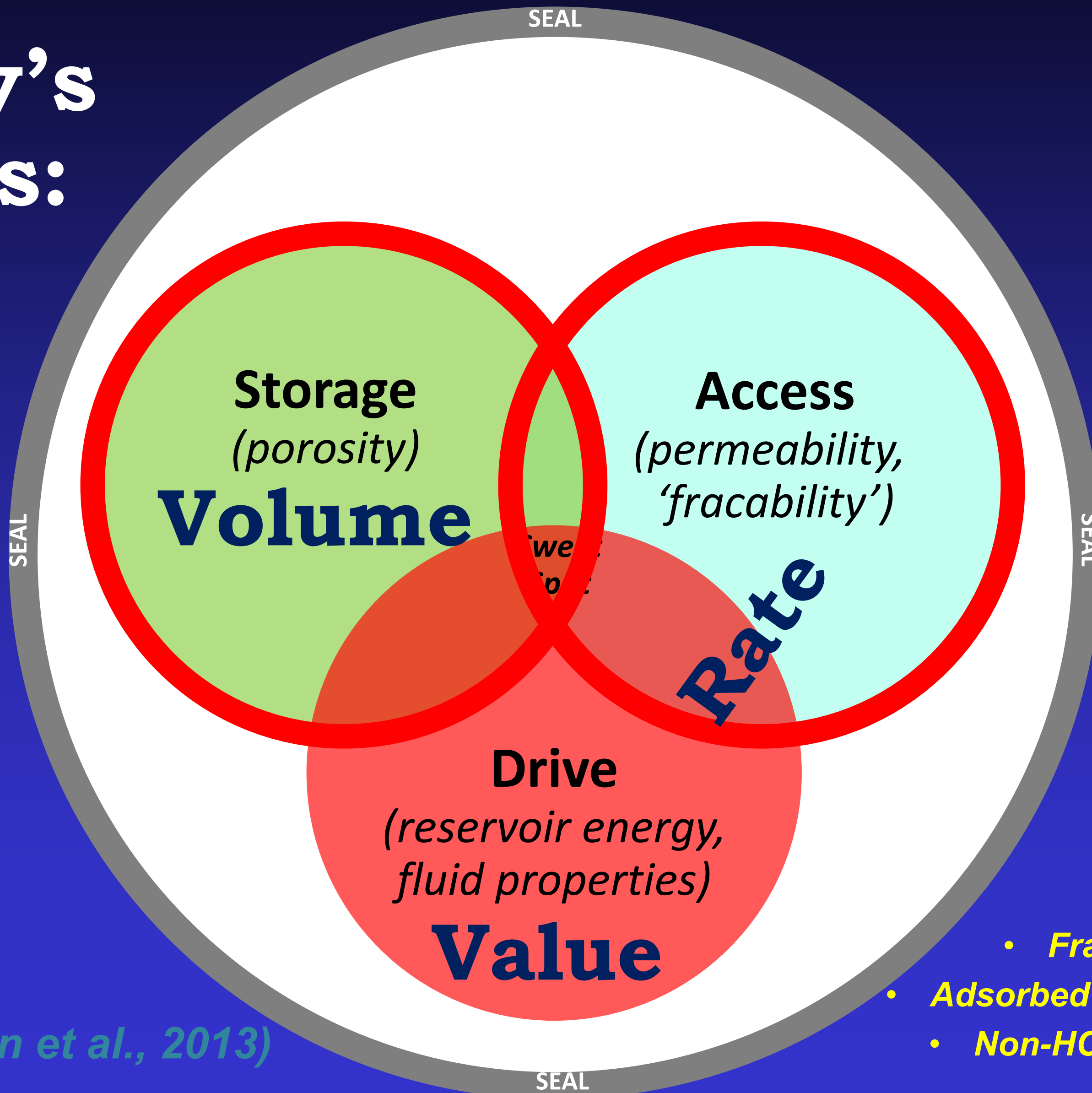
- ☞ *Enough fluid* - Volume
- ☞ *of sufficient value* - Value
- ☞ *fast enough* - Rate
- ☞ *to make $$$* - Cost

$$\$ = \frac{\text{Volume} \times \text{Value} \times \text{Rate}}{\text{Cost}}$$

In slightly more geological detail…

Essential components of effective reservoirs

Today's Focus:



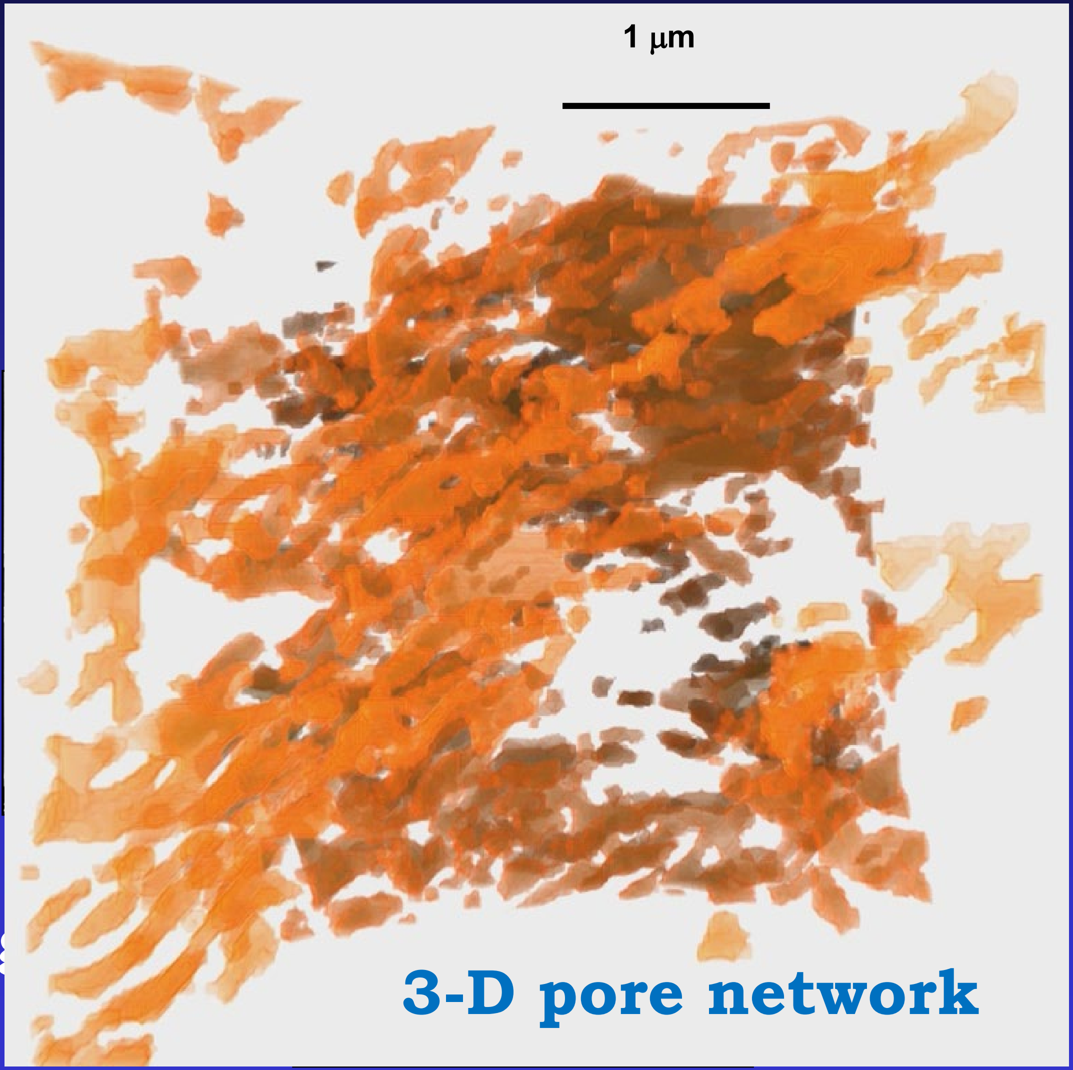
Modifiers:

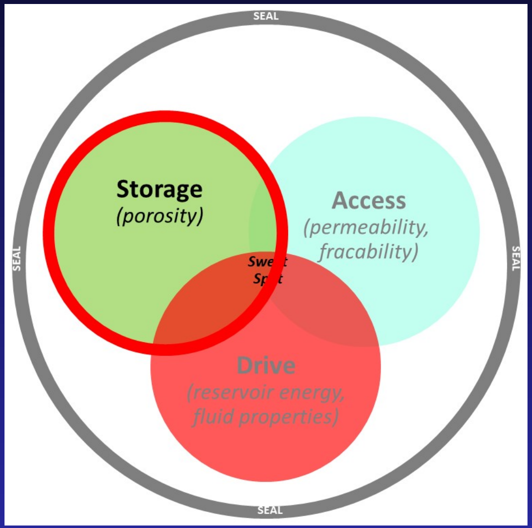
- *Fractures (and type)*
- *Adsorbed Gas vs. Free Gas*
- *Non-HC Gas Distribution*

(after Ottmann et al., 2013)

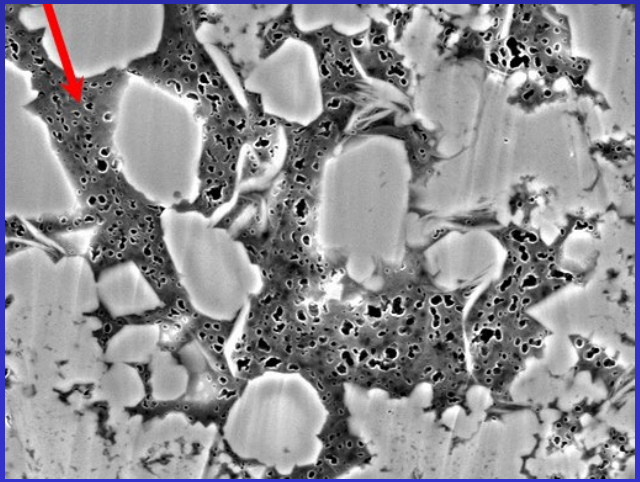
Essential components – Storage

Porosity types:

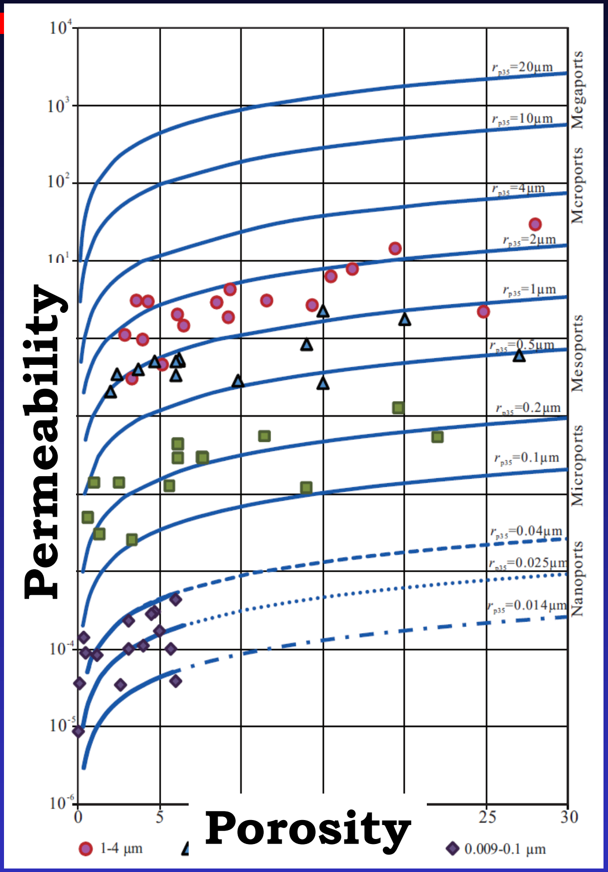




Intra-organic matter



Essential components – Access



Permeability:

- ☞ Relation of flow to pressure gradient, fluid viscosity (± other factors)
- ☞ $v = k (\nabla P/\mu)$ for viscous flow
- ☞ *∝ how well pores are connected*
- ☞ *∝ pore throat sizes*

Fracability:

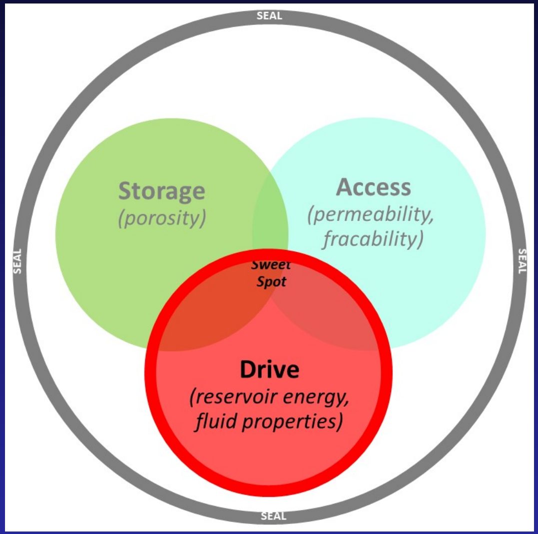
- ☞ Strength *(will it break?)*
- ☞ Toughness *(will break stay open?)*
- ☞ *∝ rock composition, cementation, bedding*
- ☞ *∝ 1/porosity, clay-mineral content*

Essential components – Drive

$$v = k\,(\underline{\nabla P}/\mu)$$

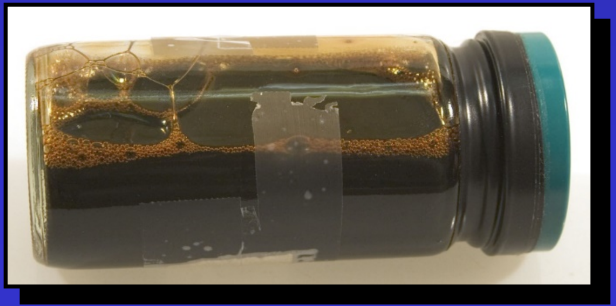
Reservoir Energy:

- Water drive
- Gas expansion
- Solution gas
- Rock or compaction drive
- Gravity drainage



Viscosity:

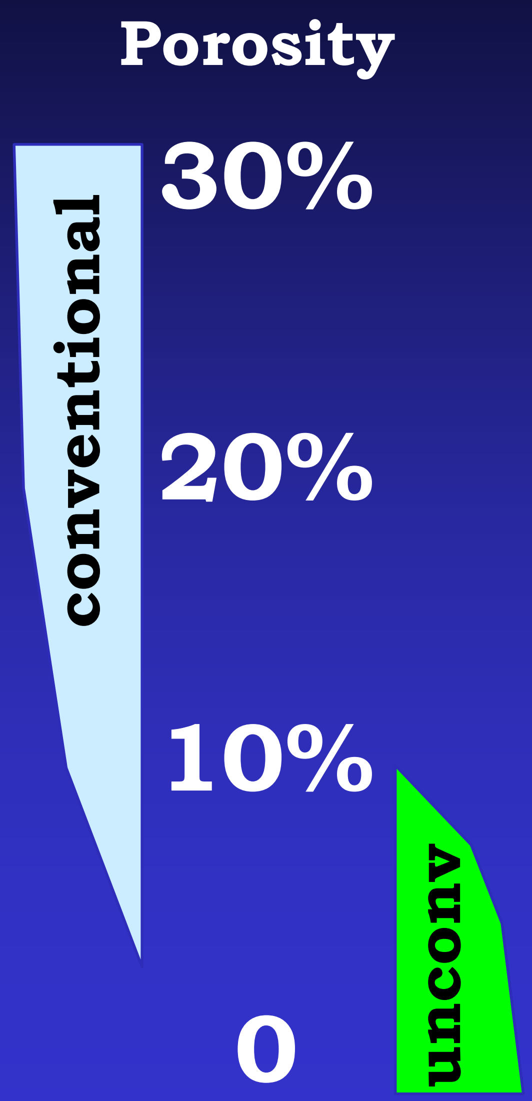
- Resistance to flow
- *$\propto$ fluid composition, phase*
- *$\propto$ 1/temperature*
- *(related to value of commodity)*

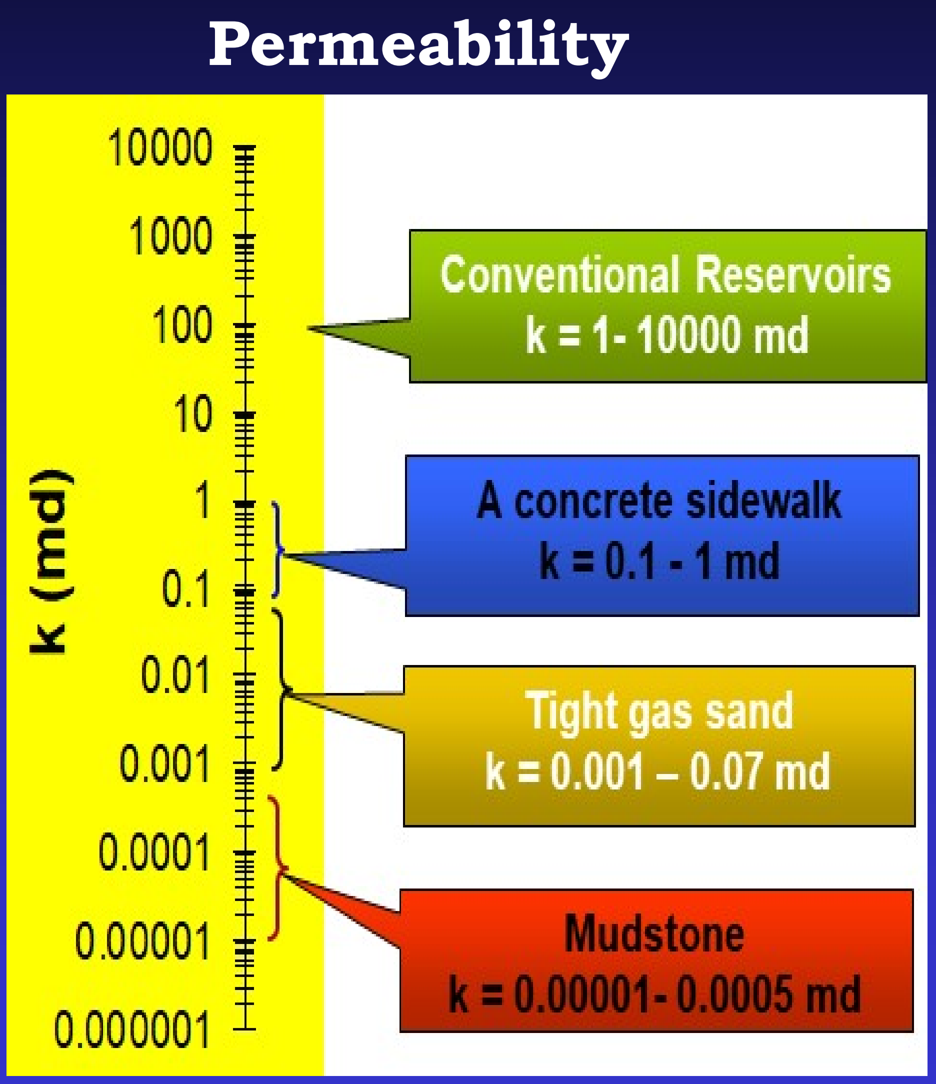


Outline

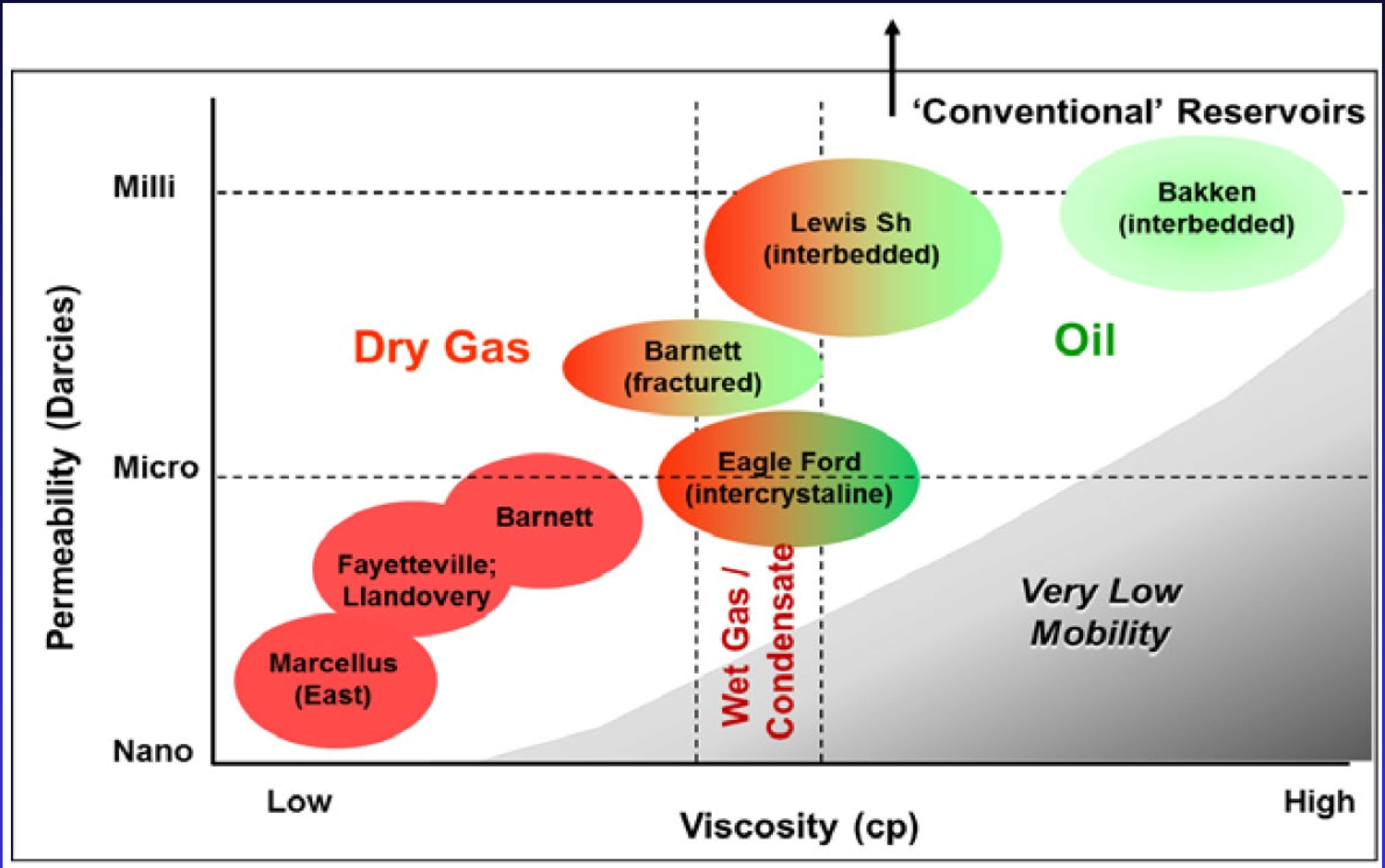
- ☞ Essential components of effective reservoirs
- ☞ **Differences between conventional and unconventional reservoirs**
- ☞ Where, when, and why unconventional reservoirs occur
- ☞ Research opportunities

Conventional vs Unconventional





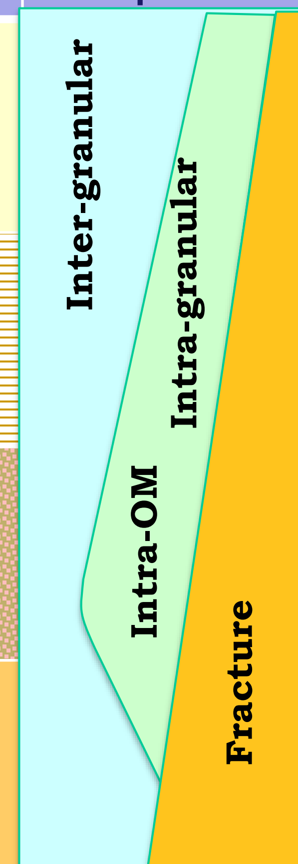
Spectrum of Effective Reservoirs ∝ Rate



Bohacs et al., 2013

Spectrum of Effective Reservoirs ∝ Geology

System Type	Characteristics	Secondary migration	Poro-Perm Components	Examples
Conventional Tight **Reservoir ≠ Source**	Tight SS, siltstone, carbonate interbedded w/ lean, immature source rock	Significant		*Spraberry* *Lewis Shale* *Mancos* *Mesa Verde*
Hybrid/Interbedded **Reservoir ≈ Source**	Tight SS, siltstone, carbonate interbedded w/ rich, mature source rock	Moderate		***Bakken*** ***Bone Springs*** ***2nd White Specs***
Porous Shale **Reservoir = Source**	Source rocks with significant inter/intra-grain porosity at oil to gas/condensate level of maturity	Minimal		***Eagle Ford*** *Haynesville* *Wolfcamp* *Woodford*
Fractured Shale **Reservoir = Source**	Mature source rocks with significant fracture porosity	Minimal		***Monterey*** ***Woodford*** *Mowry* *Barnett* *Marcellus*



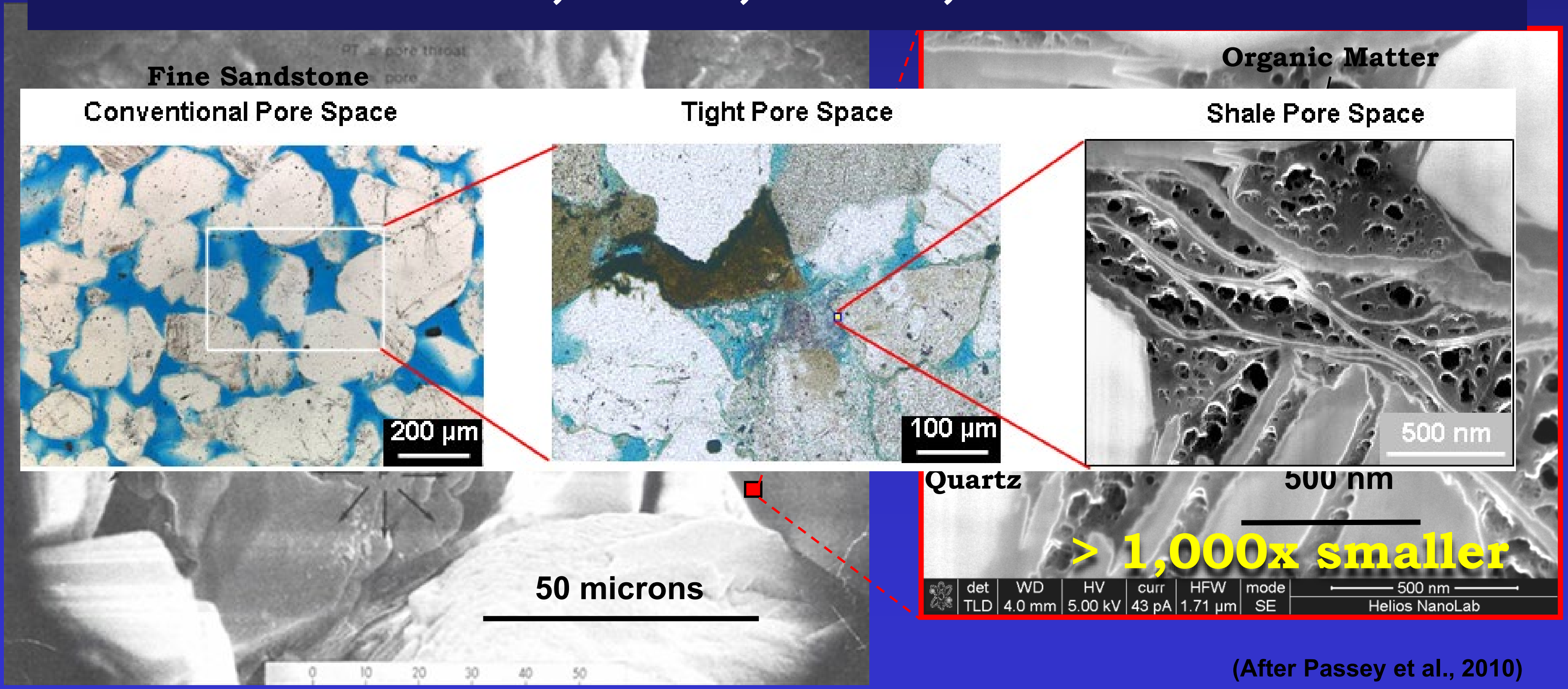
Note that all plays have some component of inter/intra-granular porosity as well as some natural fracture permeability – they are named for the dominant or distinctive component

Bohacs et al., 2013

Conventional vs Unconventional: Storage

Porosity = function of:

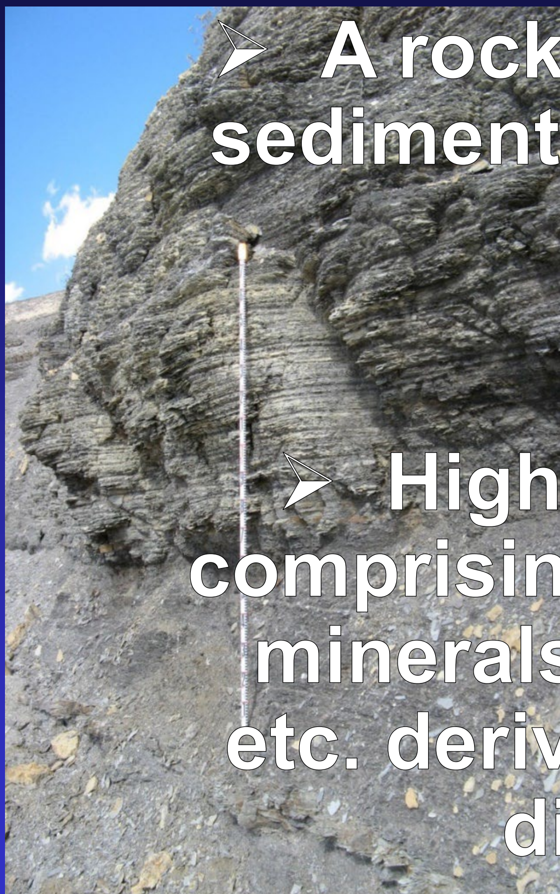
- **Grain Size**
- **Composition: mineral, organic matter**
- **Cementation, Grain packing**
- **4 scales: macro, meso, micro, nano**

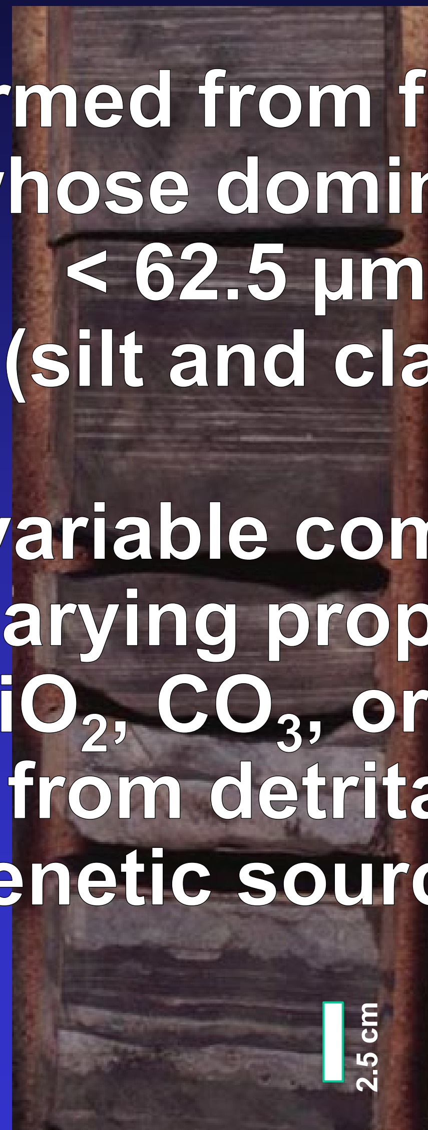


(After Passey et al., 2010)

What Is a Mudstone ?

Ms Primer p. 3-17





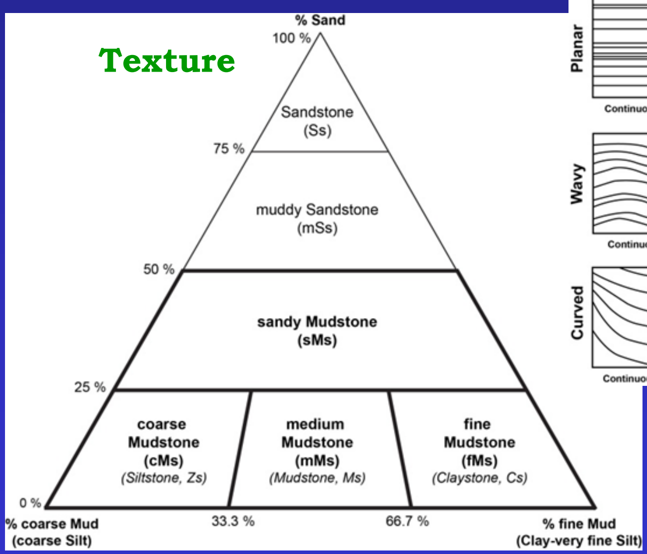
- A rock formed from fine-grained sediments whose dominant grain size < 62.5 µm (silt and clay)
- Highly variable composition, comprising varying proportions of clay minerals, SiO_2, CO_3, organic matter, etc. derived from detrital, biogenic, & diagenetic sources.

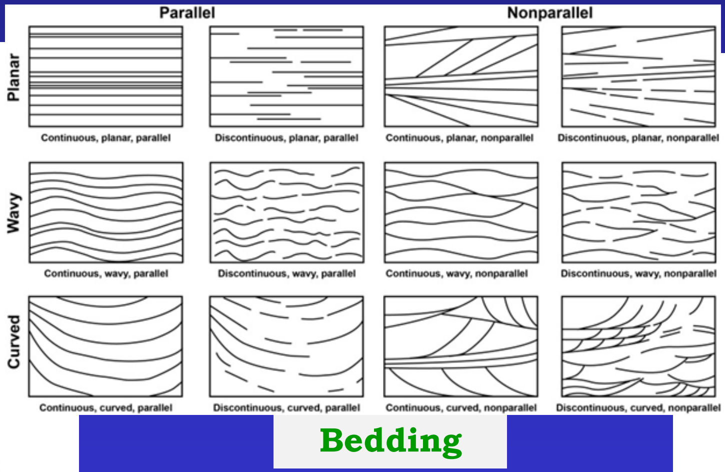
Mudstones: Nomenclature Guidelines

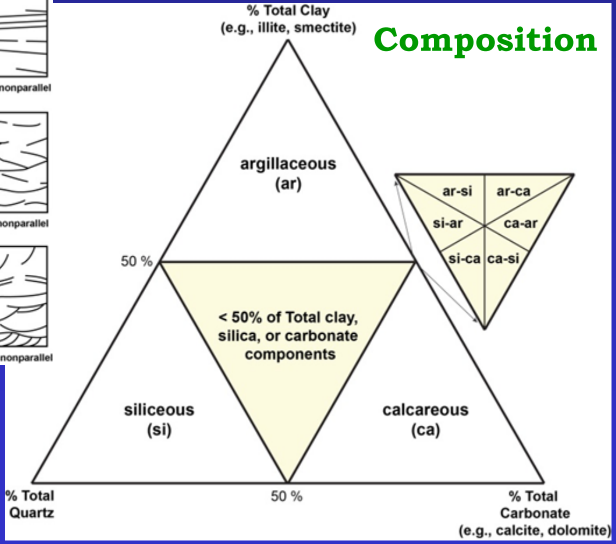
Shale (*sensu stricto*) = field term for fissile fine-grained rocks (FGRs)

Mudstone = class name for FGRs *(analogous to sandstone, limestone)*

FGR name = **texture (root)** + **bedding** + **composition**
+ additional modifiers (*grain origin, degree of bioturbation, macro, micro, and trace fossils, diagenetic components, fracability, color, etc)*







After Lazar et al., 2010, 2013, 2015

Ms Primer p. 3-17

Mudstones: Texture (grain-size)

Grain-size: sand- silt- clay-size:

Grain-size boundaries…

2000 µm

Sand

62.5 µm

coarse Mud *(coarse Silt)*

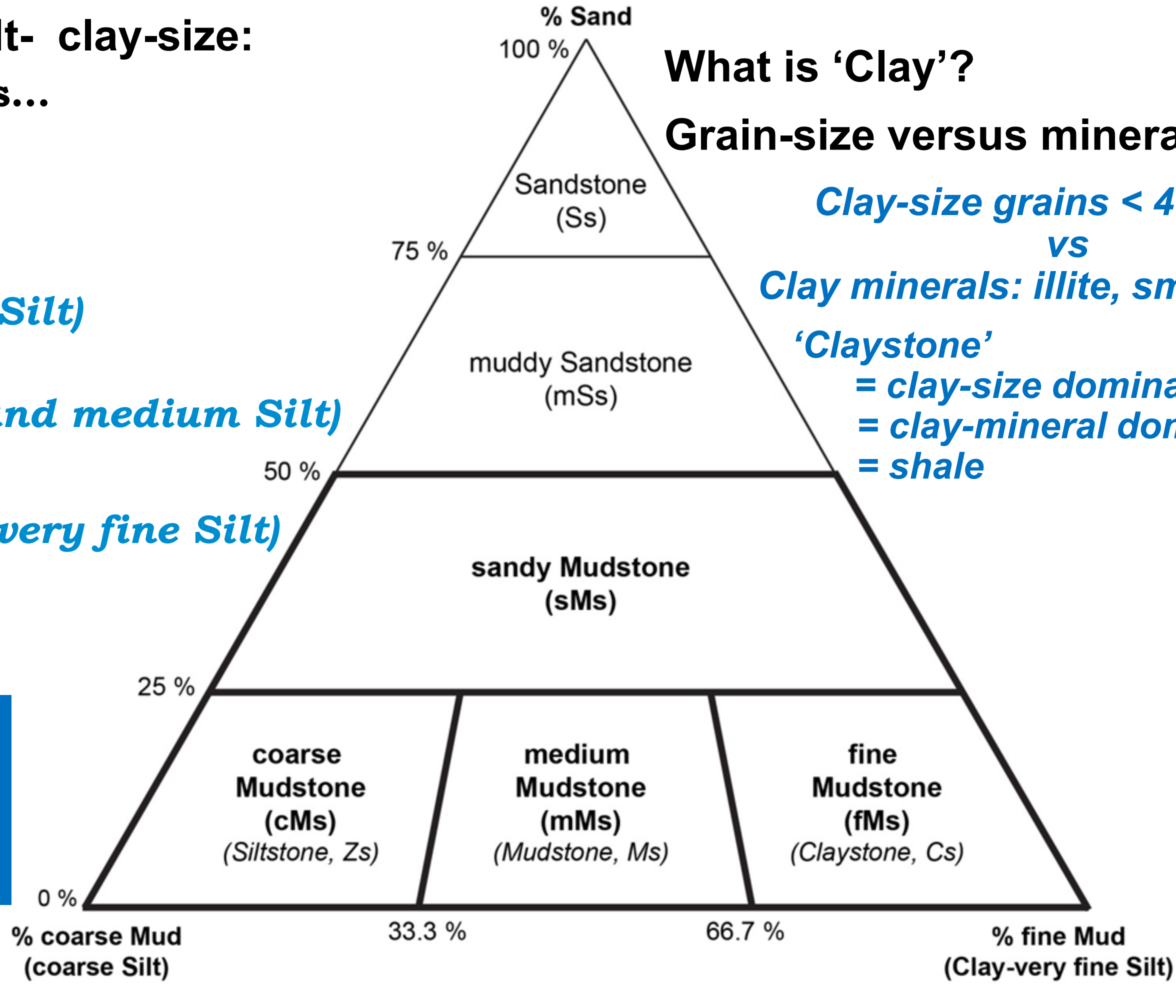
32 µm

medium Mud *(fine and medium Silt)*

8 µm

fine Mud *(Clay and very fine Silt)*

Dunham, 1962:
- Mud: < 20 µm
- Mudstone: > 90% grains < 20 µm



What is 'Clay'?

Grain-size versus mineralogy:

Clay-size grains < 4 to 2 µm
vs
Clay minerals: illite, smectite, etc.

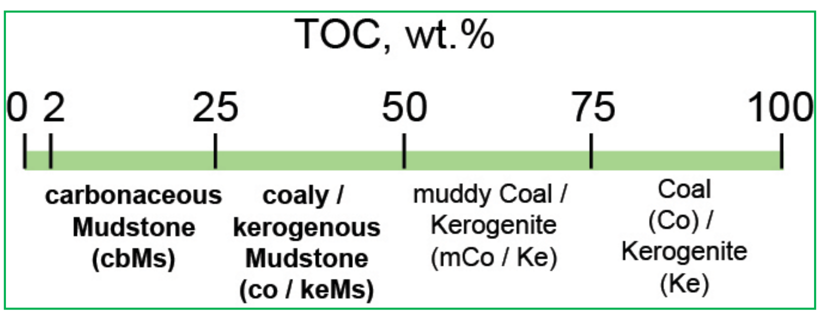
'Claystone'
= clay-size dominated FGR
= clay-mineral dominated FGR
= shale

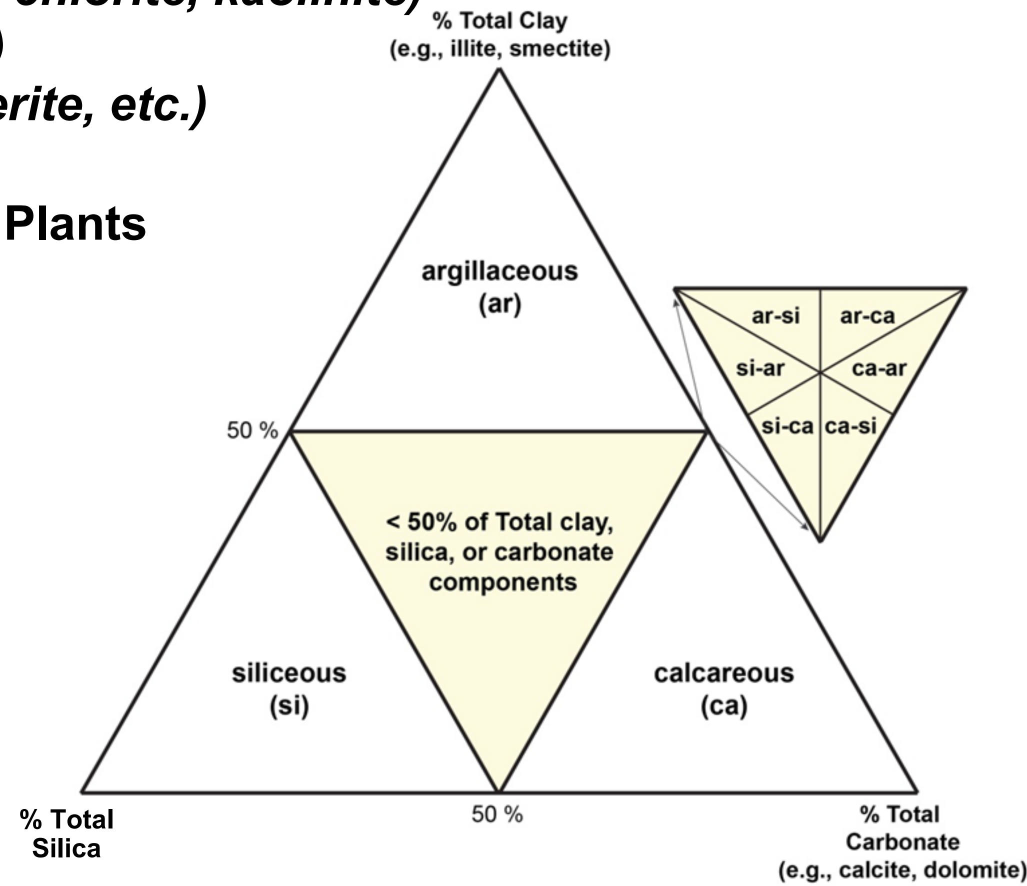
After Lazar et al., 2010, 2013, 2015

Mudstones: Composition

4 Major components:

- Clay minerals *(illite, I/S, smectite, chlorite, kaolinite)*
- Silica *(quartz, opal, feldspar, etc.)*
- Carbonate *(calcite, dolomite, siderite, etc.)*
- Organic Matter:
  - Algae, Bacteria, Archaea, Land Plants *(cuticle, wood, charcoal)*





After Lazar et al., 2010, 2013, 2015

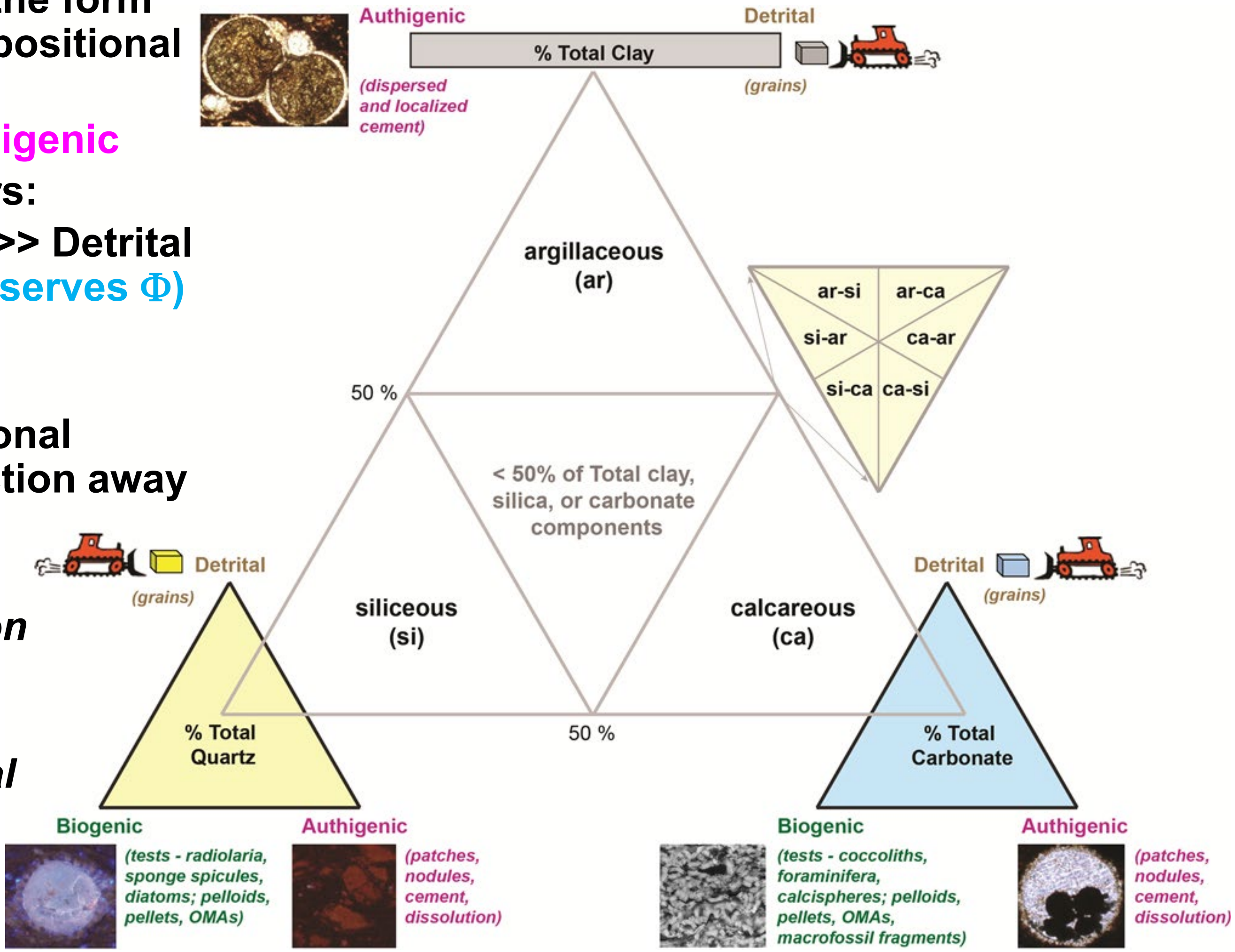
Ms Primer p. 14

Mudstones: Composition, Origin

- Essential to determine the form and origin of each compositional component:
  detrital / biogenic / authigenic
- ➢ Effective Ms reservoirs:
- ❖ Biogenic, Authigenic >> Detrital SiO_2 (biog. reacts, preserves Φ)
- ❖ Biogenic, Detrital > Authigenic CO_3
- ➢ insights into depositional conditions and prediction away from sample control.

**Thin section examination is particularly useful in distinguishing the composition of individual particles and cement*

After Lazar et al., 2013, 2015



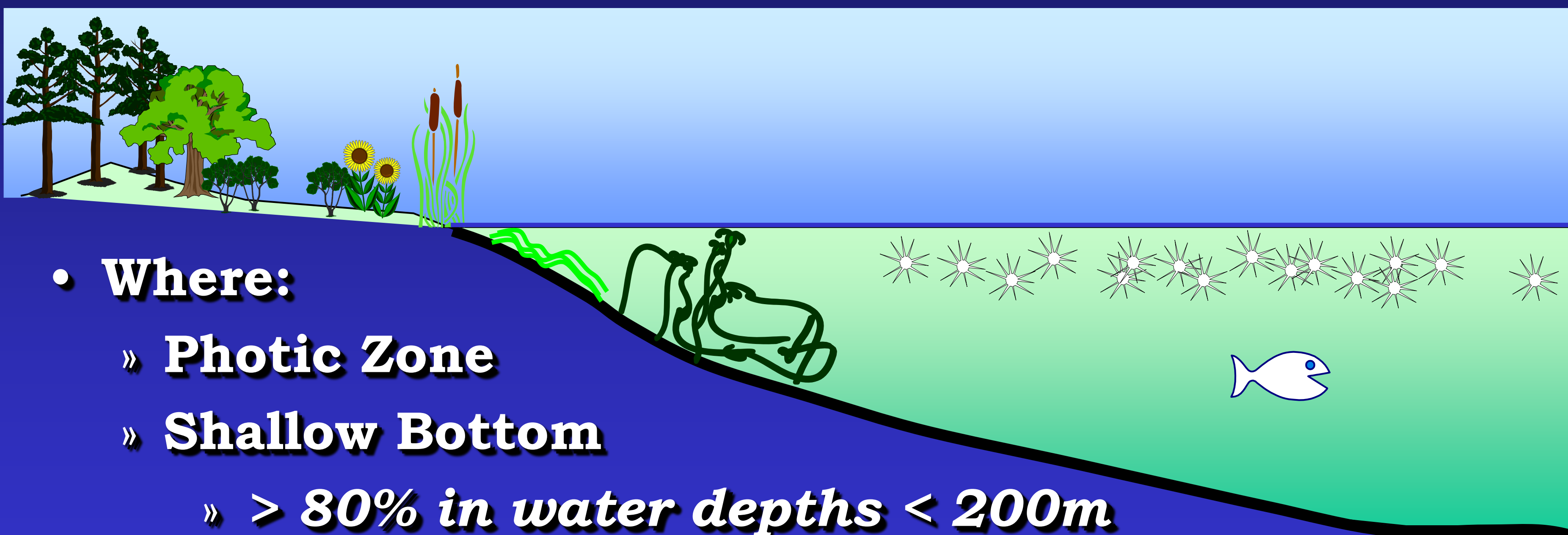
Ms Primer p. 15

Organic Matter Origins

☞ **What:**

- » **Algae**
- » **Cyanobacteria**
- » **Vascular plants**

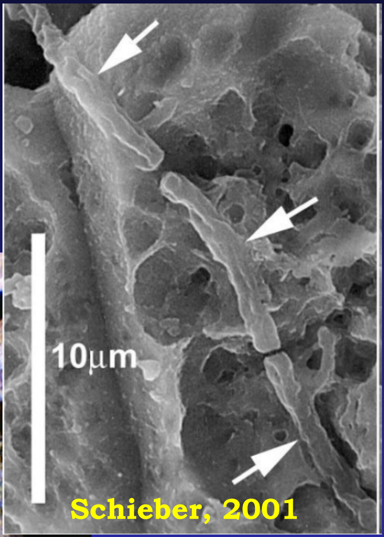
☞ **So What? More H = more HC, more OM Φ**



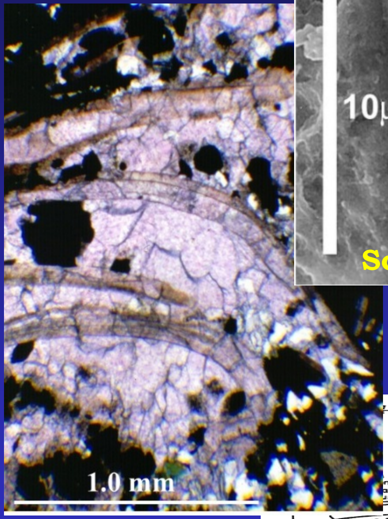
- **Where:**
  - » **Photic Zone**
  - » **Shallow Bottom**
    - » ***> 80% in water depths < 200m***
  - » **Land**
    - » **Lakes *(oil shale)*; Swamps *(coal)***

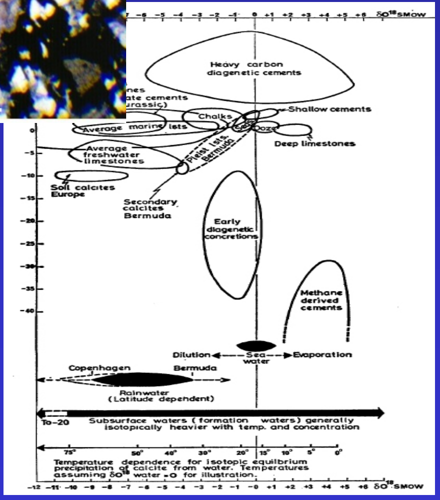
Early Diagenesis in Mud: Key Points

- Muds are microbial incubators
- Microbial respiration:
  - » driven by:
    - **reductants** (mainly organic carbon) *and*
    - **oxidants** (either derived by diffusion or buried with the sediment)
  - » drives many diagenetic reactions in mudstones:
    - calcite, dolomite, siderite and pyrite.
- Early cement (< 10 m burial) can preserve or occlude poro-perm and generally increase ‘fracability’



Schieber, 2001



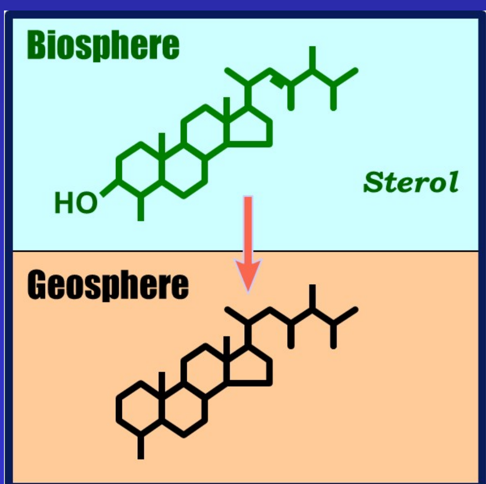


Hudson, 1977

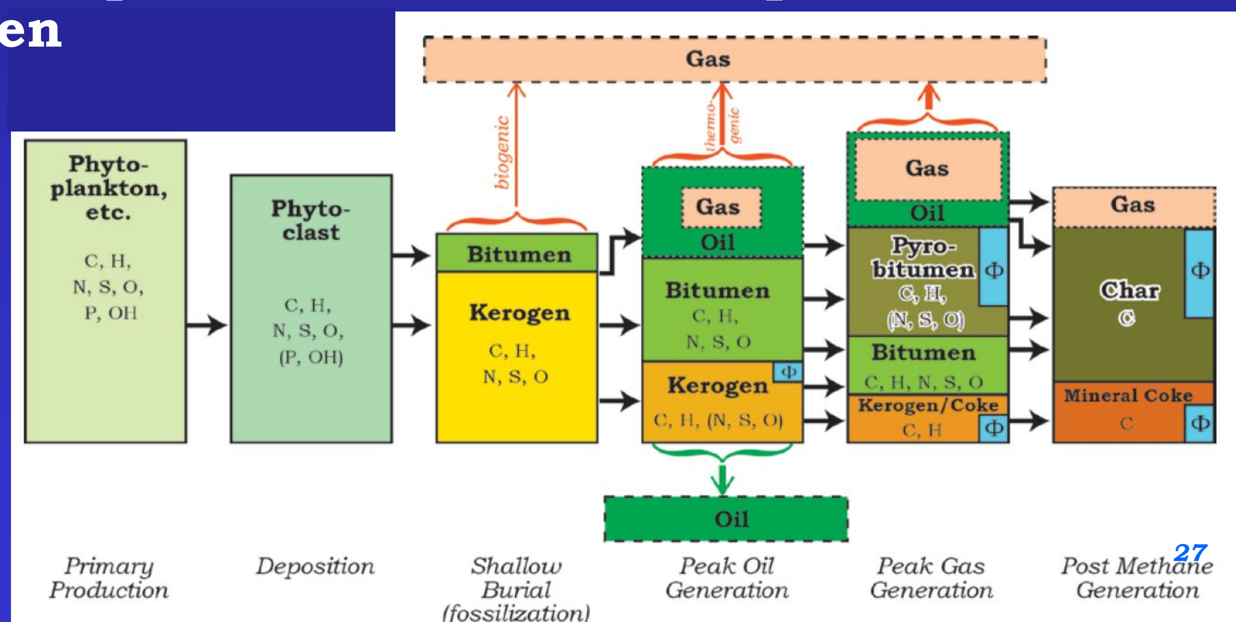
Ms Primer p. 180-181

Later Diagenesis: HC Generation, Porosity Evolution

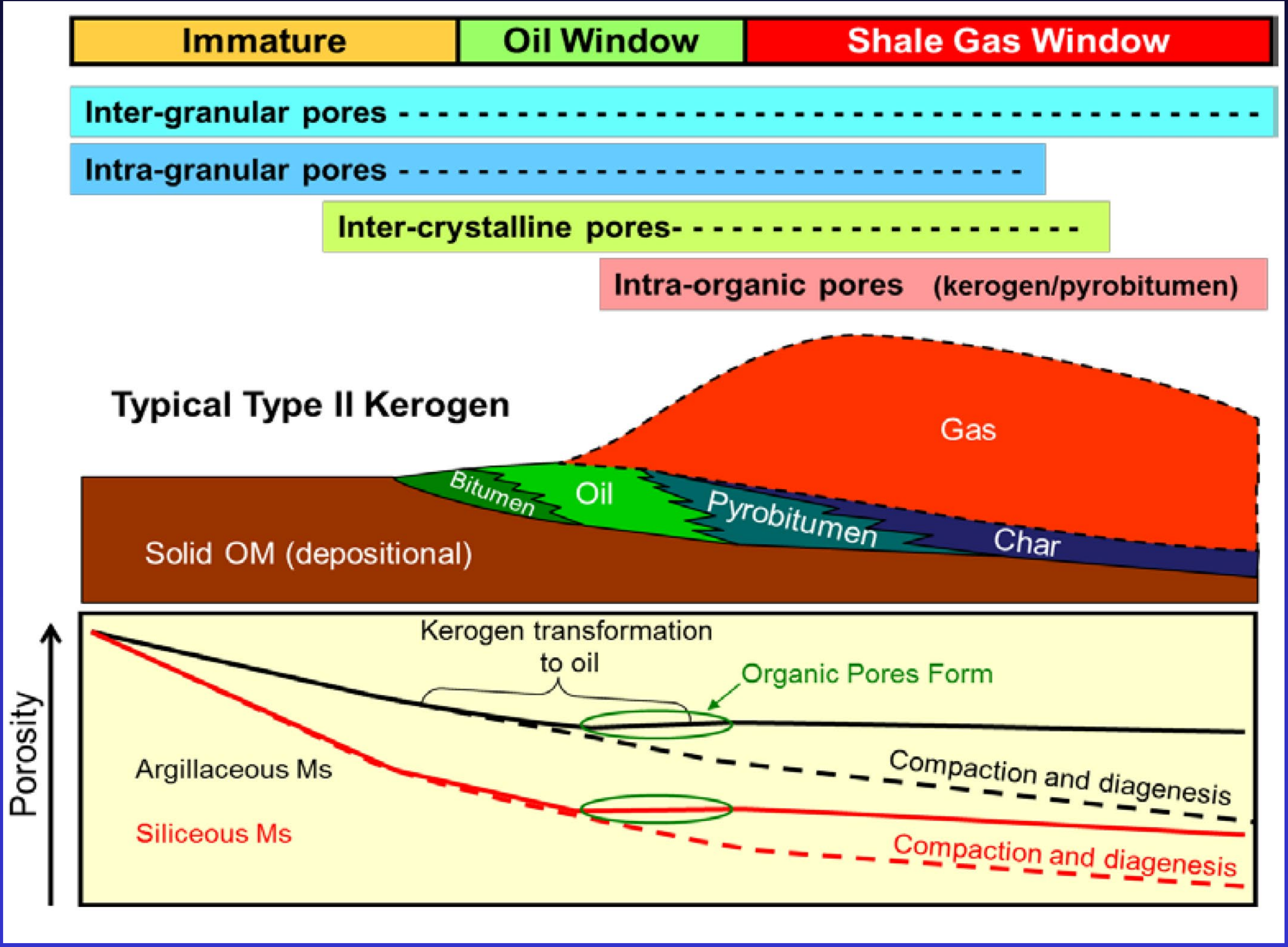
- Organic matter consolidates into Kerogen
- Kerogen cooks to generate HCs
- Generated HCs expelled to inter-granular pores
  - after saturating kerogen with HC
  - Expelled HCs leave pores behind in kerogen
- HCs saturate a path out of the source bed and migrate away
  - > 5% of HCs retained in pores
- Retained HCs in pores and kerogen crack to gas
  - Gas expelled
  - Pores and some gas left behind in spent HCs



Bohacs et al., 2013



Diagenesis, HC Generation, Porosity Evolution



Bohacs et al., 2013

So What ? Organic-Matter Porosity is Key

OM has outsized influence

TOC volume% = ~2x TOC wt%

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

5 wt% TOC

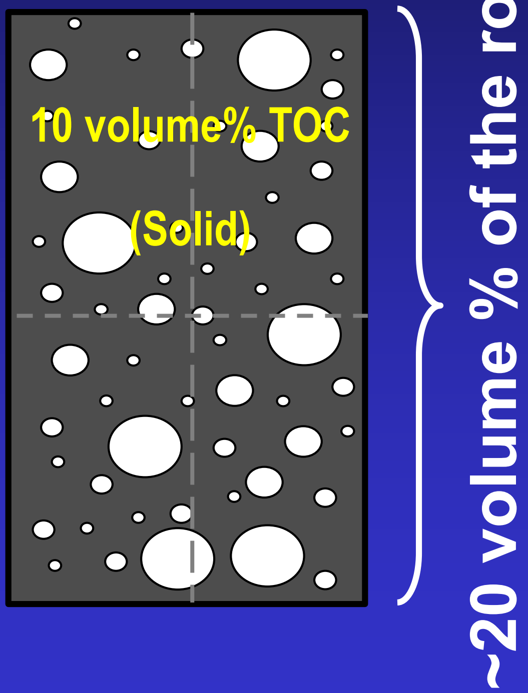
(Solid)

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

10 volume% TOC

(Solid)

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

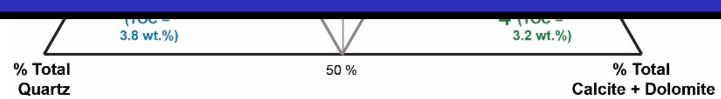


(after Passey et al., 2010)

A "Typical" Ms Reservoir Composition ?

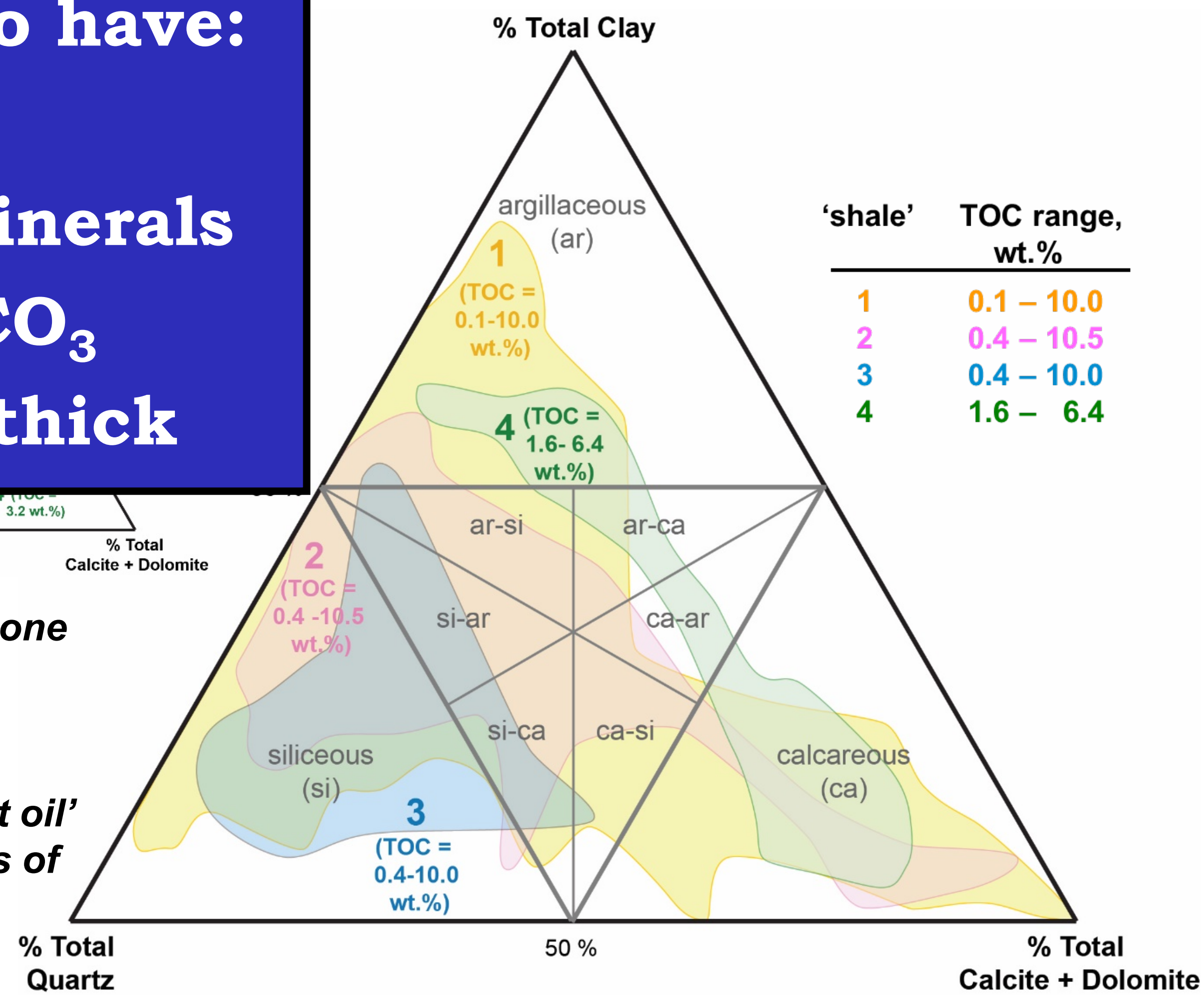
☞ **They DO tend to have:**

- » > 2% TOC
- » < 50 % Clay minerals
- » > 50% $SiO_2 + CO_3$
- » 10s of meters thick



- *Comparison of average values alone doesn't capture the observed compositional variability*

- *The highlighted 4 'shale-gas/tight oil' examples have significant ranges of composition with considerable overlap*



Lazar et al., 2013, 2015

Pop Quiz!

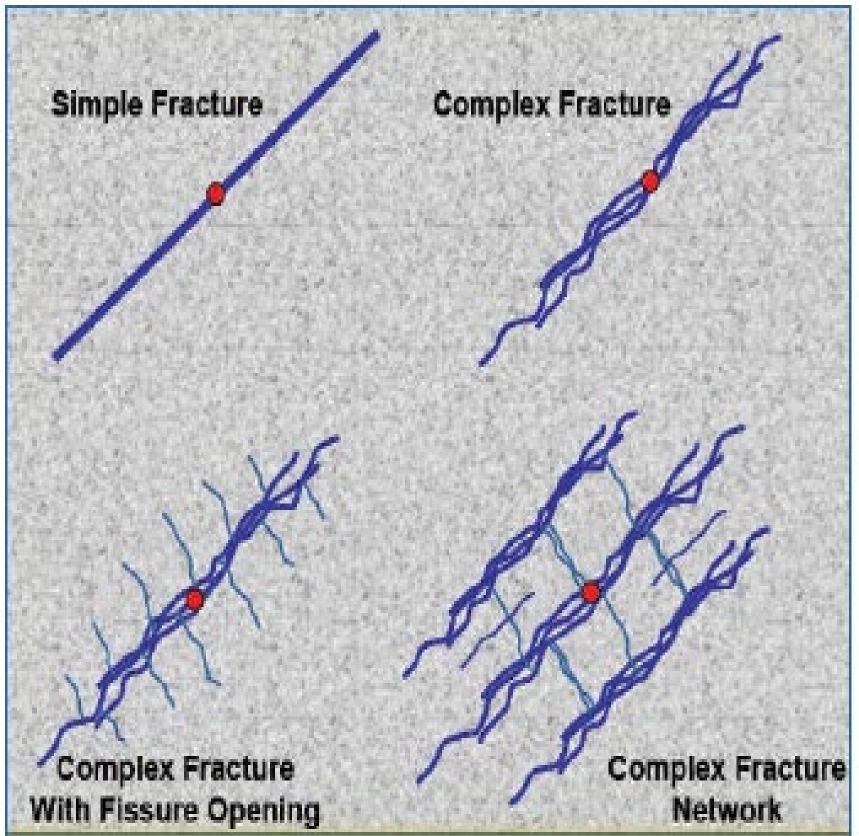
Effective reservoir?

	likely	*maybe*	*unlikely*
a) 72% SiO_2, 12% Clay, 10% TOC	☐	☐	☐
b) 55% Clay, 42% CO_3, 1.5% TOC	☐	☐	☐
c) 35% TOC, 58% SiO_2, 4% Clay	☐	☐	☐

Conventional vs Unconventional: Access

Access = existing and induced permeability

Unconventional:



Mayerhofer, et el, 2011

'Fracability':

- Rock composition, fabric, (cementation, bedding)
- Fluid pressure, temperatur
- Natural fractures
- Natural stress field

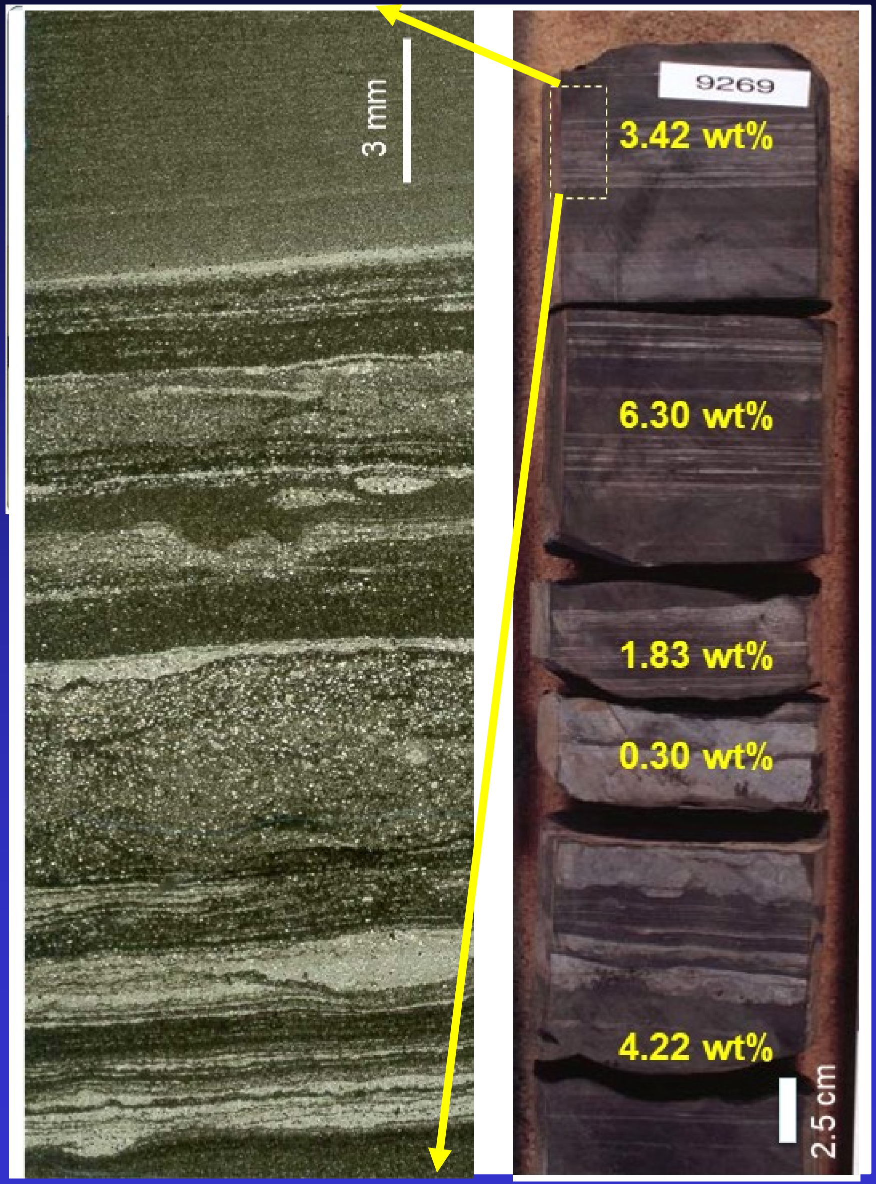
Conventional vs Unconventional: Scales

Conventional:

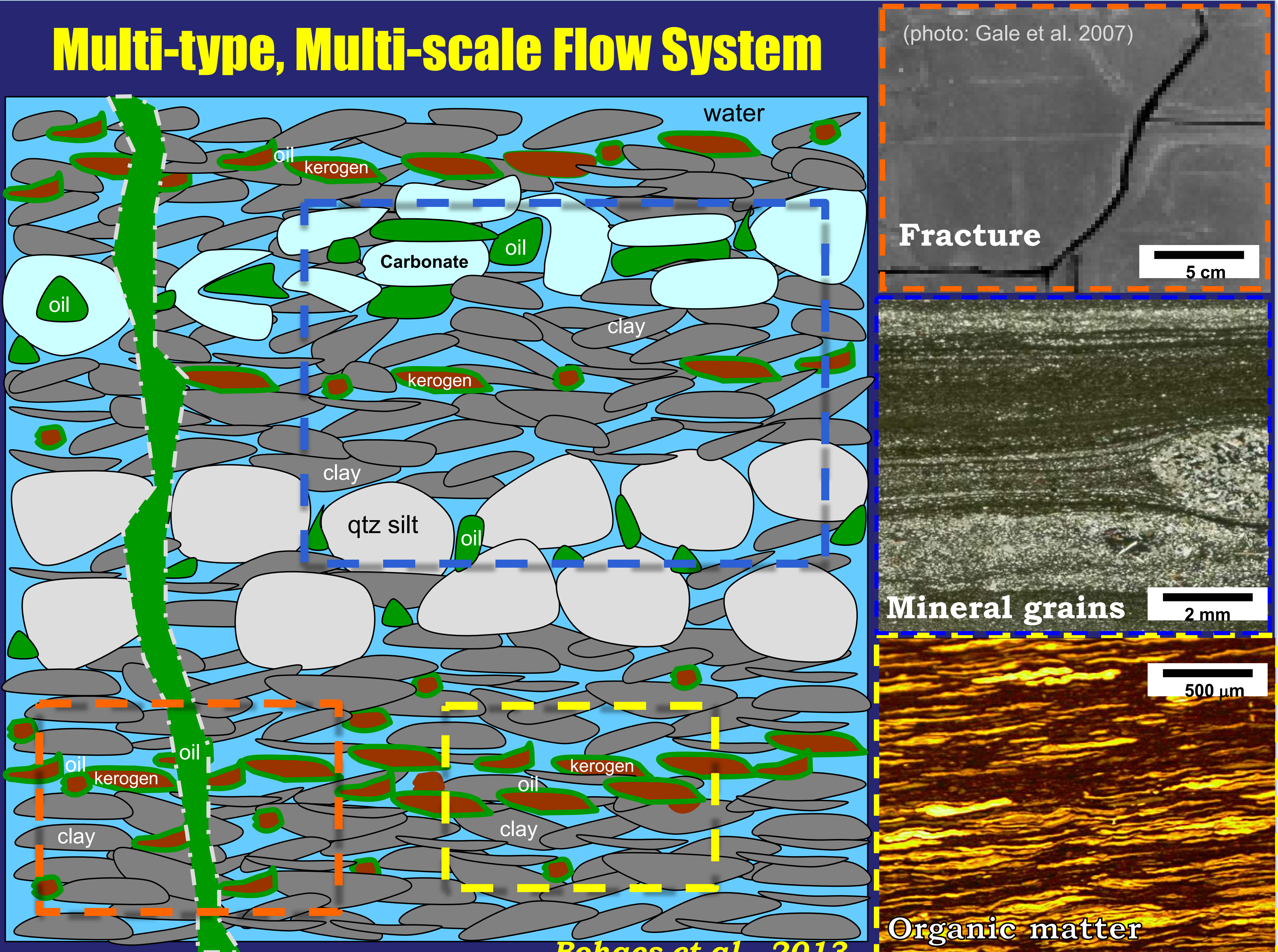
- Concentrated resource
- Tens of km^2 area
- Vertical variation at ~m scale

Unconventional:

- Diffuse resource
- Thousands of km^2 area
- Vertical variation at ~mm scale or less…



Multi-type, Multi-scale Flow System



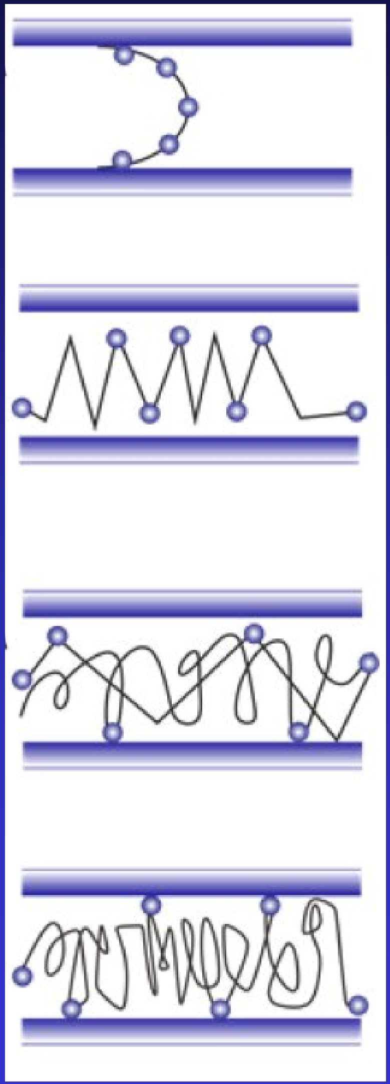
Bohacs et al., 2013

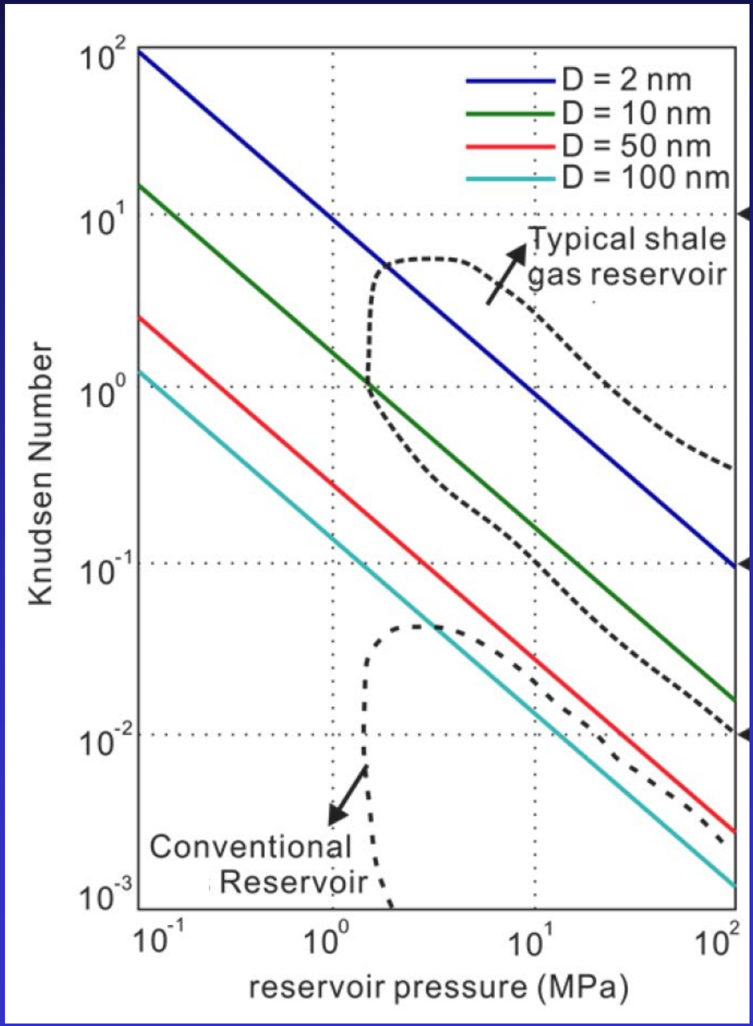
Conv vs Unconv: Flow Types, Rates

Flow type *Pore size*

- ☞ **Continuum ('D'Arcy')**
- ☞ **Slip**
- ☞ **Transitional**
- ☞ **Knudsen flow**

^ *diffusion-like* v



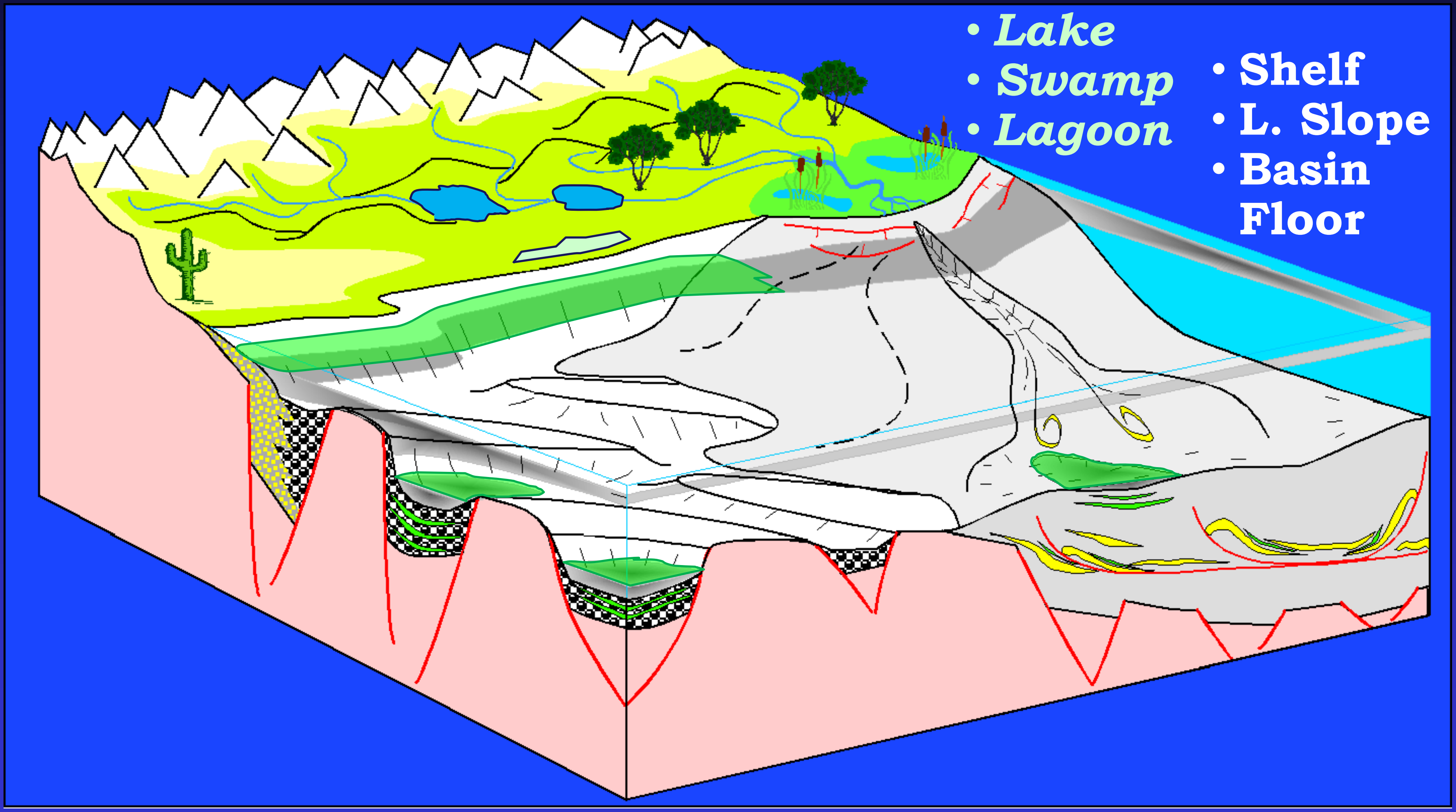


after Feng et al., 2019

Outline

- ☞ Essential components of effective reservoirs
- ☞ Differences between conventional and unconventional reservoirs
- ☞ **Where, when, and why unconventional reservoirs occur**
- ☞ Research opportunities

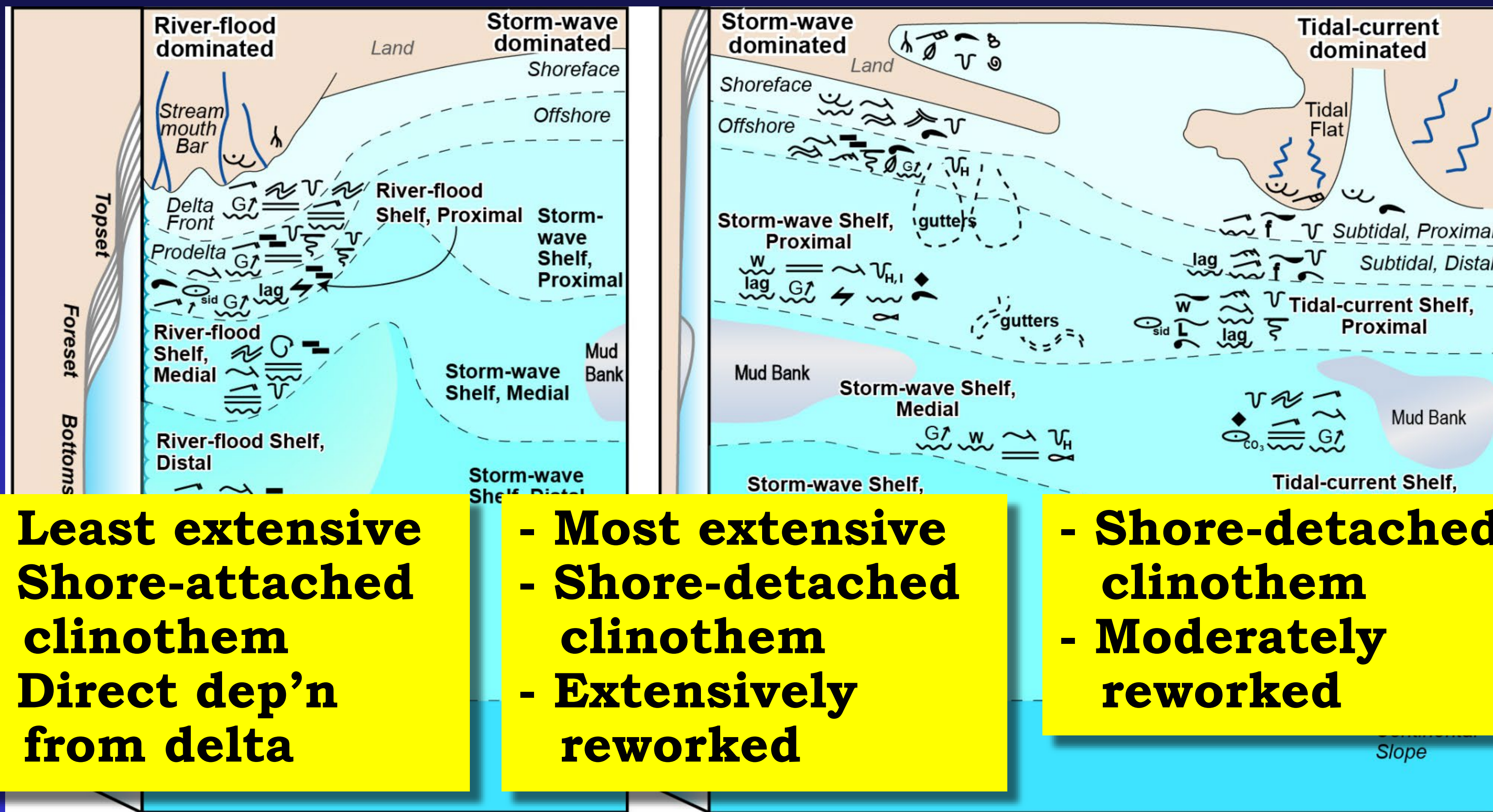
Source-Rock Settings



Bohacs et al., 2014

Shelfal Parasequence Types

→ Different map patterns…



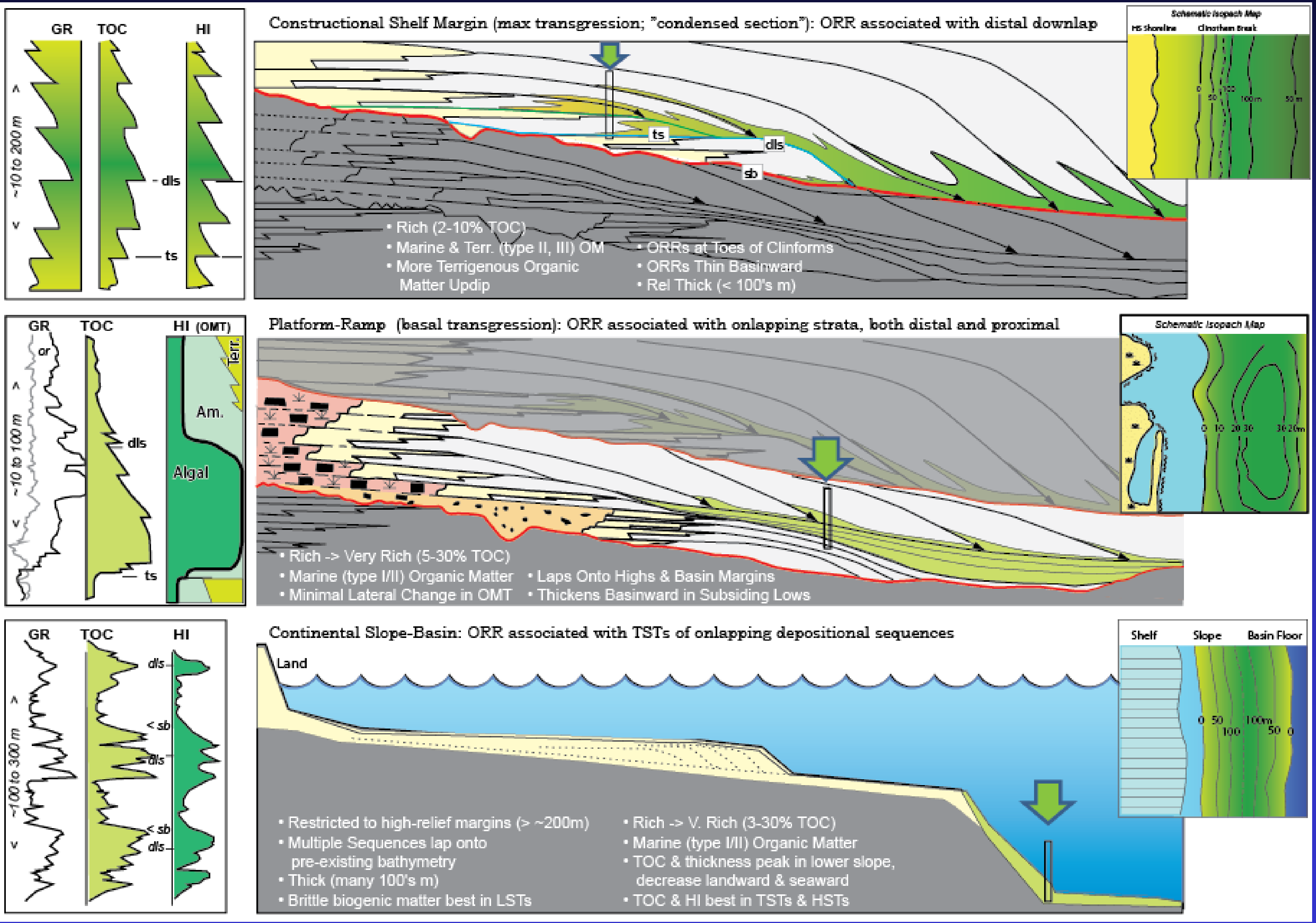
- Least extensive
- Shore-attached clinothem
- Direct dep'n from delta

- Most extensive
- Shore-detached clinothem
- Extensively reworked

- Shore-detached clinothem
- Moderately reworked

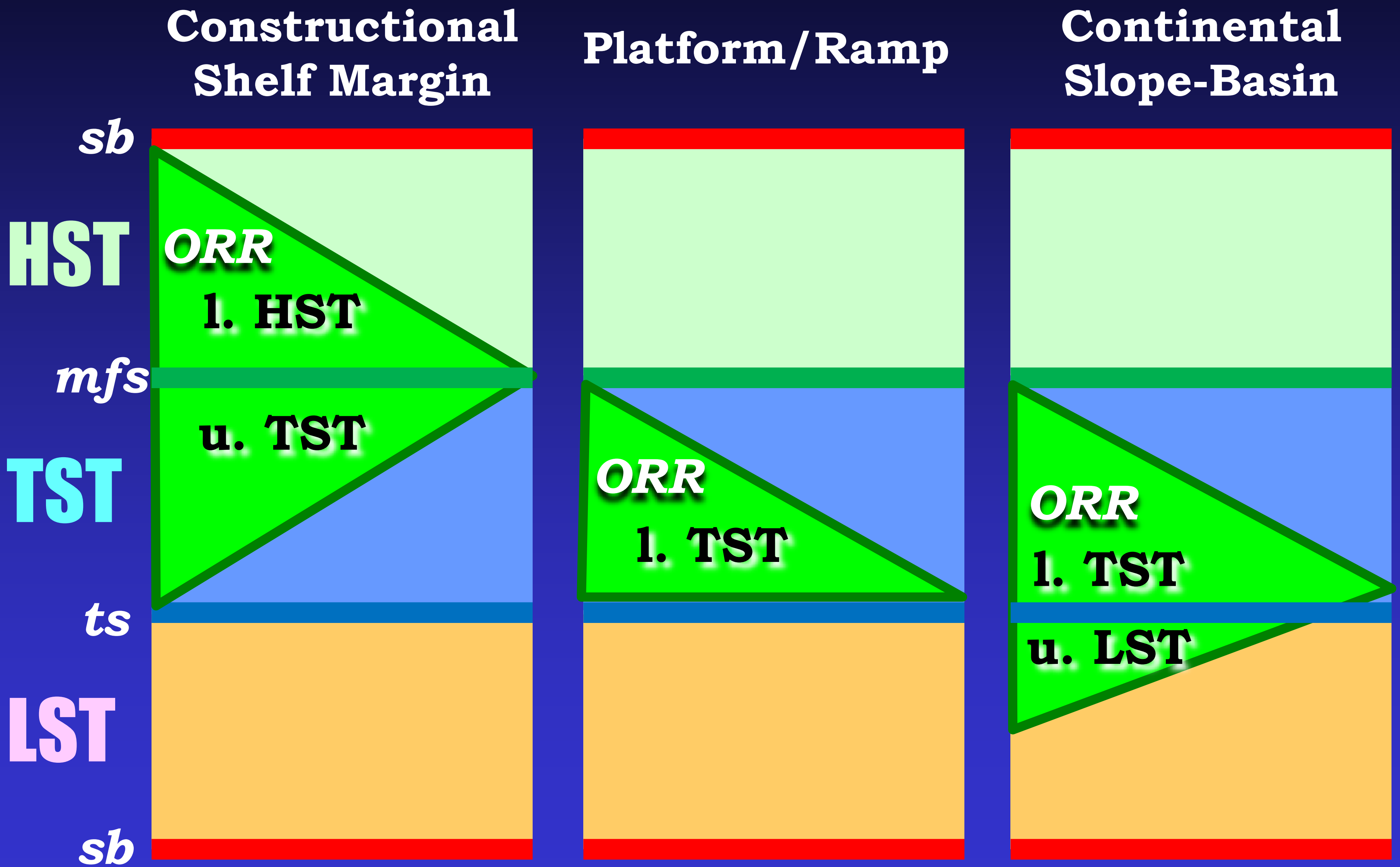
Bohacs et al., 2014

Marine Source Rock Settings: Characteristic Patterns at Dep'l Sequence Scale



(Bohacs, 1998; Bohacs et al., 2012)

Different Settings = Different ORR Distribution



Pop Quiz !

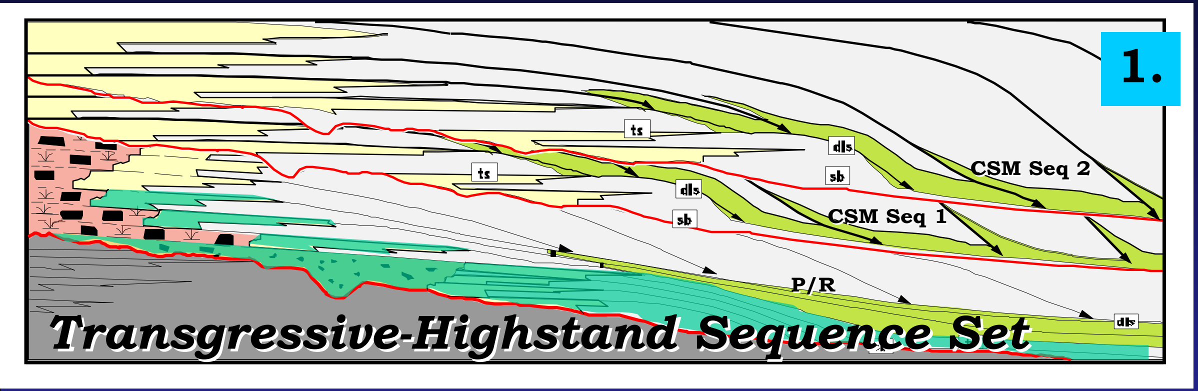
T	F	
☐	☒	All Clastic Reservoirs occur in LST?
☐	☒	All Carbonate Reservoirs occur in HST?
☐	☒	All Source Rocks occur in TST?

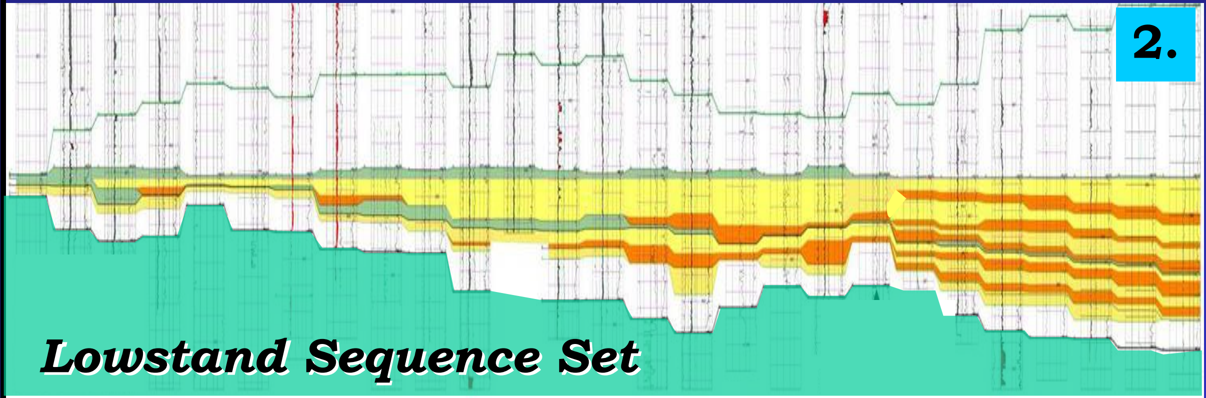
Sequence Stratigraphy is a good place to START your HC system analysis…

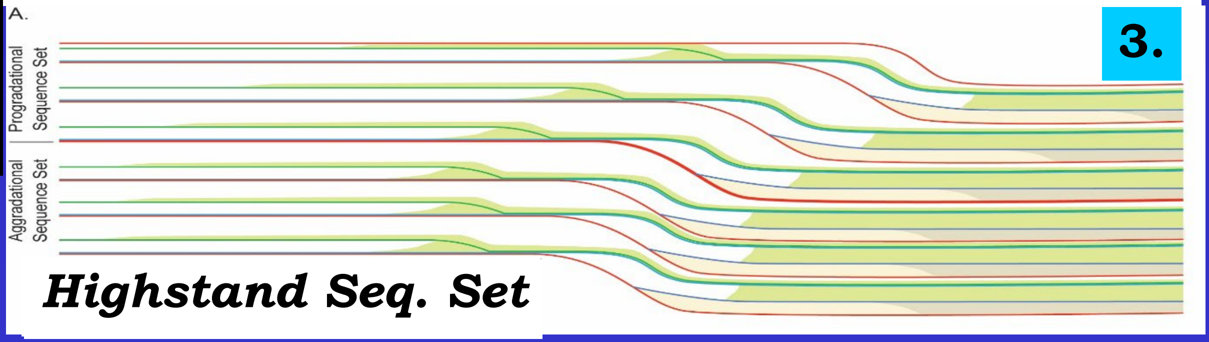
'Shale' Reservoir Familes: Repeated Patterns at Sequence-Set Scale

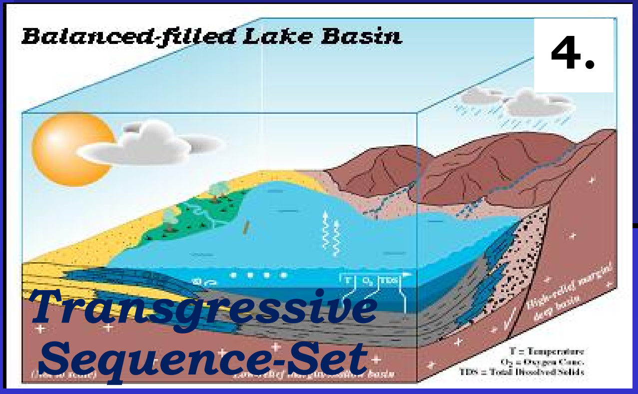
≃ Play-scale Distribution of Biogenic Matter

1. Marine, Basal Platform-Ramp overlain by Distal CSMs sequences
 (e.g., Horn River, Haynes-ville, Marcellus, etc.)
2. Marine, Distally onlapping stacked Lowstands
 (e.g., Barnett, Floyd/Neal)
3. Marine, Highstand Seq. Set -- *TST-- lower HST*
 (e.g Niobrara, Spraberry, etc)
4. Lacustrine, Balanced-Filled (± Overfilled) Sequence Set *(e.g., Green River Fm, Horton Bluff Fm, LSB Wealden)*





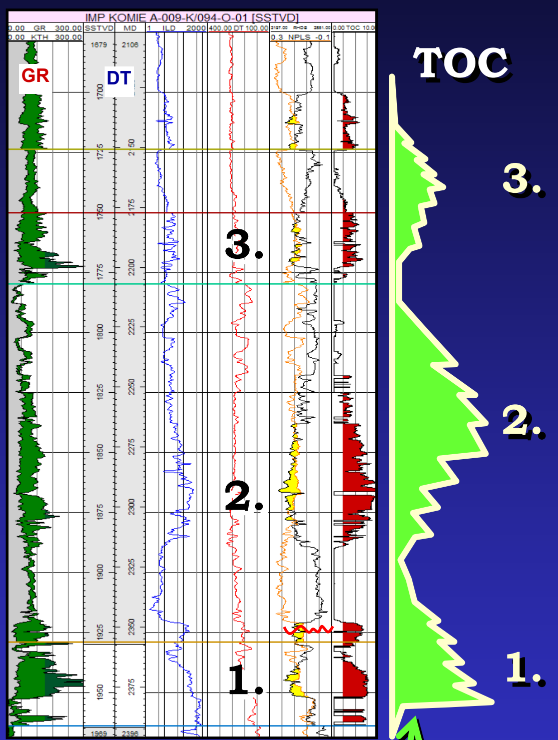




(Bohacs, 1998; Bohacs et al., 2012)

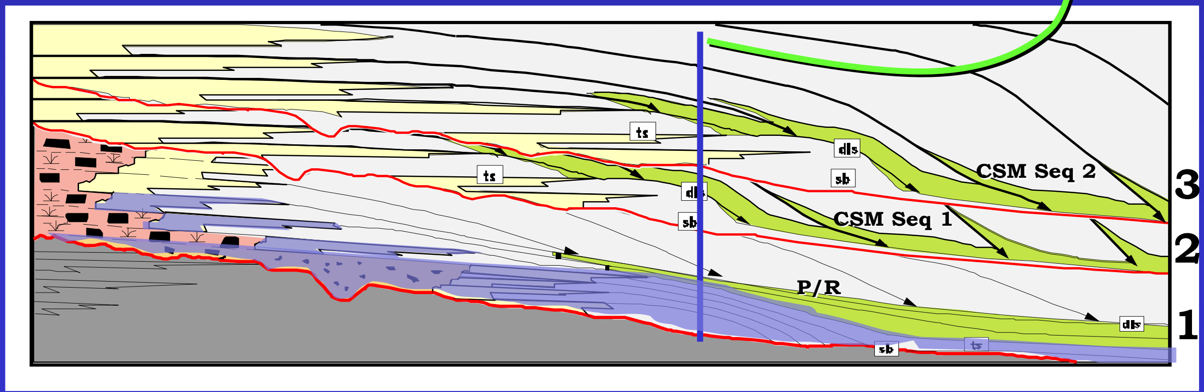
Family 1: Transgressive to Highstand Seq. Set

- ✓ **Basal carbonate platform or ramp, *overlain by a* Platform-Ramp TOC-rich sequence, *overlain by* several Constructional Shelf Margin TOC-rich Sequences**
- ✓ **At seismic scale, characterized by Several levels of Downlap over basal Onlapping Mudstone reservoir strata**
- ✓ **Transgressive to Highstand Sequence Set *[~3-9 My duration]***



Examples:

Alum, Utica-Pt Pleasant, Marcellus, Horn River, Antrim, Woodford, Fayetteville, Posidonia, Haynesville-Bossier, Eagle Ford, Vaca Muerta

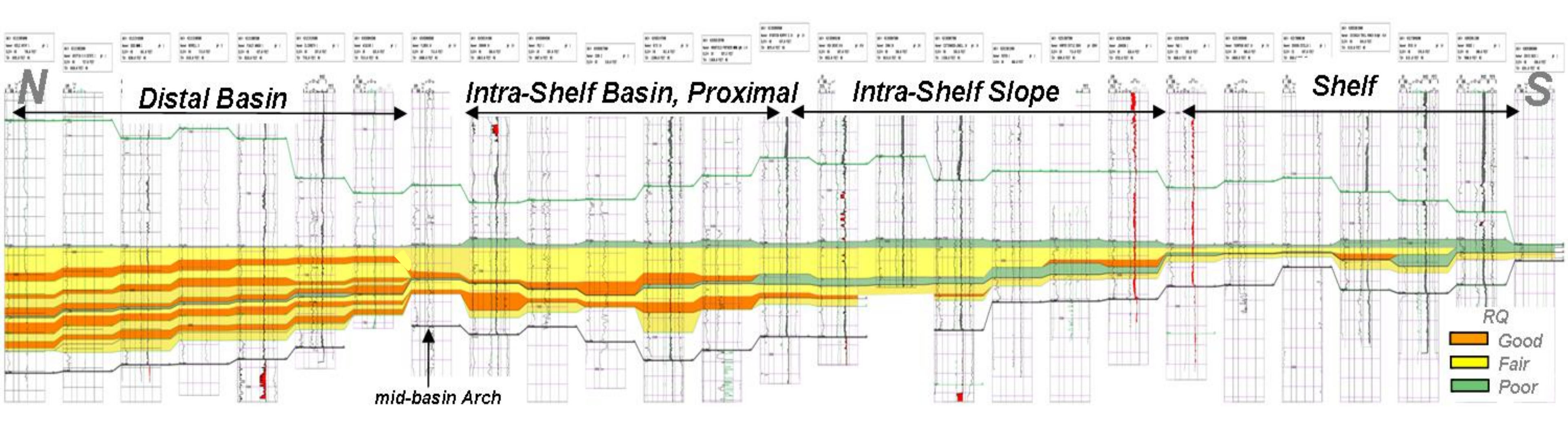


Family 2: stacked Lowstand Systems Tracts

- ✓ **Lowstand Sequence Set** ***[~10-20 My duration]***
- ✓ **Distal Constructional Shelf Margin TOC-rich Sequences, aggradationally stacked**
- ✓ **Several levels of Onlapping Reservoir strata, interspersed w/ downlap**

Examples:

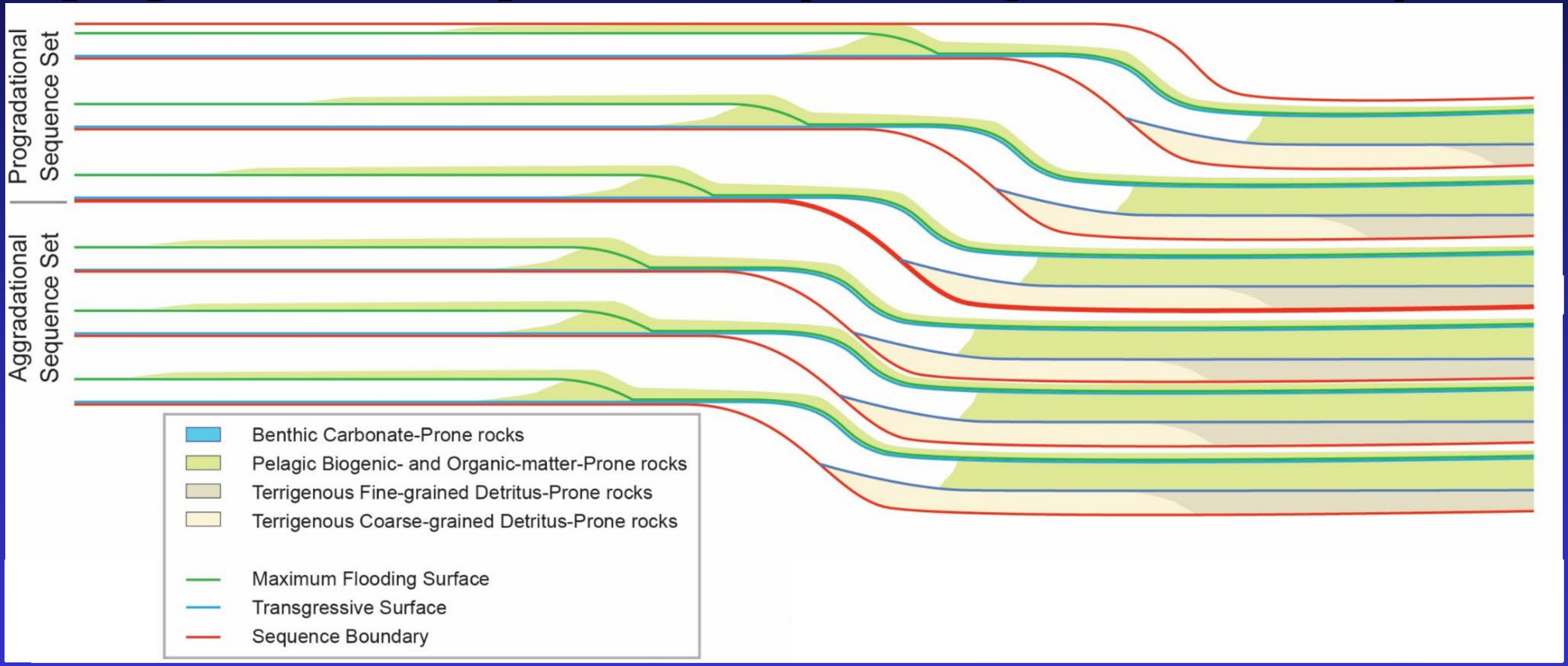
Barnett
Floyd/Neal



Ottmann & Bohacs, 2010

Ms Rsvr Family 3: CSM sequence sets

✓ **Constructional Shelf Margin sequences in aggradational to progradational sequence sets** ***[~1– 6 My total duration]***

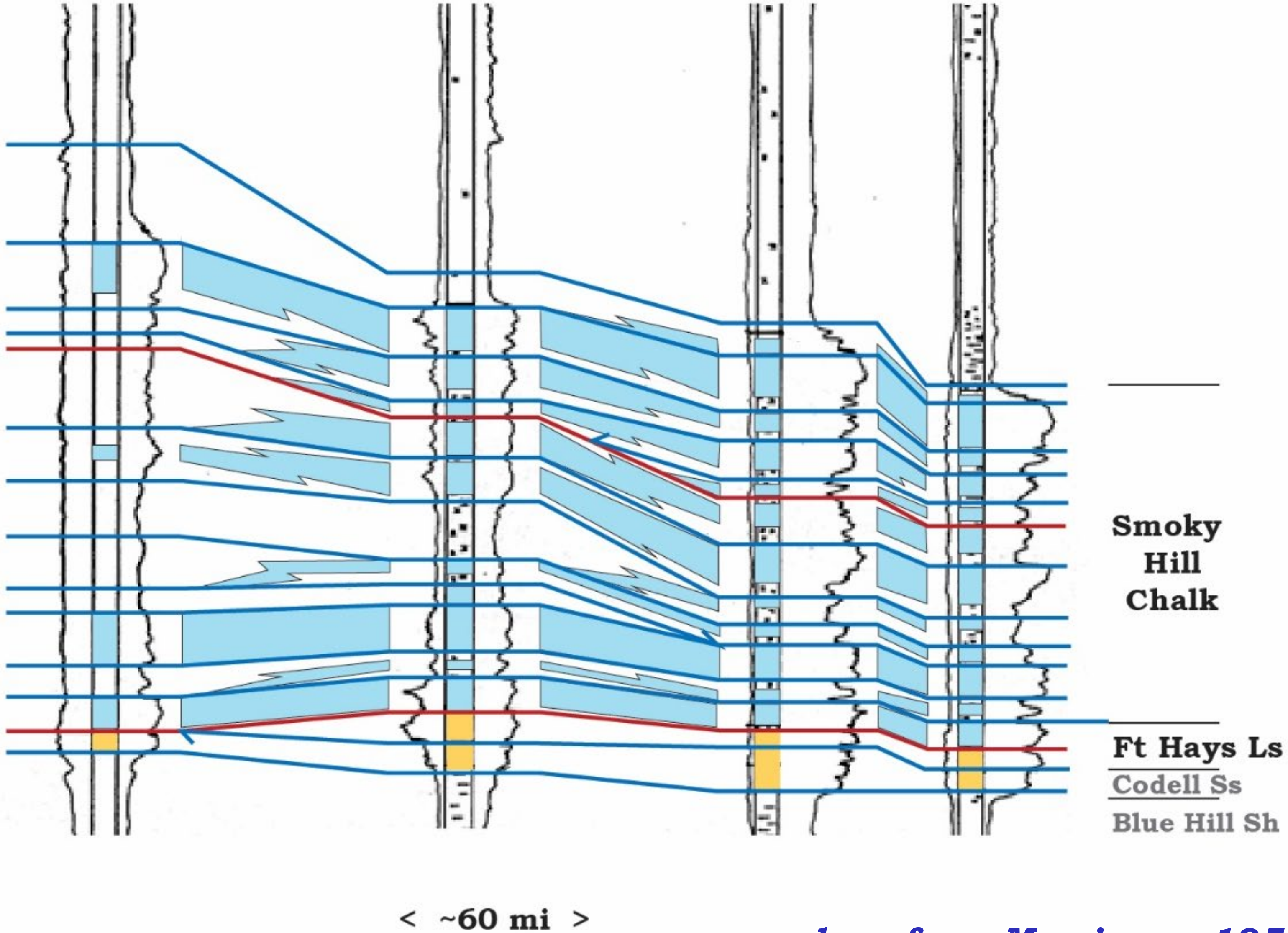


Examples:
Niobrara, Mancos, Lewis (low relief)
Wolfcamp, Spraberry, Bone Spring (high relief)

✓ **1 to 3 sequence sets (Family 1: 2+; Family 2: only 1)**

Bohacs et al., 2012, 2020

Ms Rsvr Family 3: Niobrara Formation



logs from Merriman, 1957

Spraberry Detailed Stratigraphy

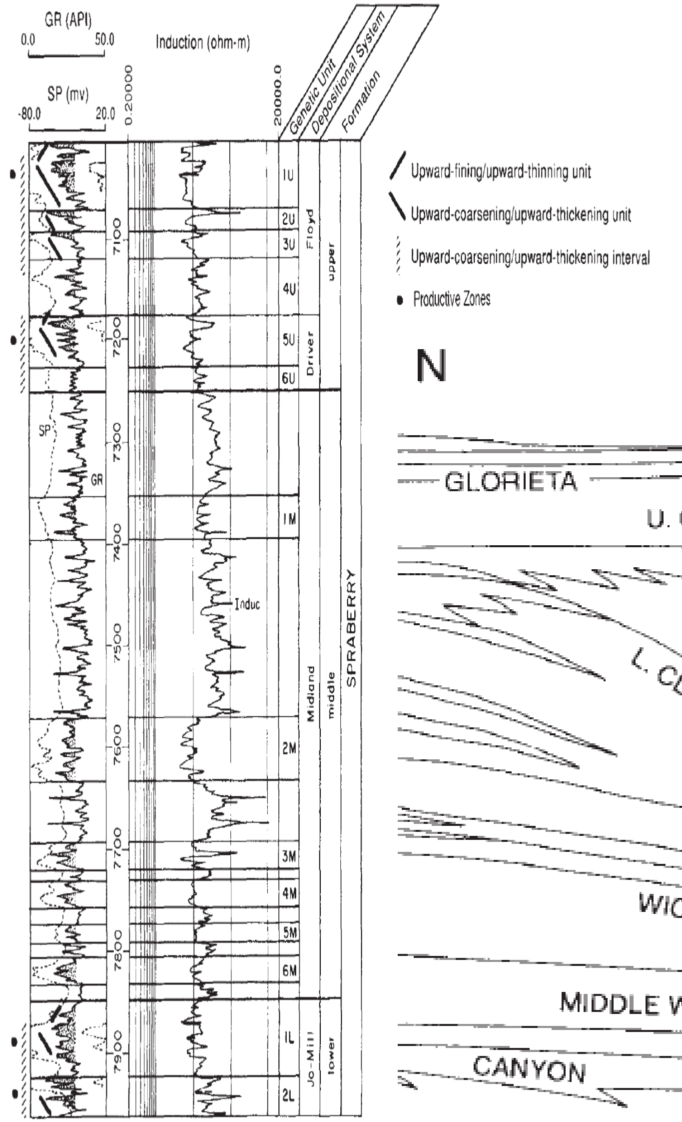
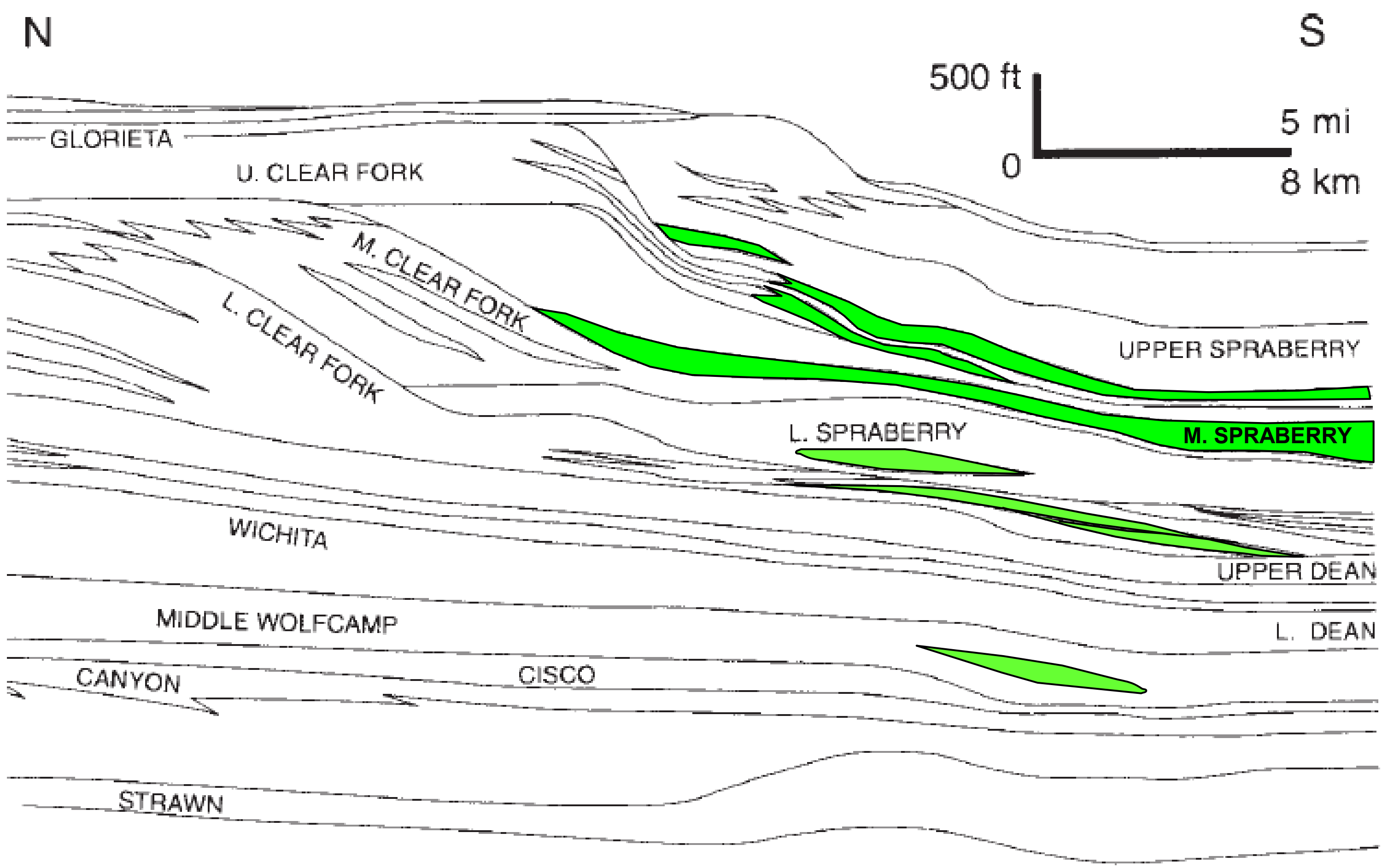


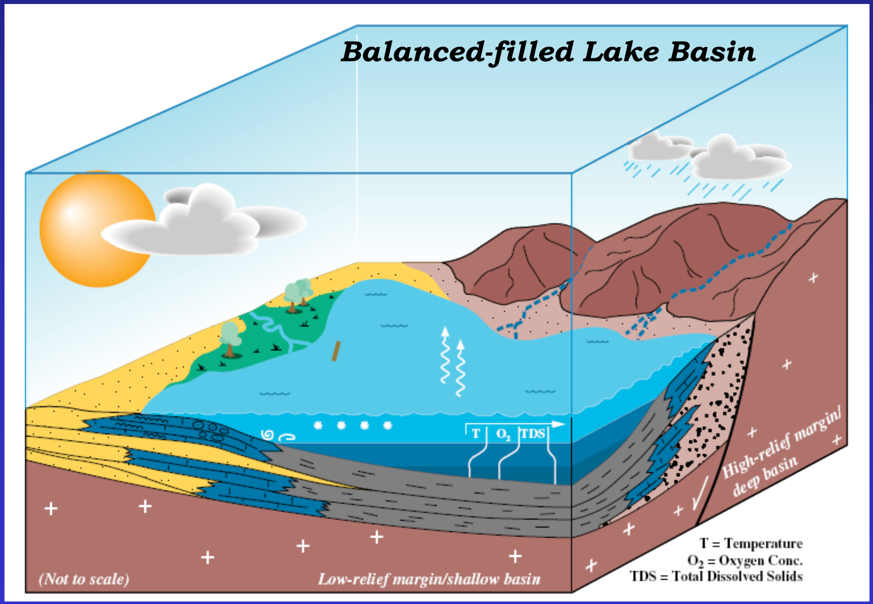
Figure 3—Stratigraphic divisions and generalized vertical depos
Midland basin, west Texas), shown on type log. Also indicated are
Tyler et al. (1997).



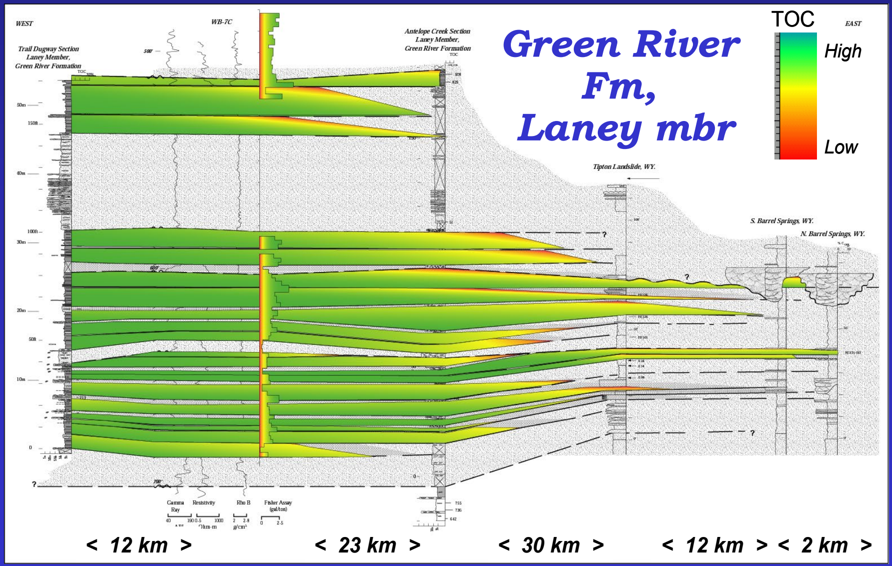
SG Family 4: Lacustrine sequences

- ✓ **Transgressive to Highstand Sequence Set**
  [~1-3 My duration]
- ✓ **Balanced Filled Lake Basin**
- ✓ **Multiple levels of downlapping parasequences**
- ✓ **Occur in both Divergent or Convergent settings**

Examples:* USA *(Green River Fm)*, China, E. Canada *(Horton Bluff Group)

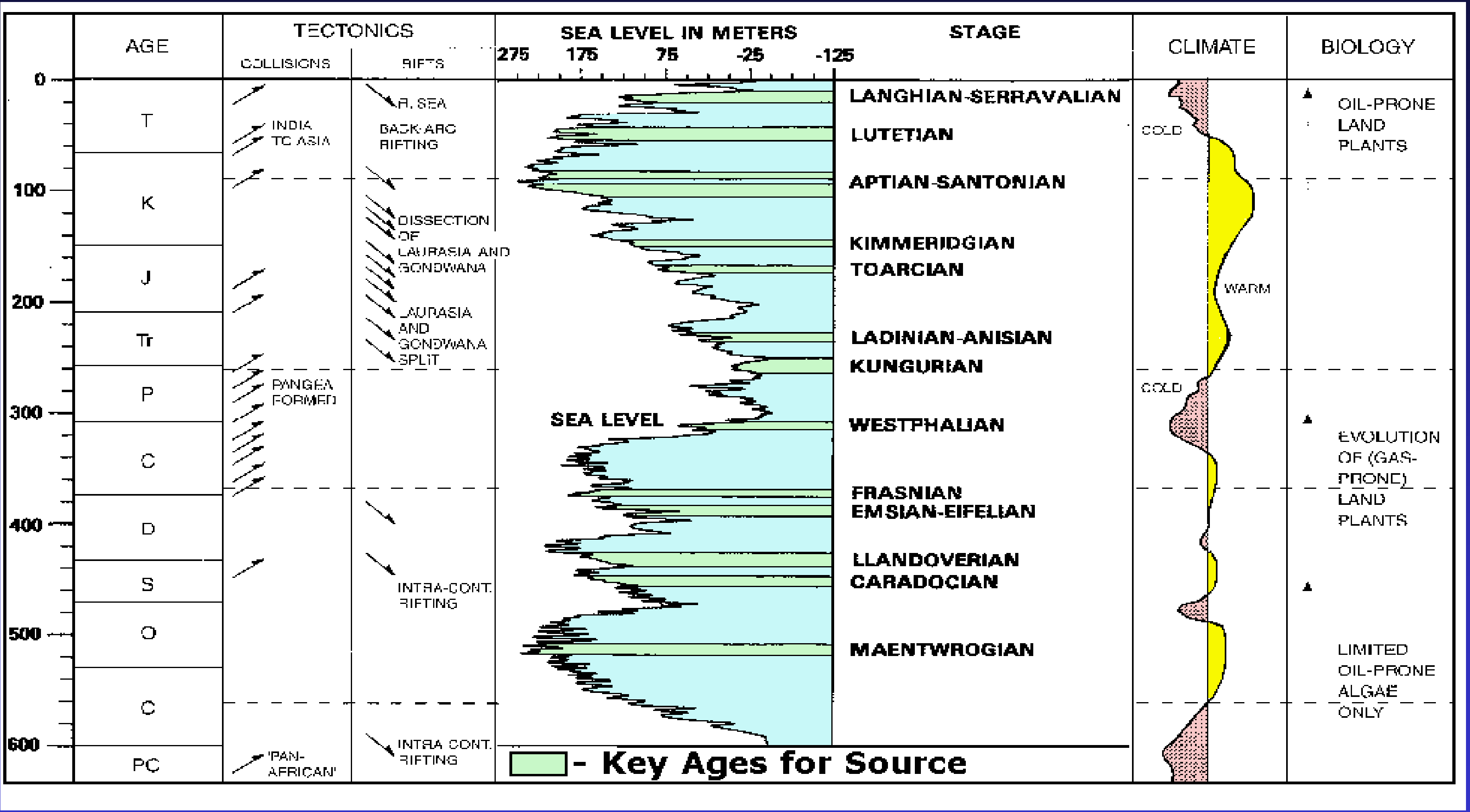


Bohacs et al., 2000



Bohacs et al., 2000

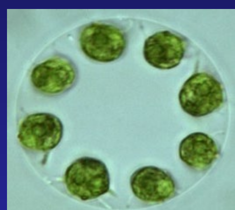
When Mudstone Reservoirs Occur



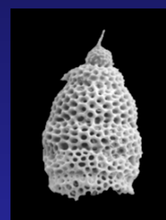
Loutit et al., 1989

Geological Age Matters…

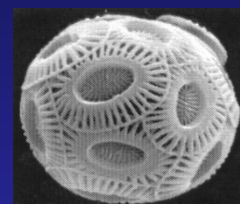
✓ **Significant Changes in Mudstone Components over Geological Time**



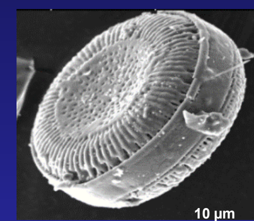
Green Algae



Radiolarian

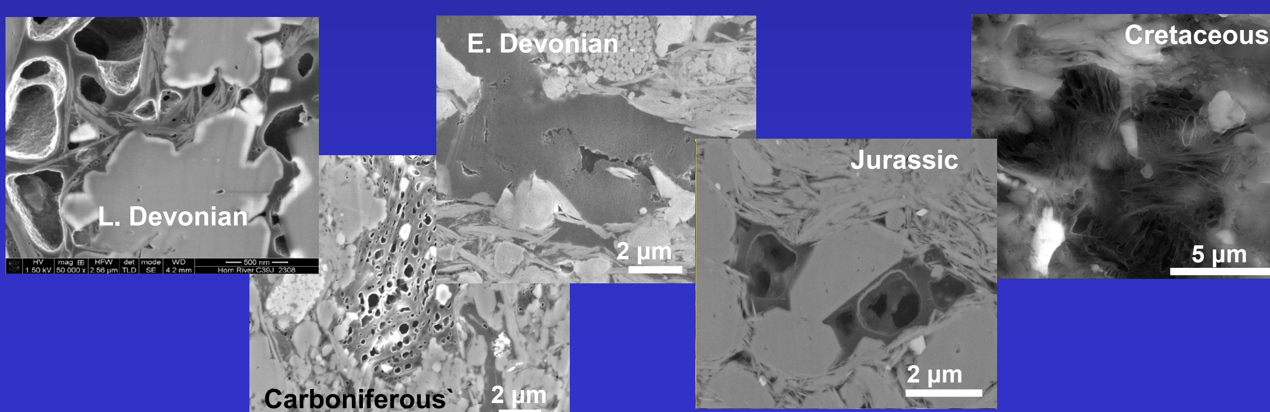


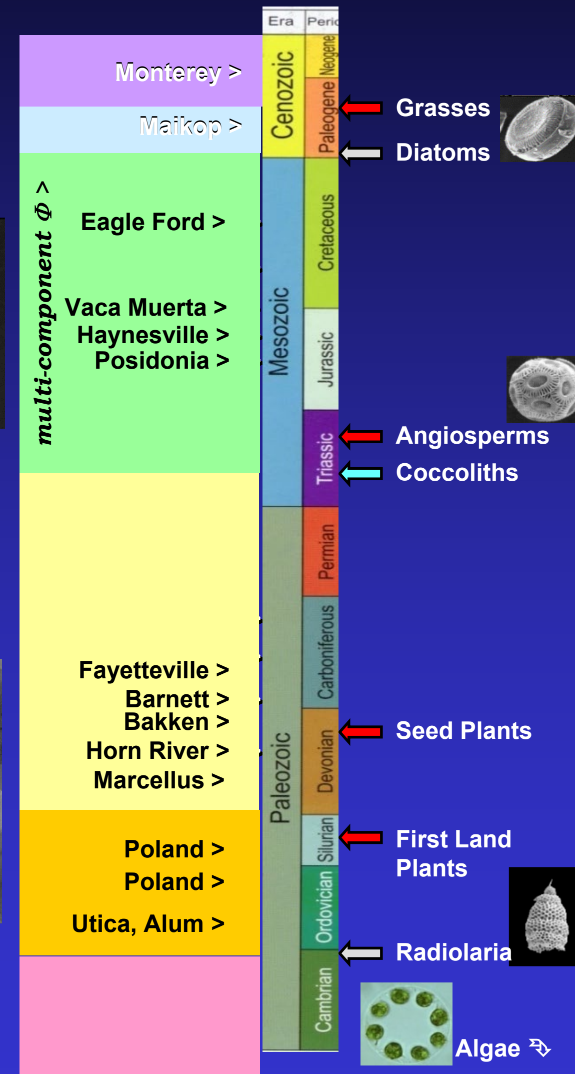
Coccolithophore



Diatom

≅ **Different & multi-component Φ types, lithofacies, TOC-mineral relations…**



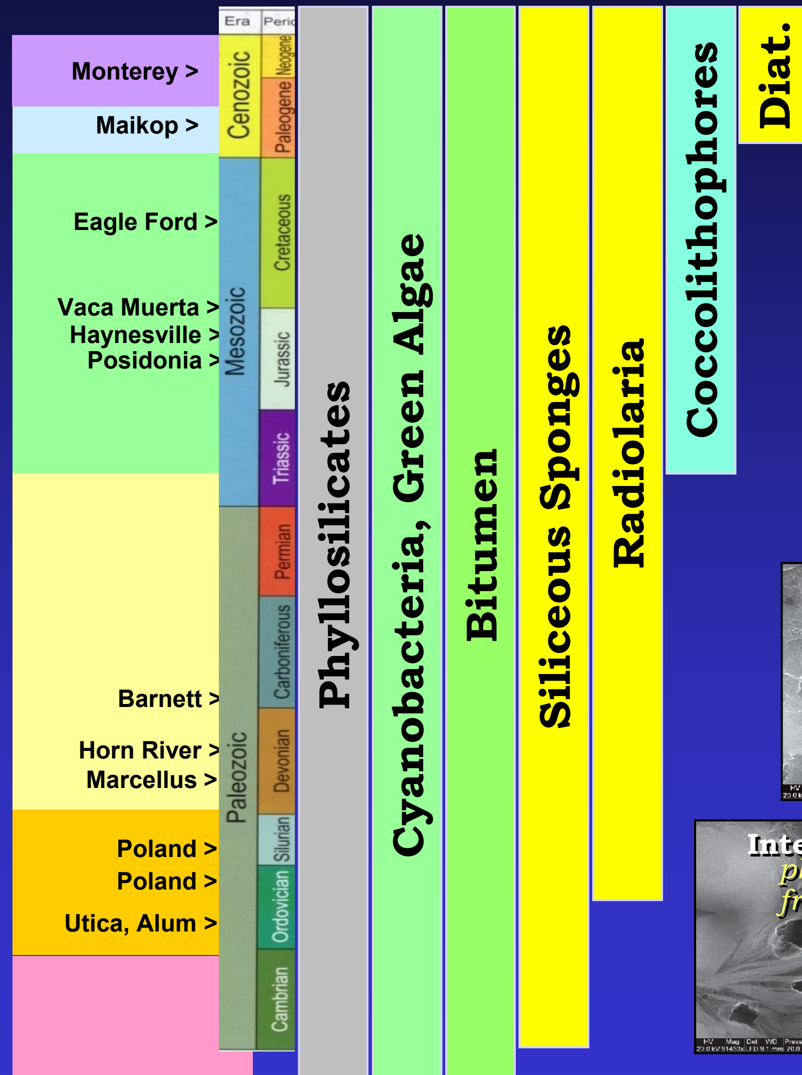


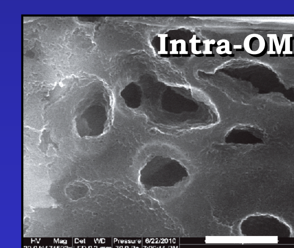
Bohacs et al., 2013b

Pore Types Diversify with Time…

- ☞ Inter-granular, intra-granular, *and* intra-organic matter
- ☞ More components in younger rocks…

… tend to work better





Bohacs et al., 2013b

Why Source Rocks Accumulate

$$\text{Source Rock Quality} = \frac{\text{Production} - \text{Destruction}^*}{\text{Dilution}}$$

*(Preservation = 1 – Destruction)

Bohacs et al., 2005

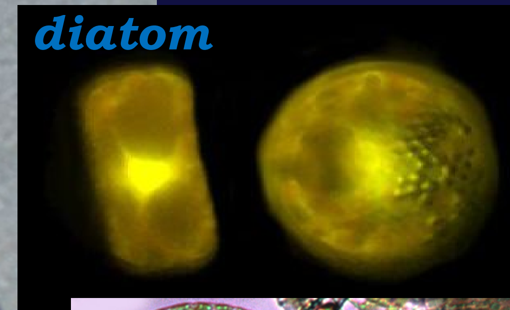
Why Ms Reservoirs Accumulate: Meat vs Bones

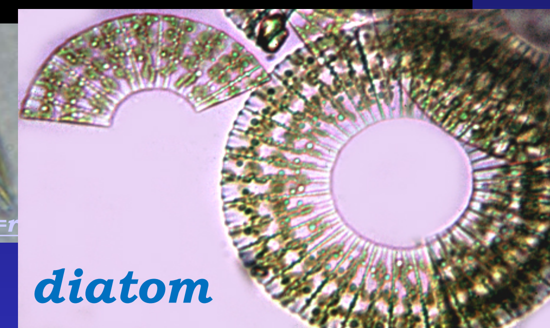
‘Soft’ vs ‘Hard’ parts:

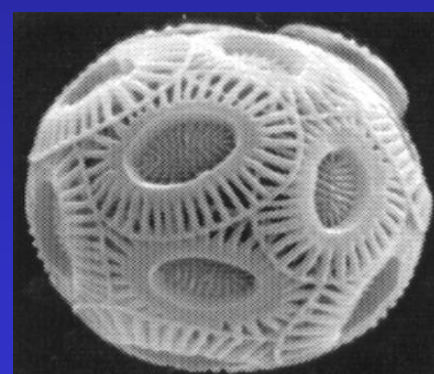
‘Meat’ = TOC (H-rich)
‘Bones’ = SiO_2, CO_3
(non-H rich)

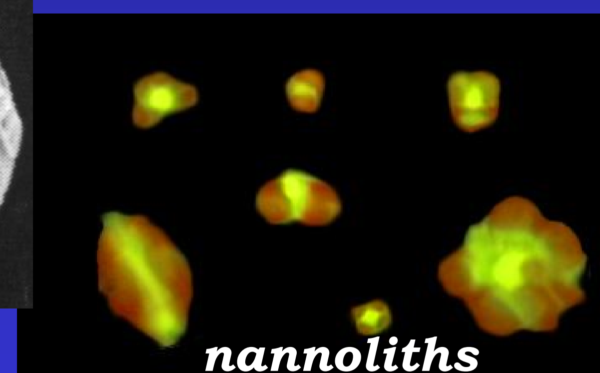
Diatoms and coccolithophorids are ~ 2/3rds ‘bones’

Need moderate primary production to accumulate appropriate concentrations of both ‘meat’ and ‘bones’:
-Too much = chalk
-Too little = lean source






coccolith



Bohacs et al., 2005

Why Ms Reservoirs Accumulate

Ms Reservoir Rock Quality =

-------------------- Biogenic --------------------

$$\frac{\{\text{Production}_{(\text{H-rich})} + \text{Production}_{(\text{non H-rich})}\} - \text{Destruction}^{*}}{\text{Dilution}_{(\text{non H-rich})}}$$

*(Preservation = 1 – Destruction)

Bohacs et al., 2005

There are Many Paths to ORRs & Ms Rsvrs…

Dilution	Production	Destruction	Likely Product
Low (< ~5 mg/cm²/yr)	Low (< ~1 mg/cm²/yr)	Low (< ~1 mg/cm2/yr)	Thin ORR (Sapropel)
		Moderate	Thin ORR?
		High (> ~5 mg/cm2/yr)	Shale
	Moderate	Low	Rich ORR
		Moderate	ORR
		High	Shale
	High (> ~5 mg/cm²/yr)	Low	Chalk/Chert/ORR?
		Moderate	Chalk/Chert
		High	Chalk/Chert
Moderate	Low (< ~1 mg/cm²/yr)	Low	Shale
		Moderate	Shale
		High	Shale
	Moderate	Low	ORR
		Moderate	ORR/Shale
		High	Shale
	High (> ~5 mg/cm²/yr)	Low	Marl/Porcelanite
		Moderate	Marl/Porcelanite
		High	Marl/Porcelanite
High (> ~30 mg/cm²/yr)	Low (< ~1 mg/cm²/yr)	Low	Shale/Zs/Ss
		Moderate	Shale/Zs/Ss
		High	Shale/Zs/Ss
	Moderate	Low	Shale/Zs/Ss
		Moderate	Shale/Zs/Ss
		High	Shale/Zs/Ss
	High (> ~5 mg/cm²/yr)	Low	Shale/Zs/Ss
		Moderate	Sh/Zs/Ss/Marl/Porcelanite
		High	Sh/Zs/Ss/Marl/Porcelanite

Notes: ORR = organic-matter-rich rocks, Sh = shale, Ss = sandstone, Zs = siltstone

(Bohacs et al., 2005)

Outline

- ☞ Essential components of effective reservoirs
- ☞ Differences between conventional and unconventional reservoirs
- ☞ Where, when, and why unconventional reservoirs occur
- ☞ **Research opportunities**

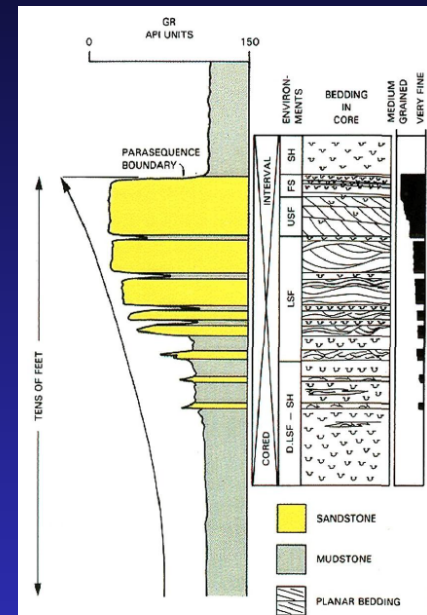
Heisenberg Uncertainty Principle for Mudstones

☞ The very act of bringing a mudstone sample to the surface alters its fabric irreversibly.

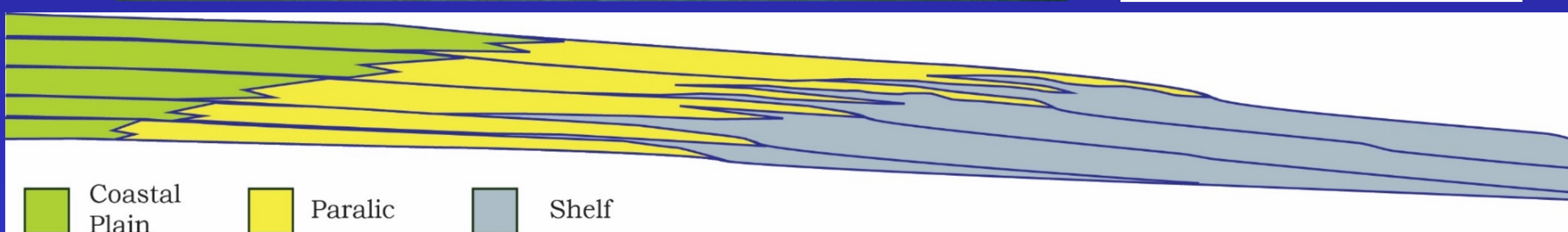
- ❖ Downhole direct measurements would be better, but very challenging or impossible to obtain
- ❖ Scale of compositional variation << sample size
  - Effectively impossible to obtain exactly duplicate samples
- ❖ Scale of flow system >> sample size
  - Flow systems > cm-scale not sampled
  - Well-bore permeability ≠ Sample permeability

How Do We Interpret Mudstone Environments ?

☞ **Wave-dominated Shoreline ?**



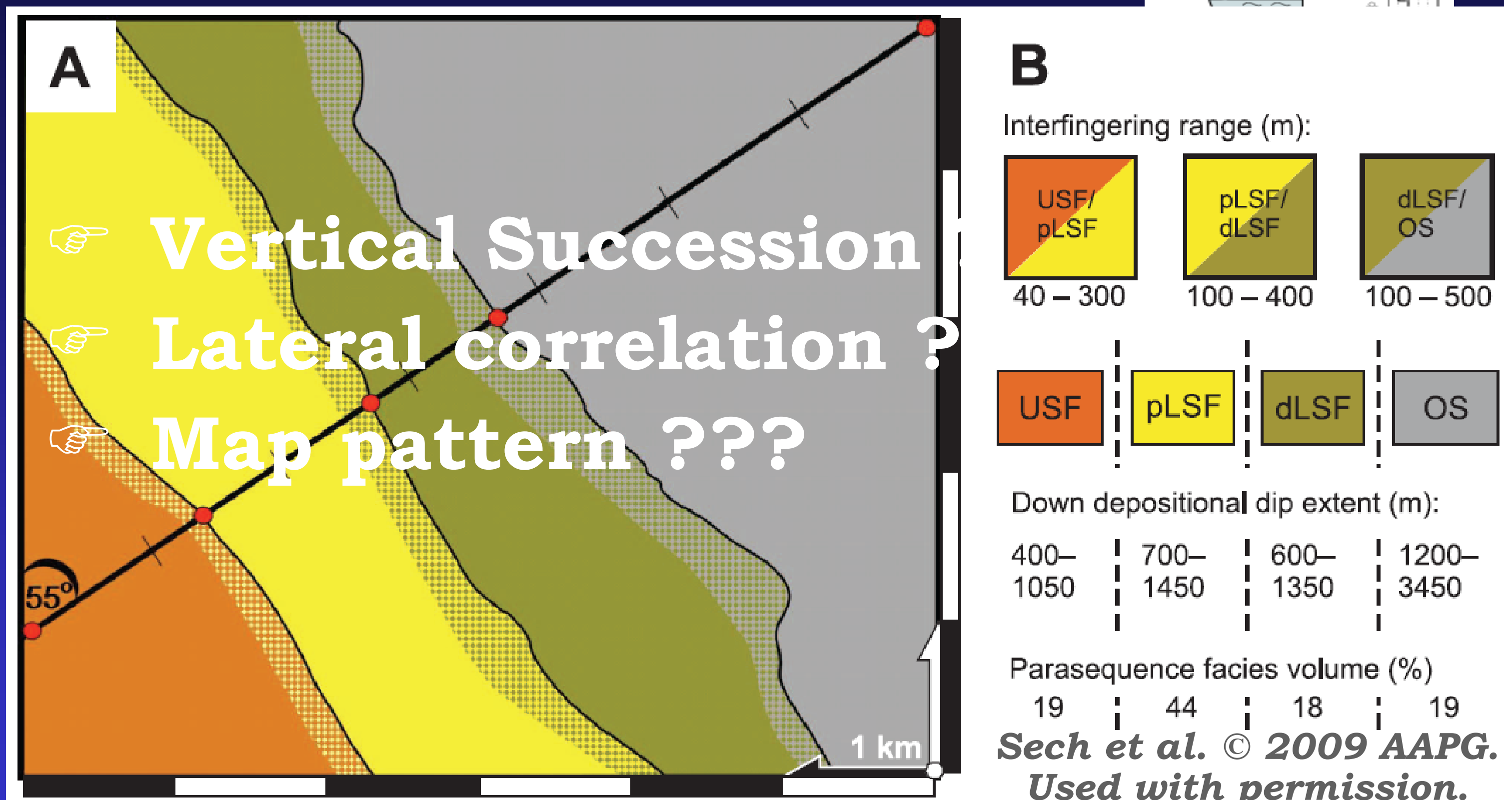
VanWagoner et al. © 1990 AAPG. Used with permission.



Bohacs and Macquaker, 2017

How Do We Interpret Mudstone Environments ?

- ☞ **Wave-dominated Shoreline ?**



- ☞ **Vertical Succession ?**
- ☞ **Lateral correlation ?**
- ☞ **Map pattern ???**

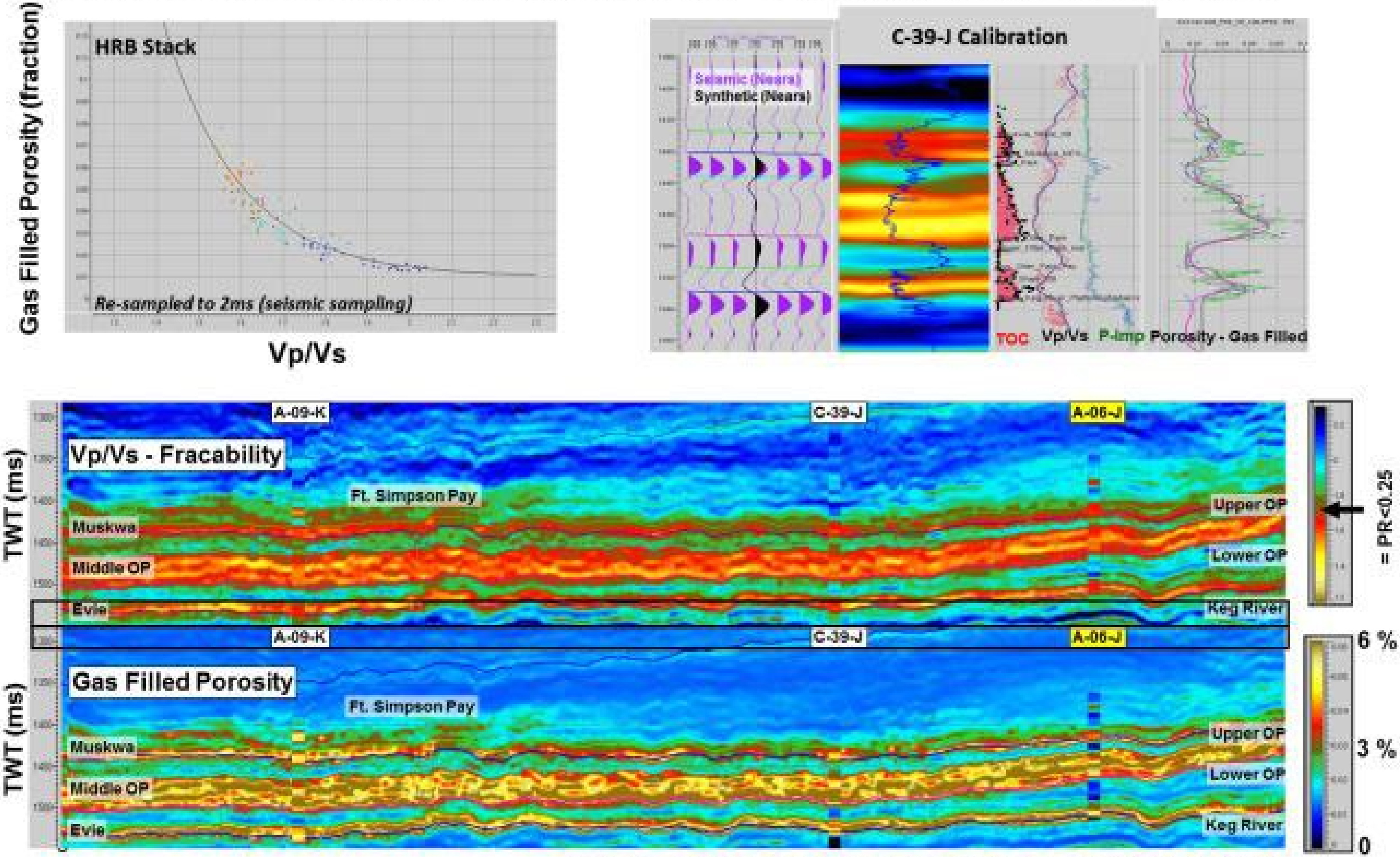
Sech et al. © 2009 AAPG. Used with permission.

- ☞ **Storm-Wave-dominated mid-shelf Clinothem ???**

Bohacs and Macquaker, 2017

Prediction Away from Sample Control ?

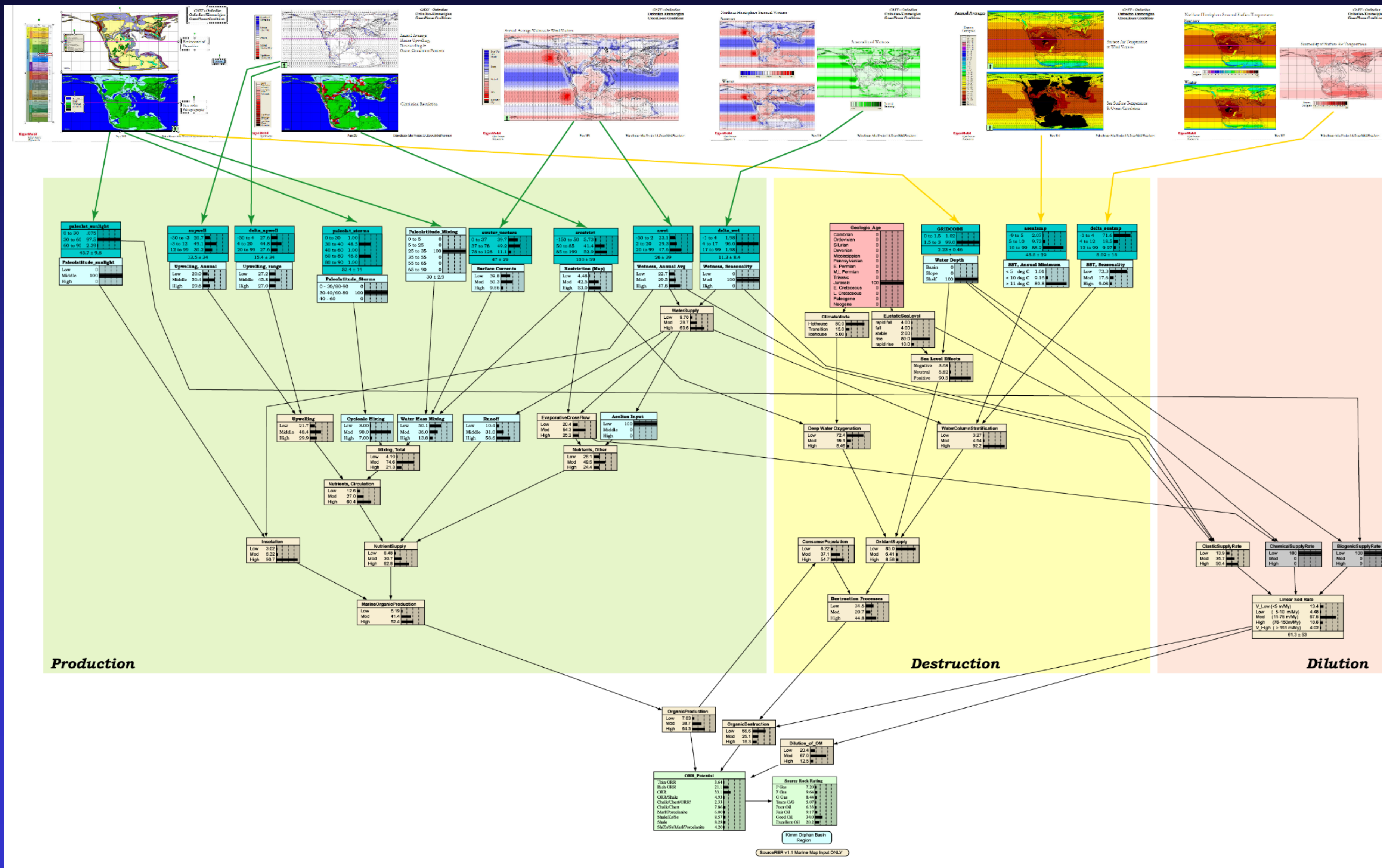
☞ Seismic prediction of brittleness, gas-filled porosity & TOC calibrated from elastic properties of 3D seismic inversion volumes. Calibration relies on core dataset.

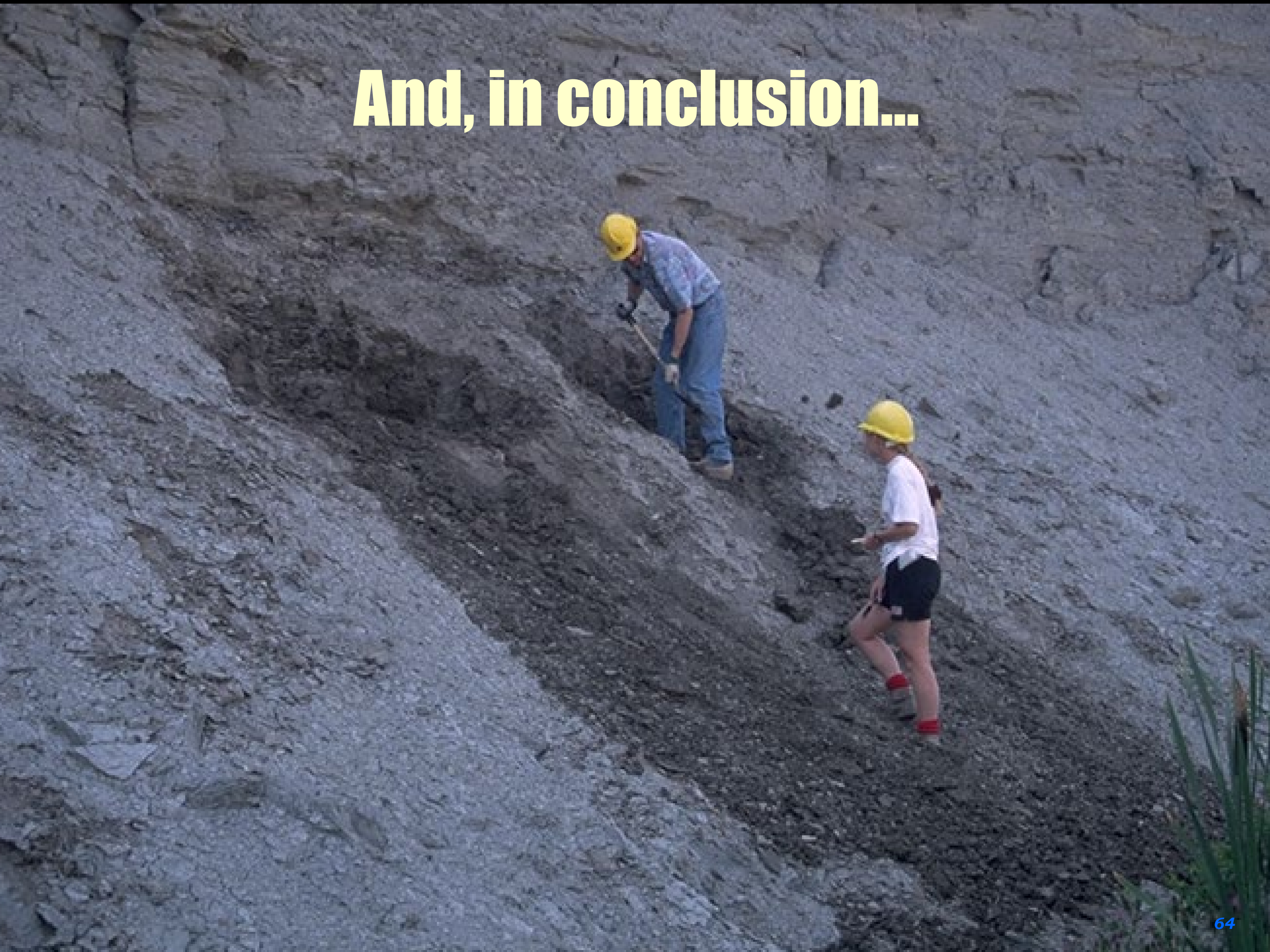


Permission to show 3D seismic courtesy of Arcis and Olympic Seismic

Both are rendered from AVO inversion

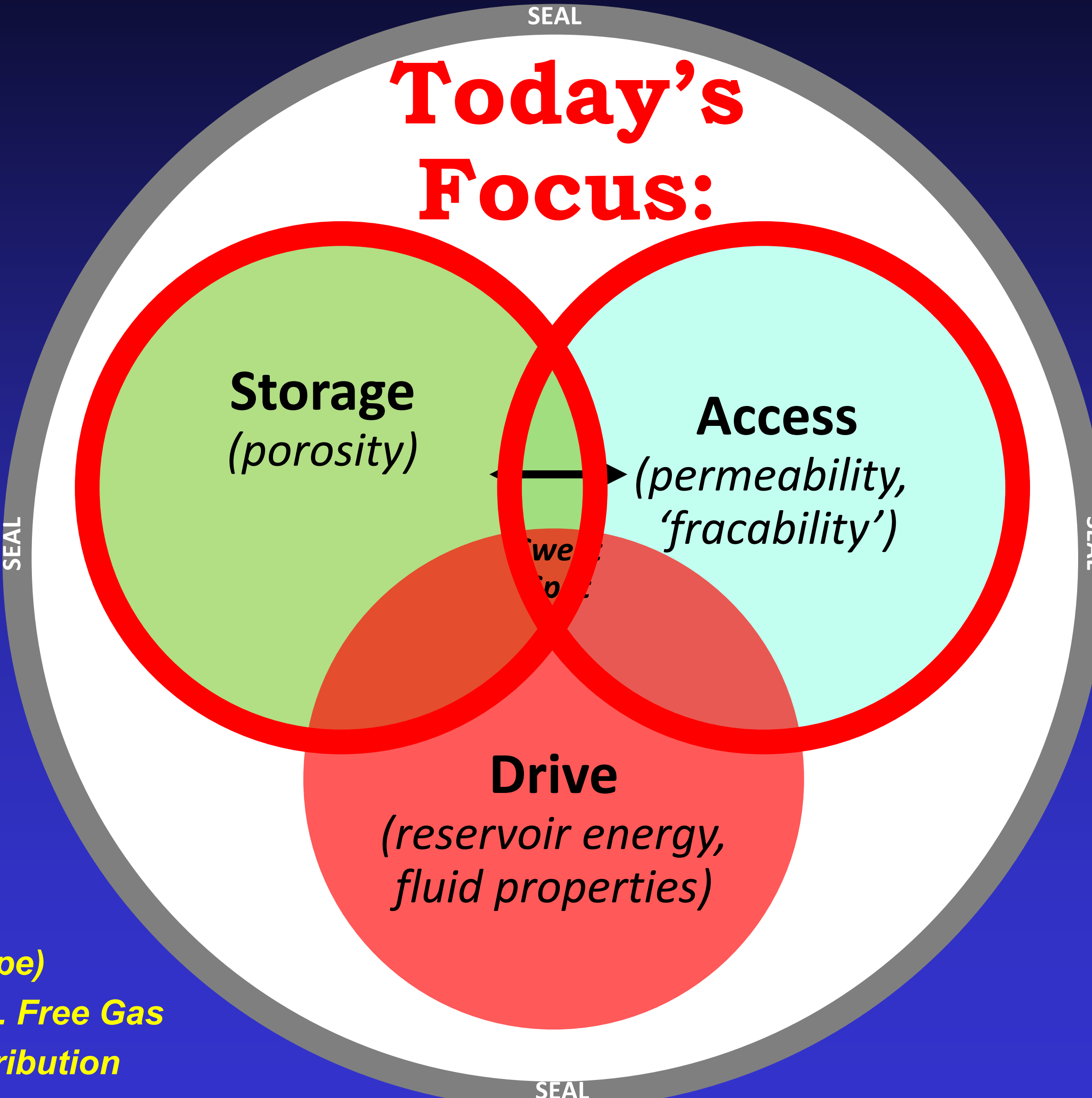
Prediction Away from Sample Control ?




And, in conclusion…
64

Essential components of effective reservoirs

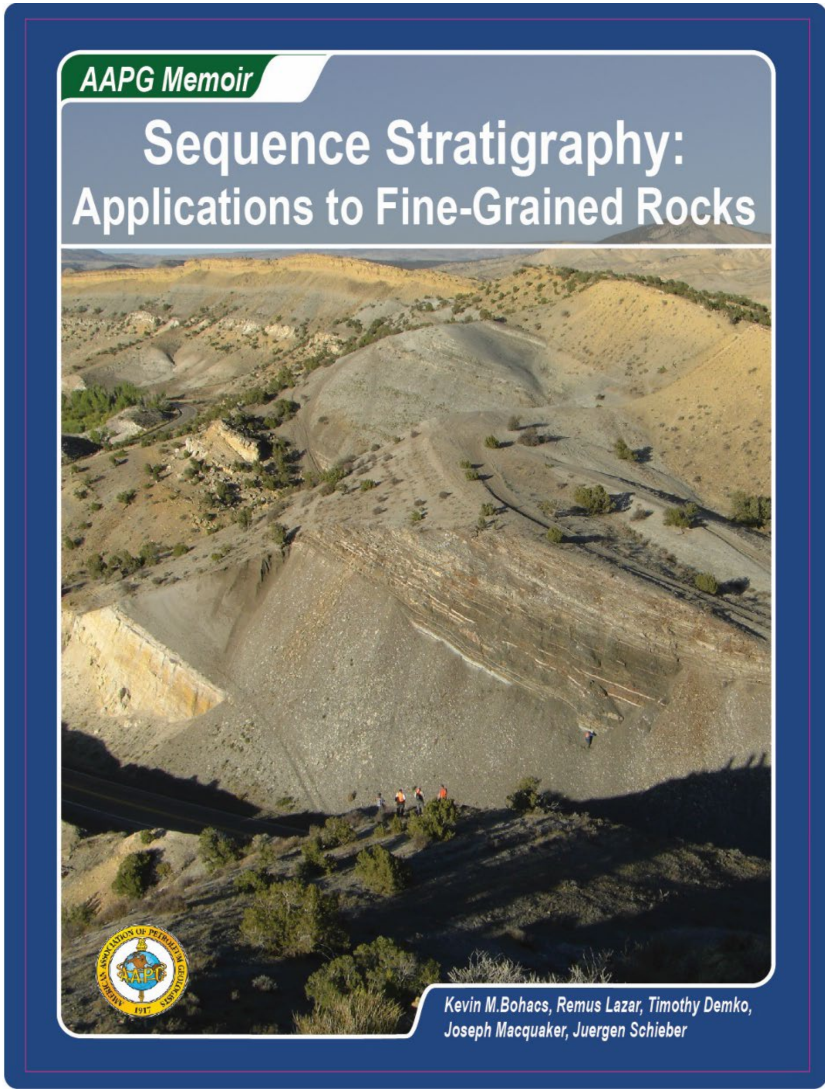
- ☞ *Enough fluid*
- ☞ *of sufficient value*
- ☞ *fast enough*
- ☞ *to make $$$*

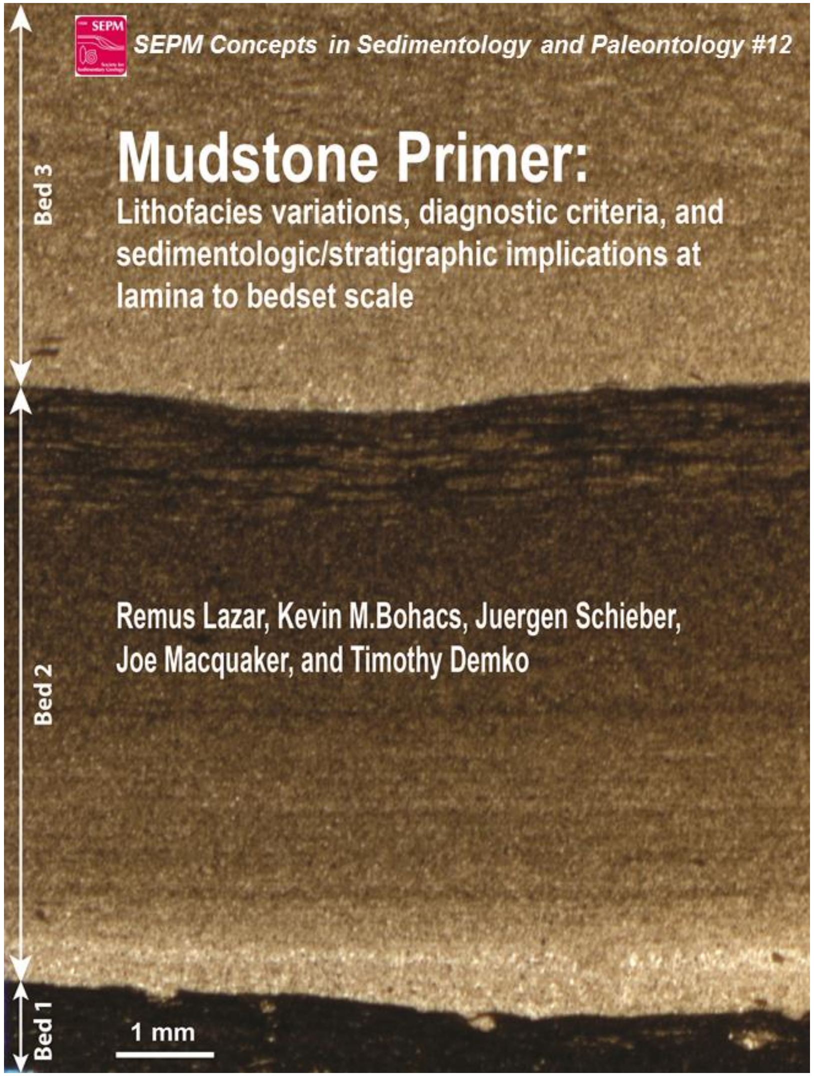


Modifiers:
- *Fractures (and type)*
- *Adsorbed Gas vs. Free Gas*
- *Non-HC Gas Distribution*

(after Ottmann et al., 2013)

For More Information . . .





Bohacs et al., 2020…