

Mudrock Reservoirs — Why Depositional Fabric and Sequence Stratigraphic Framework Matter*

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Abstract

Mudrocks comprise any deposit with >50% of grains <62 microns in size. Composition, fabric, and texture often are extremely variable. Major influences on these parameters include tectonic setting, source terrane, basin physiography, water depth, circulation and upwelling, oxygenation, climate, eustasy, and detrital influx. Thus, mudrock character - which ultimately controls the distribution and deliverability of hydrocarbons - is anything BUT homogeneous.

Macroscopic core description, tied to stratigraphic framework and integrated with lab analyses and petrophysical interpretation, is critical in understanding variability and deciphering patterns in composition, fabric, and texture. A rich diversity of facies can be discerned. Sedimentary structures, such as ripple cross laminae, graded bedding, scour surfaces, rhythmic couplets, and minute burrows to "cryptobioturbation," are common. Stratigraphic variations in these features relate directly to changing depositional conditions and sequence position.

Mudrocks do not simply fill basins passively. Competition between extrabasinal input and intrabasinal biogenic productivity creates conditions for lithologic cycles, clinoform geometries, and water-column stratification. Benthic fauna colonize the seafloor during dysaerobic to aerobic periods, then experience "terror" during periods of mass transport. An understanding of these stratigraphic relationships requires regional correlations that commonly cover thousands of square miles.

Depositional patterns from basins of the Rocky Mountains, Gulf of Mexico, and Canada suggest that mudrock reservoirs are associated with distinct sequence stratigraphic hierarchies. Most prospective mudrock intervals develop during 2nd-order transgressions. In basins with strong extrabasinal sediment influx, the better reservoirs require load-bearing grains and typically form during either 3rd-order highstands or lowstands. By contrast, in basins dominated by intrabasinal biogenic material, the best reservoirs often occur in 3rd-order condensed sections. Such units are frequently brittle, with low clay content, high TOC, and abundant microfossils. Thus, the integration of rock description and sequence framework provides better insight into lateral and vertical changes in mudrock character and reservoir targeting.

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[schieber.indiana.edu](http://www.shale-mudstone-research-schieber.indiana.edu)

Mudrock Reservoirs - Why Depositional Fabric & Sequence Stratigraphic Framework Matter

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Key Points

- **rich diversity of lithologies & depositional facies occurs in mudrocks**
- **core description critical to understanding distribution & controls on composition & texture (i.e., rock fabric)**
- **fabric controls pore systems & rock mechanics (storage & deliverability)**
- **depositional fabric related to sequence position**
- **sequence stratigraphy provides framework for interpretation & targeting**

Mudrock – Not Just Shale!

> 50% of grains less than 62.5 microns

		<i>silt:clay ratio</i>	
		2/3	1/3
nonlaminated	siltstone	mudstone	claystone
		mudshale	clayshale



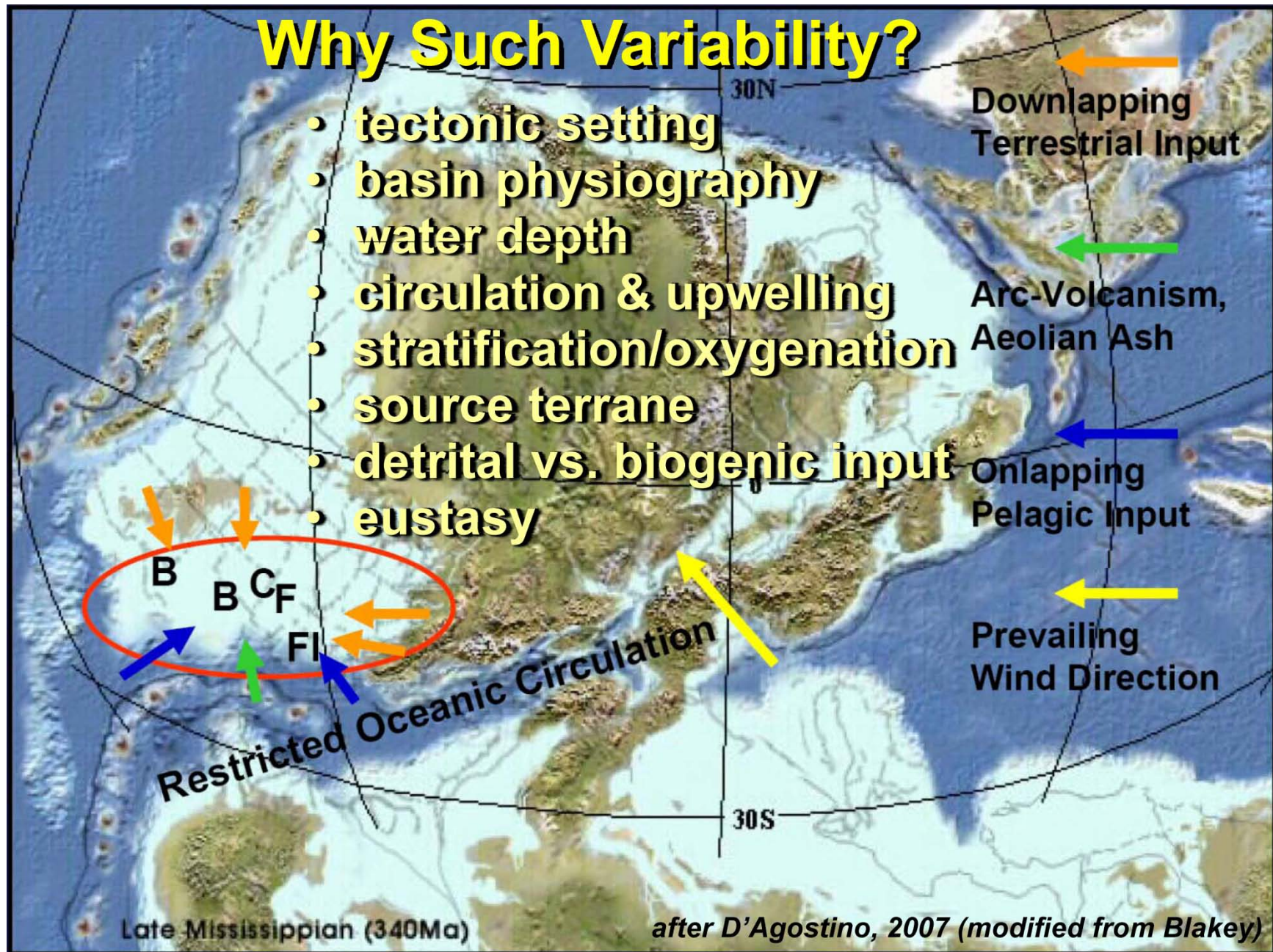
Variable Mudrock Reservoirs

(one size does not fit all)

- **siliciclastic mudrocks**
 - biogenic quartz (radiolarite, diatomite, porcellanite, chert)
 - biogenic quartz + clay
 - detrital quartz + clay
- **carbonate mudrocks**
 - detrital carbonate (micrograinstones)
 - biogenic carbonate (chalk)
 - biogenic carbonate + clay (marl)
 - dolomite
- **hybrid reservoirs**
 - siliciclastic + carbonate mixtures
 - interlaminated mudstone-siltstone/sandstone
 - phosphorite

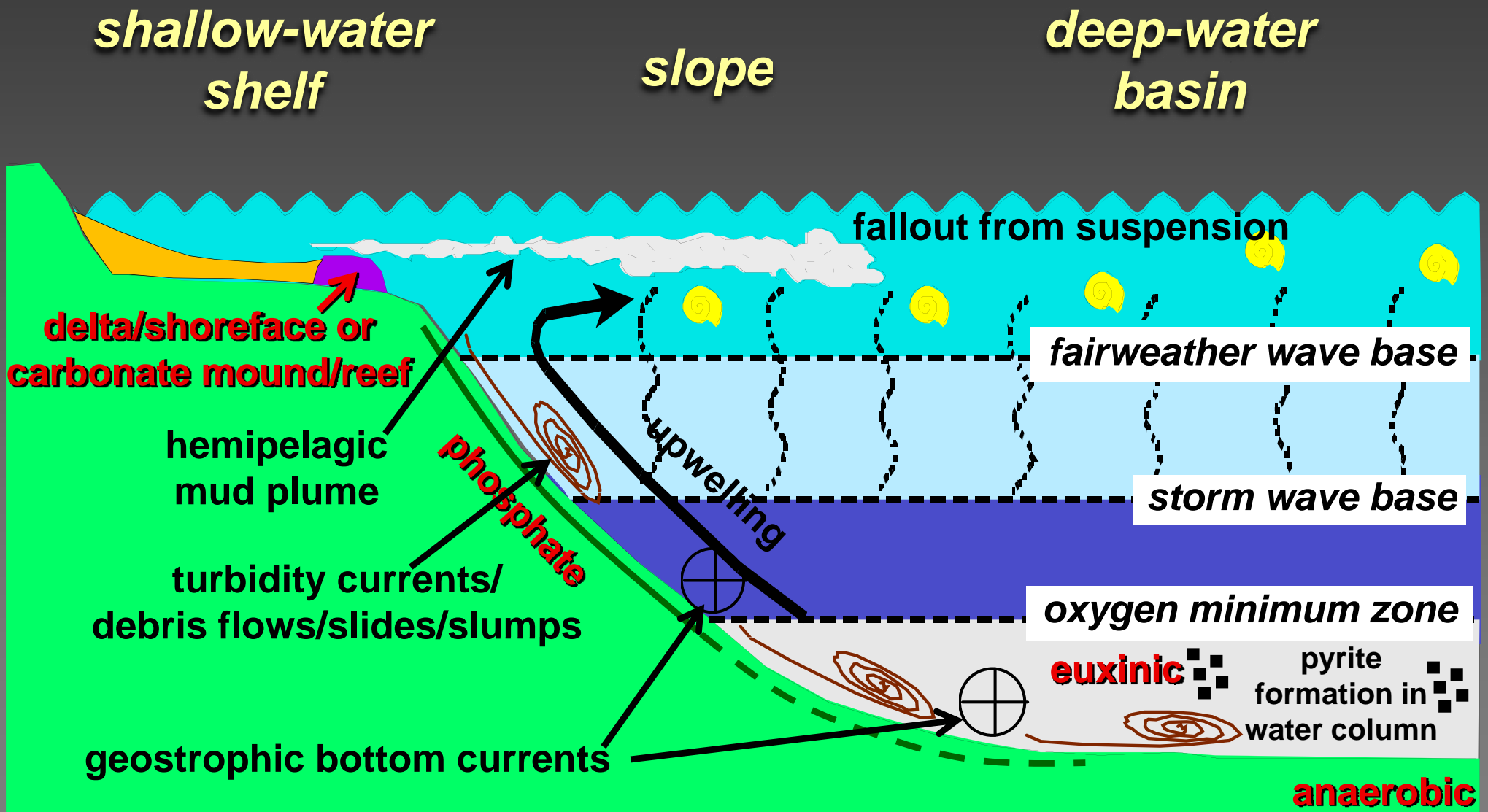
Why Such Variability?

- tectonic setting
- basin physiography
- water depth
- circulation & upwelling
- stratification/oxygenation
- source terrane
- detrital vs. biogenic input
- eustasy



Presenter's notes: Variable controls – and thus resulting composition and reservoir character - for the coeval Barnett (B), Caney (C), Fayetteville (F), and Floyd (FI) shales.

Depositional Effects on Variability



after Loucks & Ruppel, 2007



eogresources

Goals of Mudrock Core Description

- **systematic description of composition, texture, & fractures (documentation beyond core photos)**
- **interpret depositional processes & lithofacies**
- **calibrate the rocks to the well logs**
- **integration w/ lab analyses & petrophysics**
- **relate reservoir & mechanical properties to basinal & sequence position**
- **prediction & assessment of target(s)**

One Problem with Mudrocks in Core



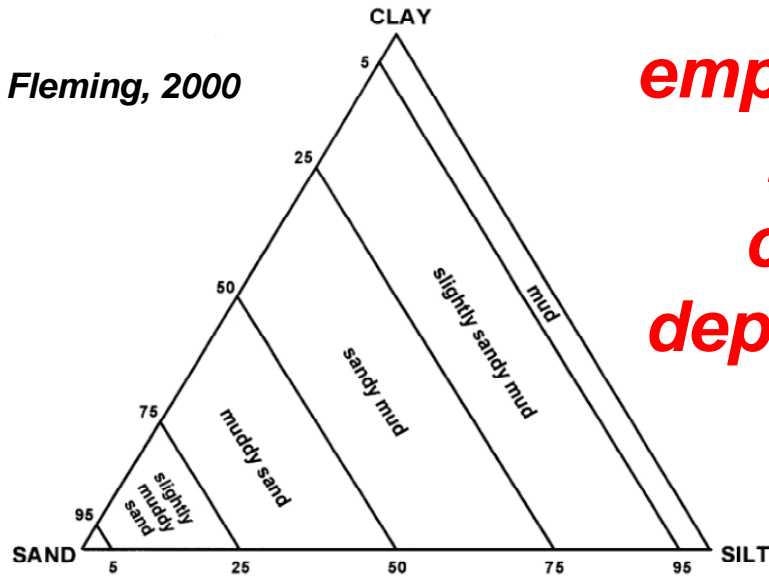
Rock fabric difficult to
see with the naked eye,
so . . . they look pretty
boring!

BUT

there is a **RICH** diversity
of lithofacies,
if you just look.

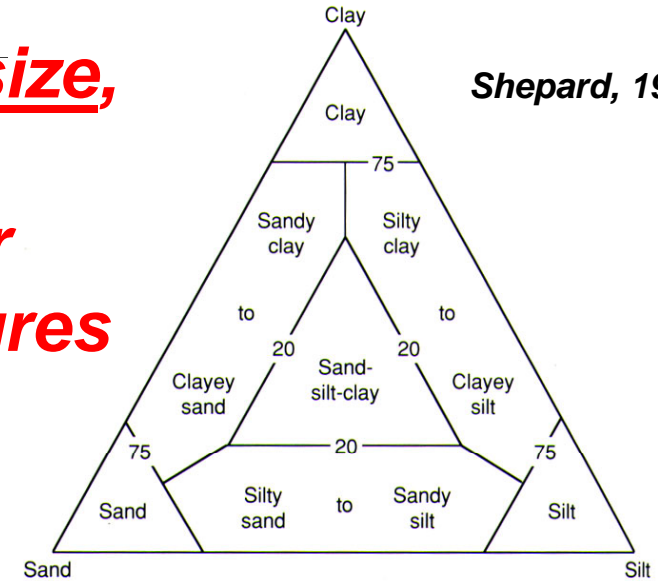
No Good Existing Mudrock Classification

Fleming, 2000

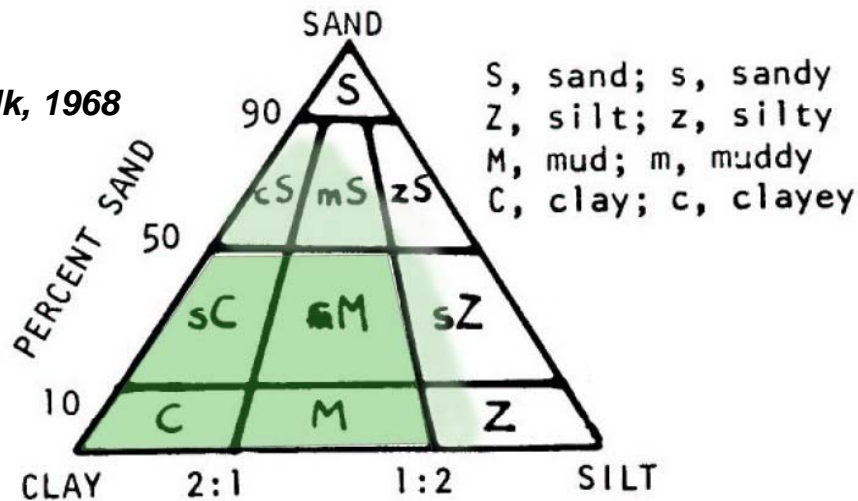


*emphasize grain size,
nothing about
composition or
depositional features*

Shepard, 1954



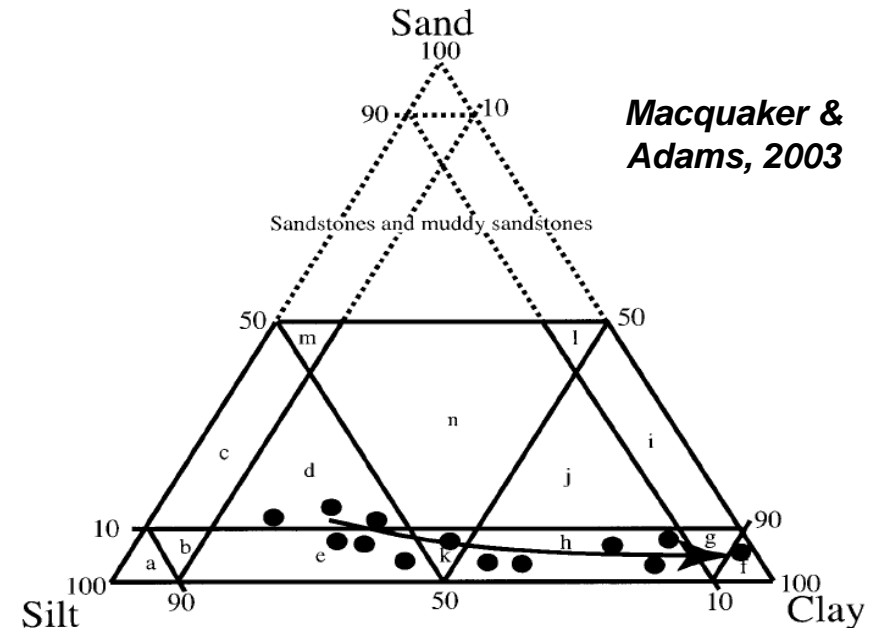
Folk, 1968



Indurated
Siltstone
Mudstone
Claystone

Fissile
Silt-shale
Mud-shale
Clay-shale

Macquaker & Adams, 2003



- a) silt-dominated mudstone
- b) silt-rich mudstone
- c) sand-bearing, silt-rich mudstone
- d) sand and clay-bearing, silt-rich mudstone
- e) clay-bearing, silt-rich mudstone
- f) clay-dominated mudstone
- g) clay-rich mudstone
- h) silt-bearing, clay-rich mudstone
- i) sand-bearing, clay-rich mudstone
- j) sand and silt-bearing clay-rich mudstone
- k) silt and clay-bearing mudstone
- l) sand and clay-bearing mudstone
- m) sand and silt-bearing mudstone
- n) sand, silt and clay-bearing mudstone

from Milliken, 2010

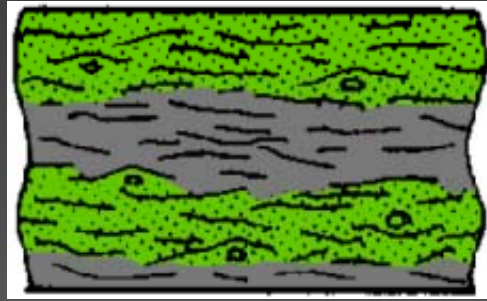
Facies Scheme

➤ texture (sedimentary structures), composition, grain size

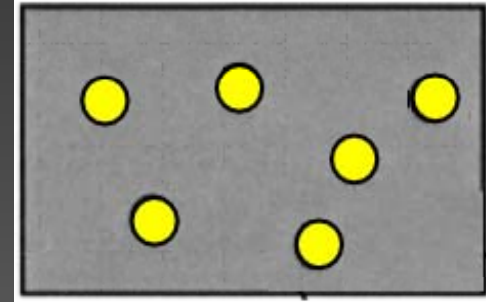
Color Fill	Numeric Code	Facies Code	Facies Name	Geologic Description	Micro Fabric	Detrital Qtz	Amorp Qtz	(Bio) Ca	Dol CaMg	Clay
	1	D	Dolostone	White, massive-appearing dolomite; thin beds: No reaction in 10% HCl. Present at distinct stratigraphic horizons in beds < 20 cm thick.	massive				100%	
	3	Ch	Chalk (pure)	White, burrowed, recrystallized to highly fossiliferous chalk, almost 100% biogenic-derived carbonate. No organic material, silt, or clay.	massive			100%		tr
	5	BCPCh	Burrowed Calcareous Pelletal Chalk	Light gray, finely interlaminated foraminiferid and coccolithoporid tests and copepod pellets: XRD analysis > 75% total carbonate with minor clay. TOC >> 2% TOC, and may range up to 30%. Burrowing up to 75%	massive	<5%		>75%		<5%
	6	FPMa	Foraminiferid Pelletal Marlstone	Medium gray, finely interlaminated foraminiferid and coccolithoporid tests and copepod-pellets: XRD analysis 25 to 75% carbonate relative to clay fraction. May also contain quartz silt grains and >> 2% TOC. Burrowing is rare.	mm-cm lam	<5%		25-75%		<25%
	8	SPMa	Silty Pelletal Marlstone	Medium to dark gray, finely & rhythmically interlaminated clay, foraminiferid and coccolithoporid tests and copepod-pellets: XRD analysis 25 to 50% total carbonate. Contains up to 30% quartz silt grains. May also contain glauconite, pyrite, and inoceramid prisms, and >2% TOC. Burrowing is < 25%.	mm-cm lam	<30%		25-50%		<35%
	20	BCSlt	Burrowed Clayey Siltstone	Gray, bioturbated clayey siltstone, trace of radiolarians. Common <i>Schaubcylindrichnus</i> burrows within otherwise completely burrowed matrix. Up to 5% detrital plagioclase, > 90% XRD quartz is detrital	massive	60%	(<10%)			>30%.
	21	IVF	Interlaminated VF Ss and Silty Claystone	Gray alternating with white, cm-scale interlaminated beds of claystone and vf Ss, yielding 20-50% net ss. Claystone may be normally or ungraded. Ss consists of 1-2 grain thick starved, incipient ripples, appearing as "streaks" with indistinguishable formsets. Burrowin rare, consists of isoplated Planolites or Chondrites, associated exclusively with Ss fraction.	massive	20-50%				50-80%

Mudrock Description

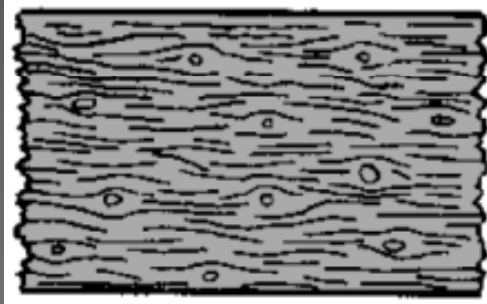
color



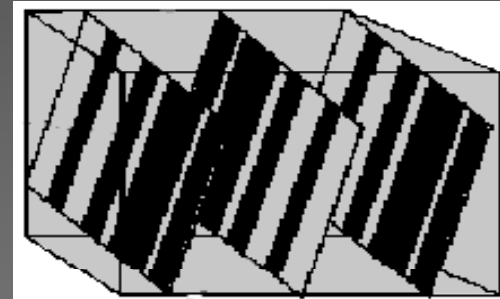
accessories
(pyrite,
fossils, etc)



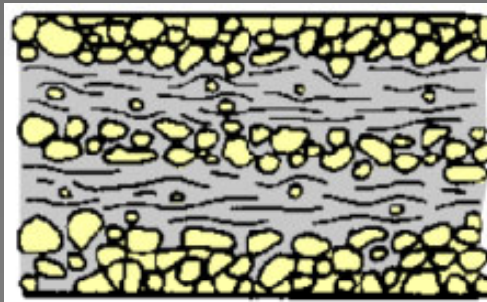
lithology
(composition)



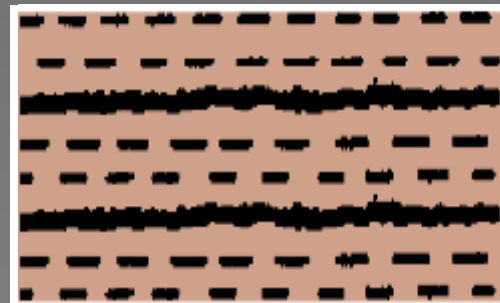
natural
fracturing



texture
(sedimentary
structures
& grain size)



partings/
coring
response

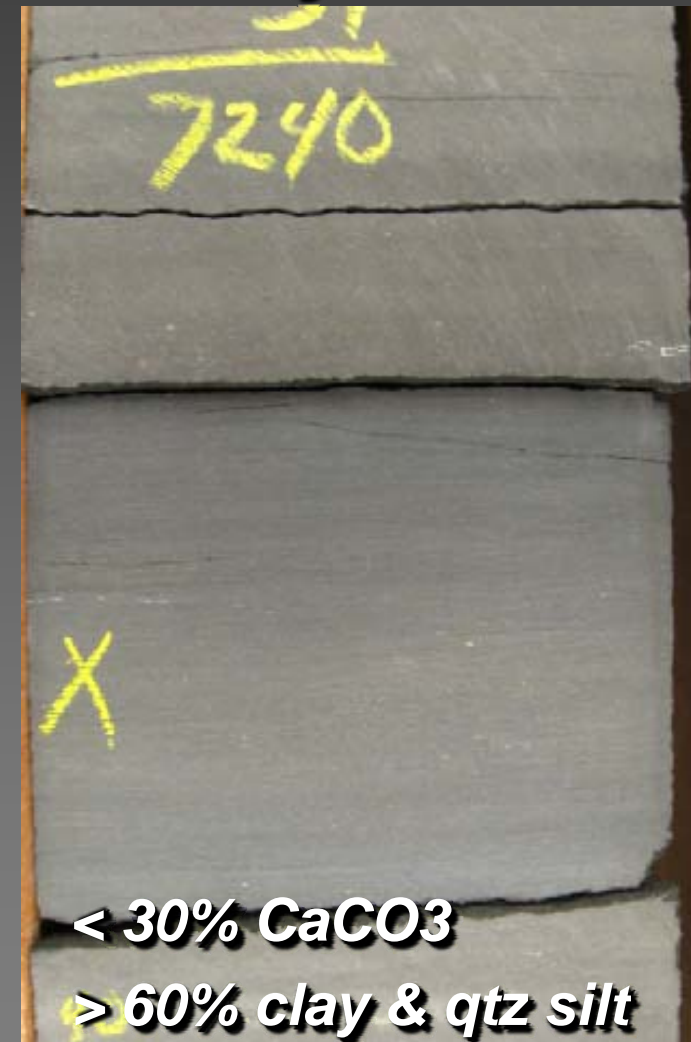


Color & Lithology

chalk

marl

claystone



all are Niobrara Fm

detrital carbonate

Lithology (Framework)

detrital quartz

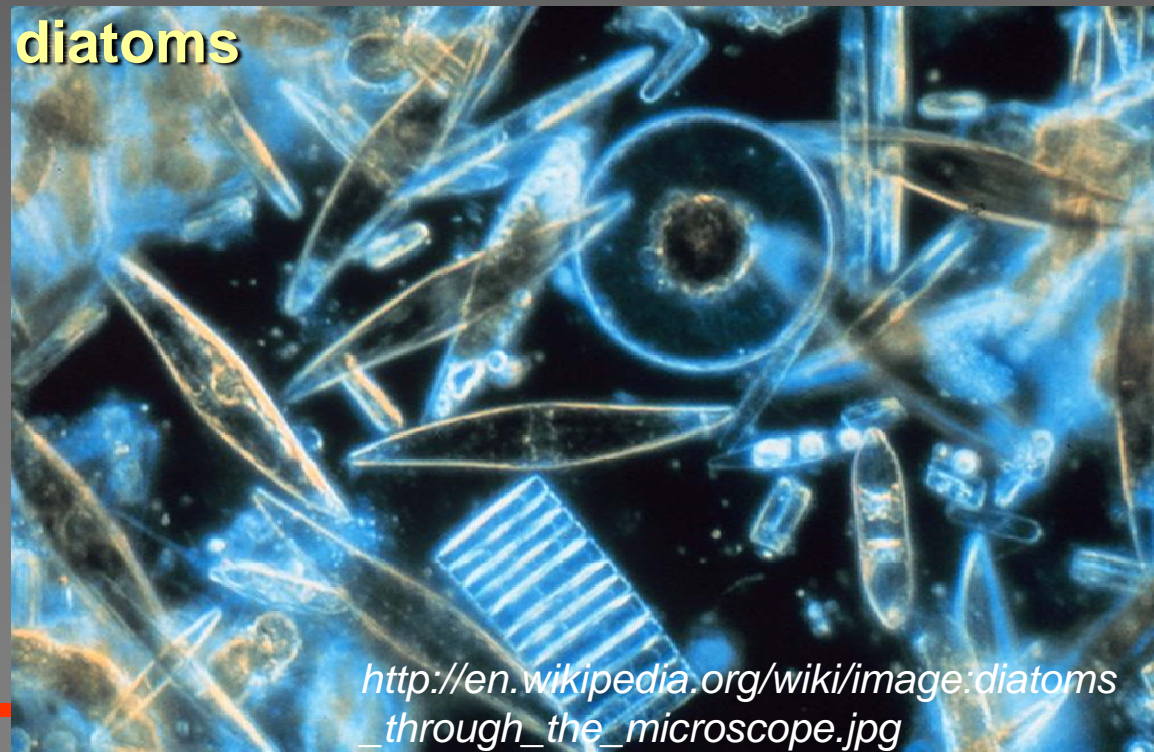
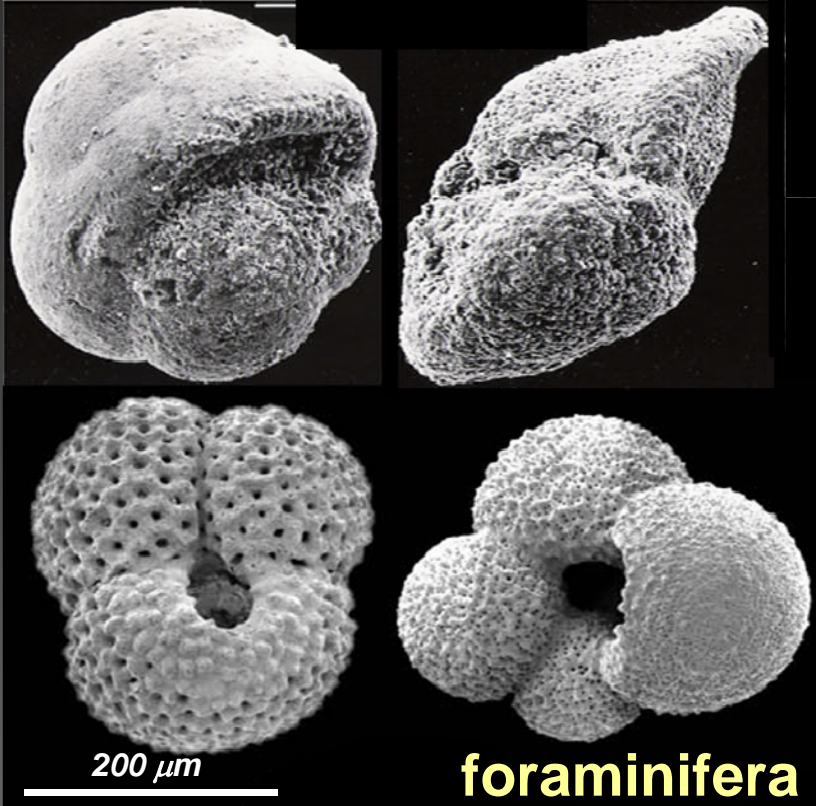


detrital clay

20 microns

from Milliken, 2010

Lithology (Framework)

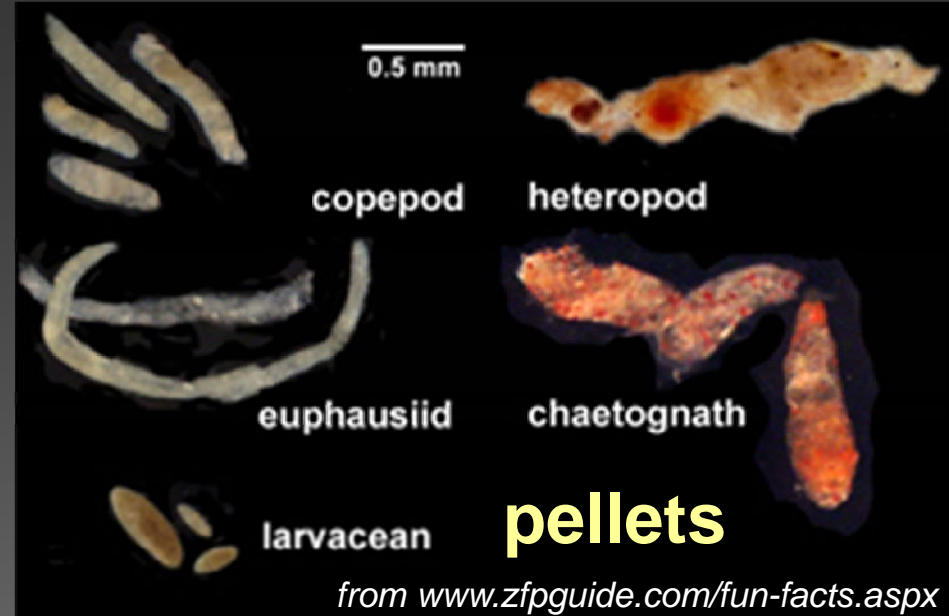


Lithology (Organic Matter)

from <http://www.whoi.edu/oceanus>

“marine snow”

55 m, Monterey Bay (pellets = 1/2-7 mm)



Mowry Shale

0.1 mm

from Spain &
Anderson, 2010

pellet

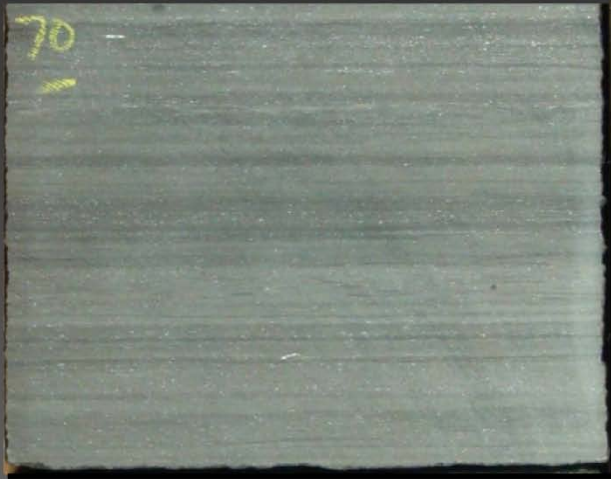
pellet

pellet

0.5 mm

0.5 mm

Sedimentary Structures (Texture)



laminations



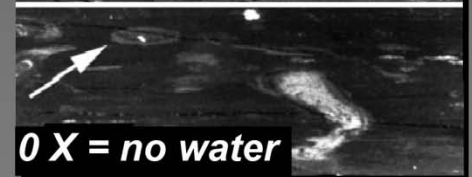
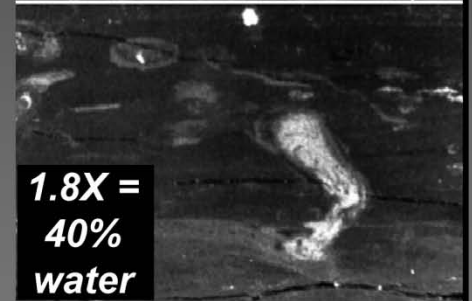
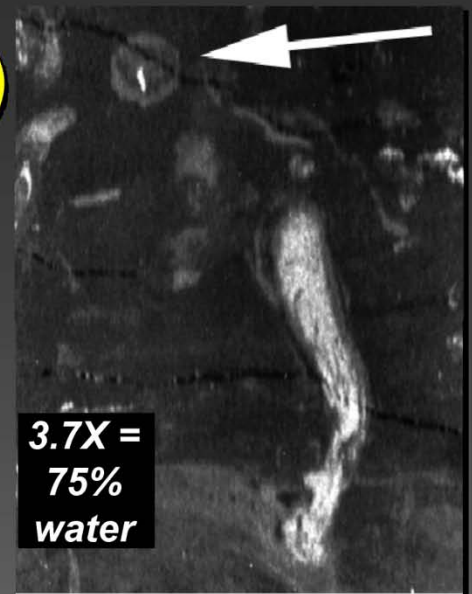
grading



ripples



deformation

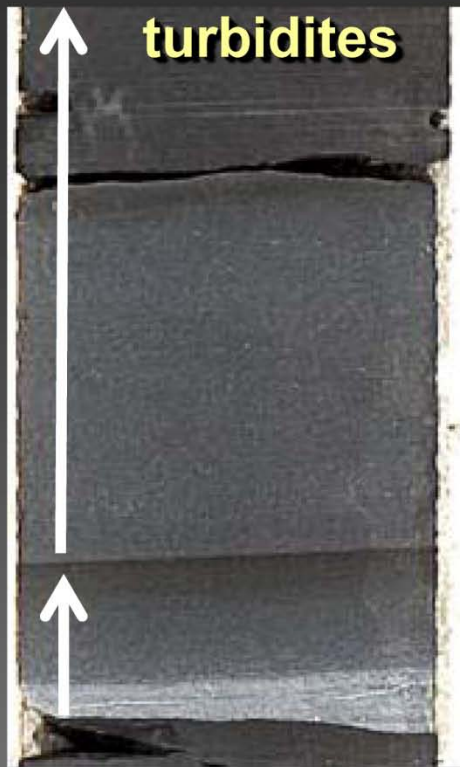


“burrows”

from www.shale-mudstone-research-schieber.indiana.edu

Presenter's notes: Detailed examination of cores reveals a wide variety of primary & secondary sedimentary structures, which can be used to interpret depositional processes. In addition, each depositional feature produces a unique pore network.

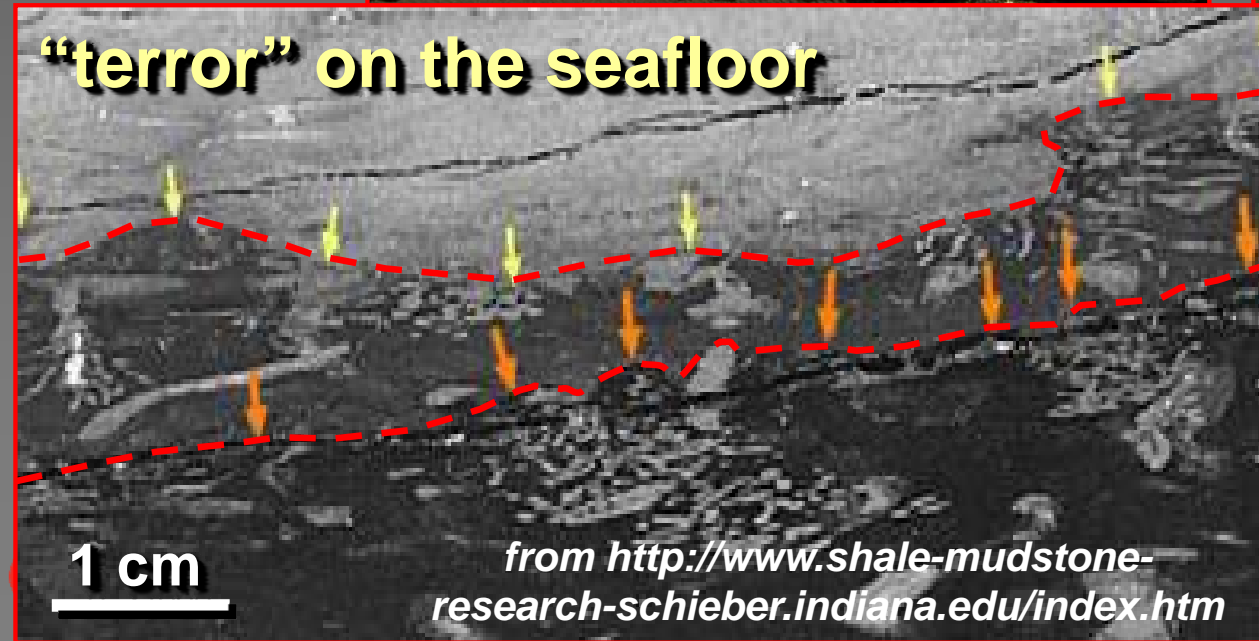
Event Sedimentation



Presenter's notes: Many primary sedimentary structures provide evidence of event sedimentation.



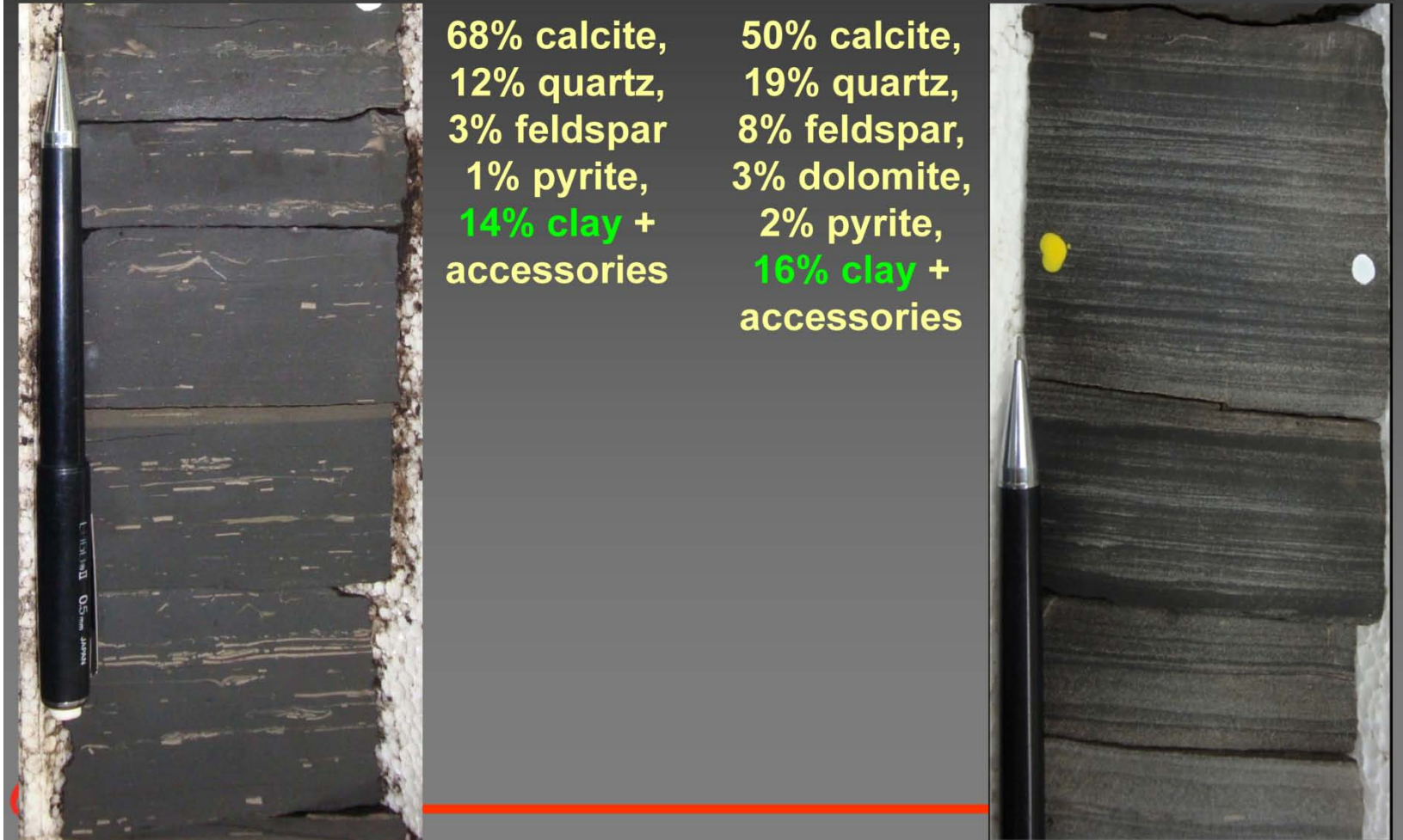
“terror” on the seafloor



from <http://www.shale-mudstone-research-schieber.indiana.edu/index.htm>

**Erosional
Surfaces**

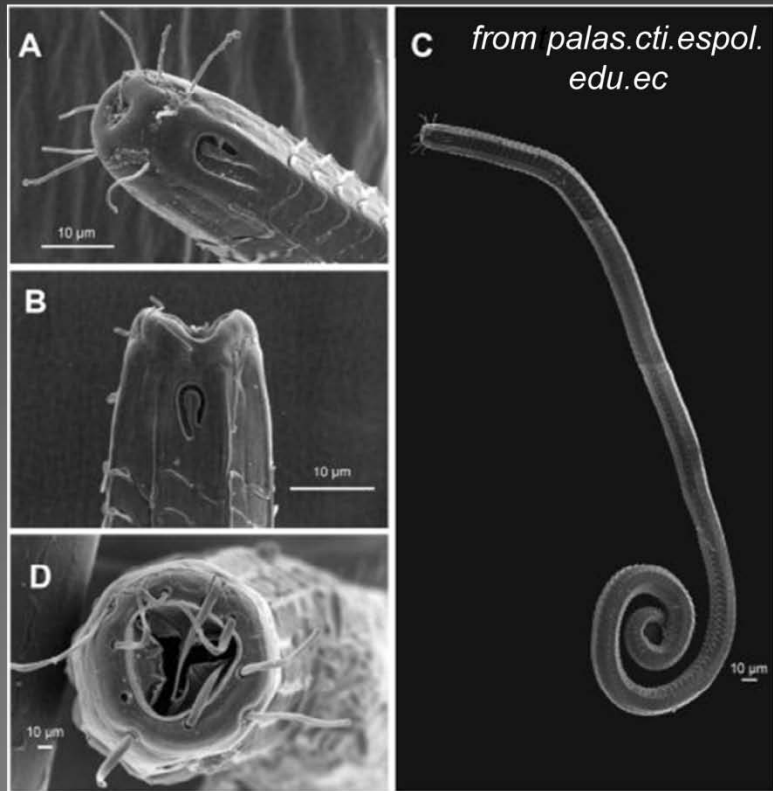
Depositional Fabric Affects Mechanical Properties



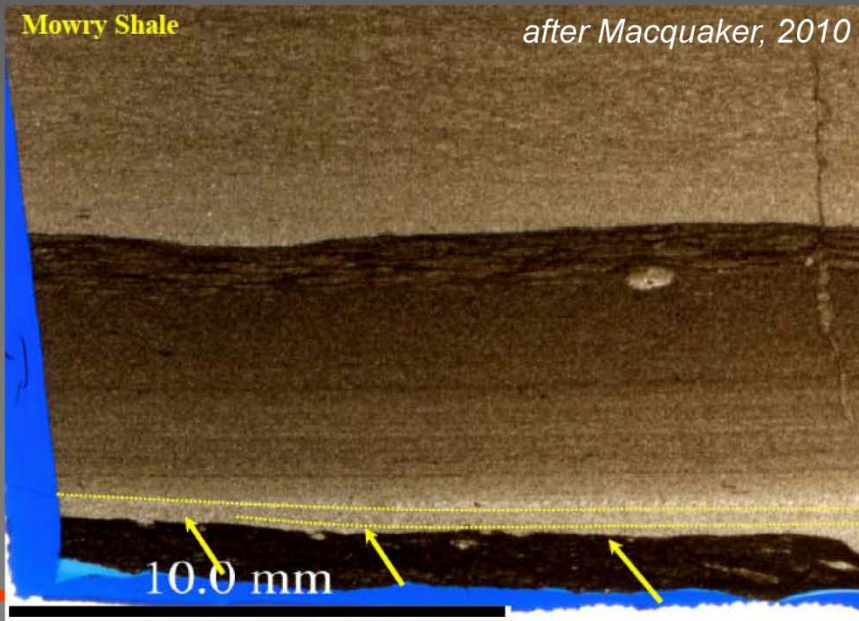
Presenter's notes: XRD data suggest these two intervals from the same formation have comparable percentages of brittle and ductile material, and thus should behave mechanically in a similar manner. However, contrasts in grain types and fabric actually create quite disparate mechanical properties. The sample on the left is from a zone that exhibits "sticking" problems during horizontal drilling; the sample on the right is from the target zone where drilling is much easier, and complex fractures can be produced. Core description helps discern the differences.

Bioturbation

nematodes



polychaetes



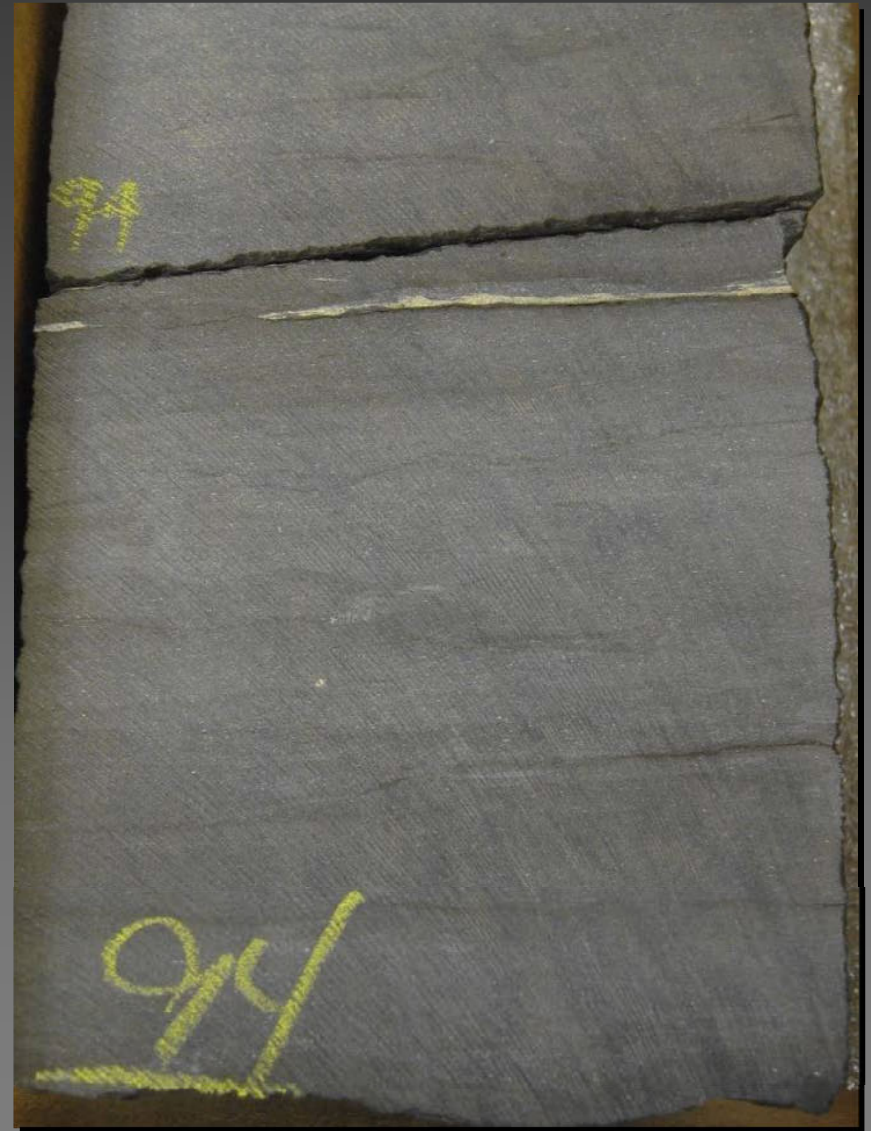
Presenter's notes: In dysoxic to anaerobic environments, large metazoan burrowers (e.g., echinoderms, mollusks, crustaceans) disappear. Two of the more common burrowing organisms in such settings are much reduced in size: nematodes and polychaete worms. Diminutive to cryptic burrows result.

Laminated vs. Burrowed

laminated marlstone



burrowed marlstone



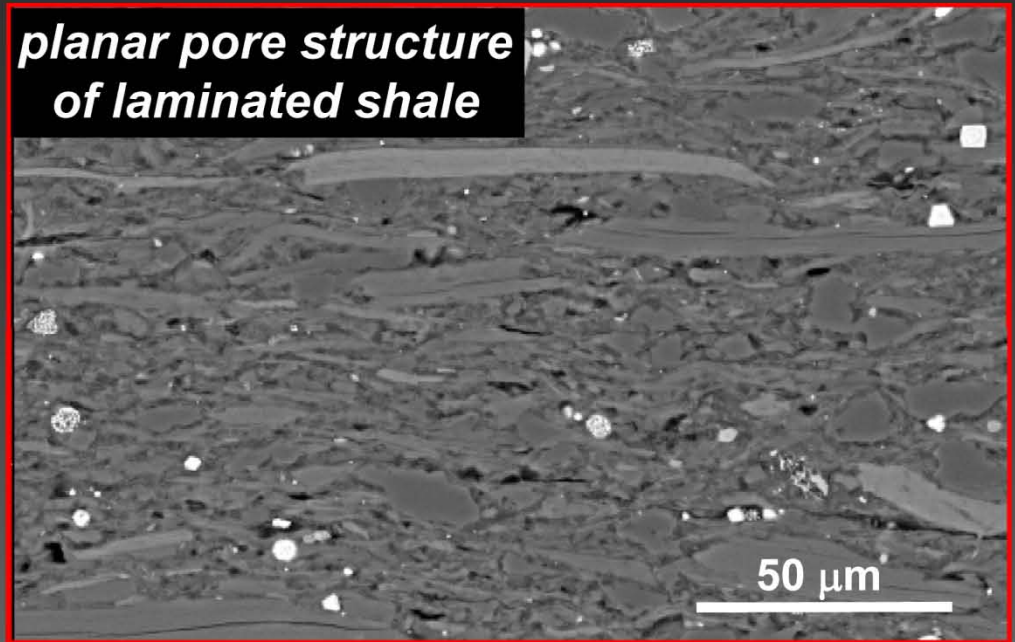
Niobrara Fm. - both provide same well-log response & XRD pattern

Fabric Affects Distribution & Production of Hydrocarbons

from Day-Stirrat, 2010



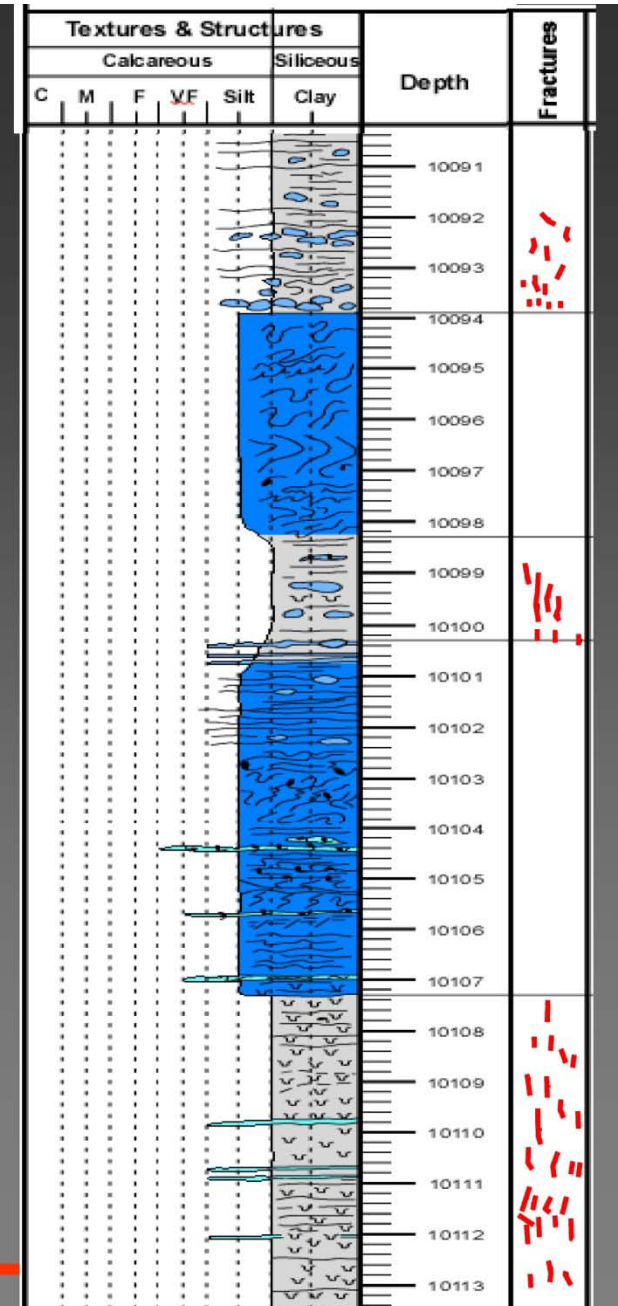
*planar pore structure
of laminated shale*



*open pore structure of
bioturbated mudstone*

Presenter's notes: Contrasting fabrics and resulting pore networks in laminated vs. bioturbated mudrocks, which in turn affect the distribution and production of hydrocarbons.

Composition & Texture Control Mechanical Properties



Presenter's notes: Information on styles, numbers, and lithologic controls on natural fractures can be gathered from core and should be shared with drilling and completion engineers.

Partings/Coring Response - Lithology & Mechanical Properties

Argillaceous (low YM, high PR)



Siliceous (high YM, low PR)



Presenter's notes: A quick examination of the margins of a core and how it breaks can provide qualitative information on lithology and mechanical properties.

Relate Description to Strat Framework

decipher vertical & lateral
cycle variations

identify stratigraphic cycles

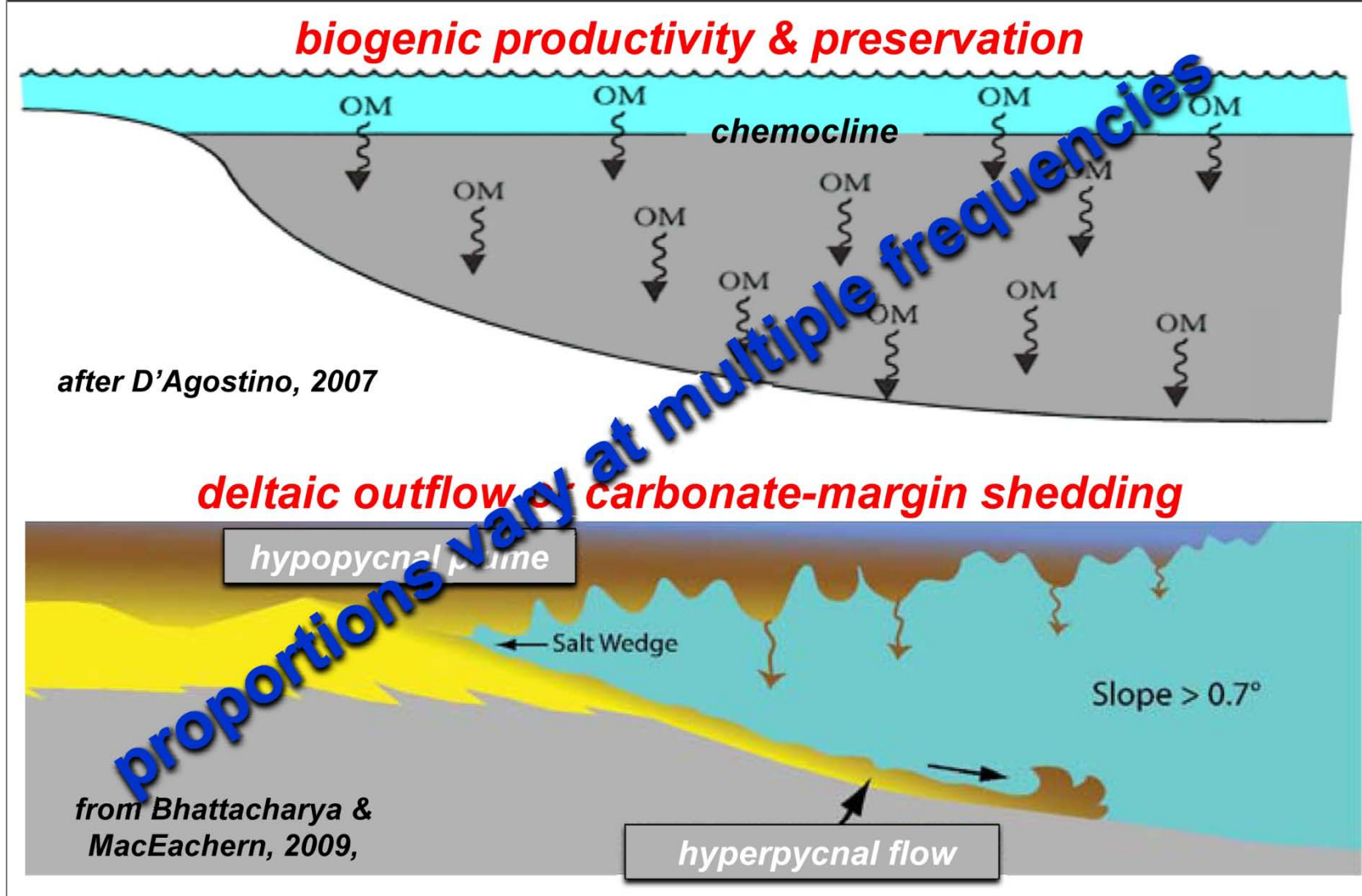
- frequency (high vs. low)
- cycle hierarchy

relate cores to log
patterns (calibration)

ITERATION

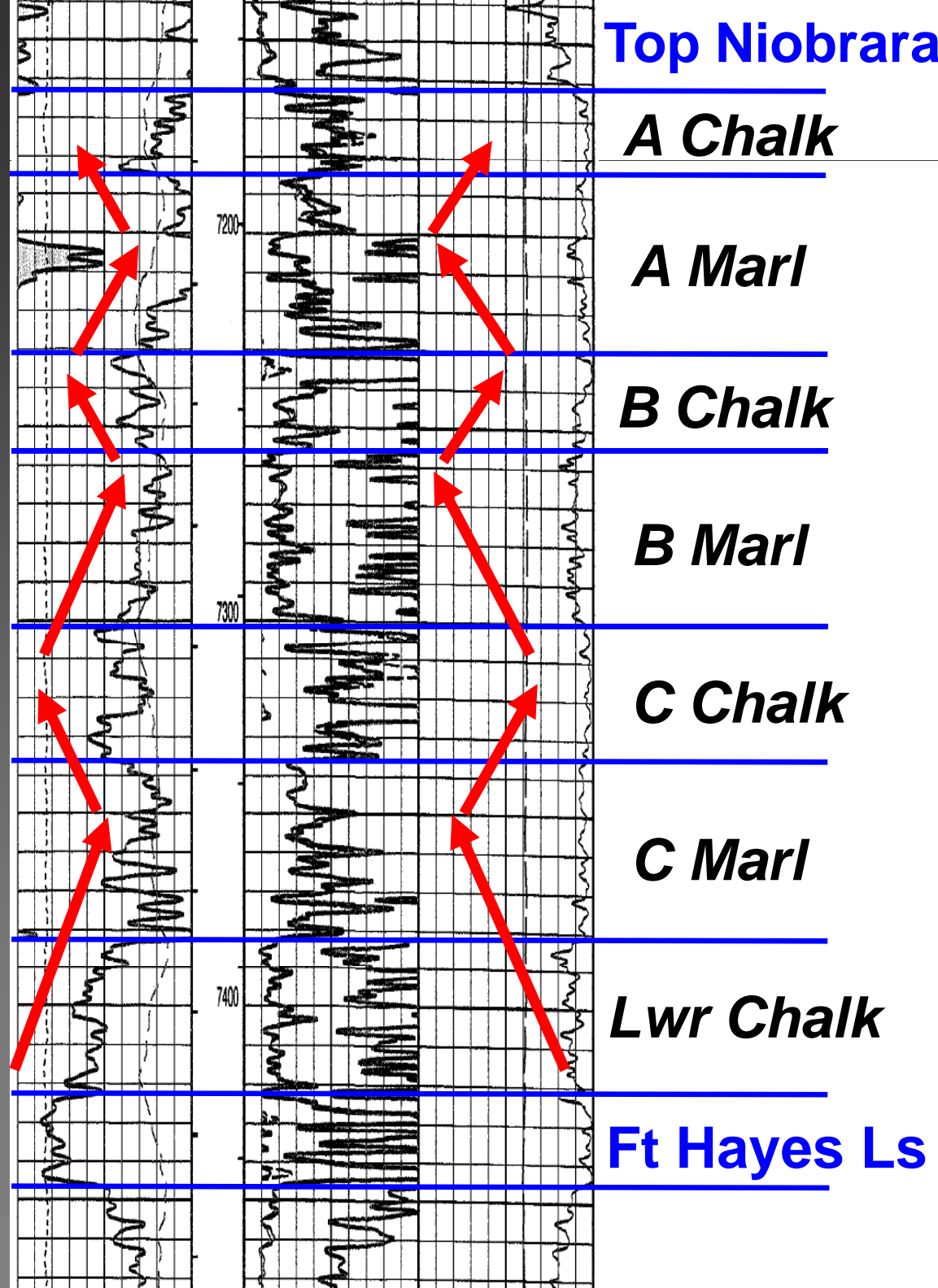


Strat Cycles = Depositional Competition

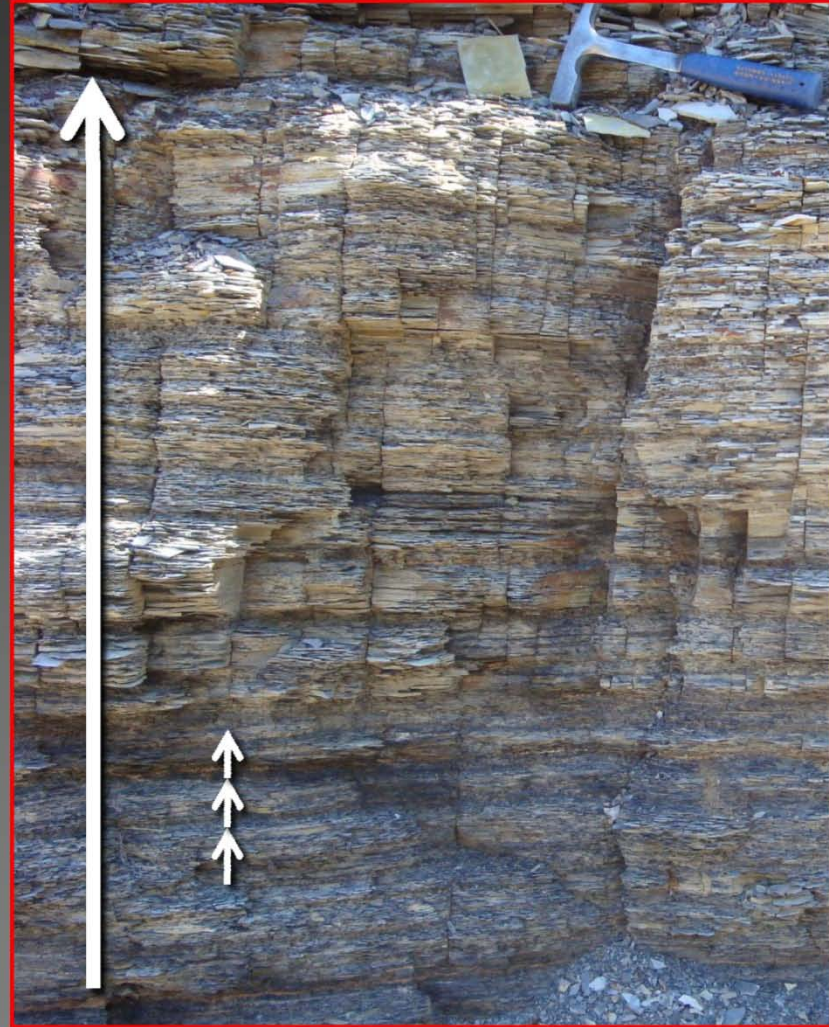


Presenter's notes: Fine-grained material is delivered into the central basin far from the margin by a variety of processes. Deltaic outflow and shedding of materials from carbonate ramps or platforms produce bottom-hugging sediment-gravity flows as well as sediment plumes that float near the water surface. In addition, organic material (from algae, bacteria, pellets, spores, etc.) is produced in shallow water, drops through the sediment column, and, in reducing bottom waters, is preserved.

Stratigraphic Cycles in Logs = Biogenic Fallout vs. Dilution by Clays



Stratigraphic Cycles on Outcrop



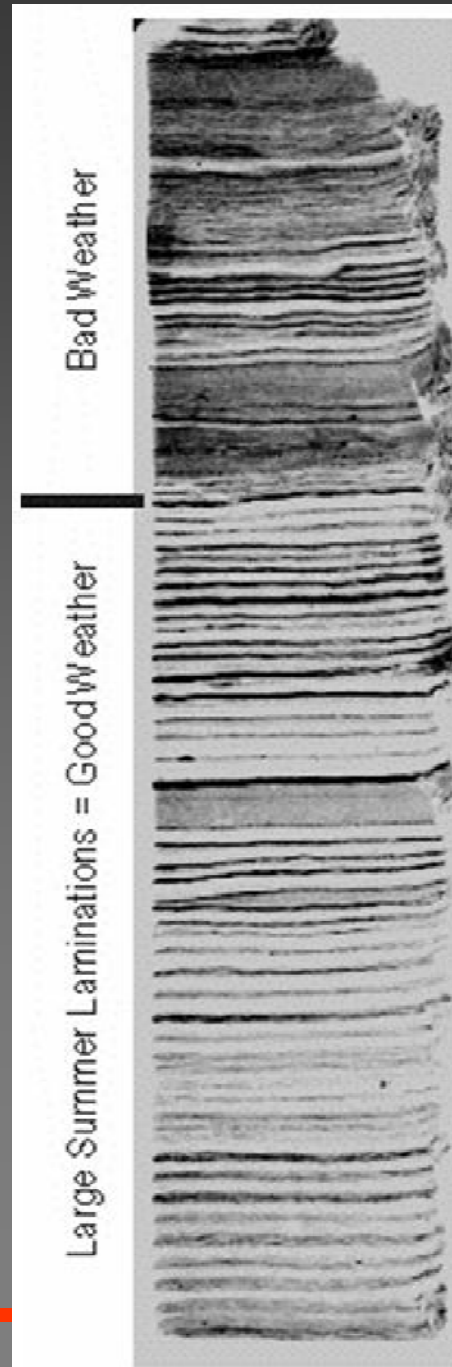
Stratigraphic Cycles in Core

Offshore Vancouver Island

light layers =
summer diatom
blooms

dark layers =
winter terrigenous
influx (heavy
rainfall)

from http://sst-ess.nrcan-nrcan.gc.ca/2002_2006/rcvcc/j27/2_2_e.php

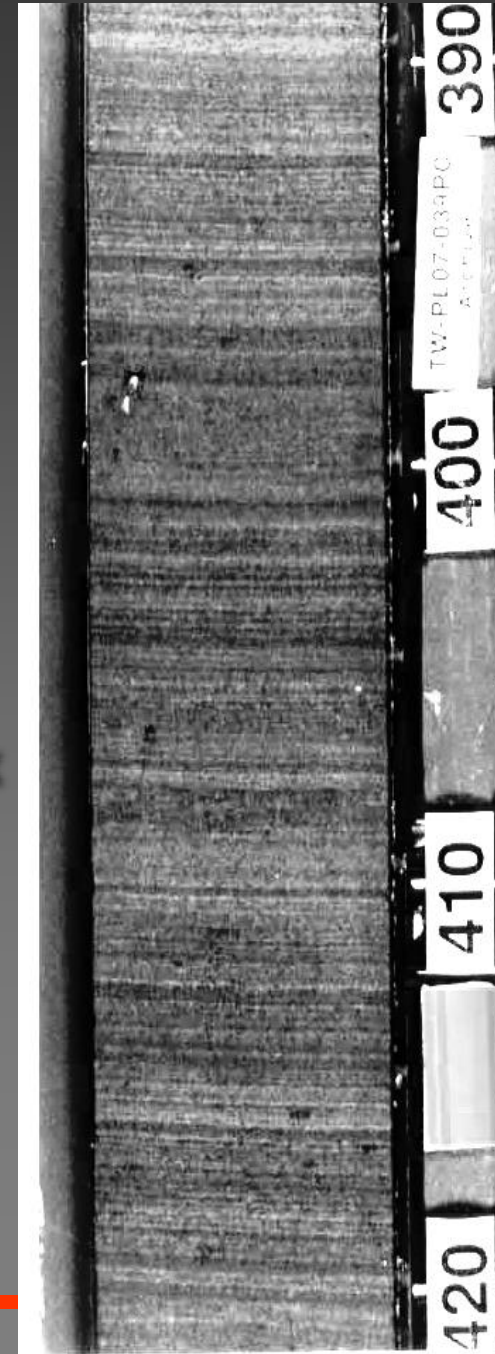


Cariaco Basin

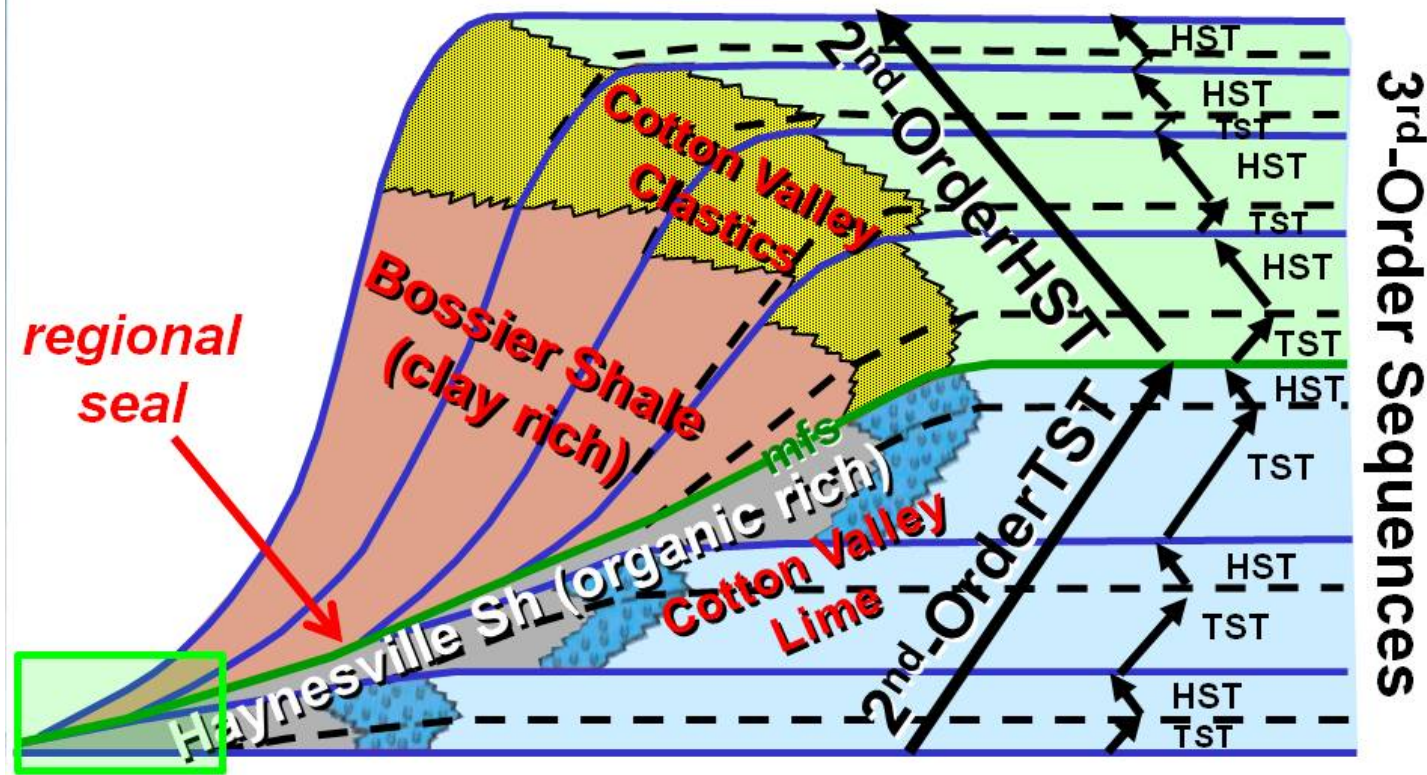
light layers =
winter & spring
diatom blooms
(upwelling)

dark layers =
summer
terrigenous influx
(heavy rainfall)

from <http://www.ncdc.noaa.gov/paleo/pubs/lea2003/lea2003.html>



Hierarchy of Cycles - Haynesville/Bossier



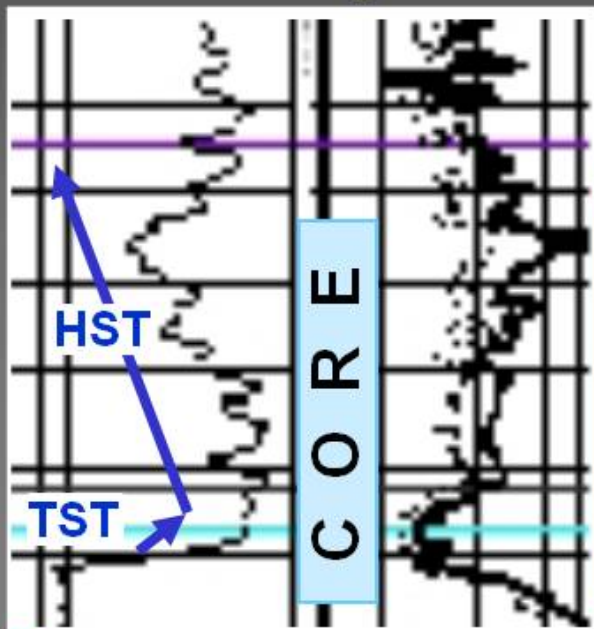
after Goldhammer, 1999

Presenter's notes: The Haynesville-Bossier stratigraphic system represents a 2nd-order transgression (Haynesville Shale and Cotton Valley lime) followed by a 2nd-order highstand (Bossier Shale and Cotton Valley clastics). We see similar paired intervals of a transgressive systems tract overlain by a highstand systems tract in a variety of mudstone systems, e.g., the Muskwa-Ft. Simpson, Mowry-Belle Fourche, Niobrara-Pierre, Barnett-Marble Falls, etc.

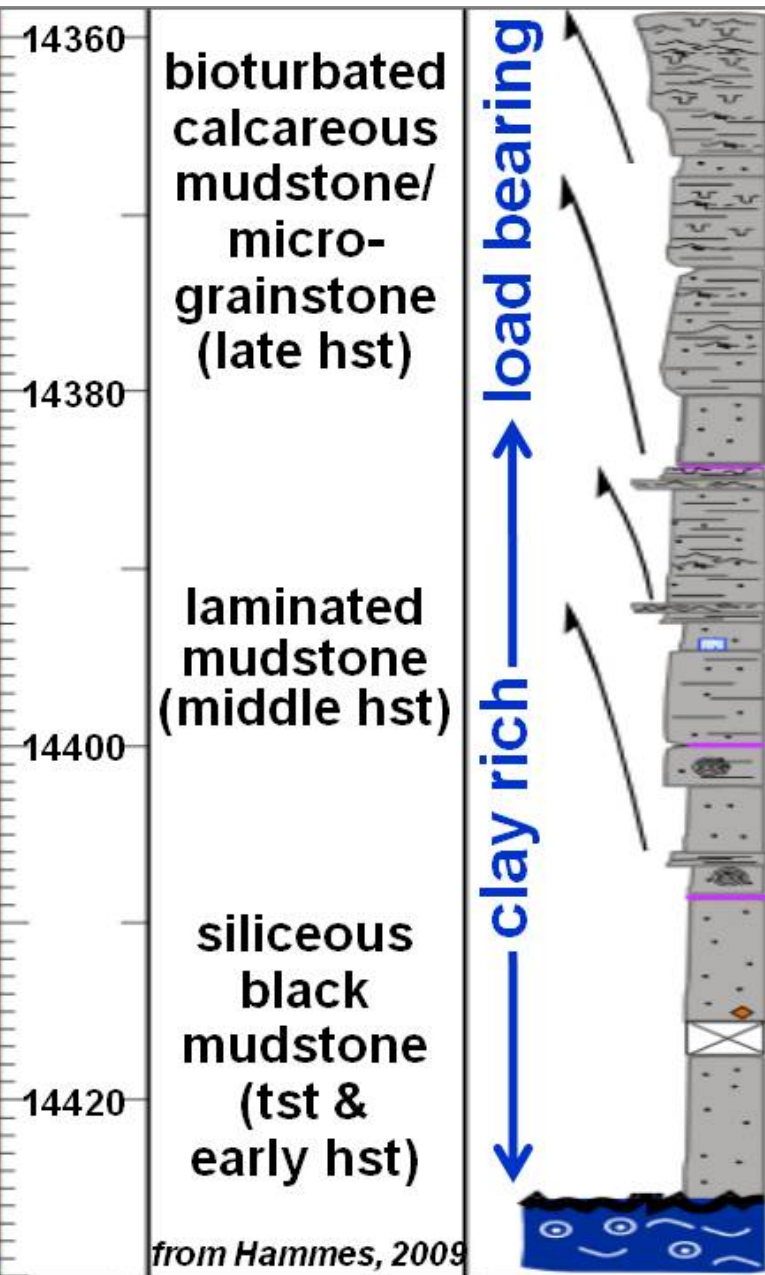
Note that at the turnaround from 2nd-order transgression to highstand, a regional maximum-flooding surface (condensed section) is developed. In many basins, unless breached by faulting or erosion, this interval forms a regional seal with normal pressure above and overpressure below. The green box outlines the distal portion of this depositional system, the area where our mudrock reservoirs typically are found. When the 3rd-order transgressive and highstand systems tracts are added to the picture, note that the distal (most basinal) position is dominated by the higher frequency highstand packages.

Third-Order Cycles Control Reservoir/Targets

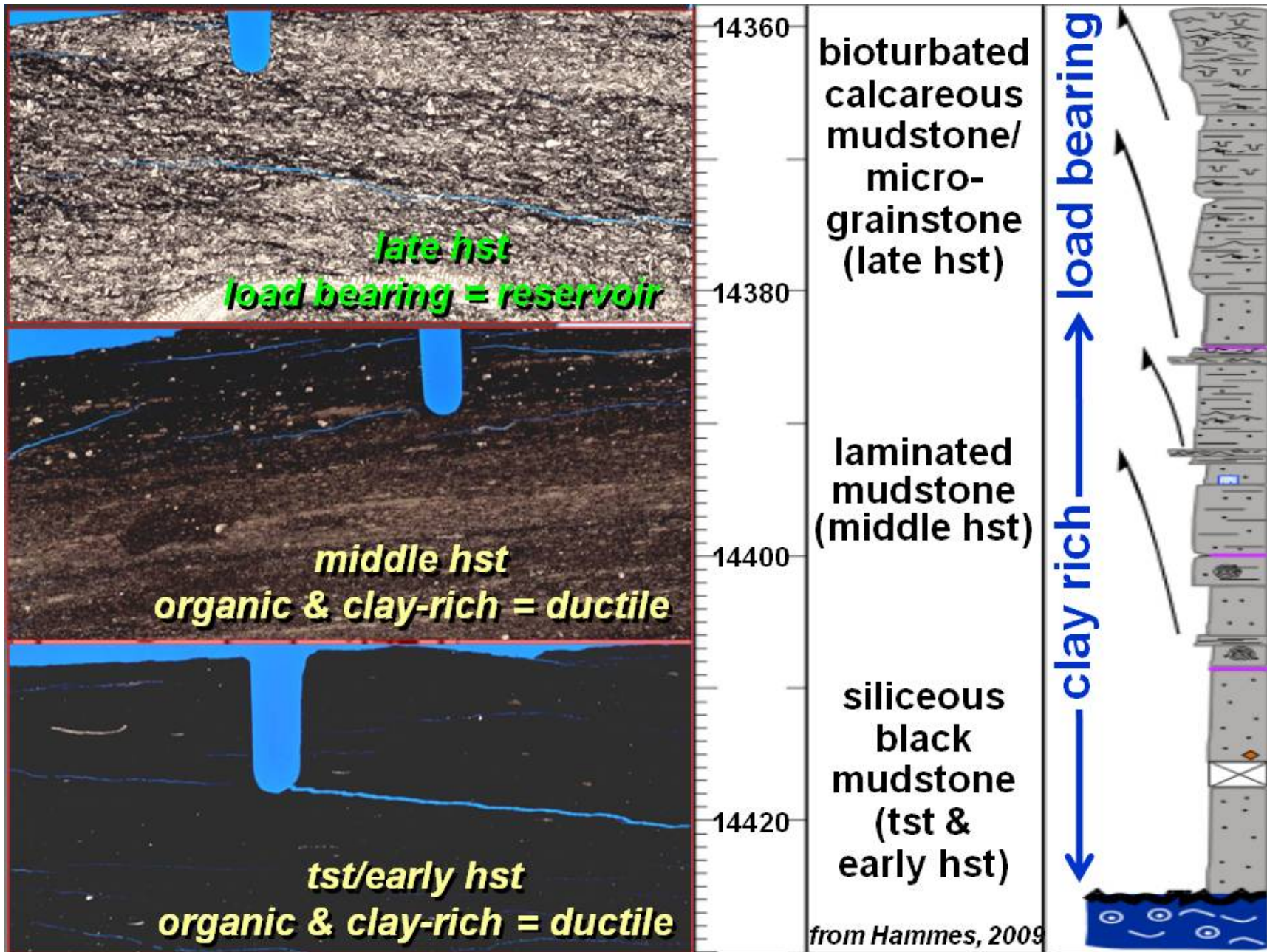
Shell Temple #1



 **eogresources**



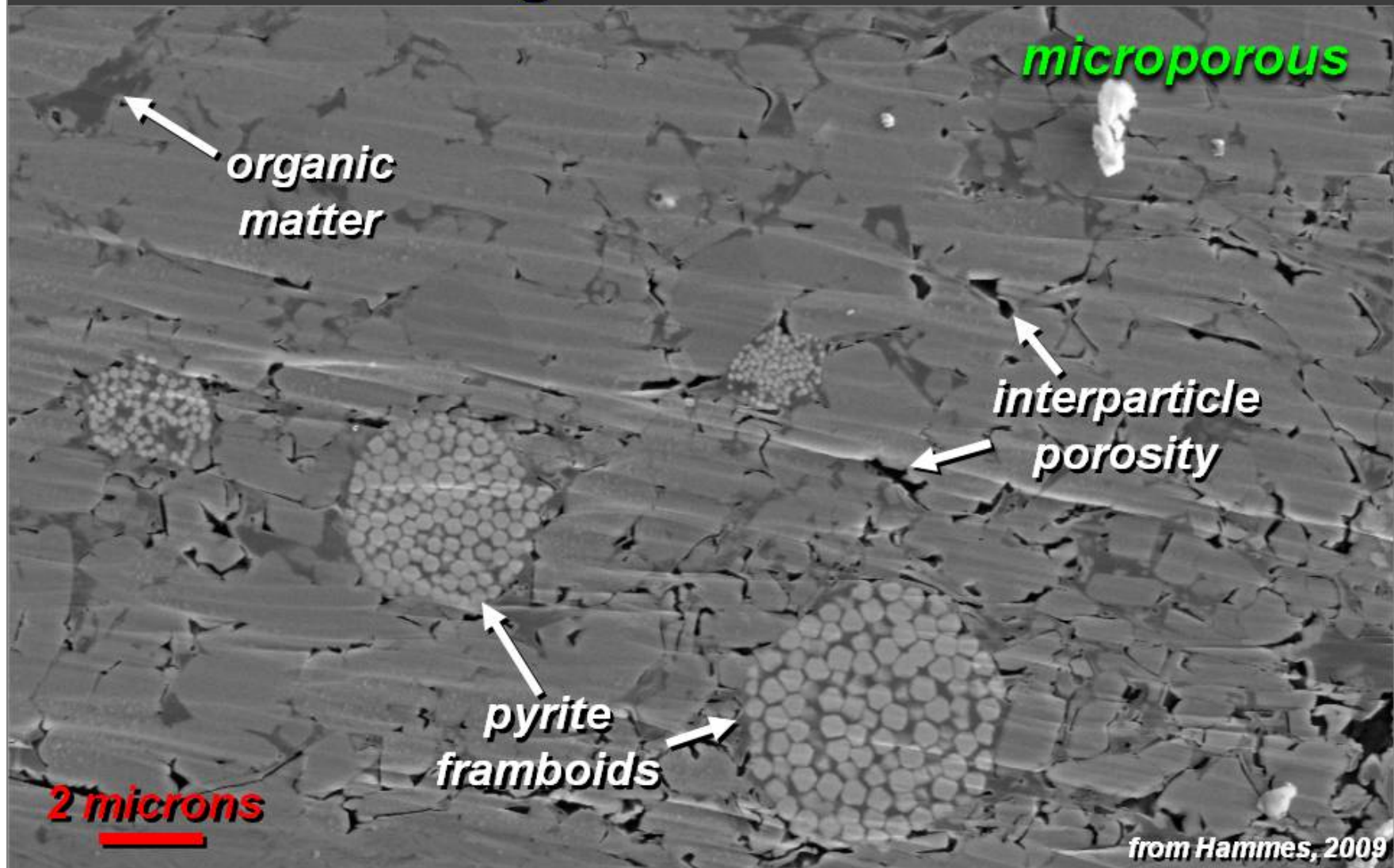
Presenter's notes: Log and core example of a third-order transgressive to highstand package in the Haynesville-Bossier system. Note the vertical change in lithology and fabric related to systems tract.



Presenter's notes: Representative thin sections from the cored example of a third-order transgressive to highstand package. Note the vertical change in lithology and fabric related to systems tract.

Bioturbated Carbonate Mudstone

– Late Highstand = Reservoir



Presenter's notes: SEM of an argon-ion-beam milled sample of Haynesville bioturbated carbonate mudstone. Pore throats are on the order of $\frac{1}{4}$ micron – which falls in the realm of tight sandstone reservoirs (see figure later adapted from Nelson, 2009).

Relate Description to Strat Framework

identify stratigraphic cycles

relate cores to log patterns (calibration)

- log “markers”
- stacking patterns
- basinal correlation

ITERATION

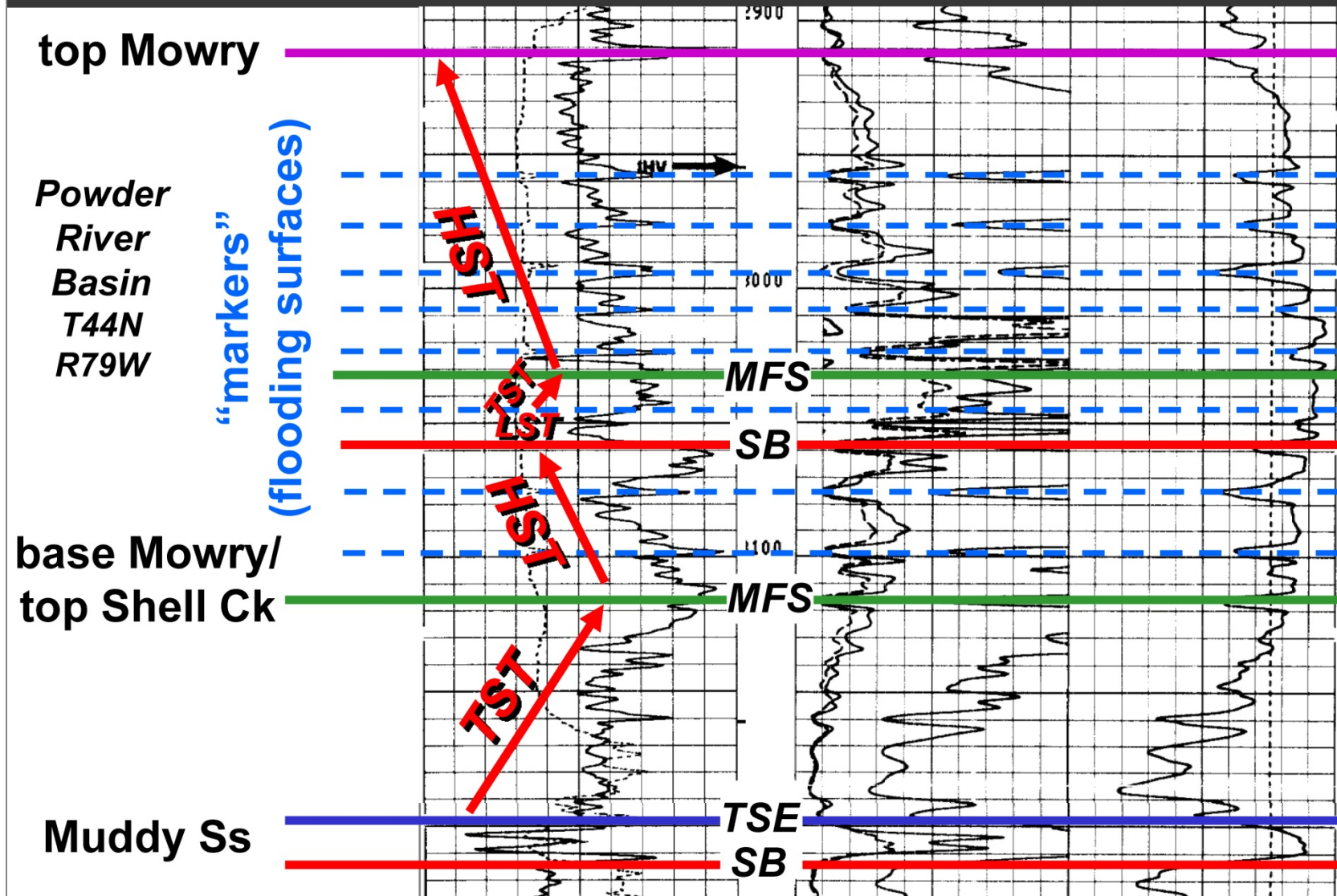
decipher vertical & lateral cycle variations



Core Calibration to Log

What do “log markers” represent & which are most important?

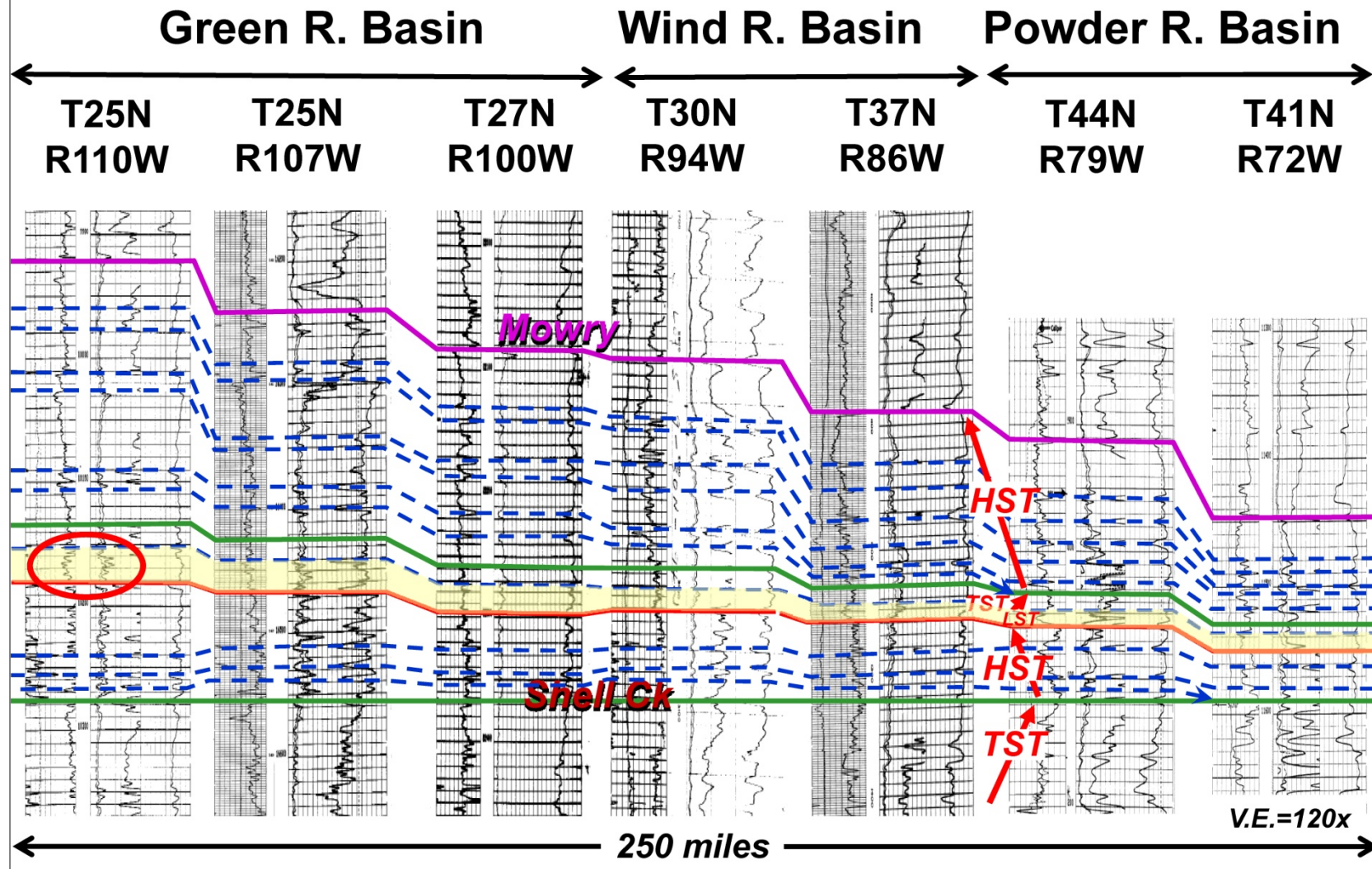
Parasequences & Stacking Pattern (Sequences)



Presenter's notes: This example of a Mowry Shale log from the Powder River Basin shows changes in gamma-ray, resistivity, and conductivity. As in shallow-water environments, the high gamma-ray/low-resistivity spikes can be interpreted as flooding surfaces (in this case, with concentrations of bentonite). Then, using basic concepts of sequence stratigraphy, the stacking patterns of the parasequences between the flooding surfaces can be interpreted as to their corresponding systems tracts.

Presenter's notes: Basins do not fill like bathtubs. Instead, margins build out into the basin (producing clinoforms). Here is a flattened seismic line with an interpretation of clinoforms from the Woodford and an accompanying line drawing of the interpreted facies distribution.

Mowry Regional Stratigraphy



Presenter's notes: Utilizing the concept of subtle clinoformal deposition, flooding surfaces and systems tracts of the Mowry can be correlated across Wyoming for over 250 miles, from the La Barge Platform on the left to the central Powder River Basin on the right. Note downlap onto the interpreted maximum flooding surfaces. A silt-rich zone present in the middle Mowry in the Powder River basin, interpreted as a lowstand package, correlates to a distinct shoreface regression that is sandwiched between clay-rich intervals on the La Barge Platform.

Relate Description to Strat Framework

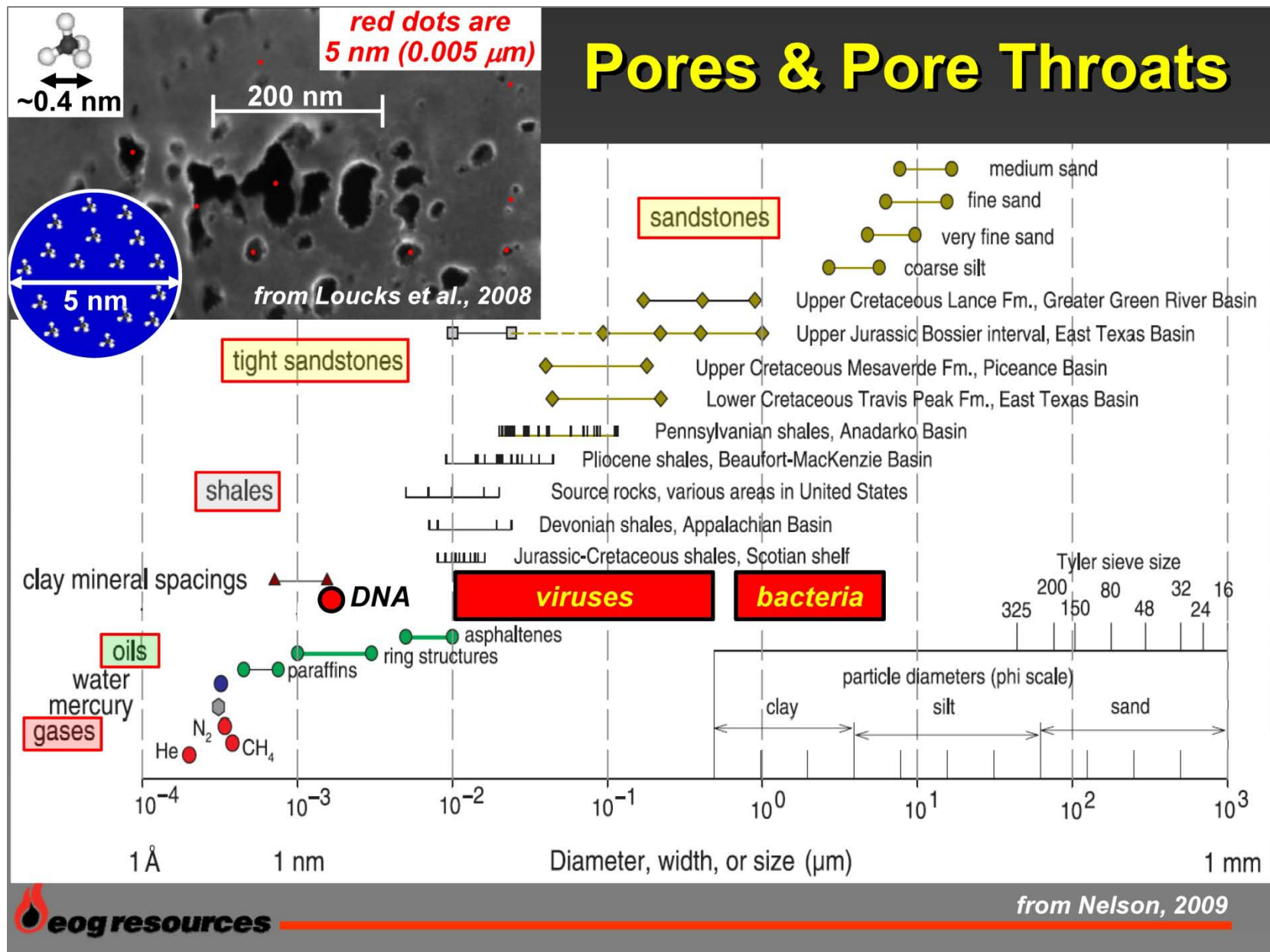
relate cores to log
patterns (calibration)

decipher vertical & lateral
cycle variations

- reservoir quality
- mechanical stratigraphy

ITERATION

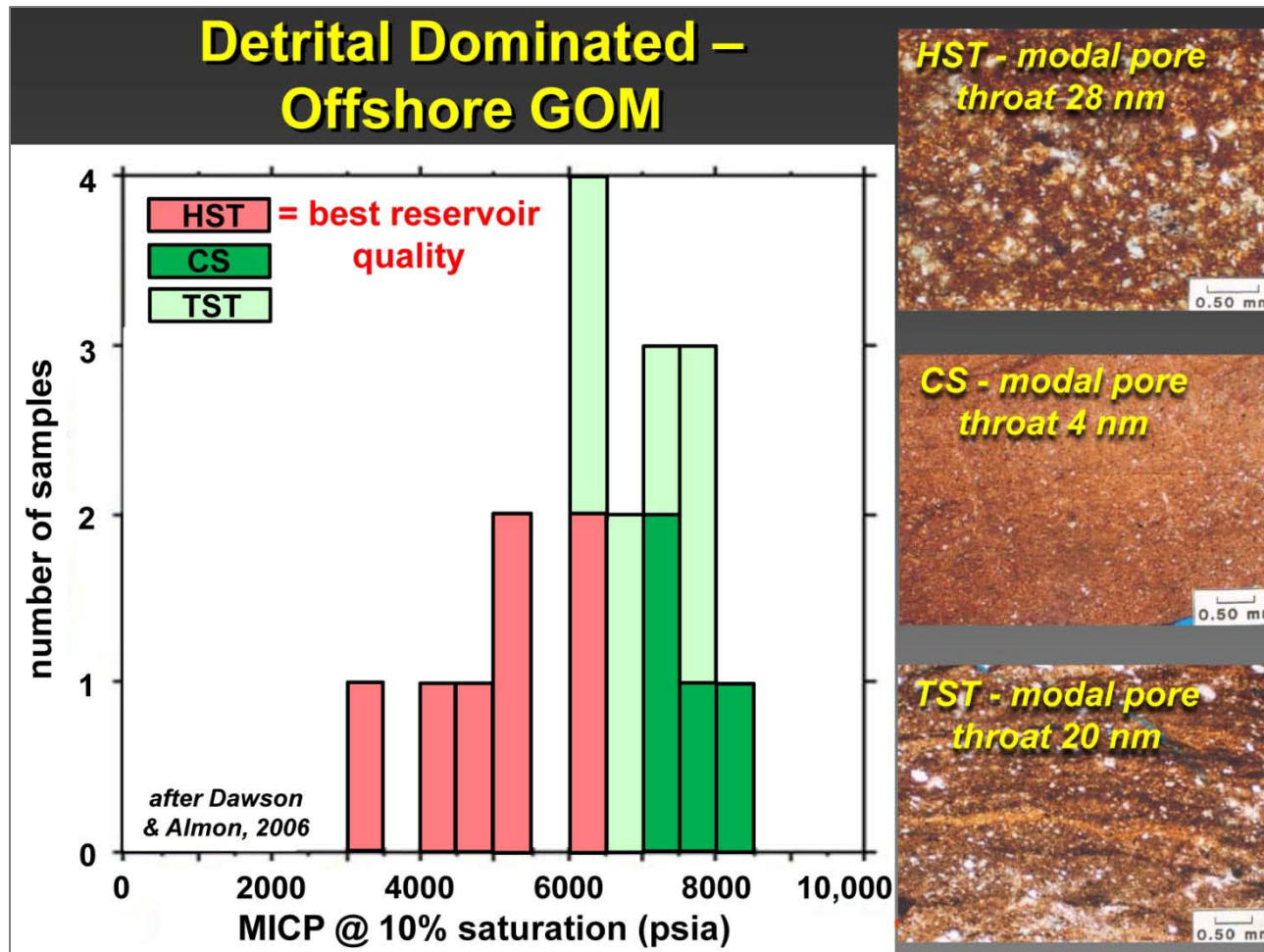
identify stratigraphic
cycles



Presenter's notes: Pore and pore-throat sizes are key components of reservoir quality. Typical sizes of pore throats for sandstones and shales are compared to diameters of clay, silt, and sand, and to molecular sizes of various oils, gases, water, and mercury. Scales of bacteria, viruses, and DNA help provide a frame of reference. SEM of an argon-ion-beam milled sample, exhibiting variations in pore size in kerogen from the Barnett, is also shown.

General Observations

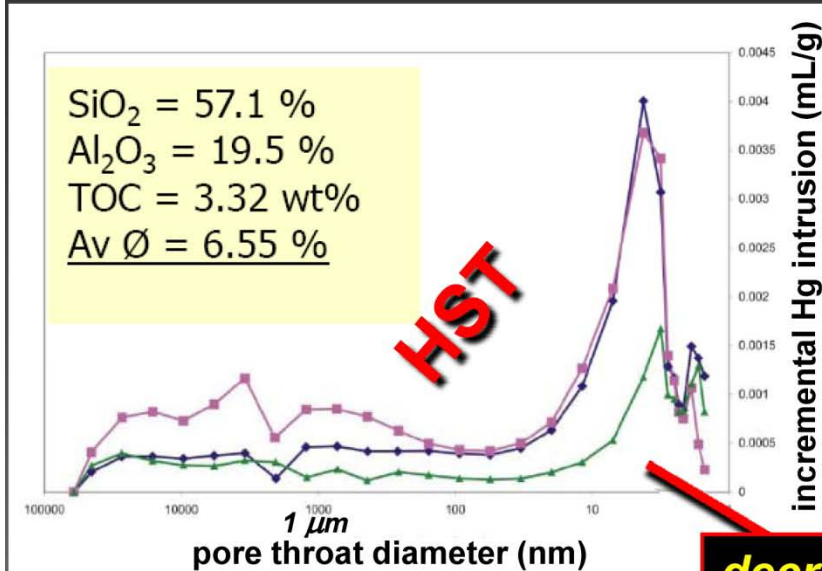
- intervals with **load-bearing, brittle framework AND large pores** provide the best reservoirs
- **input dominantly detrital:** high-frequency highstands & lowstands often contain most load-bearing **grains**
 - highstand or lowstand silica influx (detrital clay & silt)
 - highstand carbonate influx (from platform margin)
 - lowstand carbonate influx (eroded terrain)
- **input dominantly biogenic:** high-frequency condensed sections can be the best reservoirs
 - siliceous or calcareous **skeletal framework**
 - associated **organics**



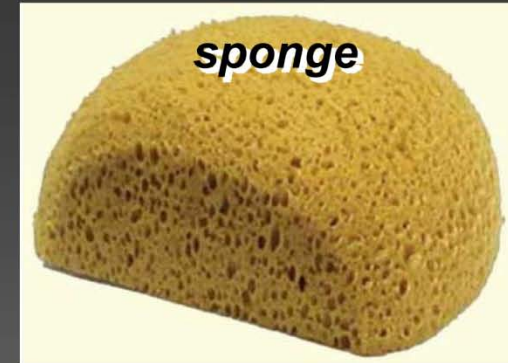
Presenter's notes: Abundant data on pore throats in mudrocks come from offshore Brazil, W. Africa, the North Sea, and Gulf of Mexico – where mudrocks have been analyzed for their sealing capacity in oil systems. For our purpose, we can look at the reciprocal of this – reservoir character of these mudstones based on pore-throat distribution.

In this example from the Tertiary of the offshore Gulf of Mexico, laminated mudstones of the transgressive systems tract have a modal pore-throat size of 20 nm; carbonaceous claystones of the condensed section have a modal pore-throat size of 4 nm, and bioturbated silty mudstones of the highstand have a modal pore-throat size of 28 nm. Mercury-injection capillary-pressure data for these samples indicate 3 distinct mudstone populations. Samples from the condensed section require the highest pressures to create a continuous thread of mercury extending through the sample (i.e., at 10% saturation) – supporting this interval as having the smallest pore throats. Samples from the highstand systems tract show the lowest pressures required to get 10% saturation – signifying that this unit contains the largest, most interconnected pore throats. Samples from the transgressive systems tract display intermediate pressures required for 10% saturation.

Biogenic Dominated – Muskwa Fm



**low YM,
high PR**



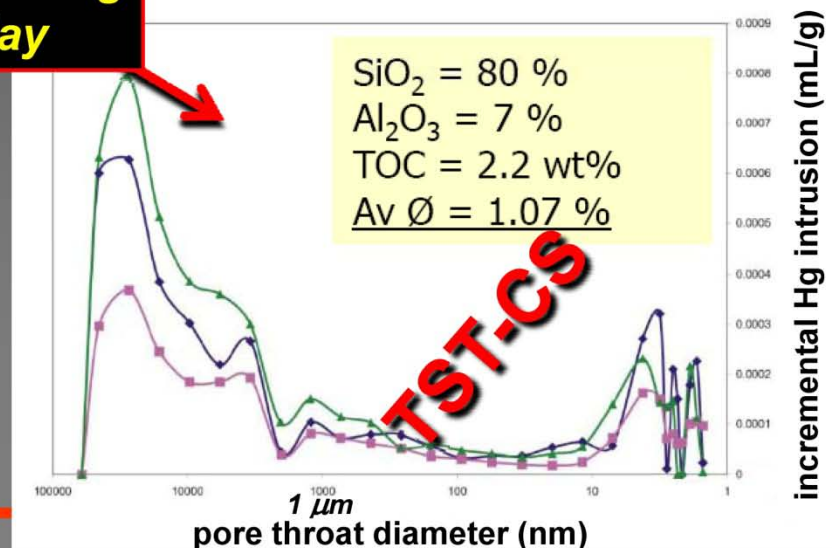
**decreasing
clay**



**high YM,
low PR**

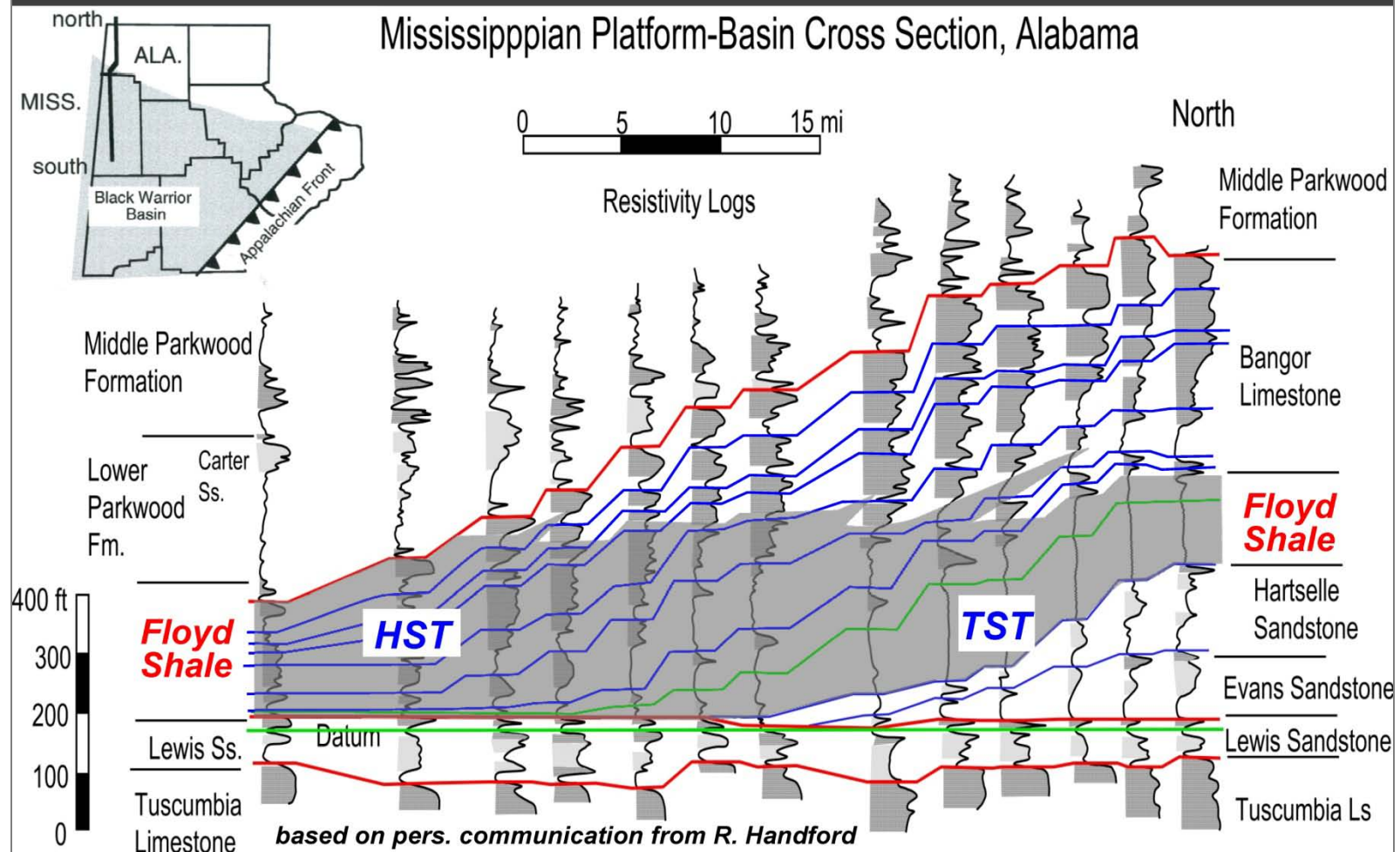


from Bustin et al., 2008



Presenter's notes: Muskwa MICP data from the published literature indicate that mixed clay-biogenic silica systems have a bimodal pore-throat distribution. Very large pore throats - but low porosity - dominate the most silica-rich (hence, strong and brittle) intervals. The smaller pore-throat mode dominates the clay-rich sections, which have the best porosity but are expected to act as "sponges" with low strength and higher ductility.

Sequence Stratigraphic Framework – Why It Makes A Difference



Presenter's notes: A chronostratigraphic (sequence stratigraphic) correlation shows that the Floyd Shale (a lithostratigraphically defined unit, highlighted in gray) encompasses two distinct systems tracts. To the north, it dominantly comprises a transgressive, clay-rich interval. Flooding surfaces that cap parasequences in the Bangor Limestone on the north can be extended southward into the Floyd Shale, where it consists of a distal, calcareous highstand package. Typical sampling and mapping of the Floyd Shale do not separate these systems tracts. "Lumping" of the changing composition, reservoir character, and mechanical properties across the maximum flooding surface (green line) is similar to comparing apples to oranges.

Conclusions

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- **calibration of core to log aids interpretation of sequence stratigraphy**
 - flooding surfaces
 - stacking patterns
 - parasequences
 - cycle hierarchy

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- **mudrock composition & texture highly variable**
- **composition & texture control reservoir & mechanical properties**
- **composition & texture vary systematically with sequence position**
- **calibration of core to log aids interpretation of sequence stratigraphy**
 - flooding surfaces
 - parasequences
 - stacking patterns
 - cycle hierarchy
- **integrate facies & sequence framework to target reservoir & understand lateral & vertical changes**