PS Evaluating the Impact of Mineralogy on Reservoir Quality and Completion Quality of Organic Shale Plays*

Helena Gamero Diaz[1], Camron Miller[2], Rick Lewis[1], and Carmen Contreras Fuentes[1]

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Abstract

Geochemical logs are fundamental to the evaluation of organic shale plays because they provide mineralogy among other measurements necessary for the petrophysical and geological evaluation of these complex reservoirs. Mineralogy impacts reservoir quality (RQ) and completion quality (CQ), which ultimately governs shale well performance. sCore is a ternary-based classification scheme for organic mudstones that will be used in this paper to define relationships between mineralogy, RQ and CQ within various U.S. shale plays. Ternary plots are useful for discriminating rock types based on normalized proportions of three main end members: i) clay; ii) carbonate; and iii) quartz, feldspar, and mica. When shale RQ parameters, such as effective porosity, total organic carbon (TOC) content, matrix permeability, hydrocarbon saturation, etc., or CQ parameters, such as minimum closure stress, Thomsen's gamma, Mineral Brittleness Index (MBI), etc. are plotted on an sCore ternary diagram, one can make observations as to how mineralogy is impacting RQ and CQ in a particular shale play. The identification of lithofacies having superior RQ and CQ is important information for identifying 'sweet spots' and targeting both vertical and horizontal well completions. A strong correlation exists between mineralogy and CQ in most U.S. shale plays. More specifically, minimum closure stress, Thomsen's gamma and MBI appear to be driven by the mineralogy of organic mudstones. The correlation between mineralogy and RQ is not as strong. Organic mudstones have complex mineralogy, consisting of a mixture of intrabasinal and extrabasinal sources of siliciclastic and/or carbonate debris, affected by diagenetic processes, resulting in highly heterogeneous rocks especially in the vertical direction. RQ in U.S. shale plays appears to be driven by both compositional and textural components of organic mudstones. RQ, as determined by other data types, can be compared to the sCore ternary to aid in interpretation of sediment source. For example, low correlation between effective porosity and silica content may imply dilution via terrigenous input, while a high correlation indicates minimal dilution and rock that is more desirable.

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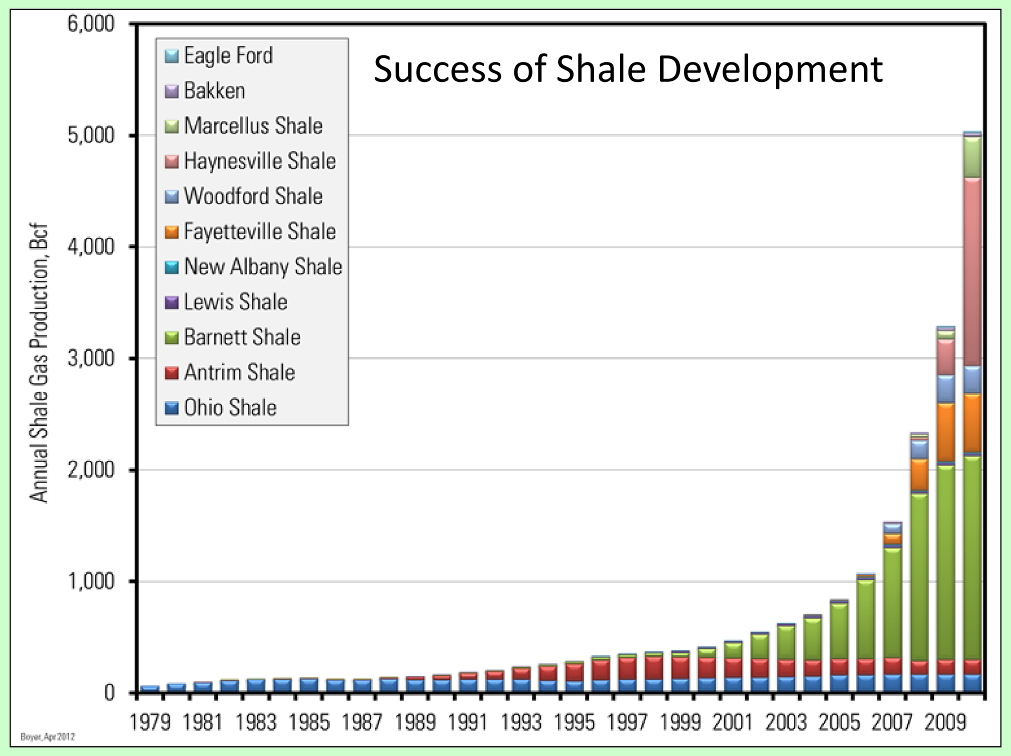
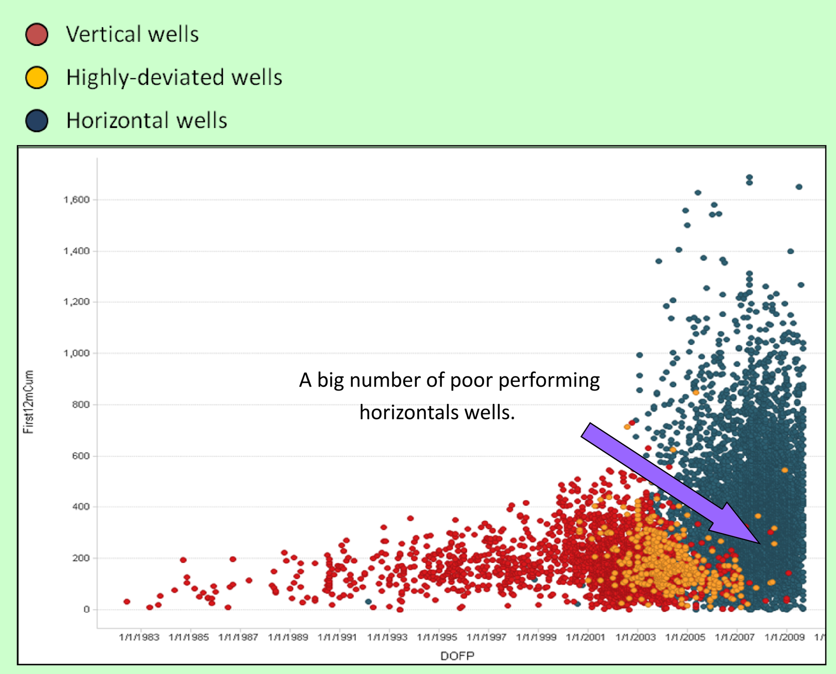
Introduction



Annual shale gas production (BCF) per year and the contribution from the main US Shale Plays (Courtesy slide from C. Boyer, 2012).

Implementing Horizontal Drilling + Multistage Stimulations is not enough to guarantee a good well

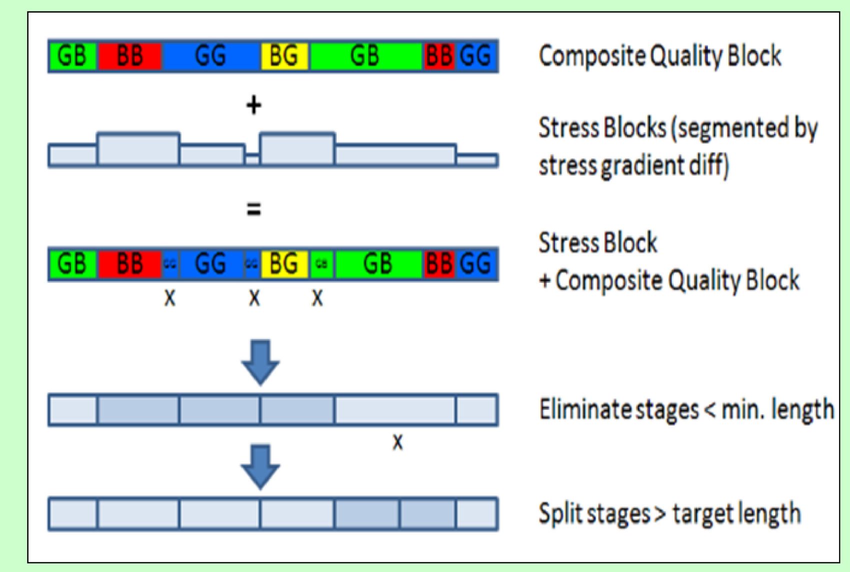


(IHS Database)

Target zone with superior RQ and CQ is the key to optimize shale production

Main Objective

Evaluate the impact of Mineralogy/Composition on Reservoir Quality (RQ) such as Effective Porosity (PIGN), Total Organic Carbon (TOC), and Completion Quality (CQ) properties such as Minimum Closure Stress (TXSG) and Thomsen Gamma (γ).



(from Cipolla et al., 2011)

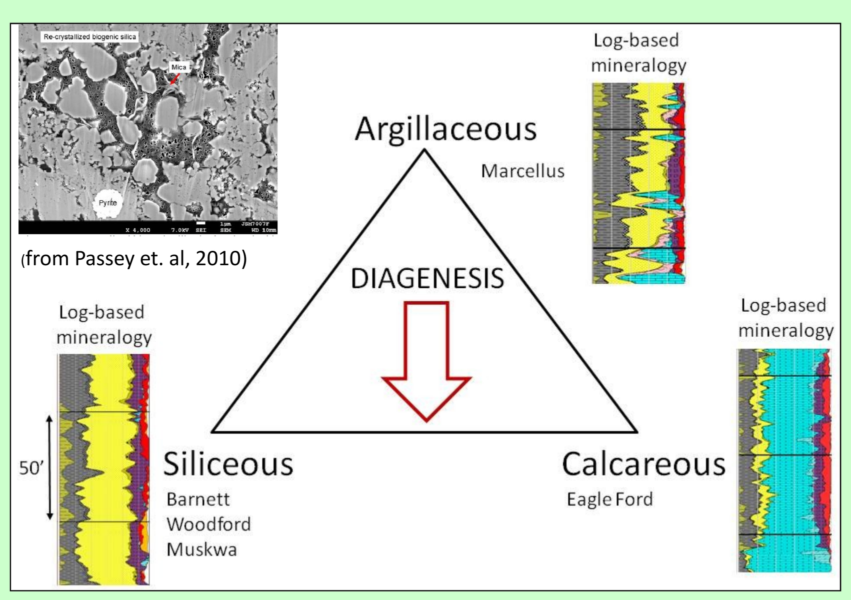
Mineralogy of Organic Mudstones is a key control on Reservoir and Completion quality.

Need of a Classification for Organic Mudstones

Organic Mudstone Definition

Fine grained sedimentary rocks with elevated total organic content (TOC), above 2%, composed of three different constituents: A) fine grained matrix composition (less than 4 microns), B) Floating silt-size grains (less than 62.5 microns) of detrital and/or biogenic origin, and C) organic matter.

A) A fine grained material (< 4 microns) composed of authigenic components, organics and clays and defined as the matrix composition.



Argillaceous Mudstone:

Dominated by clay-minerals (illite, illite-smectite, kaolinite, chlorite and smectite) originated from weathering of rocks and minerals and volcanic ash.

Siliceous Mudstone:

Dominated by microcrystalline quartz ("chert") filling intergranular pores and/or intragranular pores within skeletal remains, and bio siliceous particles (i.e., remains of foraminifera, radiolarians, tasmanites, sponge spicules, etc.)

Carbonates Mudstone:

Dominated by carbonates minerals, microcrystalline calcite, (micrite), crystalline quartz (sparite) and carbonate allochems (i.e., fragments of fossils, peloids, etc).

(B) Variable amounts of silt-size floating grains of both biogenic and /or detrital and/or volcanic in origin

Detrital derived (also called terrigenous, allochthonous or extrabasinal) are fine-grained components product of physical and chemical weathering of soils and/or from un-roofing older rocks:

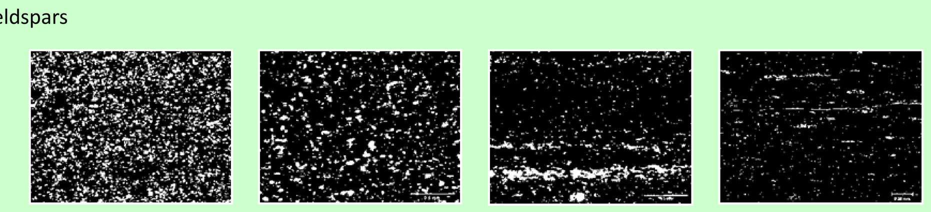
a) Quartz, feldspars, and
b) Terrigenous (kerogen Type III) organic matter.

Biogenic derived (also called production-derived, autochthonous, intrabasinal) are those originated in the photic zone and in the water-sediment interface in the basin floor:

a) Skeletal remains of plankton (i.e., coccolithophores, radiolaria, foraminifers, diatoms), and carbonate mud from lagoons
b) Macro organisms skeletal remains such as carbonaceous algae, sponges spicules, whole shells, shell debris and finely comminuted hash.
c) Non-skeletal, organic material (kerogen Type I and II) derived from soft body-organisms.

Volcanic derived (volcanic ash)

a) Quartz, feldspars

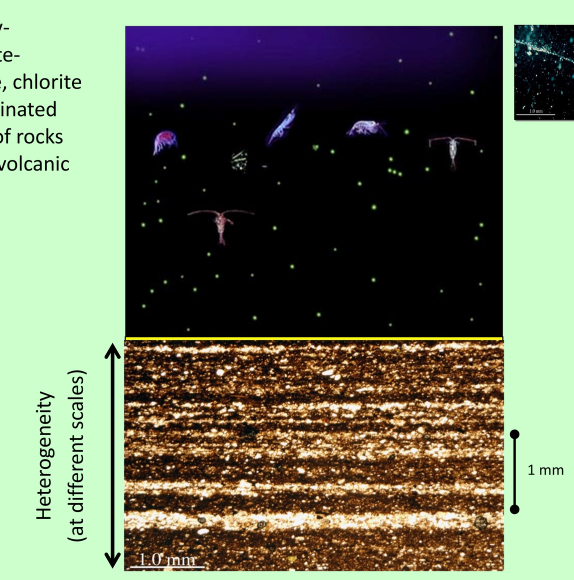


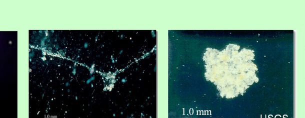
> 2/3 Silt (Siltstones) | 1/3 to 2/3 Silt (Mudstone) | >2/3 Clay (Claystone)

Decrease in amount of silt-size grains content

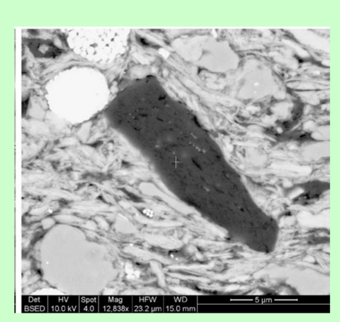
(C) Organic Matter

a) Terrestrial material/ Continental origin (Kerogen type III). Defined as particulate organic matter (Milliken et al., 2012).
b) Algae and soft-body planktonic –derived organic matter (Kerogen type I and II). Defined as dispersed organic matter filling the intergranular / intercrystalline space (Milliken et al. 2012).





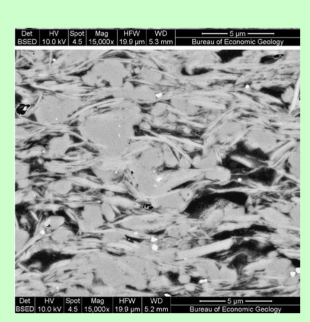
Organo-mineralic aggregates ("Marine Snow")

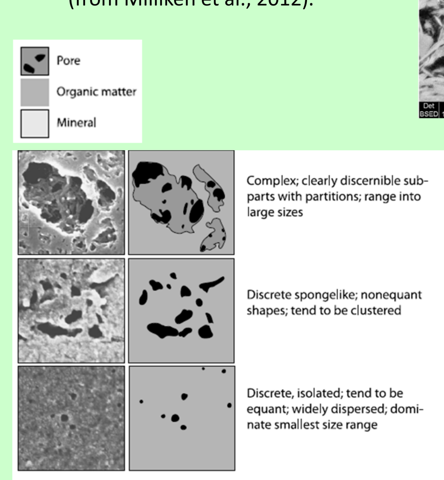


Discrete particulate organic matter (wood fragments (from Milliken et al, 2012).

Amount (richness), Type (type of kerogen), Distribution of Organic Mater and Thermal Maturity are key factors on RQ

Dispersed organic matter filling the intergranular space between grains (from Milliken et al., 2012).



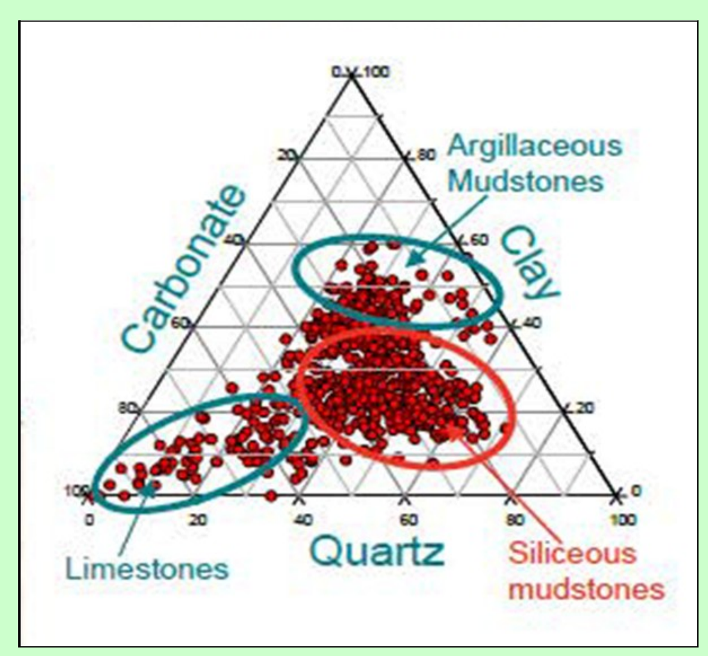


Organic-hosted porosity (from Milliken et al., 2013).

Mineral composition and organic richness of organic mudstones is a function of depositional and diagenetic processes.

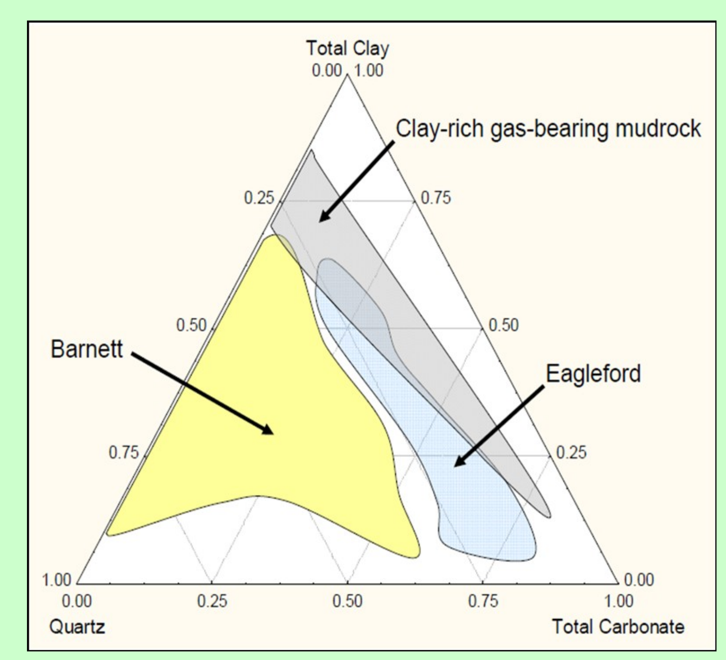
Published Classifications for Organic Mudstones

XRD Core and Cuttings, Duvernay shale in Canada



(from Dunn et al., 2012)

Range of composition for the Barnett, Eagleford and Clay-rich Mudstone



(from Passey et al., 2010)

Need to describe Organic Mudstones through down hole log measurements.

According to many researchers (Macquaker and Jones, 2002; Macquaker et al. 2007; Macquaker and Adams, 2003) using proxies such as TOC, **bulk mineralogy**, whole rock geochemistry, clay content and gamma ray response can **lead to make unreliable extrapolations**.

It is also unrealistic to perform a detailed petrographic study in every well

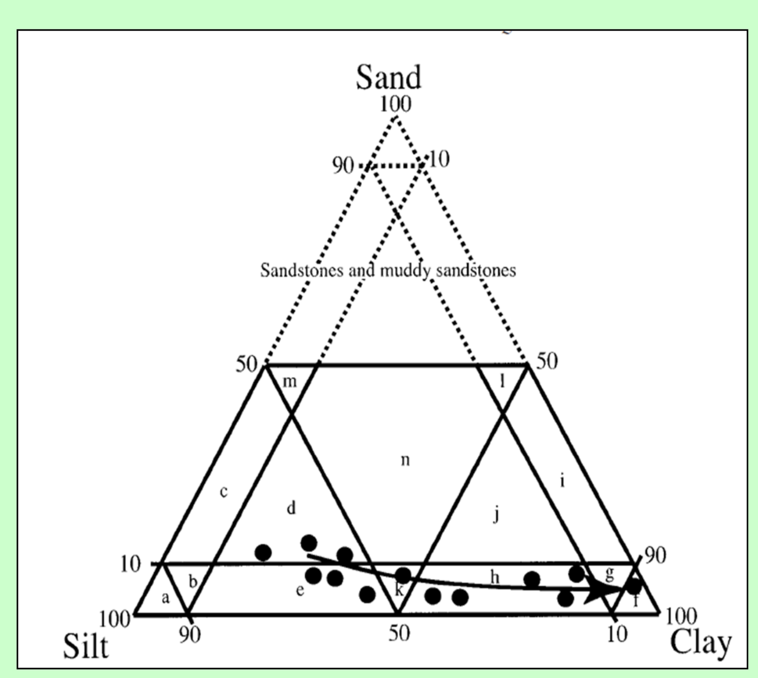
Challenge

How can textural & mineralogy variations observed in physical samples be interpreted from wireline logs.

Our industry needs to develop an acceptable solution to overcome these limitations.

Classification of fine-grained sedimentary rocks

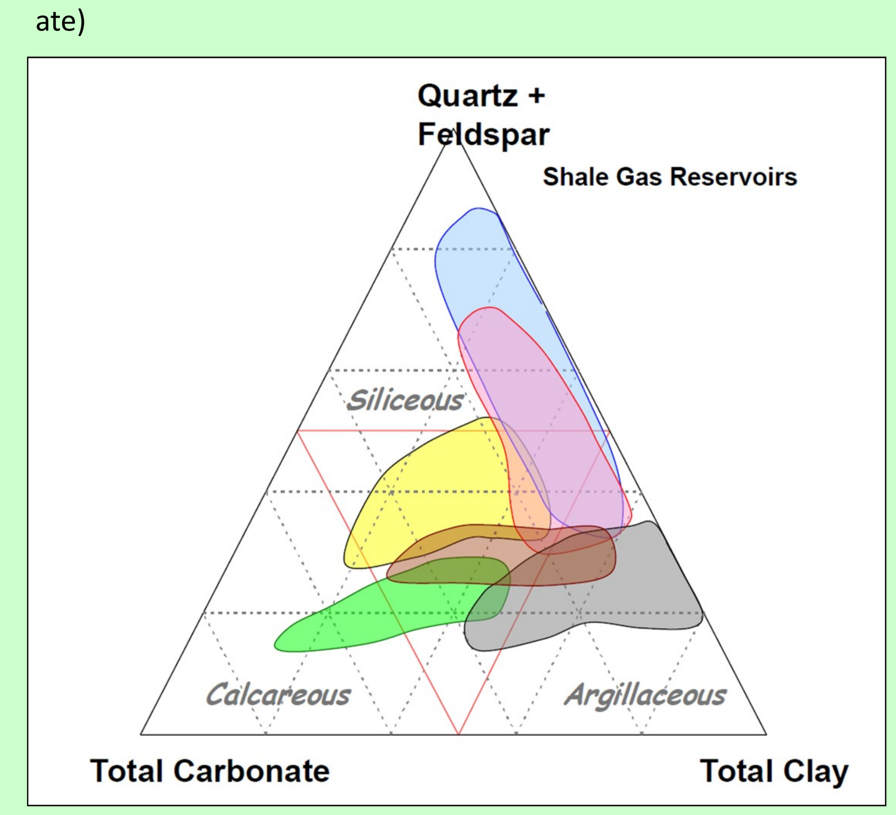
The end members represent the textural components of fine-grained sedimentary rocks (sands, silt and clay).



(from Macquaker & Adams, 2003)

Simple classification of Organic Mudstone

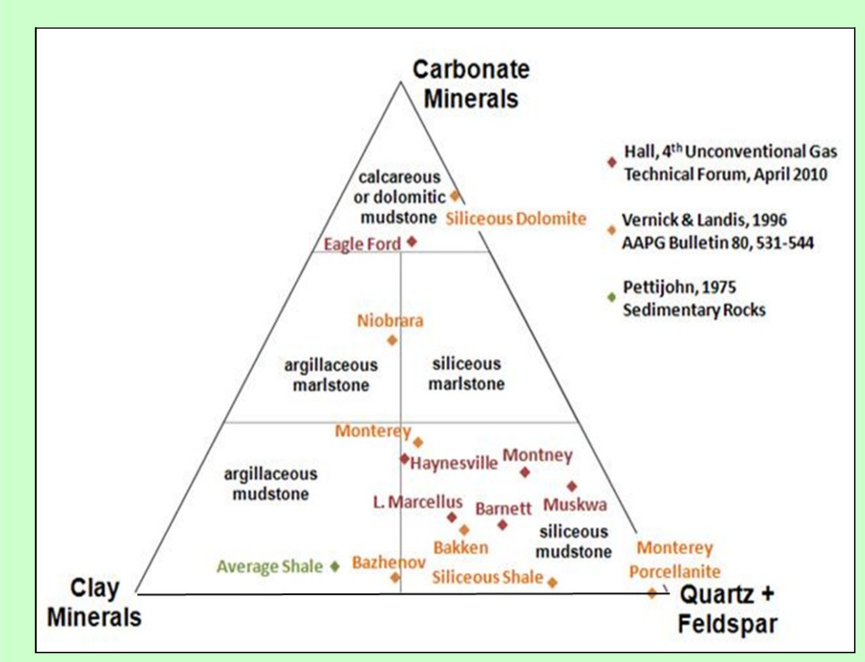
The end members represent the main mineral components of organic mudstones (total clay, quartz and feldspar, total carbonate)



(from Passey et al., 2012)

1st Classification of Organic Mudstone

The Ternary plot displays five mudstone types and the average composition of the main "Shale Plays" around the world.



(from Allix et al., 2010)

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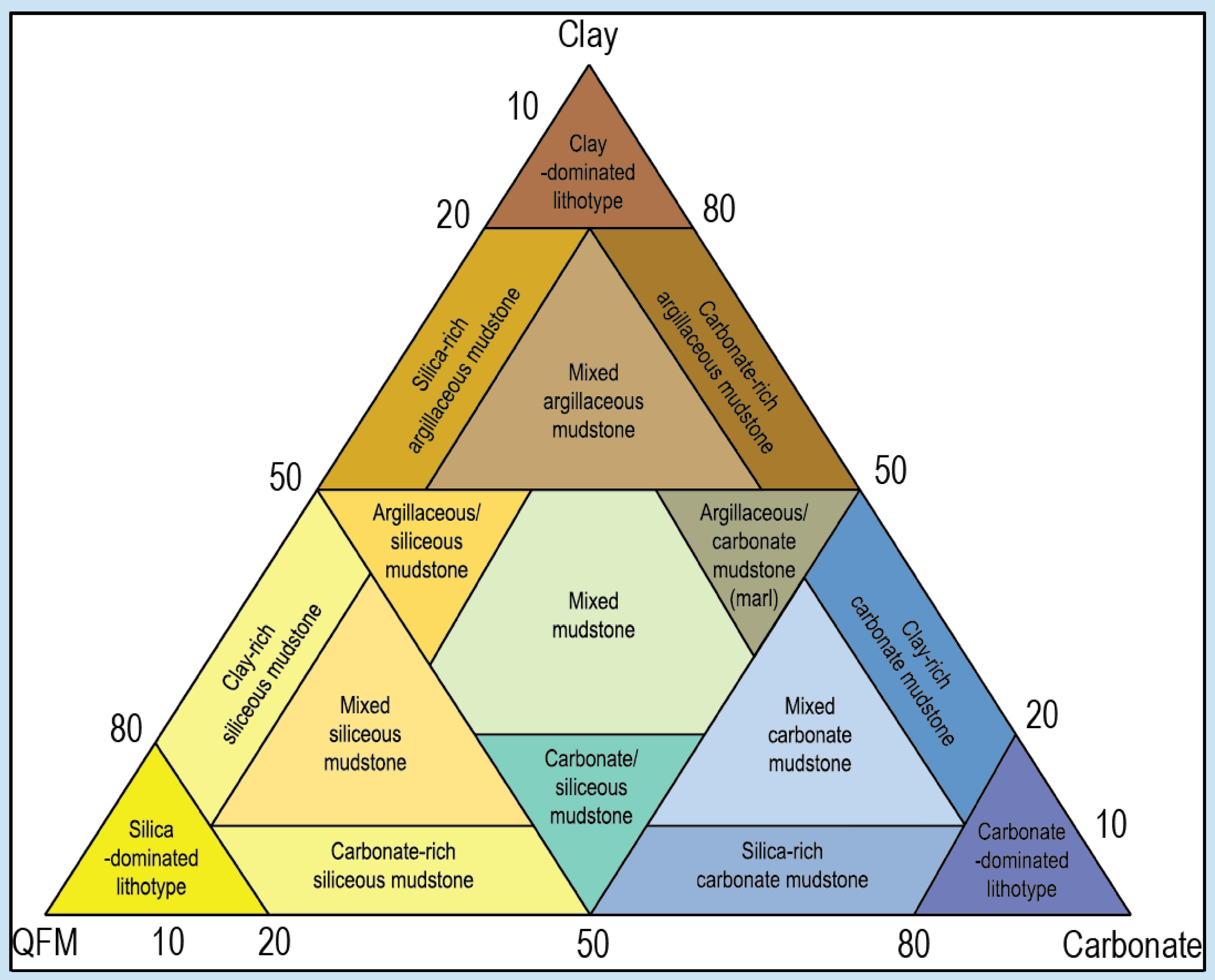
Classification Scheme for Organic Mudstone—sCore

sCore & iCore Ternary plots

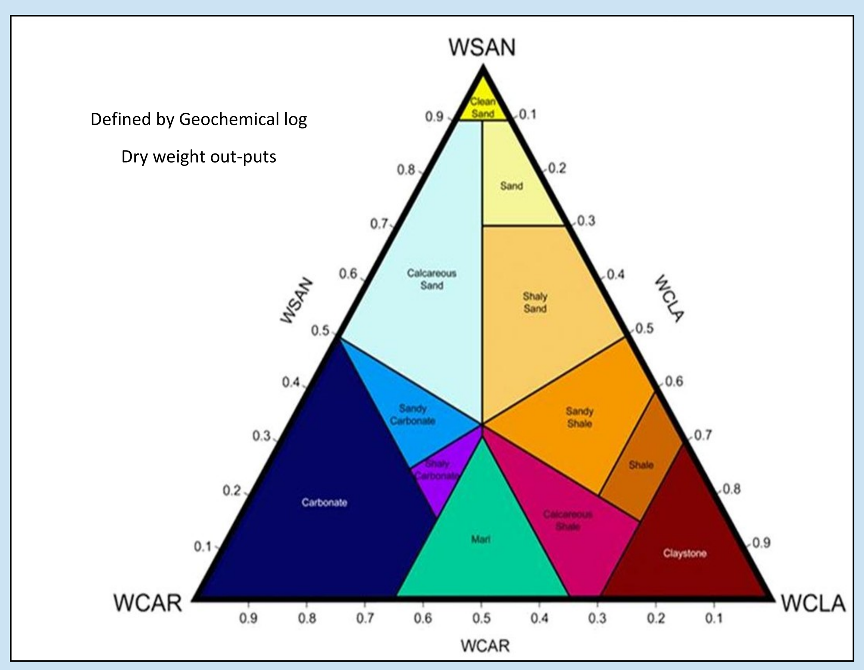
- **sCore** is a Ternary-based classification that is built based on the relationships between core and log data.
- The sCore ternary plot displays 16 organic mudstone lithofacies. The end member represent dry-weights of the main components of organic mudstones—clay (WCLA), carbonate (WCAR) and quartz, feldspar and mica (WQFM).

sCore Ternary plot to classify Organic Mudstone



(from Gamero et al., 2012)

iCore Ternary plot to classify conventional reservoirs.



(from Kumar and Kear, 2003)

sCore Facies log

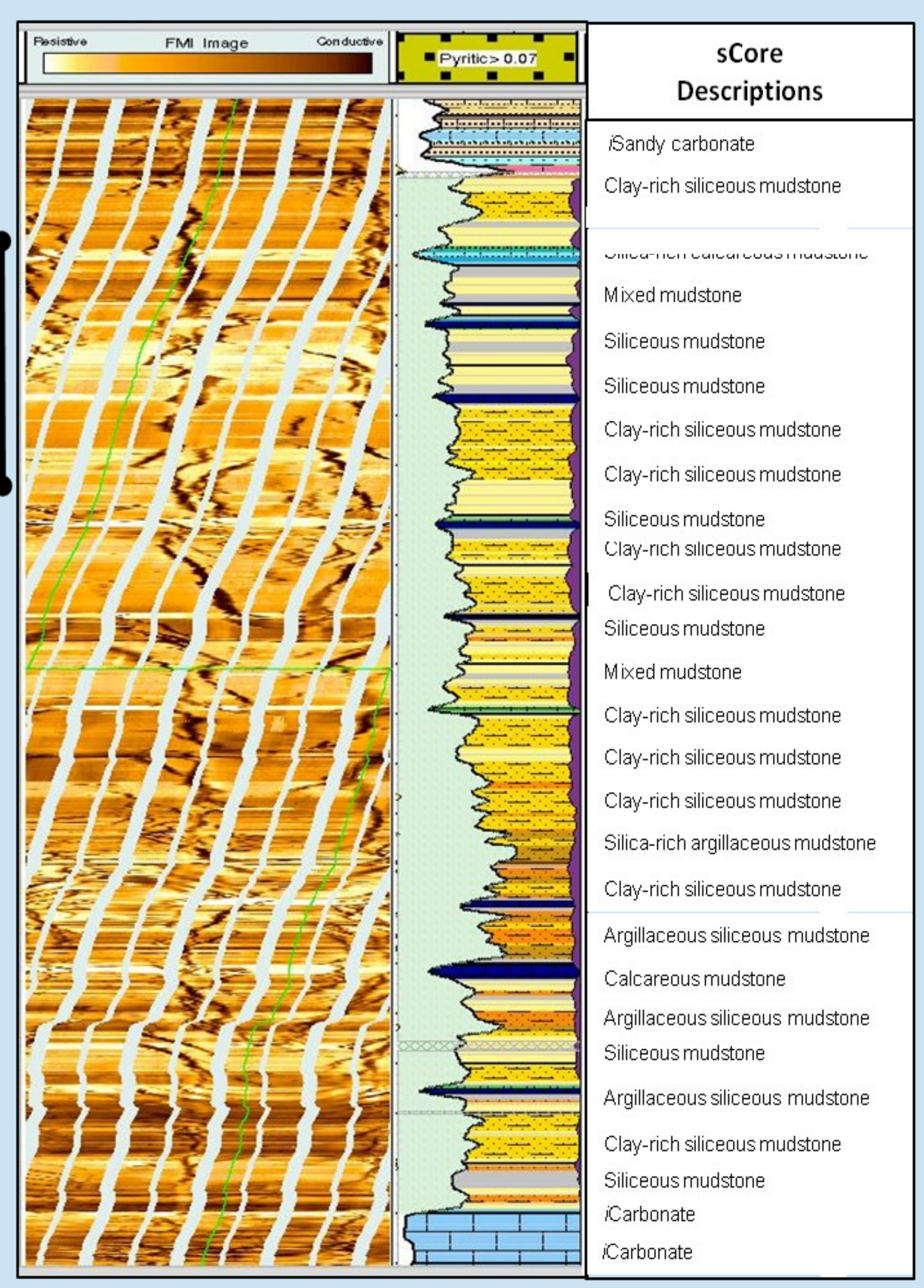
This technique uses the dry-weight mineralogy output from geochemical logging tools to generate a log that defines the different Organic Mudstone classes that exist over the interval of interest.

Log displays for a 200-ft section of a vertical Barnett shale well

- Track1. Borehole micro-resistivity static image.
- The green area shading in the left side of the Track 2 represents the organic mudstone interval to which the sCore classification was applied.
- The TOC flag, shown in purple along the right boundary of the Track 2, represents TOC > 2%.
- The gray cross hatching pattern in Track 2 indicates zones impacted by borehole rugosity.
- The left boundary of the lithofacies display in Track 2 represents a **Mineral-based Brittleness Index (MBI).**
- Track 3 list the sCore lithofacies in the text format.

Colors displayed in Facies log (track 2) keyed to sCore Ternary

sCore Facies Log Display



Mineral Brittleness Index (MBI)

Defined by the equation:

MBI = (WQFM + WCAR) / (WCAR + WQFM + WCLA + TOC)

(Modified from Wang and Gale , 2009)

WQFM = Dry weight % of Quartz-Feldspars-Mica

WCAR = Dry weight % of Carbonate (includes limestone, dolomites and phosphates)

WCLA = Dry weight % of total Clay

TOC = Total Organic Carbon in weight %.

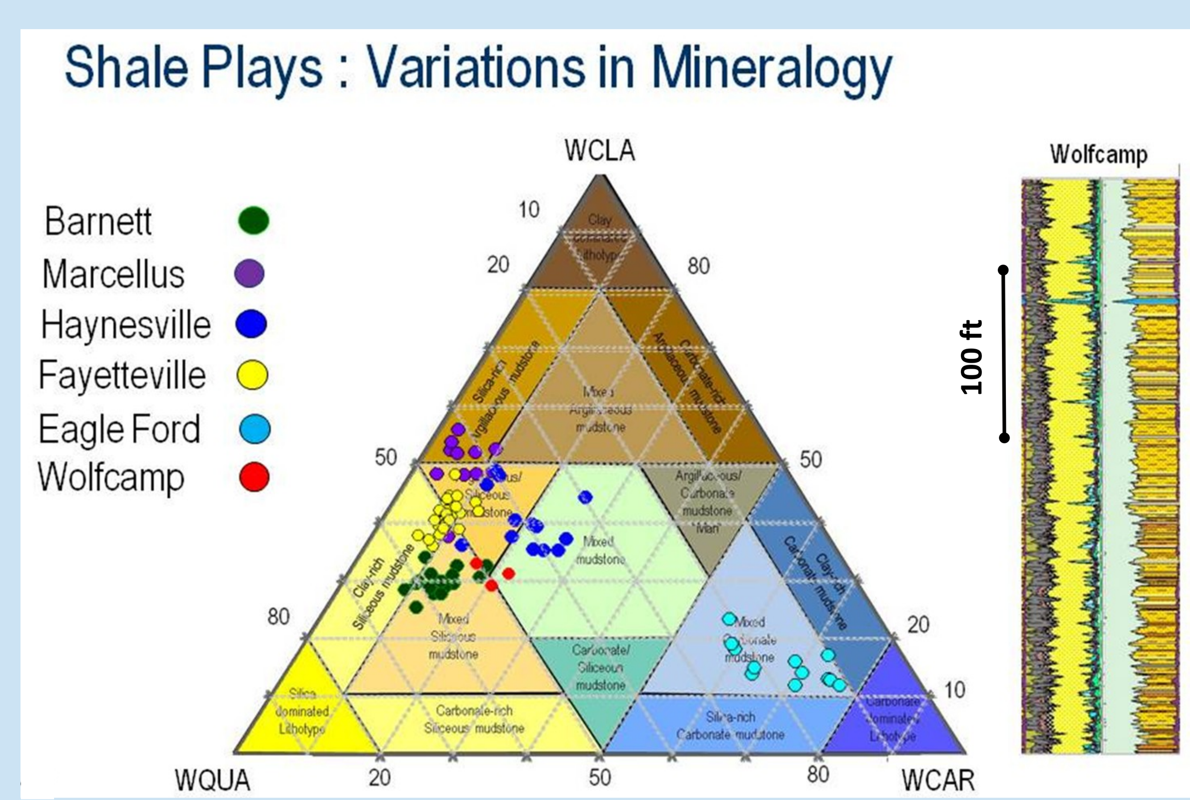
- The Organic richness or TOC is computed using the Schmoker & Hester equation (1983). It is a good indicator of RQ (above 2%) specially for gas and retrograde condensate producing Organic Shale Reservoirs.
- Modifiers such as *Organic-rich* (TOC > 7%) and *pyritic* (> 7%) are used in this applications.
- The MBI provides a highly qualitative measure of the ability of the rock to fracture during hydraulic stimulation.

MBI commonly shows a good correlation with log measurements of in-situ stress and can be used as a CQ indicator

Comparison of different U.S. Shales plays

Each dot represent the average composition for a shale in different U. S. shale plays.

- **Barnett shale** can be defined as a mixed siliceous mudstone (green dots)
- **Marcellus shale** is an argillaceous mudstone (orchid dots)
- **Haynesville shale** is a siliceous argillaceous and mixed mudstone, due to higher carbonate content (dark blue dots)
- **Eagleford shale** is a mixed carbonate mudstone (light blue dots) and
- **Wolfcamp shale** is comprised of mixed siliceous mudstones (red dots)

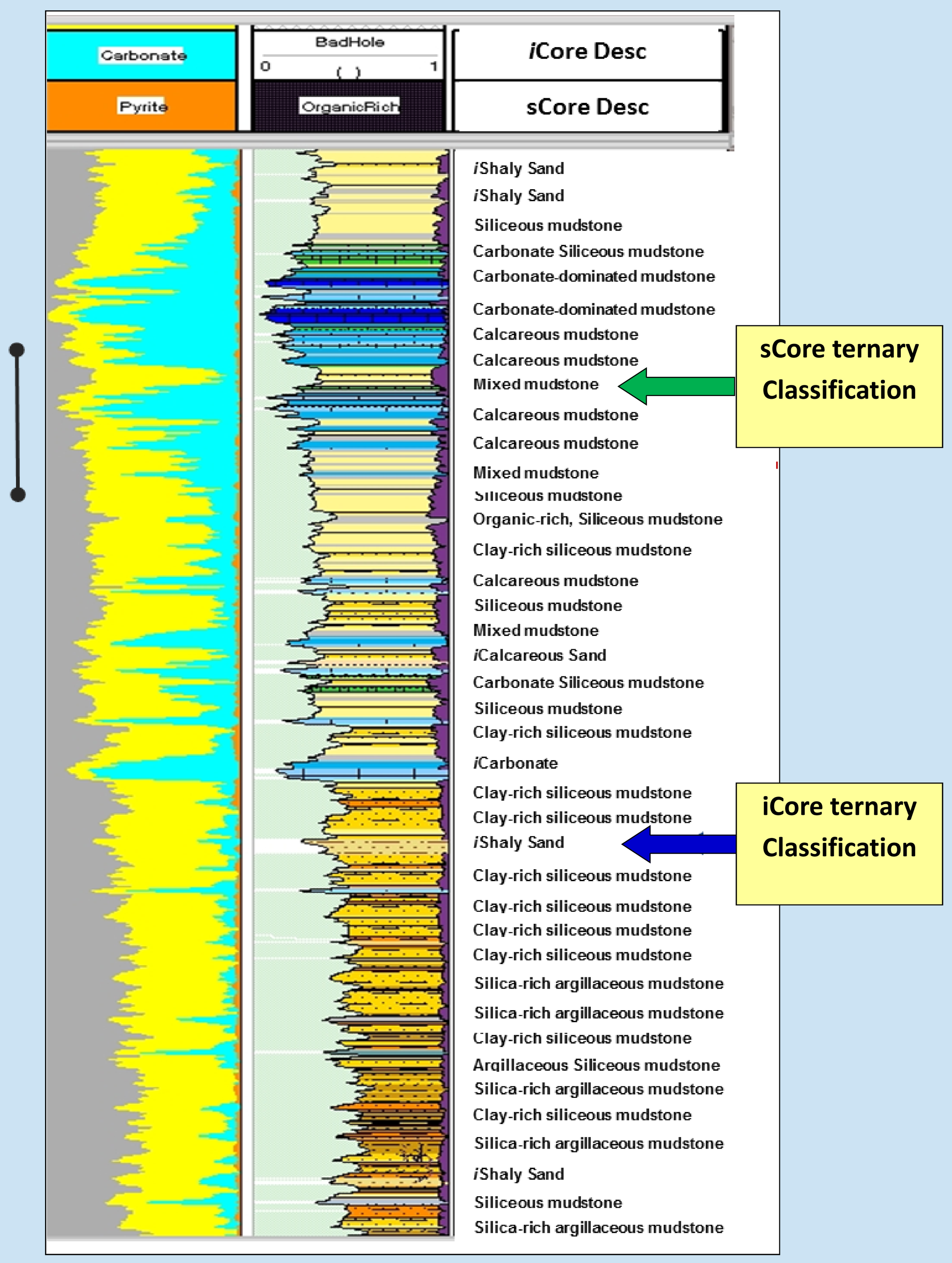


Zonation Application

Zonation can be apply automatically by using an external TOC

- TOC > 2% - sCore Ternary Diagram
- TOC < 2% - iCore Ternary Diagram

This is useful for Mixed shales plays like the Wolfcamp, Permian basin



Log display for a 600– ft section of a vertical Wolfcamp shale well

- The log– derived bulk mineralogy display is on Track 1
- The green area shading in the left side of the track 2 represents the organic mudstone interval to which the sCore classification was applied.
- The TOC flag, shown in purple along the right boundary of the track 2, represents TOC > 2% and it was measured directly with a new-generation geochemical logging technology (Radtke et al., 2012).
- The left boundary of the lithofacies display in Track 2 represents a Mineral-based Brittleness Index (MBI).
- Track 3 list the sCore and iCore lithofacies in the text format.

Advantages

- Minimal processing
- No interpretation
- Facilitates consistency when comparing different Organic Shale plays.

Limitations

- Geochemical log can not distinguish between authigenic, detrital or biogenic silica or carbonate. Needs to be combined with other Wireline logs previously calibrated with petrographic observations.
- Vertical resolution of geochemical tools is around 2 feet (60 cm) resulting in averaging heterogeneity at the core scale.

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Production Drives: RQ & CQ

Organic Lithofacies Ternary: Relationship between Mineralogy, RQ and CQ within a "Shale" Play

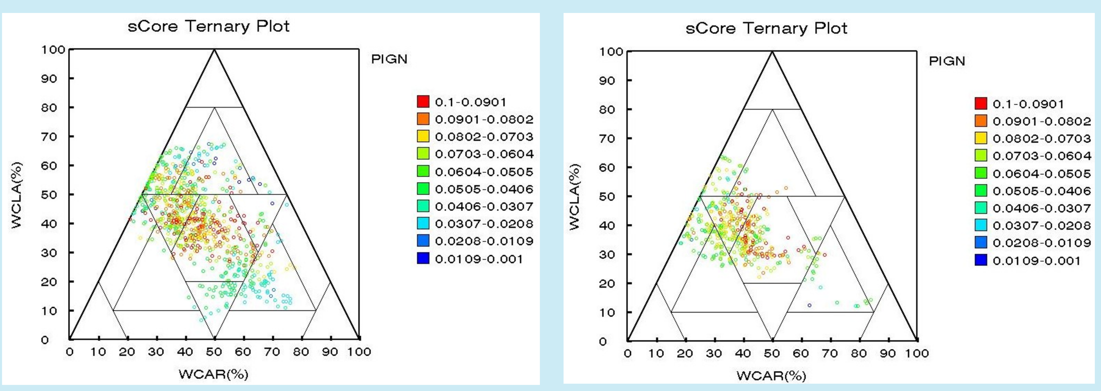
Reservoir Quality (RQ)

Is defined by the combination of properties leading to storage capacity and producibility. The properties are:

- Organic Richness (TOC)
- Effective Porosity (PIGN)
- Matrix Permeability (K) to gas
- Hydrocarbon Saturation and
- Mineralogy

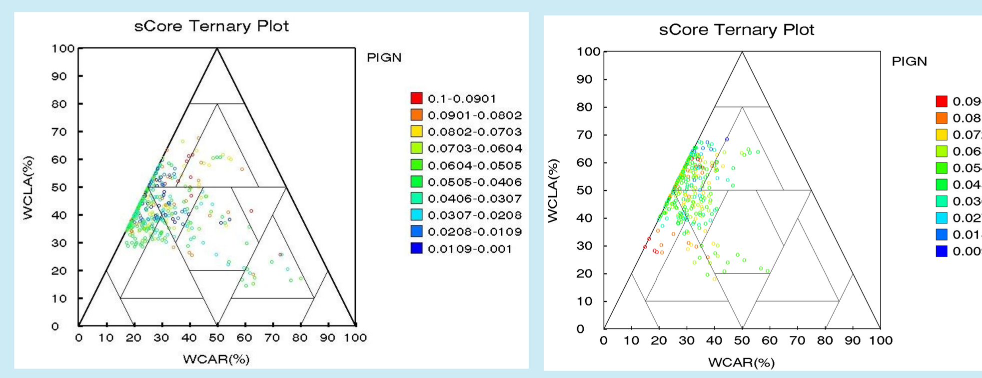
- The reservoir property, like PIGN, **might represent an indirect proxy for the textural and digenetic variations of organic mudstones;** for example: low correlation between effective porosity (PIGN) and silica content may imply high dilution (presence of Detrital or Biogenic Quartz grains). Conversely, a high correlation indicates minimal dilution (authigenic silica) and a more desirable rock.

Haynesville Shale examples



Moderate correlation between composition and RQ → Moderate correlation between composition and RQ

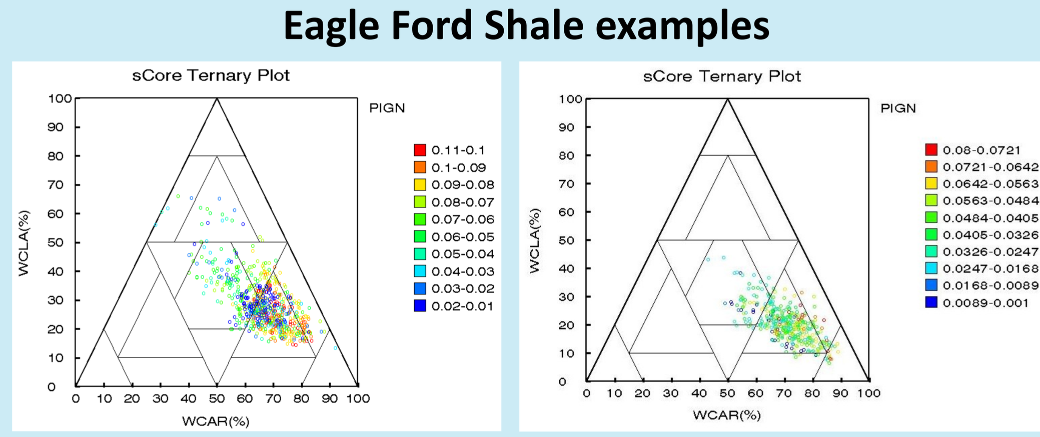
Marcellus Shale examples



Poor correlation between composition and RQ → Moderate correlation between composition and RQ

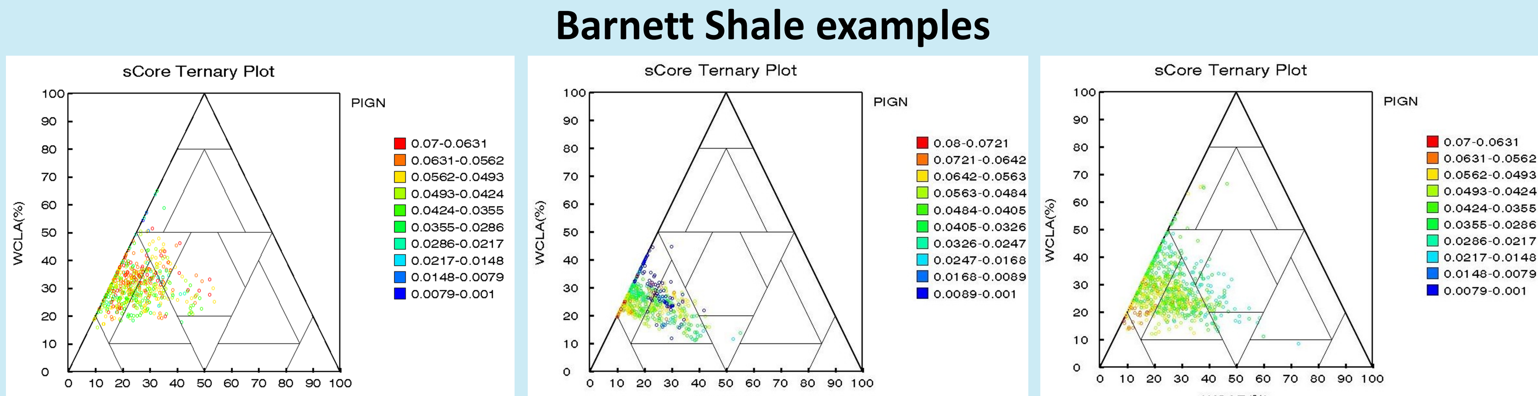
A Reservoir Quality indicator, like PIGN, on top of the ternary plot can be used to define the relationship between porosity and composition for different shale plays; an indirect proxy for textural and digenetic variations of organic mudstones

Eagle Ford Shale examples



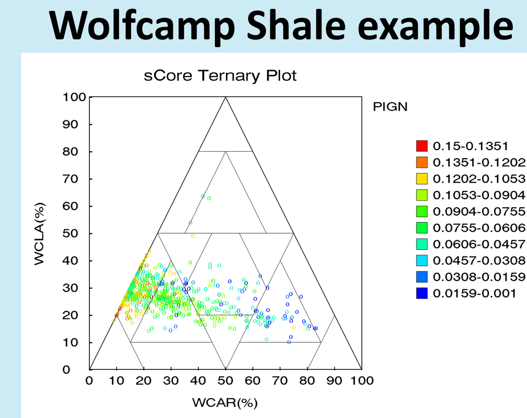
Poor correlation between composition and RQ → Moderate correlation between composition and RQ

Barnett Shale examples



Poor correlation between composition and RQ → Moderate correlation between composition and RQ → Good correlation between composition and RQ

Wolfcamp Shale example



Moderate correlation between composition and RQ

Completion Quality (CQ)

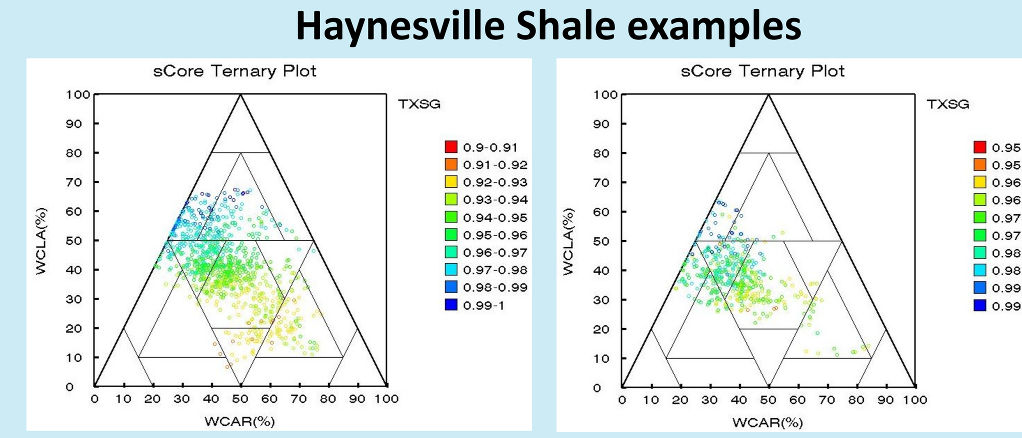
Is defined by the combination of properties leading to creation of surface area contacting the wellbore through hydraulic stimulation. The properties are:

- Fracture containment (Geomechanical Properties)
- Fracture complexity
- Retention of fracture area and fracture conductivity (minimum closure stress)

In normally extensional basins (assuming NO Tectonics)

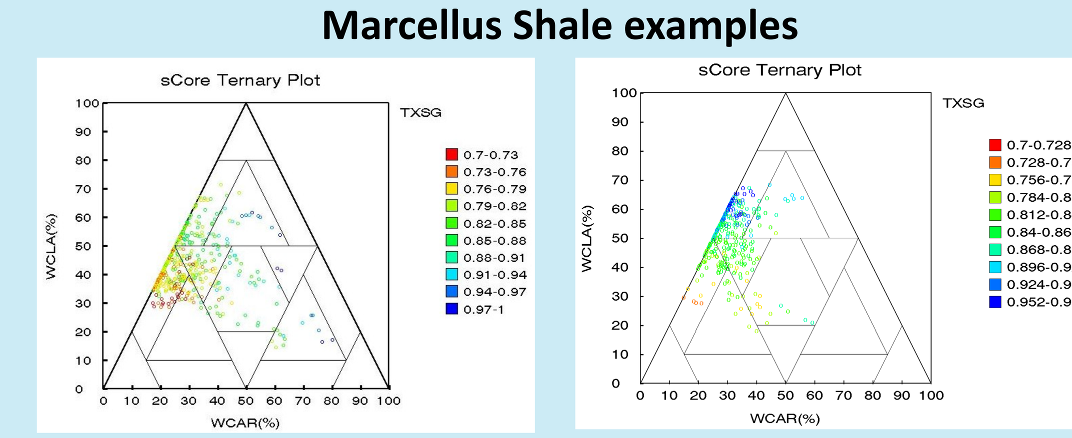
- Minimum Closure Stress (TXSG) is a function of clay content
- Thomsen Gamma (Gamma-TIV) is a measure of TIV anisotropy

Haynesville Shale examples



Good correlation between composition and CQ → Good correlation between composition and CQ

Marcellus Shale examples

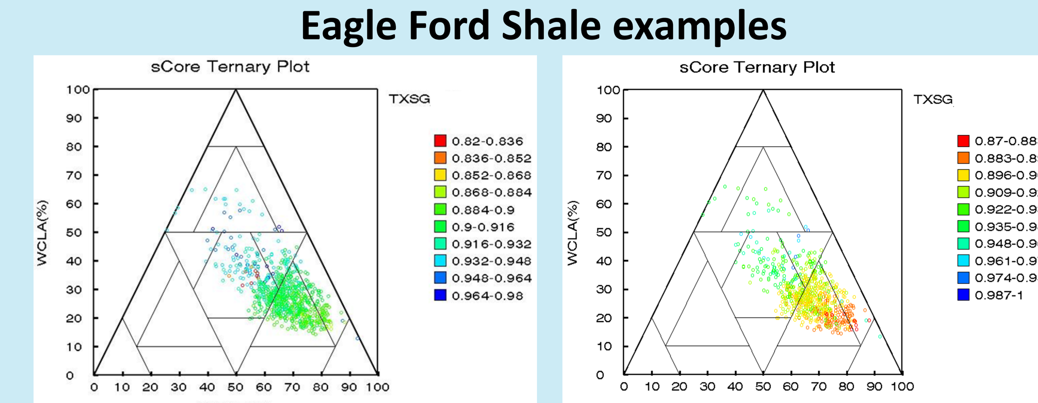


Moderate correlation between composition and CQ → Good correlation between composition and CQ

All ternary diagram plots show a strong relationship between mineralogy and minimum closure stress (TXSG)

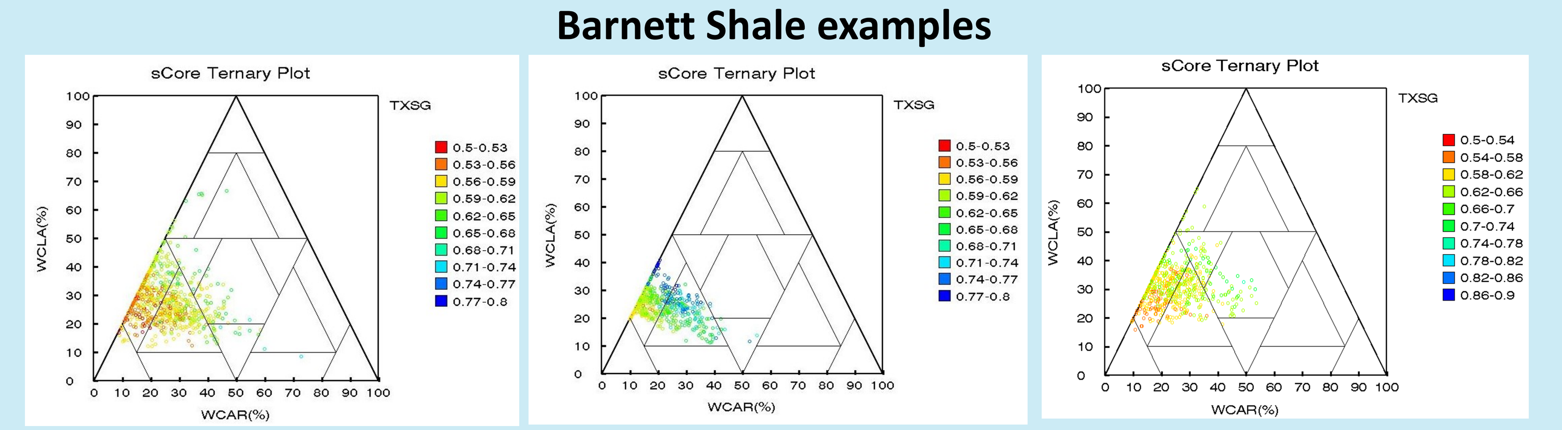
A Completion Quality indicator like Minimum Closure Stress (TXSG) on top of ternary can be used to define the relationship between stress and composition for different shale plays.

Eagle Ford Shale examples



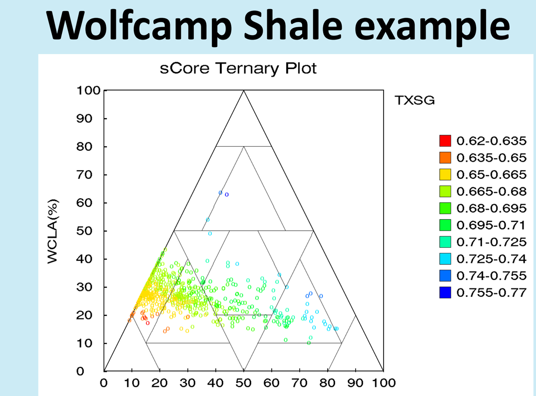
Moderate correlation between composition and CQ → Good correlation between composition and CQ

Barnett Shale examples



Moderate correlation between composition and CQ → Good correlation between composition and CQ → Good correlation between composition and CQ

Wolfcamp Shale example



Good correlation between composition and CQ

Facies A

Facies B

"Mud" Deposition

Depositional facies

Sedimentary texture (grain size: silt and clay)

Mineral composition (detrital and/or biogenic grains)

Organic material (Kerogens I, II and III)

RQ is a function of:

- Primary mineral composition & texture
- Kerogen type
- Degree of diagenesis

Increase Temperature & Pressure

T I M E

Diagenesis & Catagenesis

Burial (Chemical and Physical processes)

- **Mineralogy changes (unstable minerals)**
- **Temperature + Pressure**
- **Fluid chemistry (pH, alkalinity), and**
- **Organic matter thermal maturation (kerogen changes to Bitumen to Oil to Gas)**

Rock 1

Rock 2

Rock 3

Rock 4

Rock 5

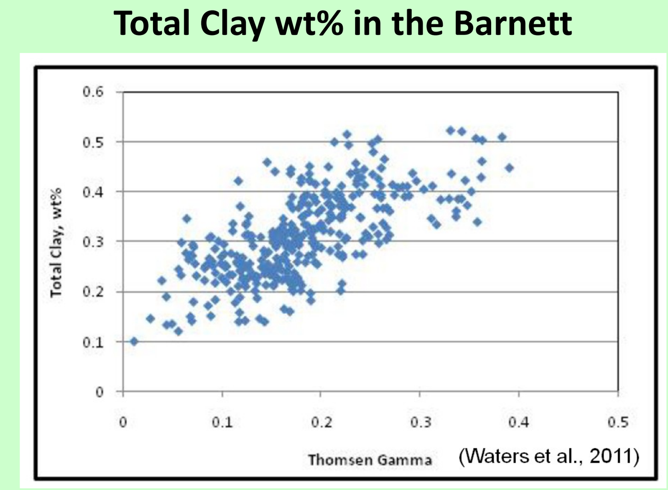
Increase Porosity
Increase TOC
Increase Permeability

Self Sourced Reservoir

Variations in Reservoir Quality

Organic mudstone mineralogy, mechanical properties and Stress

Relationship between Thomsen gamma and Total Clay wt% in the Barnett



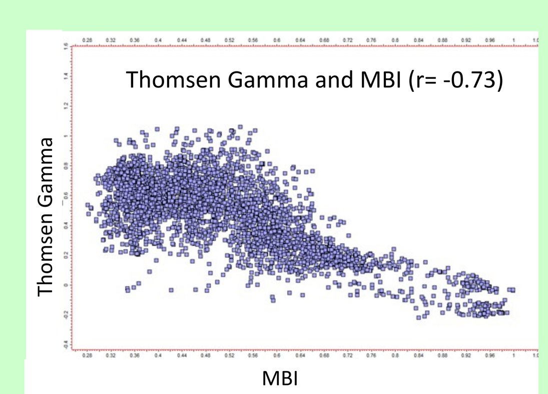
Thomsen gamma (γ) is a quantification of the TIV anisotropy (Thomsen ,1986). Is given by the equation:

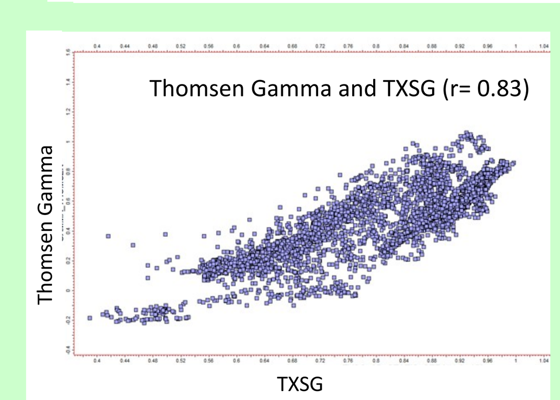
$$\gamma = (C66 - C44)/2*(C44)$$

C66 = Horizontal shear modulus

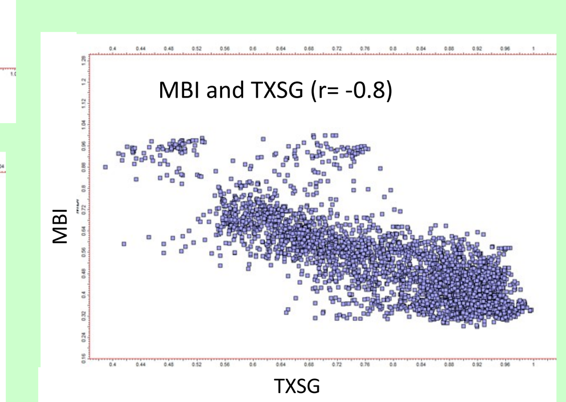
C44 = Vertical shear modulus

Clay content is a key factor in the magnitude of TIV anisotropy and consequently in the minimum closure stress (Waters et al., 2011).





Cross plots show a strong linear relationship between MBI, Thomsen gamma and TXSG



Shale Stress Index (SSI) and Mineralogy

SSI is an indicator of minimum closure stress as a function of mechanical properties, in the absence of tectonics and variable pore pressure (Waters et al., 2011).

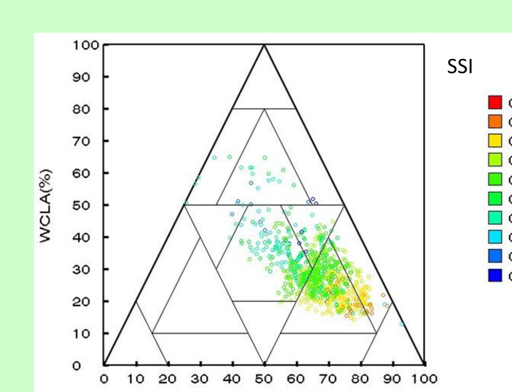
$$SSI = Eh/Ev * (\upsilon v)/(1-\upsilon h)$$

Eh = Horizontal Young Modulus

Ev = Vertical Young Modulus

υv = Vertical Poisson's ratio

υh = Horizontal Poisson's ratio



Good correlation between SSI and Clay content

CQ is a function of:

- Mineralogy (quartz, carbonates and clays)
- Presence of smectitic clays

Evaluating the Impact of Mineralogy on Reservoir Quality and Completion Quality of Organic Shale plays

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SALT LAKE CITY 2013
AAPG-RMS
ENERGY ELEVATED
September 22-24, 2013

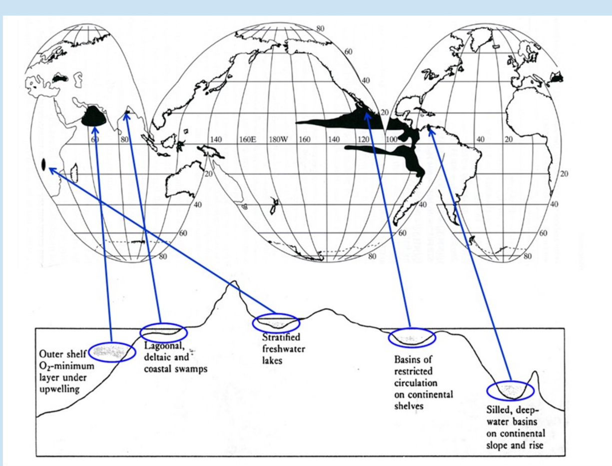
Organic Mudstone Mineralogy Implications on RQ and CQ

Mixture of mineral composition and organic components (type, distribution)

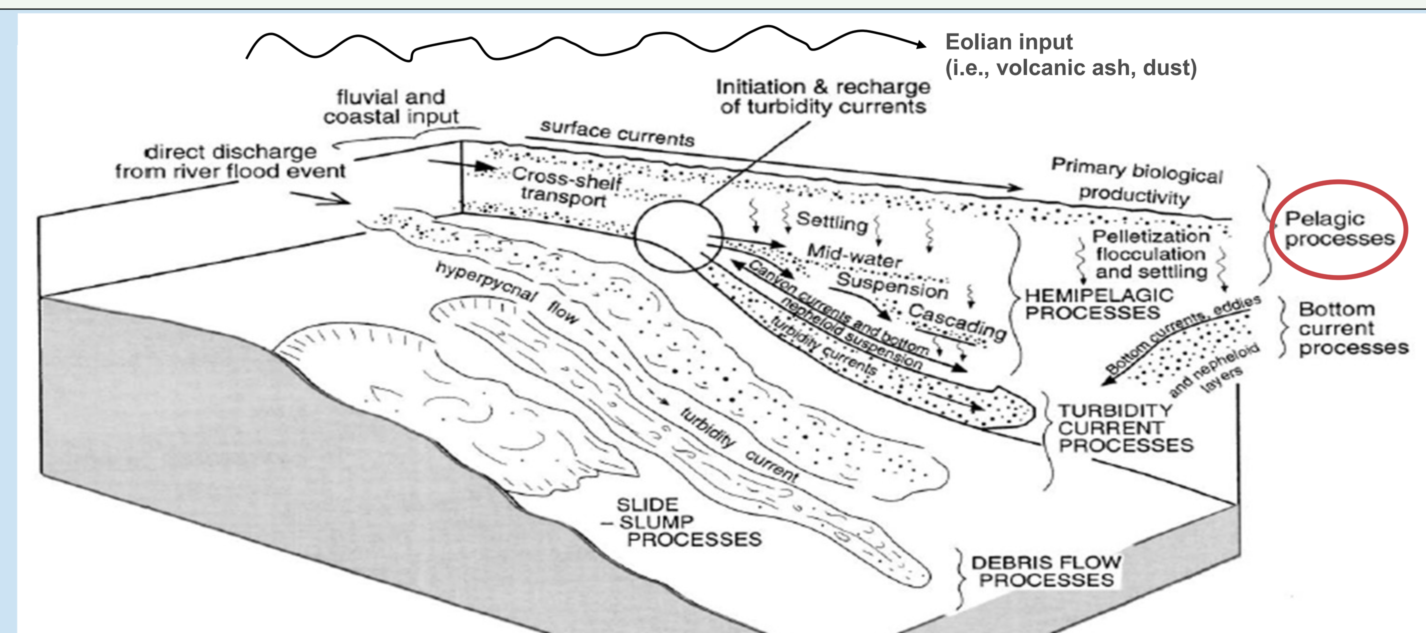
Continent

Detrital material:
Clay minerals
Quartz & Feldspars
Organic Matter (Kerogen Type III)
Origin:
Weathering rocks and minerals
Deposition:
By water
Transport by Water:
Buoyant fresh-water plumes (i.e., quartz, clays, feldspar)
Hyperpycnal flows (i.e., quartz, clays, feldspar)
Low density turbidity flows (i.e., carbonate muds; shell debris)

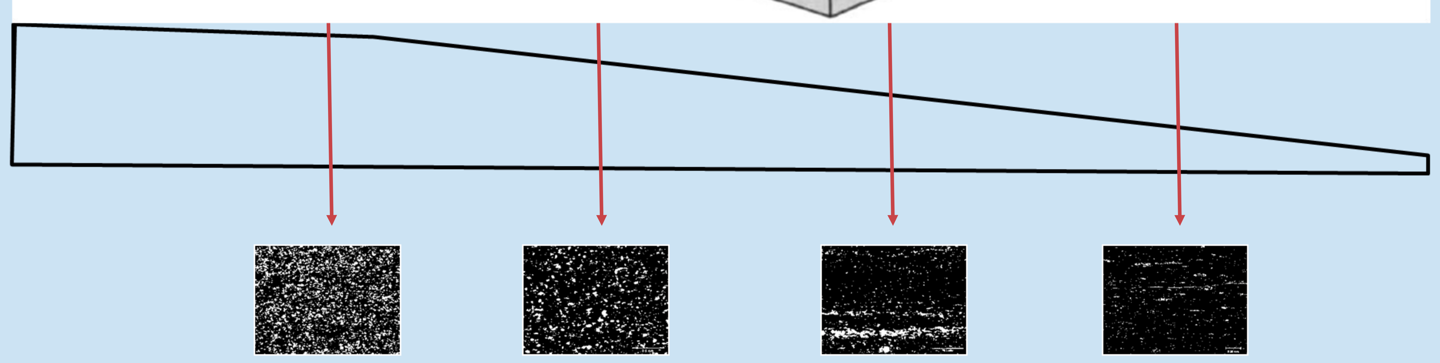
Volcanic-origin material:
Transport by Air:
i.e., Volcanic Ash



(Courtesy slide from Drenzek, 2010)



(modified from Stow et al. 2001)



Mudstone composition & Organic composition varies laterally and vertically
Variable proportions of Detrital and Planktonic-derived material
Variable proportions of kerogen Types (I, II and III)

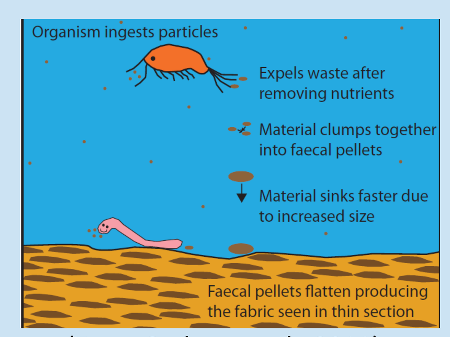
Increase of planktonic-derived biogenic Material

Decrease in amount and size of detrital material

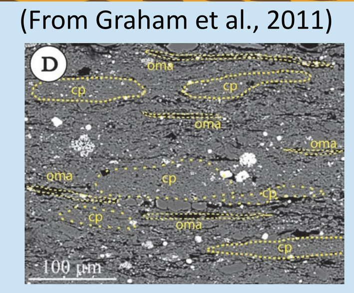
Increase on Type II Kerogen Type

Basin

Biogenic material:
Skeletal remains (i.e, calcite, silica/opal, phosphate)
Organic Matter (Type I and II)
Origin:
Photic zone during Upwelling events
Planktonic blooms (i.e., foraminifera, diatoms)
Sediment-water benthic organisms (i.e., ostracods, agglutinated foraminifera, sponge spicules)
Deposition:
Pelagic and
Hemipelagic settling
Episodic Anoxic events
Organo-mineralic aggregates +
Fecal pellets
(Macquaker et al., 2007)



(From Graham et al., 2011)



(From Macquaker et al., 2007)

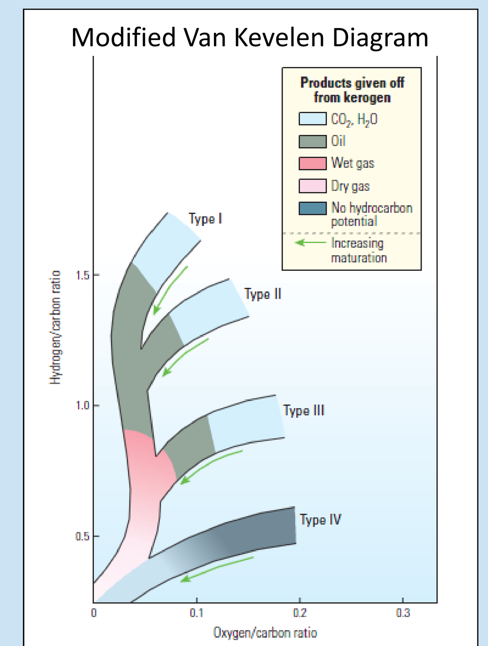
Post-Depositional Processes
DIAGENESIS/MATURATION

Original Mineral composition
- Kerogen type
- Proportions biogenic vs detrital

Pore water chemistry
- (i.e., pH, alkalinity)

Time
Temperature & pressure

Modified Van Kevelen Diagram

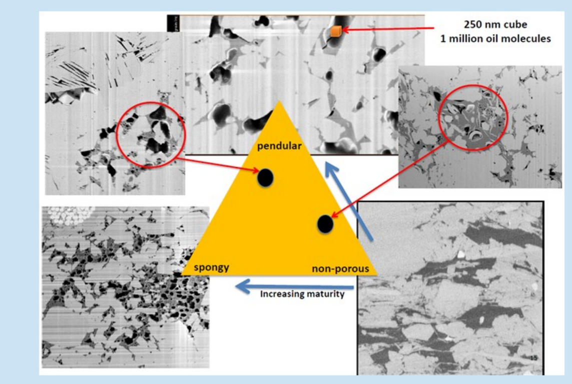


(Boyer et al, 2006)

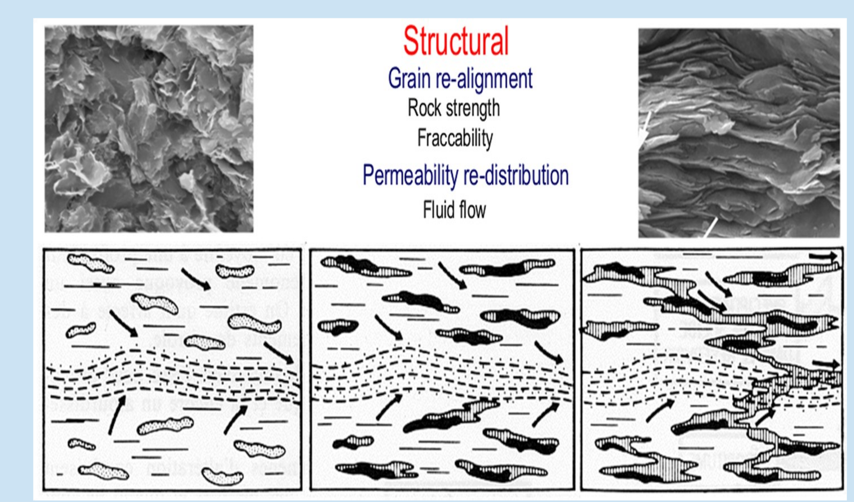
Early cementation (pyrite, carbonates)
Biogenic Gas
Carbonate cement (ferroan dolomite, ankerite or siderite)
Conversion of OM into Kerogen and bitumen (>30°C)
Hydrocarbon Formation (Oil and Gas, > 90°C and 150°C)
Clay mineralogy changes
Smectite to illite-smectite (I/S) to illite (> 70°C)
Smectite to illite-chlorite (I/C) to chlorite
Kaolinite to illite (> 130°C)
Dependent on cation availability
Water and Silica are an important by product
Re-alignment of clay minerals
Other changes
Biogenic Silica (i.e, siliceous tests of diatoms and sponge spicules) to opal-A to opal-CT to microcrystalline quartz
High Mg-Calcite to Calcite

Implications

RQ
Porosity
Pore size
Kerogen density
Bitumen content
Hydrocarbon (oil & gas)
Water saturation



CQ
Swelling Clay
Grain re-alignment
Heterogeneity
(fabric anisotropy)
Rock strength
Composition



(Courtesy slide from Drenzek, 2010)

Organic Matter (OM) = Production – Destruction / Dilution

Bohacs (2005)

\+

BURIAL

Production:	Primary production (Planktonic booms during upwelling events) Continental-derived organic matter
Destruction:	Destruction or oxidation of organic matter in the water column. Episodic periods of anoxic events.
Dilution:	Dilution of organic matter by biogenic or detrital material incoming into the basin by either distal hyperpycnal flows or low density turbidity fows
Burial:	**High sedimentation and burial rate**

Conclusions

- Organic mudstones are fine-grained sedimentary rocks with high organic content (above 2%) and a complex mineralogy (variable amounts of diagenetic, detrital and biogenic components) that impacts RQ and CQ and ultimately well performance.
- The sCore mudstone classification provides a consistent description of the organic mudstone and a common metric for the comparison of such self-sourced reservoirs worldwide. The mudstone classification scheme can be applied using any form of mineralogy data including those from logs, cores and cuttings. It requires minimal processing and no interpretation, which promotes consistency that is independent of the analyst working with the data.
- The sCore ternary plots resulted in a qualitative mean to visualize the relationship between composition and RQ or composition and CQ.
- A Reservoir Quality indicator, like effective porosity, on top of the ternary plot can be used as an indirect proxy for textural and digenetic variations of organic mudstones.
- Good correlation between reservoir quality and composition would imply that the organic mudstone is dominated by diagenetic/authigenic cements over the proportion of floating grains (i.e., claystone) and, conversely, a poor correlation will reflect an organic mudstone dominated by silt-size biogenic and/or detrital floating grains.
- The main U.S. Shale plays show a good correlation between CQ indicators, such as minimum closure stress, and composition. Composition is driven by clay content; therefore, clay content and clay type strongly affect the magnitude of stress anisotropy and minimum closure stress.
- A mudstone classification ternary plot allows the identification of lithofacies with the best RQ and CQ. This information is critical when selecting both vertical and horizontal drilling and completion targets.
- The main limitation of the compositional-based mudstone classification is that its not possible to distinguish between diagenetic, detrital and/or biogenic phases of either silica-rich or carbonate-rich shale reservoirs; therefore, additional combination of wireline logs and petrographic analysis are needed.
- More work is needed for the interpretation of textural variations in organic mudstones through additional integration of core, logs and other data.

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