

Characteristics of Tight Gas Reservoir in the Upper Triassic Sichuan Basin, Western China*

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Abstract

The western Sichuan Basin is a foreland basin formed in the Late Triassic at the front of the Longmen Mountain in the western Sichuan Province of China. The Upper Triassic Xujiahe Formation in the basin is an ultralow-permeability and low-porosity tight sandstone and shale gas reservoir. Tight gas reservoirs are often defined as gas-bearing sandstones or carbonates having in situ permeabilities to gas less than 0.1 mD. This article offers an integrated approach to describe microstructure characteristics of a tight sandstone and shale gas reservoir. In particular, the primary and secondary porosity of a tight gas sandstone are identified and quantified in three dimensions using X-ray Nano-CT imaging and visualization of core material at the pore scale. 3D images allow one to map in detail the pore and grain structure and interconnectivity of primary and secondary porosity. Once the tomographic images are combined with SEM images from a single plane within the cubic data set, the nature of the secondary porosity can be determined and quantified.

In-situ mineral maps measured on the same polished plane are used to identify different microporous phases contributing to the secondary porosity. Once these data sets are combined, the contribution of individual clay minerals to the microporosity, pore connectivity, and petrophysical response can be determined. Insight into the producibility may also be gained. This illustrates the role 3D imaging technology can play in a comprehensive reservoir characterization program for tight gas. Three types of microfractures, intragranular, grainedge, and transgranular microfractures, developed in the tight-gas sandstones of the western Sichuan Basin. Microfracture formation reflects tectonism, overpressuring, and diagenetic processes. Tensional microfractures related to overpressure formed in the Middle-Late Cretaceous. The existence of overpressure reduced effective stress, promoting opening-mode fracture growth. The existence of tension fractures can also be used as an indicator of ancient overpressure in a sedimentary basin. Diagenetic fractures formed from the Late Triassic, when the foreland basin of the western Sichuan Basin formed, to the Early Cretaceous.

References Cited

Curtis, Mark E., Carl H. Sondergeld, and Chandra S. Rai, 2013, Investigation of the microstructure of shales in the oil window: Unconventional Resources Technology Conference, Denver, Colorado, August 12-14.

Desbois, Guillaume, Maartje Houben, Janos L. Urai, Susanne Hemes, Jop Klaver, and Ben Laurich, 2012, Variability of microstructure characteristics in sandy and shaly facies of Opalinus clay inferred by BIB-SEM - An alternative concept of porosity: *Materials Science*, v. 44.

Klaver, Jop, Guillaume Desbois, Janos L. Urai, and Ralf Littke, 2012, BIB-SEM study of the pore space morphology in early mature Posidonia Shale from the Hils area, Germany: *International Journal of Coal Geology*, v. 103, p. 12-25.

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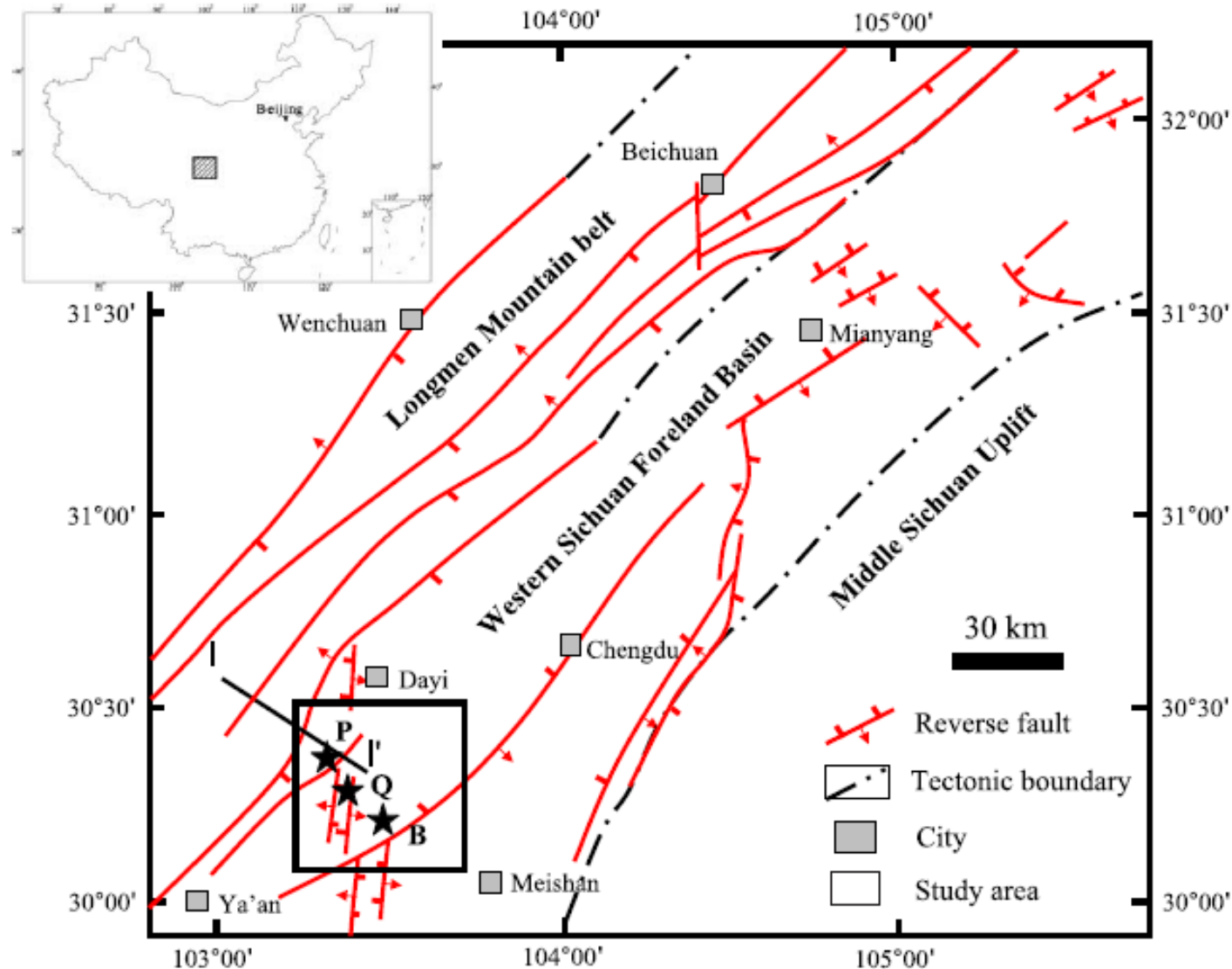
China University of Geosciences, Beijing

19-22 June 2016. Calgary, Canada

Outline

- **Background**
- **Tight sandstone and shale Gas reservoir**
- **Reservoir Microstructure**
- **Conclusions**

Background



Sichuan Basin
located at the front
of the Longmen
Mountain in the
western Sichuan
Province of China

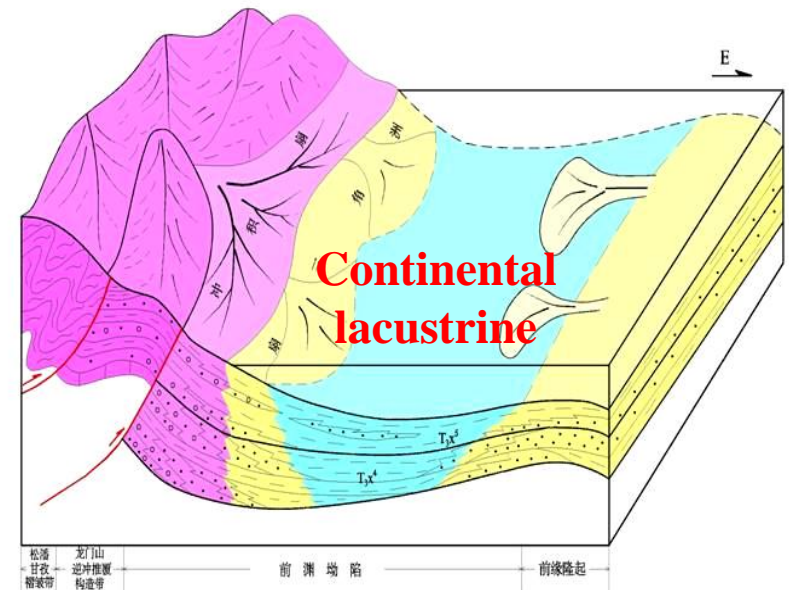
Foreland basin
formed in the Late
Triassic

Upper Triassic
Xujiahe Formation
Ultralow-
permeability and
low-porosity
tight-gas sandstone
and shale reservoir

Figure 1. Map showing location of the Longmen Mountain fold-thrust belt, western Sichuan Basin, and study area (small box). Lines are reverse faults. Bar indicates dip and arrow marks slip direction. P = Pingluoba gas field; Q = Qiongxian gas field; B = Baimamiao gas field.

Geological Setting & Facies

Erathem	System	Lithology	Thickness (m)	Source rock	Reservoir	Studied position
Cenozoic	Quaternary		0–250			
	Neogene		0–170			
	Paleogene		0–700			
Mesozoic	Cretaceous		610–2410			
	Jurassic		720–2330		◆	
	Triassic	Upper	1370–3400	▲	◆	Xujiahe Formation
		Middle	360–370		◆	
		Lower	290–370	▲		
	Permian	++++	400–900	▲		
Paleozoic	Carboniferous		0–200			
	Devonian		0–300			

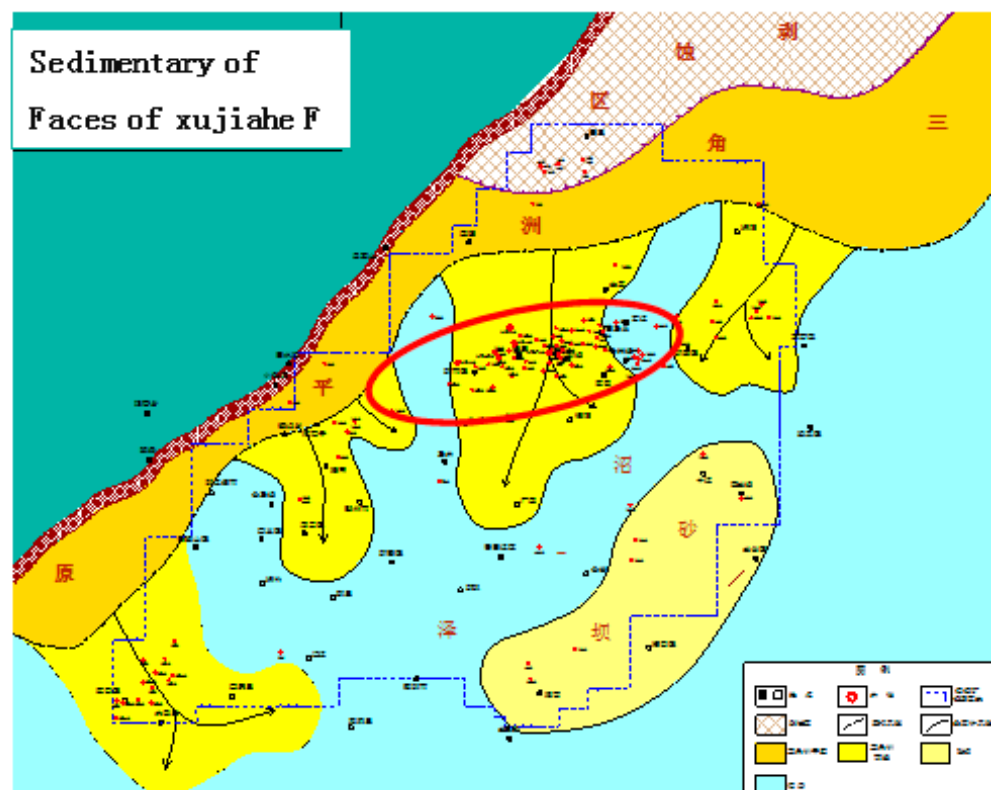
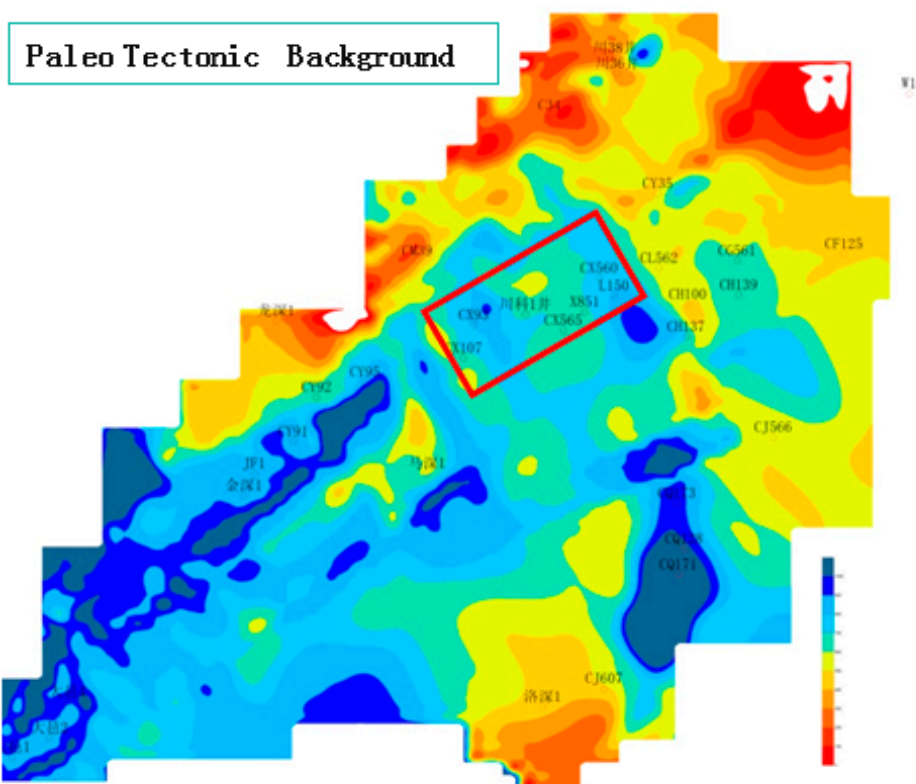


- Shales
- Sandstones
- Conglomerates
- Dolomites
- Limestones
- Volcanic rock
- Coal
- Source rock
- Main reservoir
- Secondary reservoir

- Foreland basin
- Shallow lake semi deep lake facies
- Lithology
dark grey black shale
lithic quartz sandstone
lithic sandstone
siltstone

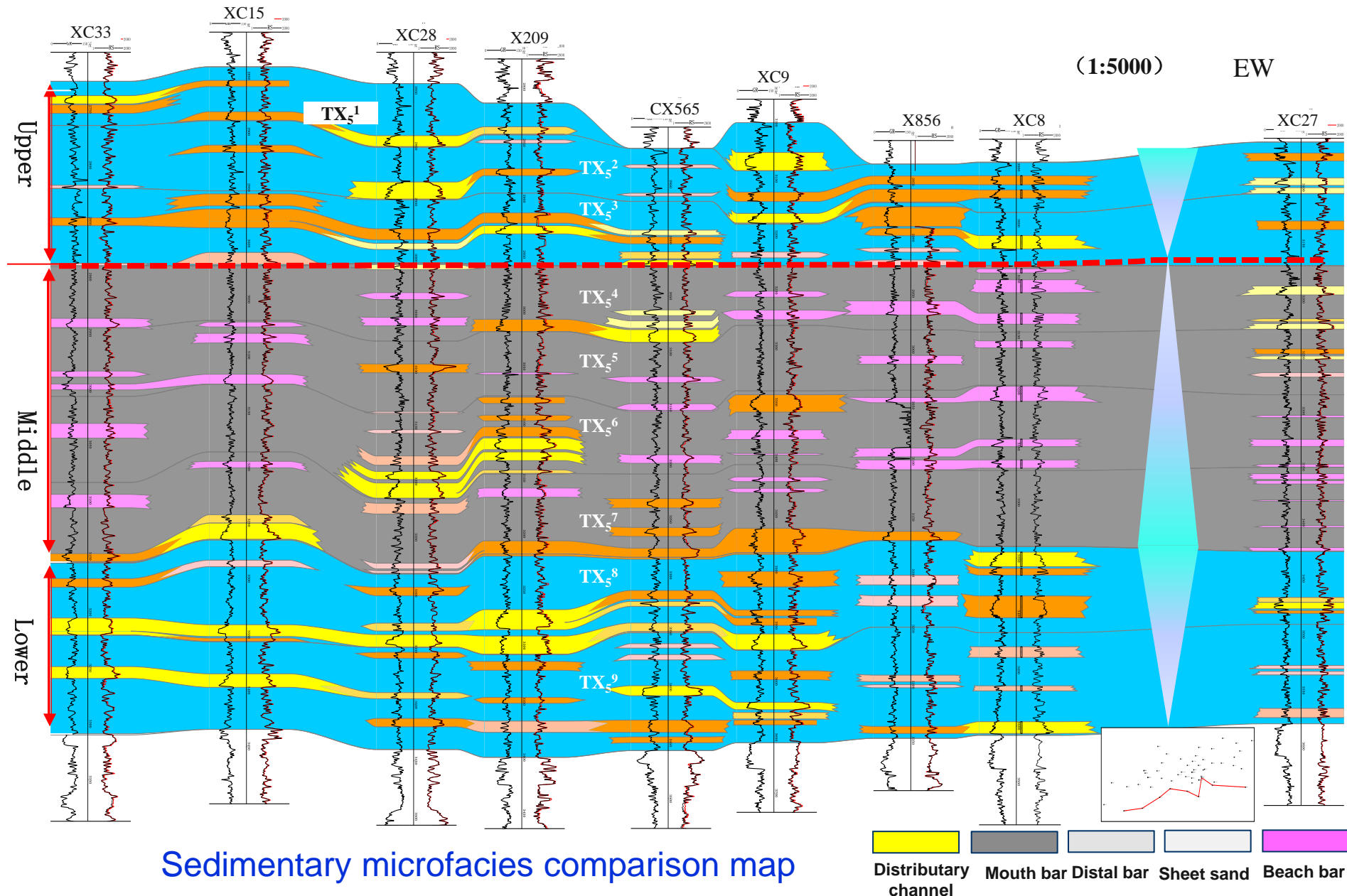
Figure 3. Schematic stratigraphy, source rock, and reservoir in the western Sichuan Basin.

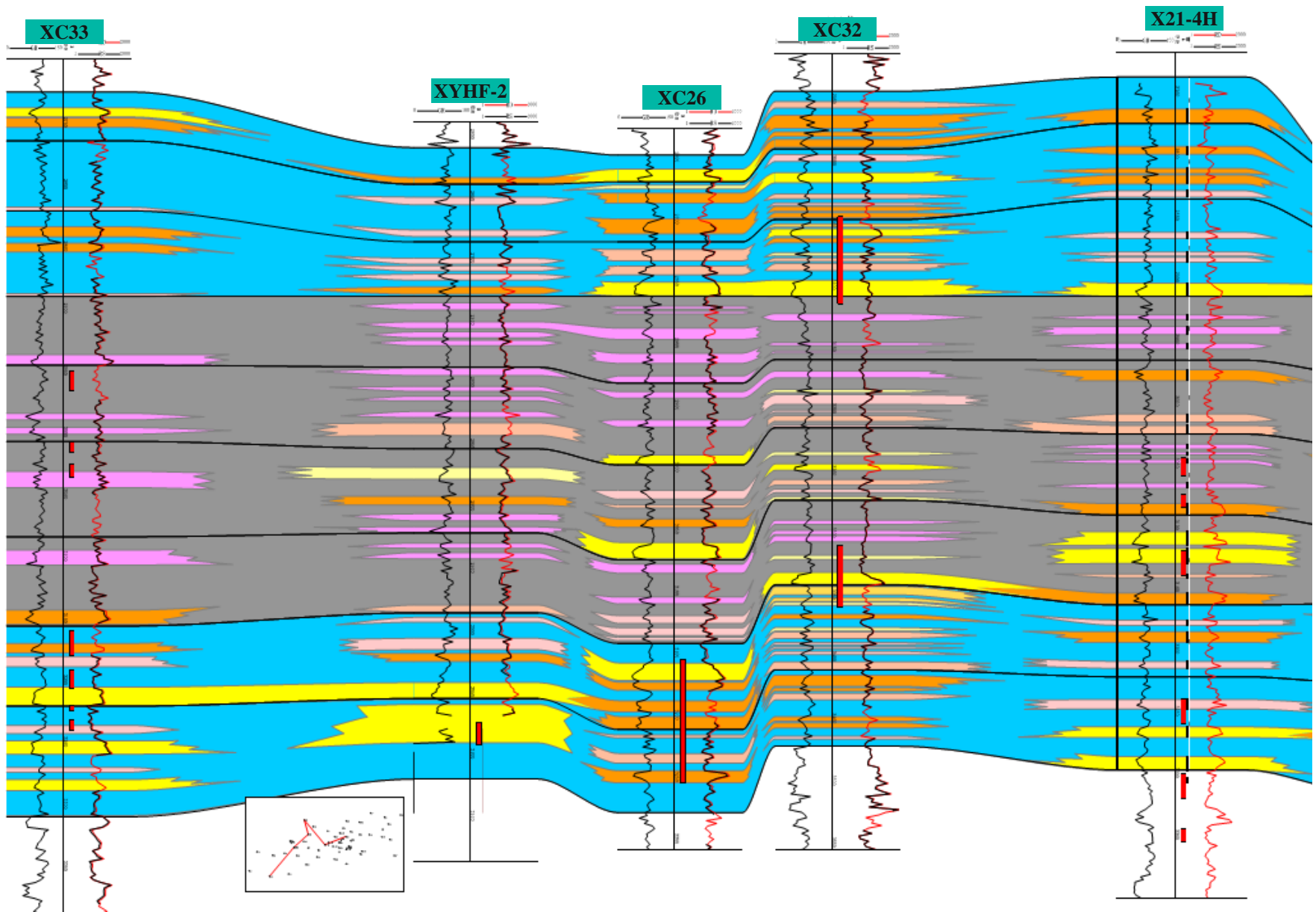
Geological Setting & Facies



Subject to frequent lake level change and the formation of the composite alternately deposited phase of the delta front and shore shallow lake

Microfacies change fast, the distributary channel and mouth bar microfacies with fine sand in the lower section, the beach bar with silt in middle Section



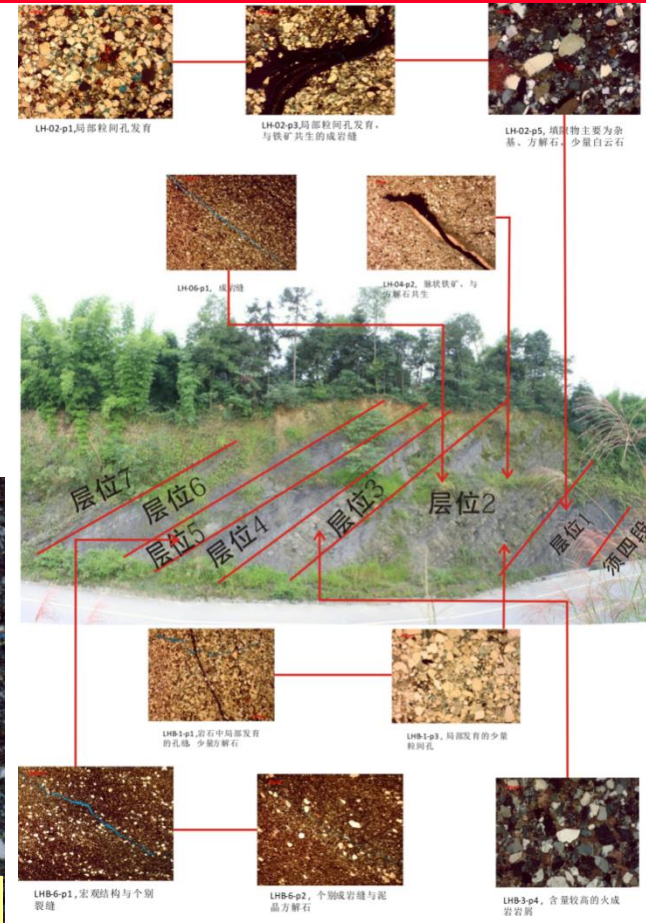
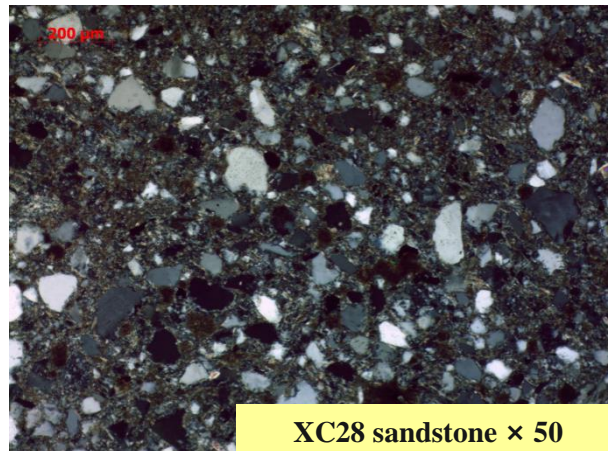
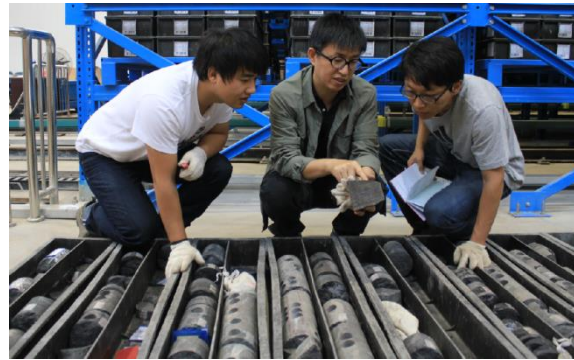
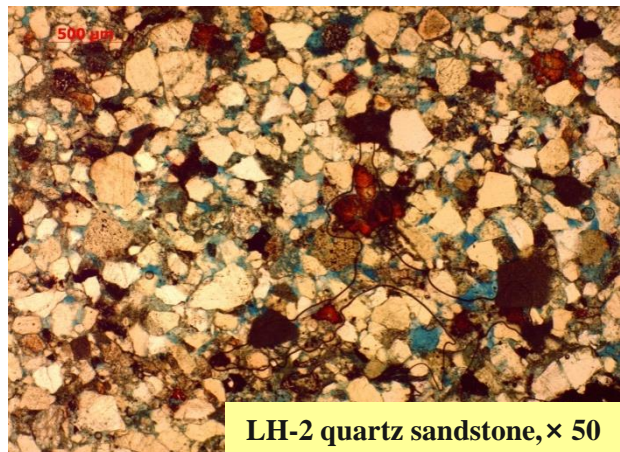
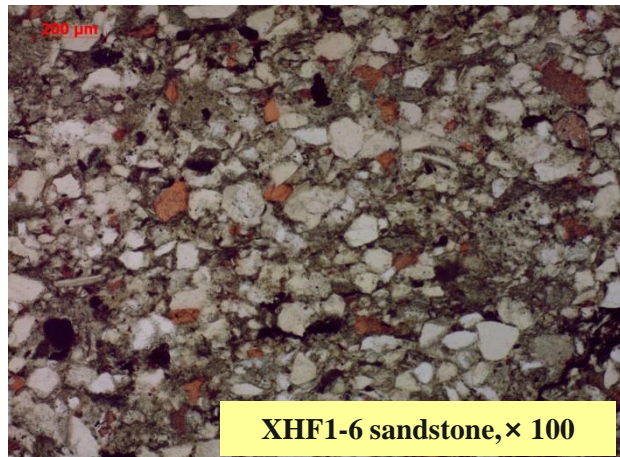


Relatively high production wells, the main test section in delta front distributary channel and mouth bar microfacies, in the relative energy environment

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Tight sandstone reservoir



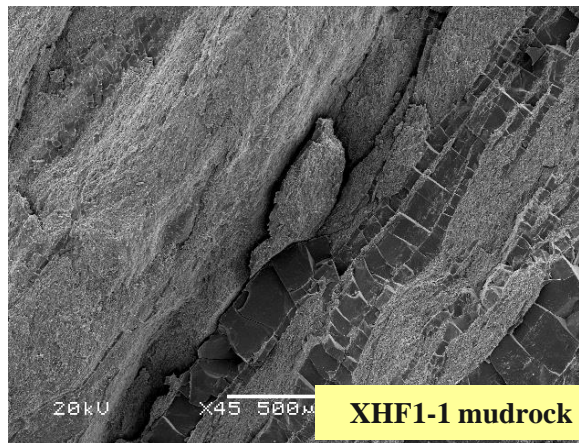
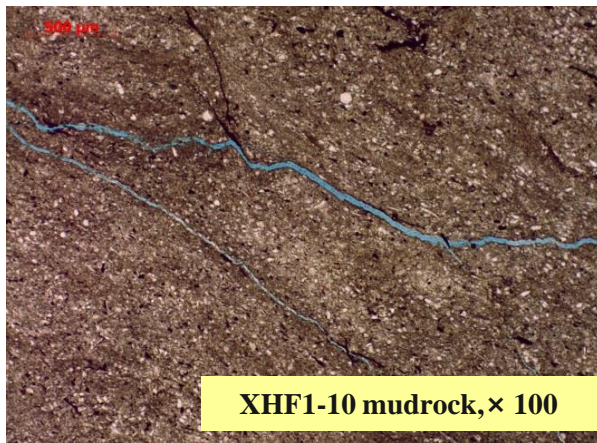
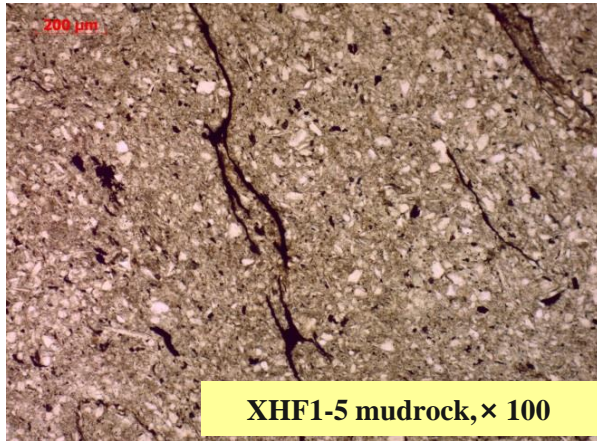
Sandstone types: Gray fine-grained, lithic sandstone, lithic and lithic quartz sandstone

Skeleton particles: quartz, clast, feldspar, poor sorting to well sorting

Fillings: the composition of clay and calcareous cements, calcareous cements include calcite, dolomite and ankerite, small amounts of silica, pyrite and siderite

Pore type cementation; High calcareous content; Tight rock; Pore undeveloped

Mudrock and shale reservoir



Rock composition: Clay mineral and Quartz; Calcite, dolomite, barite, Feldspar
secondly; a small amount of aragonite, siderite, occasionally augite and pyrite

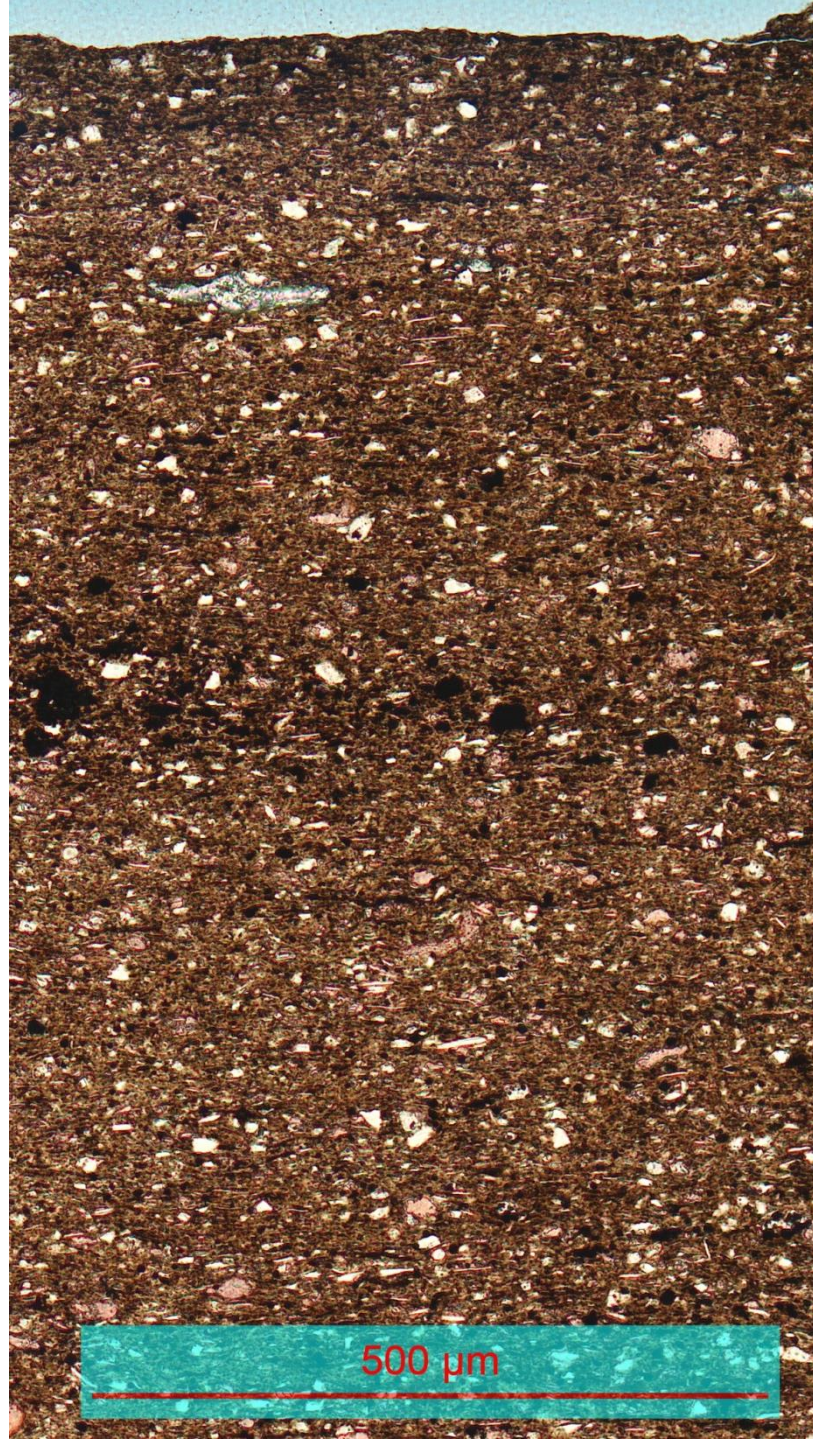
Clay minerals: Illite Smectite mixed layer mineral, illite; Chlorite and kaolinite

shale

A fissile rock composed of clay-size particles (up to 0.04 mm diameter)

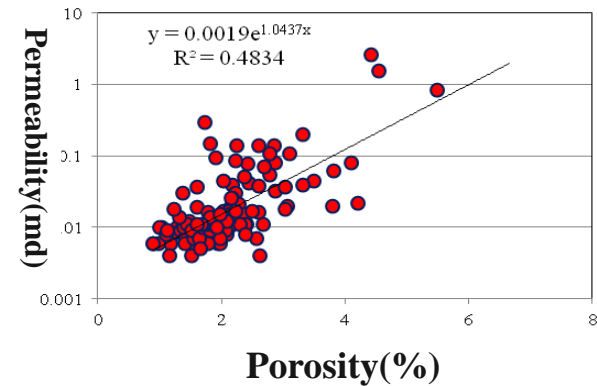
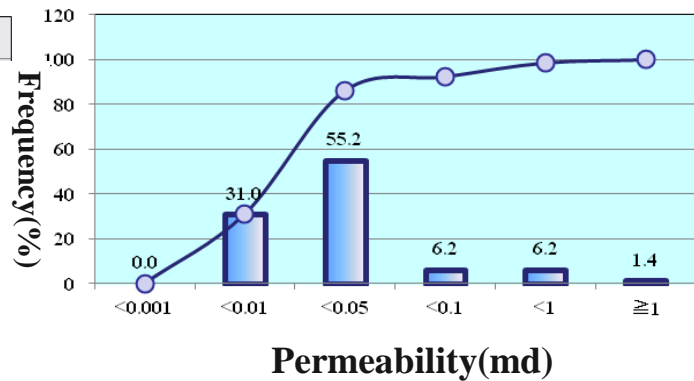
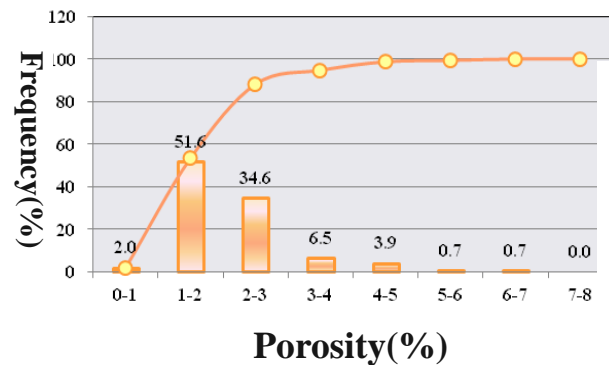
Most shales are not not fissile, so are mudstones, not true shales

Most gas shale reservoirs are composed largely of quartz and carbonate, not clay-rich (leads to better reservoir properties)



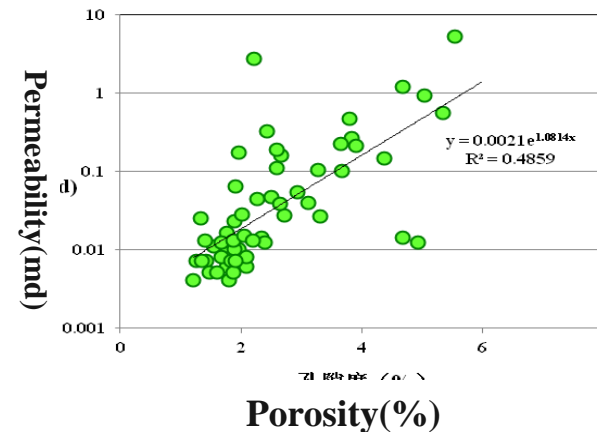
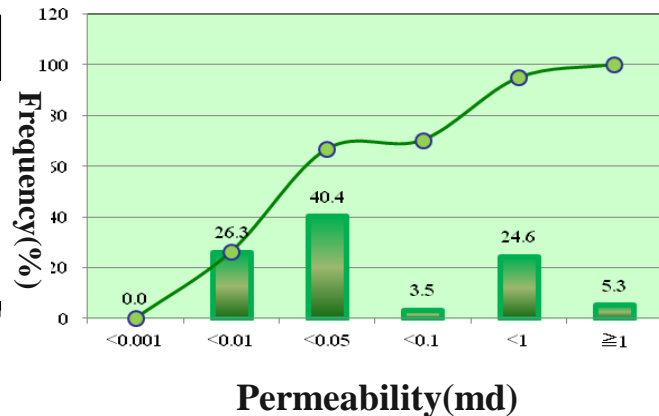
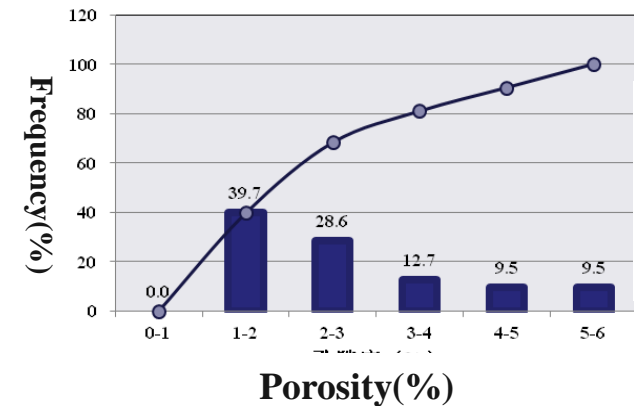
Physical Properties

Tight sandstone reservoir



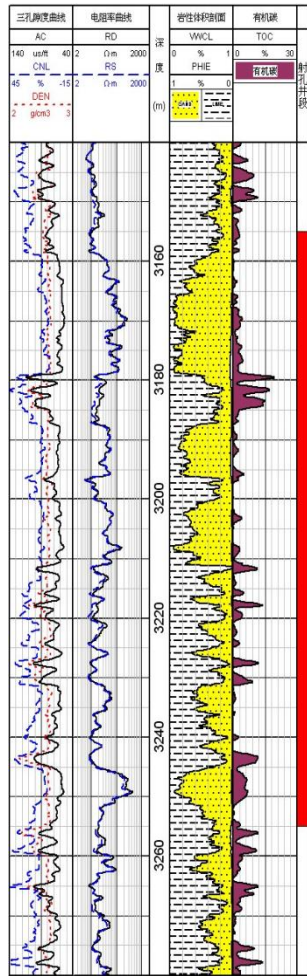
➤ Analysis of sandstone core samples, Porosity 0.08~6.65%, average 2.14%; Matrix permeability 0.004~0.84md, average 0.031md ; Porosity and Permeability correlation coefficient is 0.6953

Shale gas reservoir



➤ Analysis of mudrock core samples, Porosity 1.22~5.99%, average 2.78%; Matrix permeability 0.004~0.929md, average 0.09md,; Porosity and Permeability correlation coefficient is 0.6971

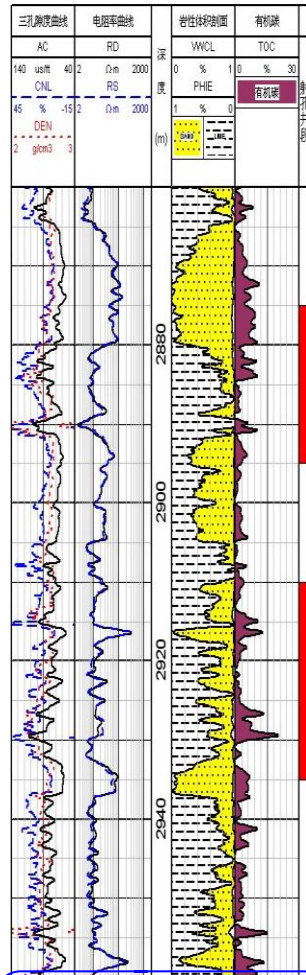
TOC content: mudstone > silt > fine sand



Sand silted

TOC: 5.9%

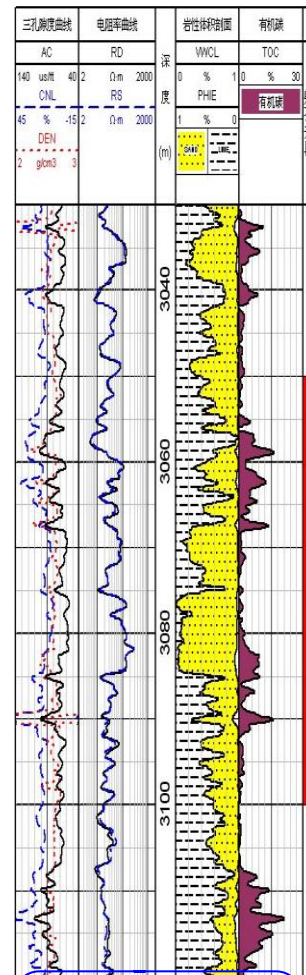
5.2 Million cubic / D



Sand mud interbed

TOC: 3.7%

1.4 Million cubic / D



Sand silted

TOC: 3.4%

1.07 Million cubic / D

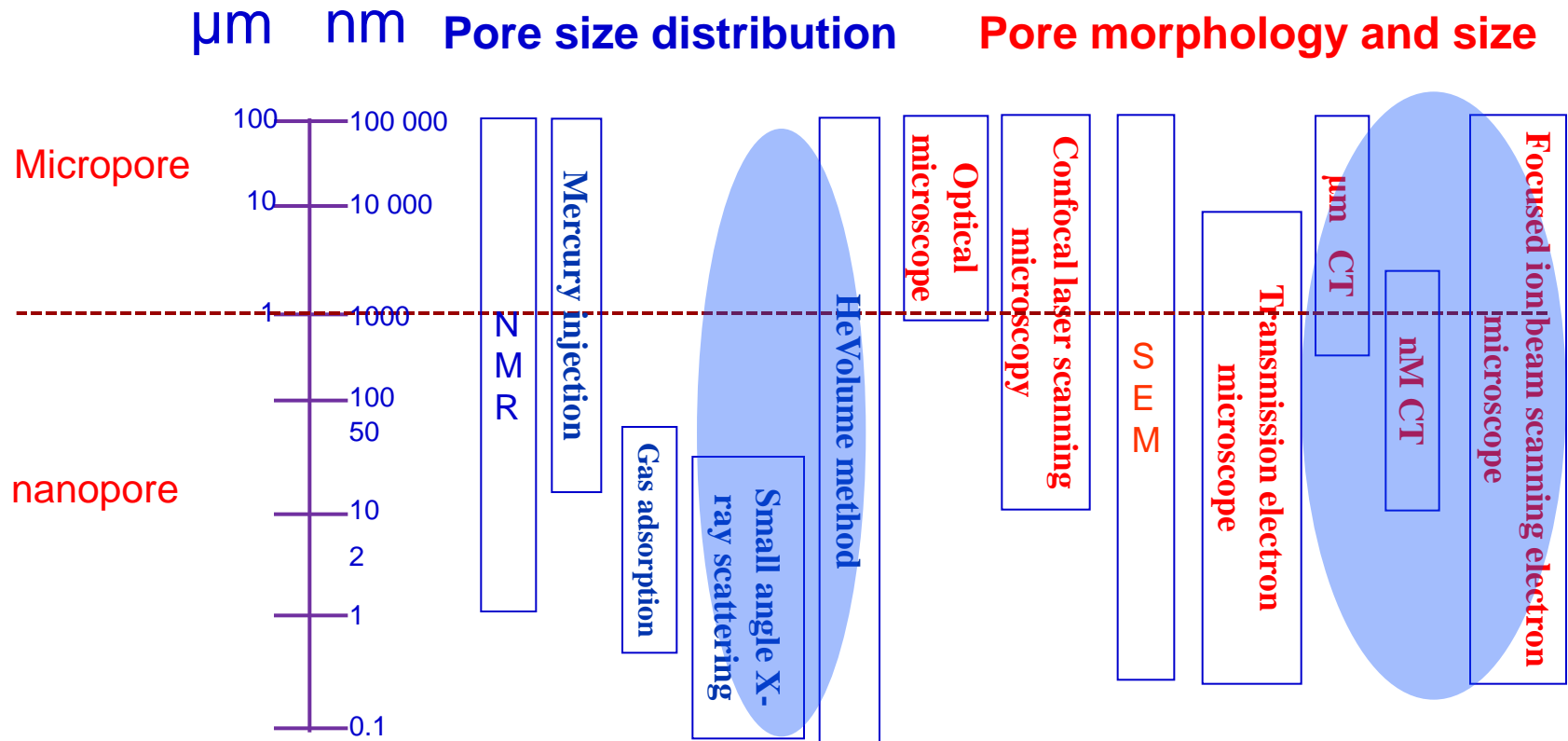
**3 type
Reservoir
Microstructure
???**

**What
How
where**

Outline

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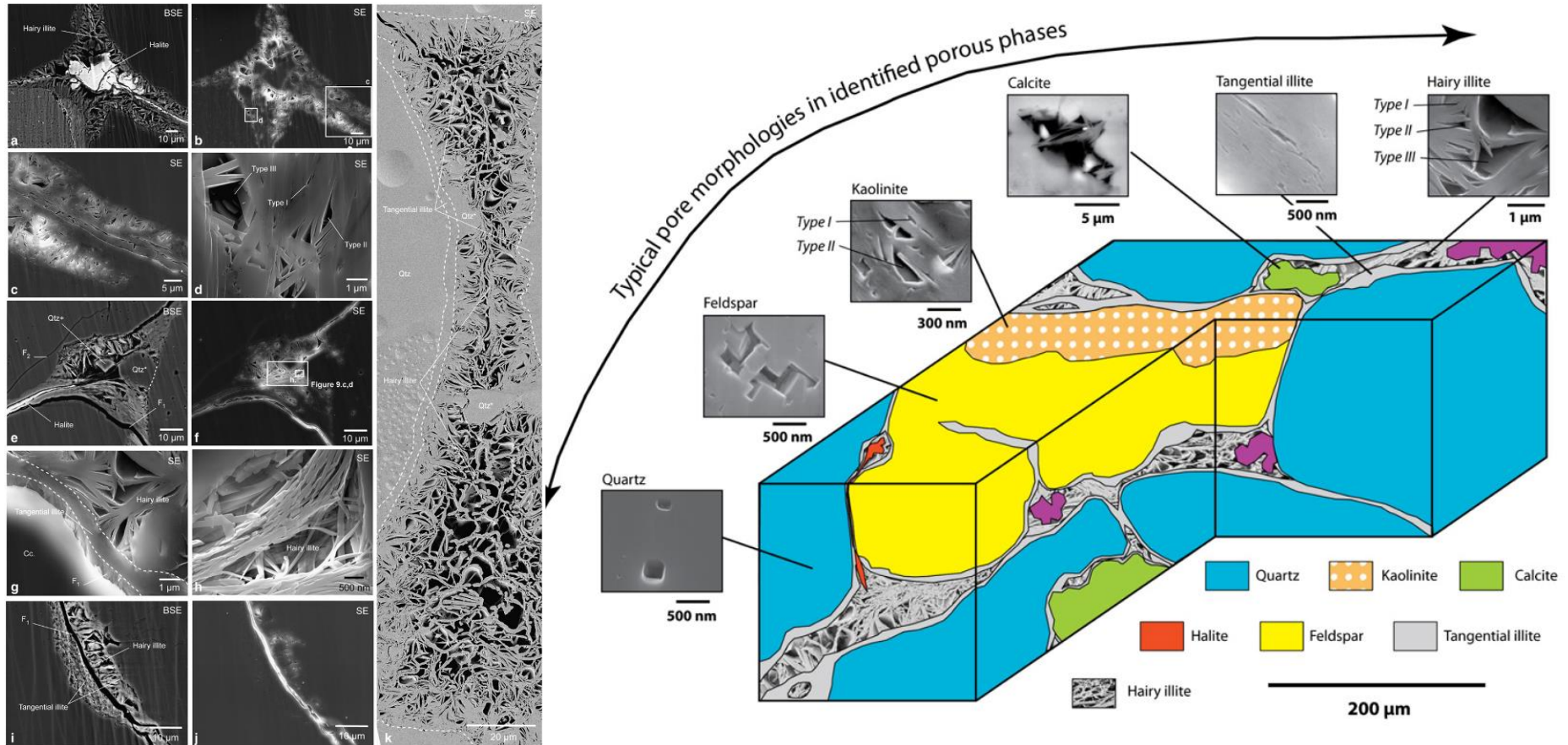
Porosity Microstructure Characterization



The applicability of various methods of measuring pore

Tight reservoir pore throat system of 2D morphology characterization

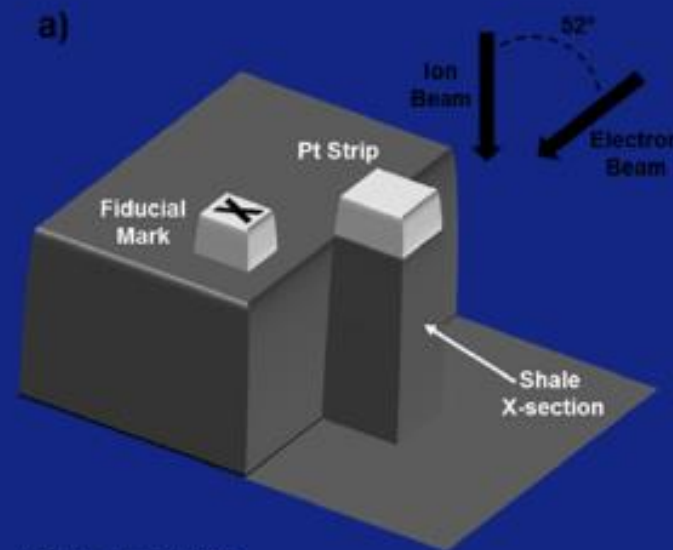
Field emission scanning electron microscope



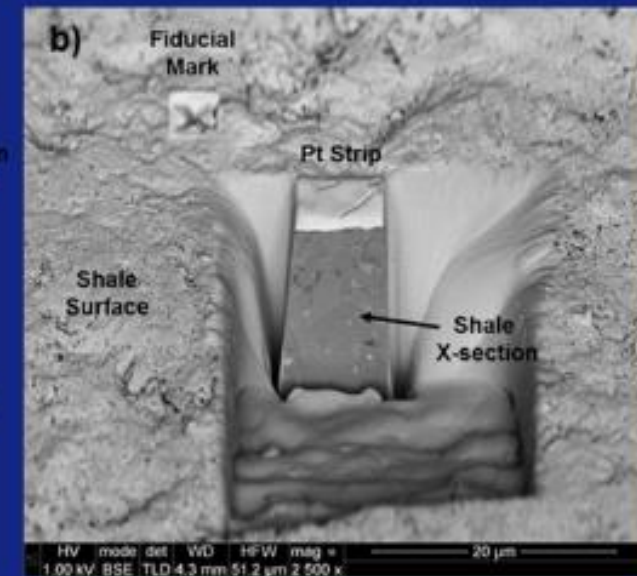
Guillaume Desbois, 2012

Imaging Shales with a Dual-Beam System

- Focused ion beam (FIB) and scanning electron microscope (SEM) integrated on same sample chamber.
- X-section shale surface via momentum transfer of high energy (30 kV) Ga^+ .
- Image x-sectioned surface using backscattered electrons (BSE) for atomic number contrast.
- Can perform other analytical techniques in situ and ion-beam induced material deposition.



Curtis et al., submitted, 2010



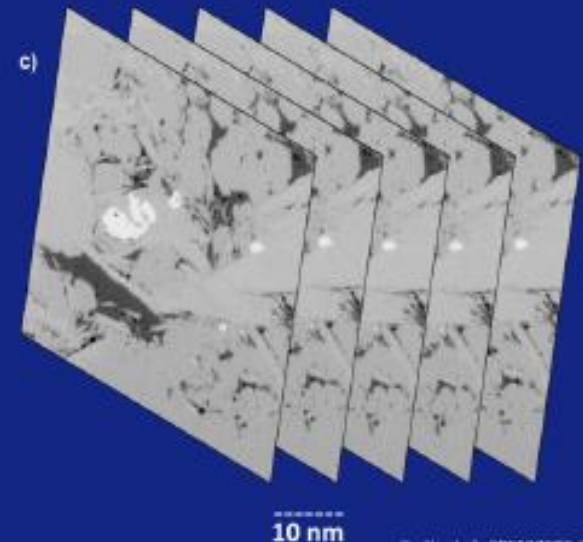
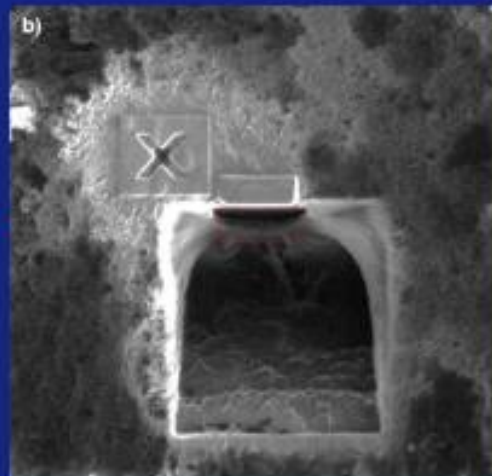
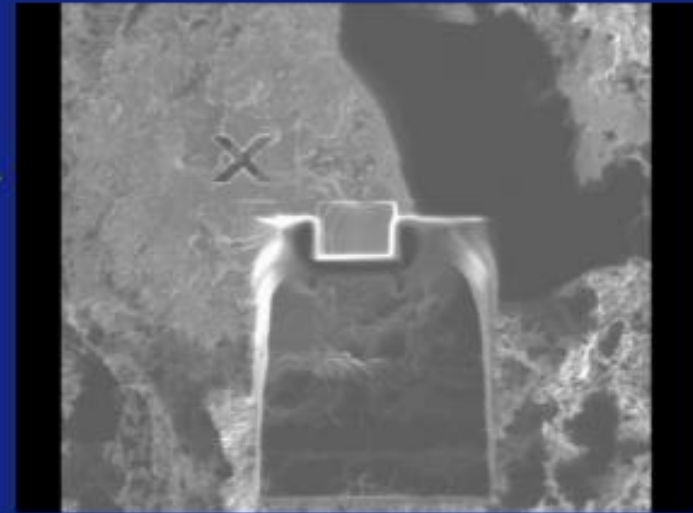
a) schematic of dual beam site preparation using FIB and imaging using SEM. b) BSE image of x-sectioned shale.

Dual-beam FIB/SEM.

From Mark E. Curtis, et al 2013

Serial Sectioning of Gas Shale Microstructure

- Want to investigate pore connectivity and kerogen distribution in 3D.
- Prepare site using Pt deposition and FIB milling.
- Image FIB x-sectioned shale face.
- Use FIB to remove a 10 nm thick layer off x-section face.
- Image x-section face and repeat procedure ~500-600 times.
- Now have a 3D data set of shale microstructure.

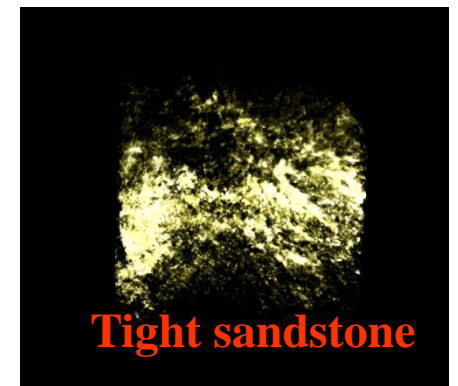
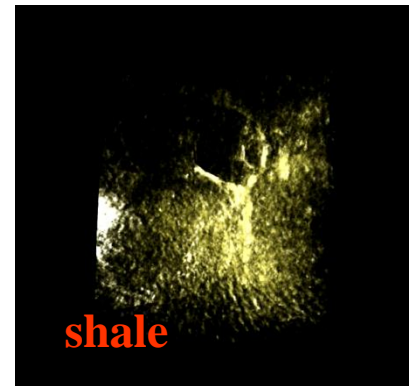
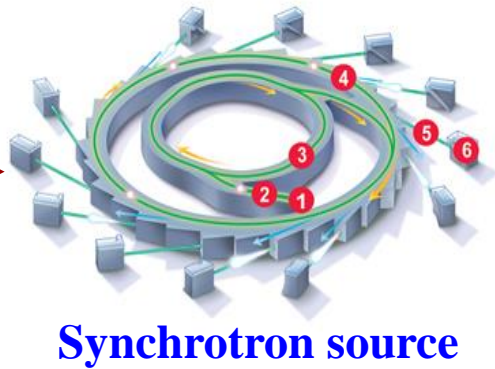


From Curtis, et al, 2010

Tight reservoir pore throat system 3-D space description

X-ray CT (Micron & Nano)

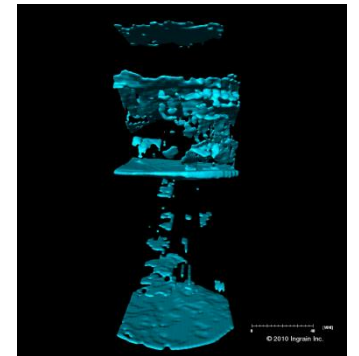
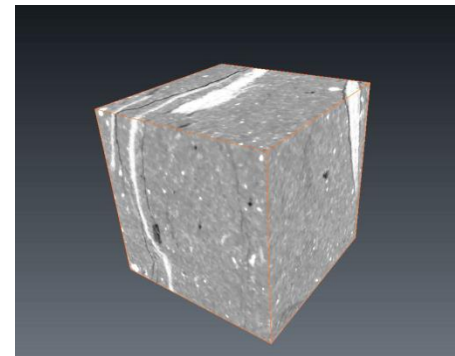
Synchrotron →



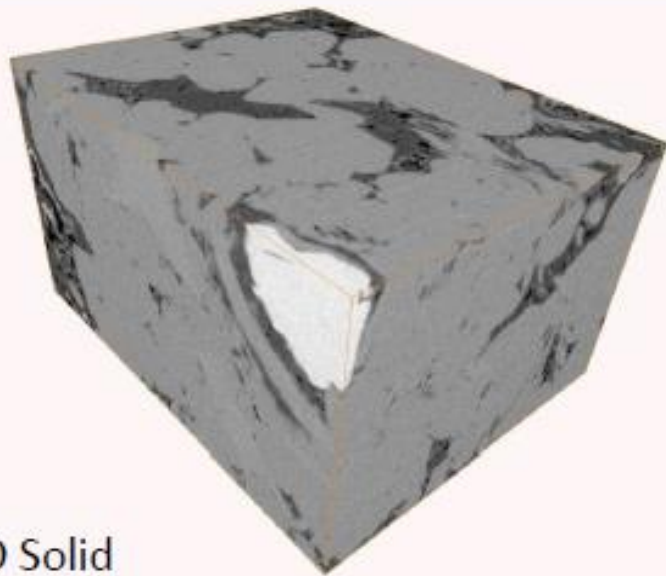
NanoCT →



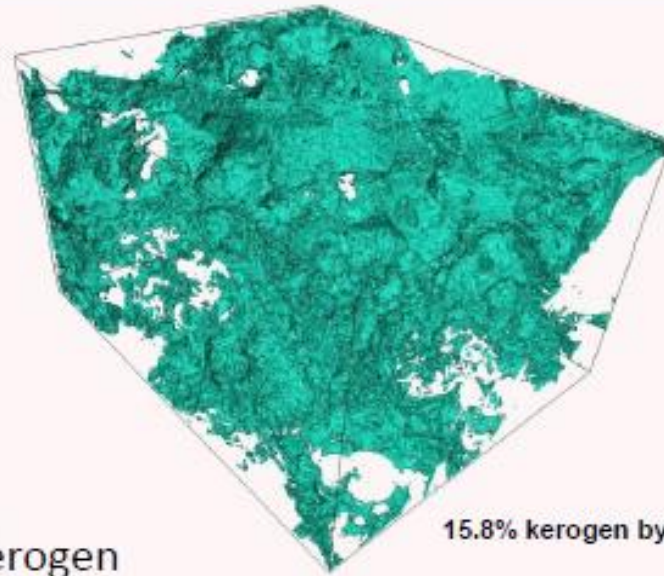
Xradio nanoXCT-200



3D Shale Microstructure

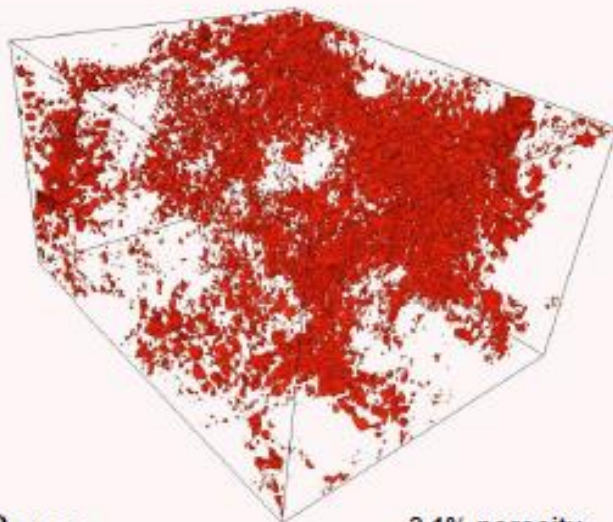


3D Solid



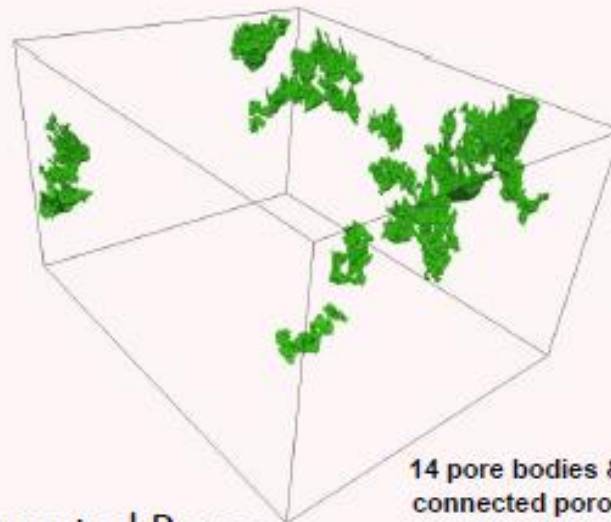
Kerogen

15.8% kerogen by vol.



All Pores

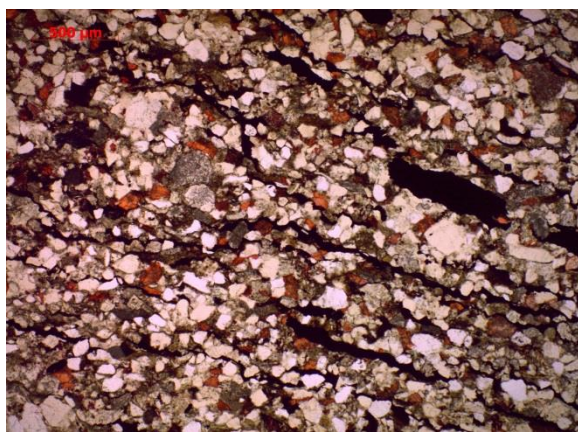
2.1% porosity



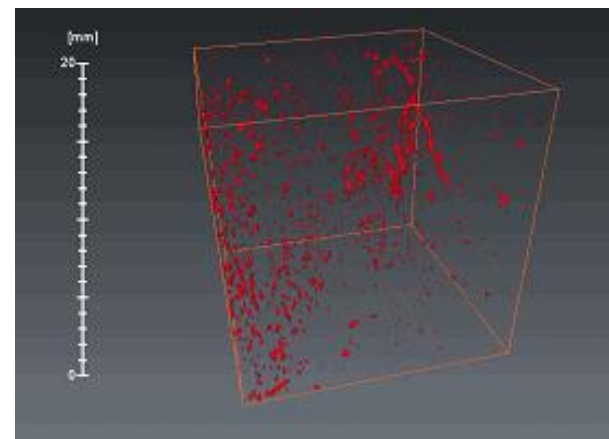
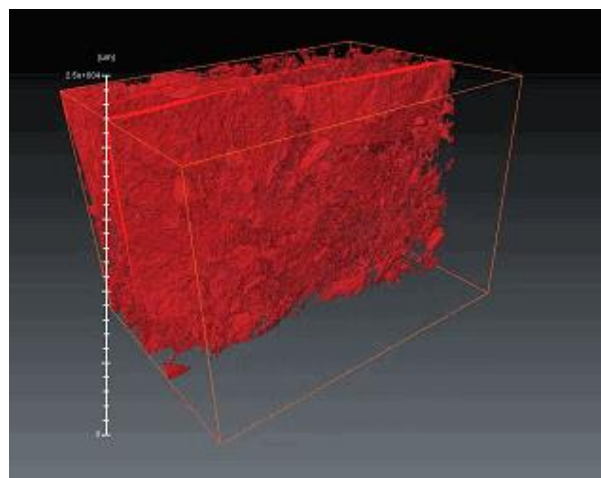
Connected Pores

14 pore bodies & 0.4%
connected porosity at
10⁶ voxel level.

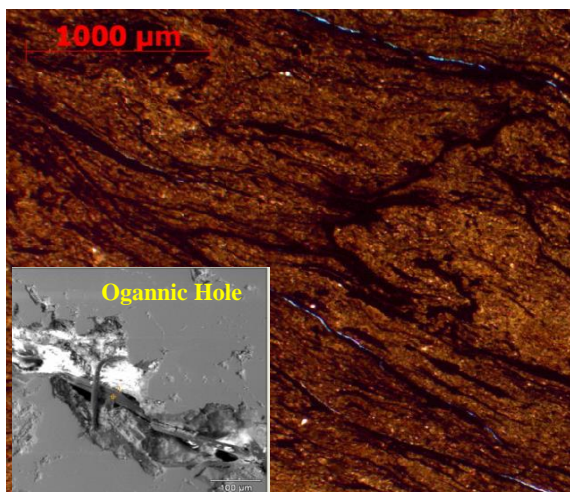
From Mark E. Curtis, et al 2013



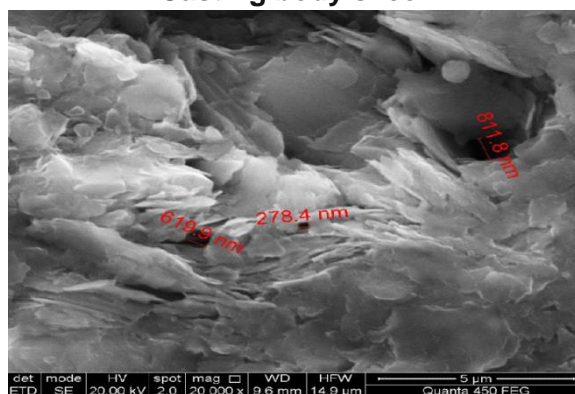
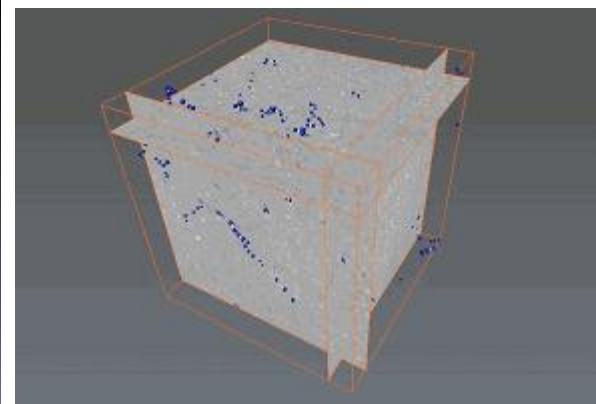
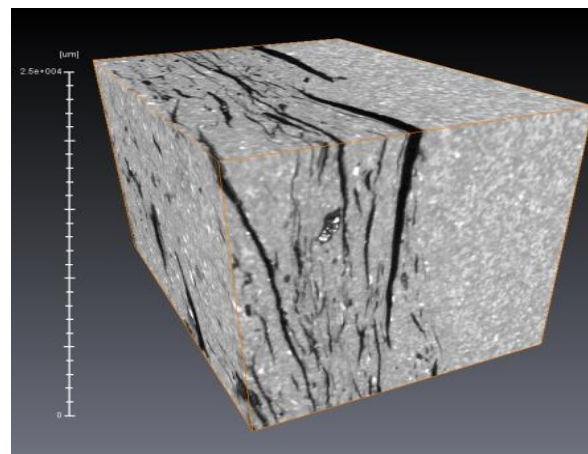
Thin slice



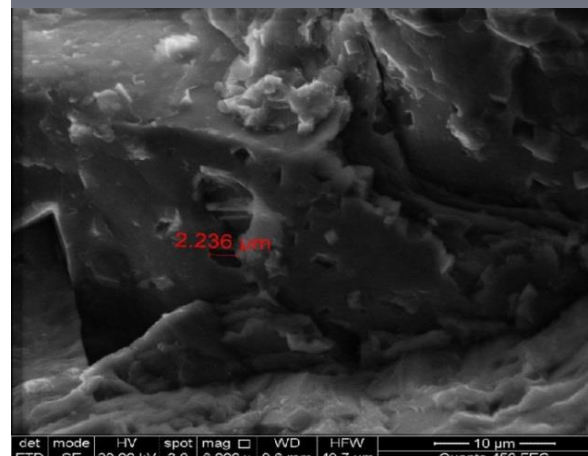
Nano micron CT scan imaging



Casting body slice

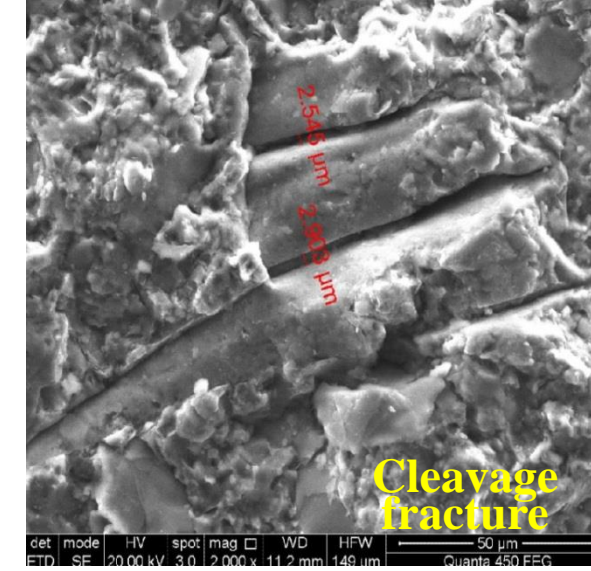
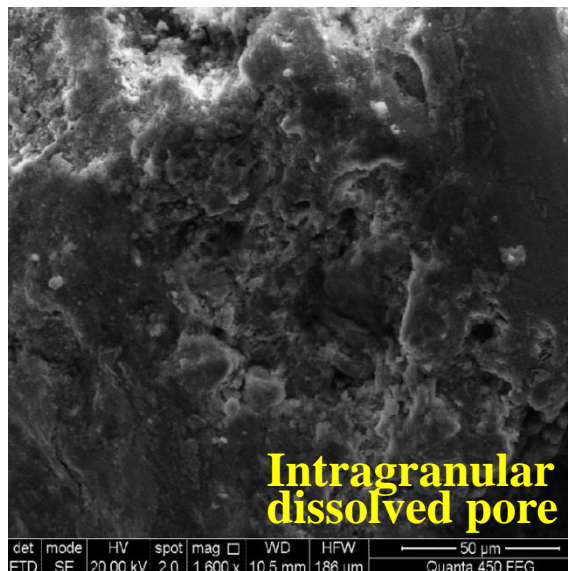
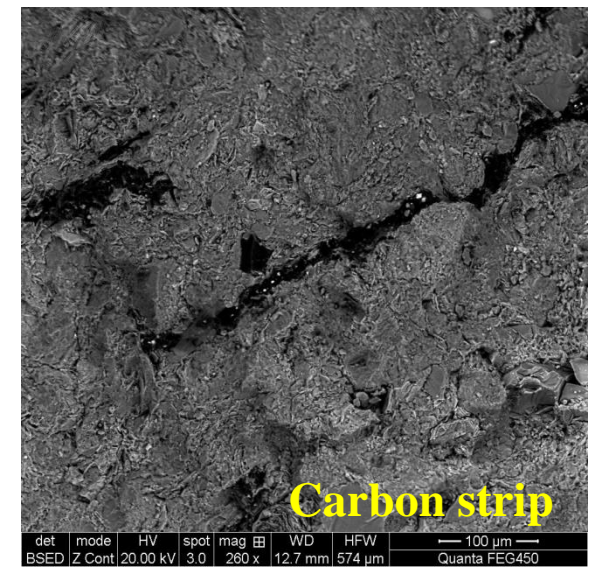
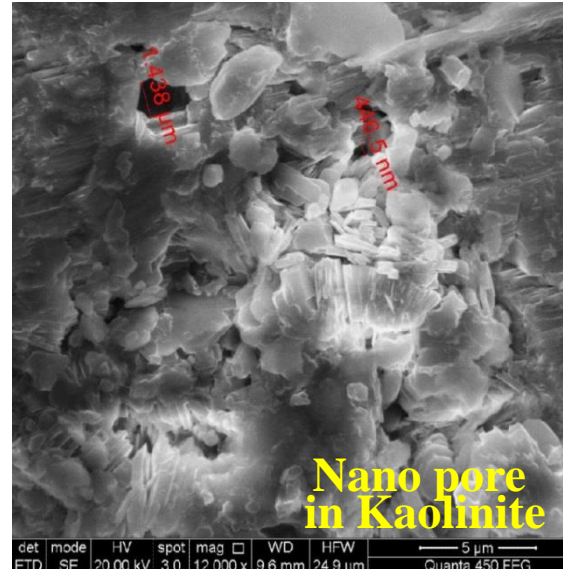
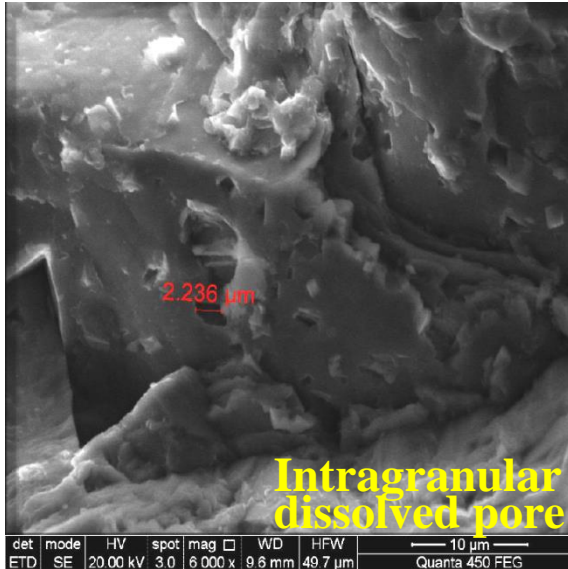


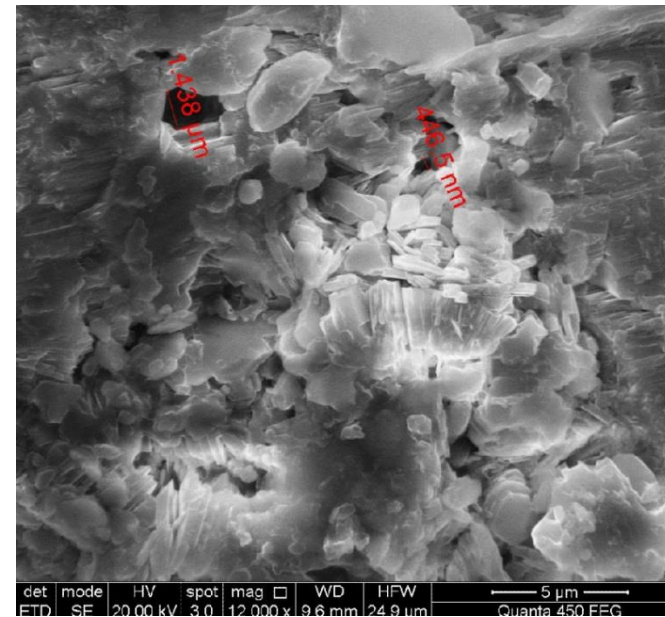
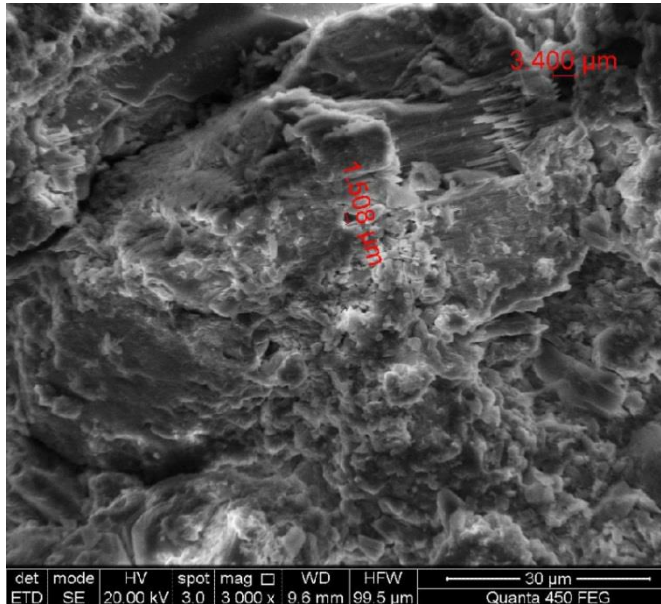
Field emission scanning electron microscope



Microstructure Characterization-- sandstone

Sandstone overall densification, aperture is not development, local development micron secondary pores and cleavage cracks, nano intercrystalline pore, organic matter joint

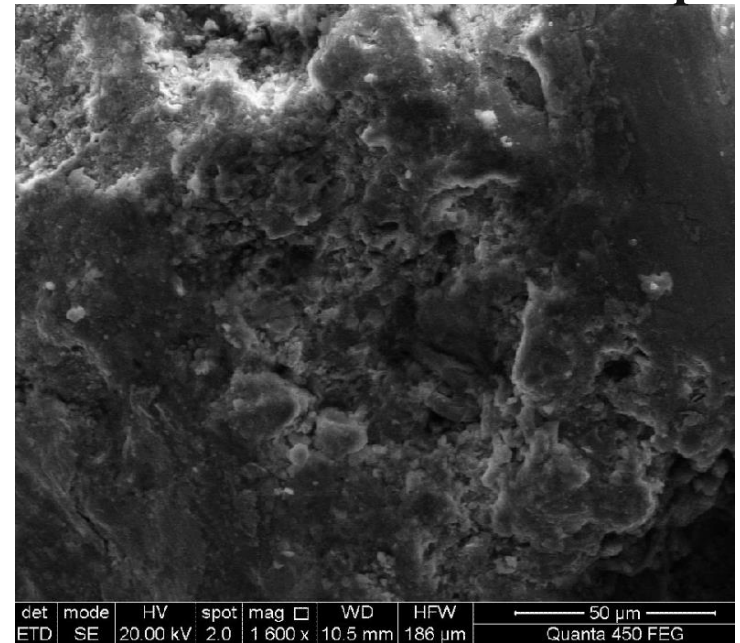
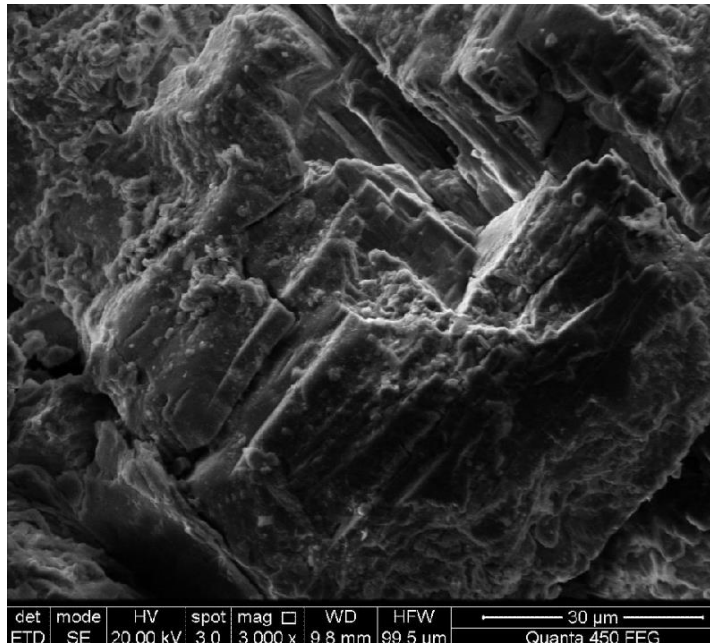




Nano pore in Kaolinite

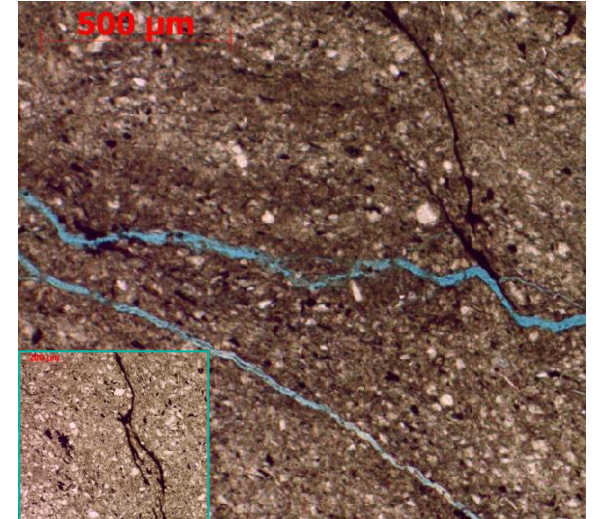
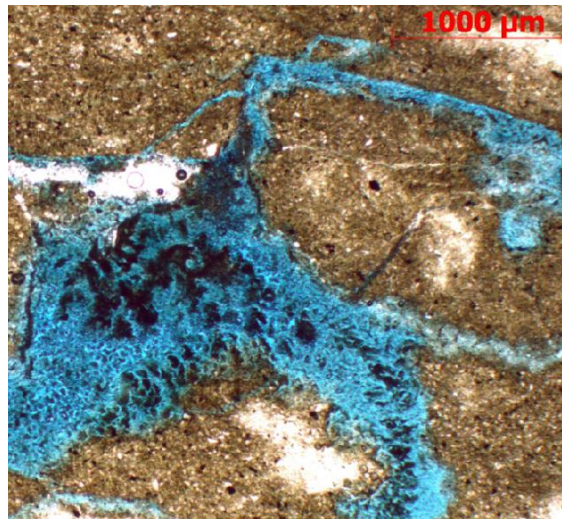
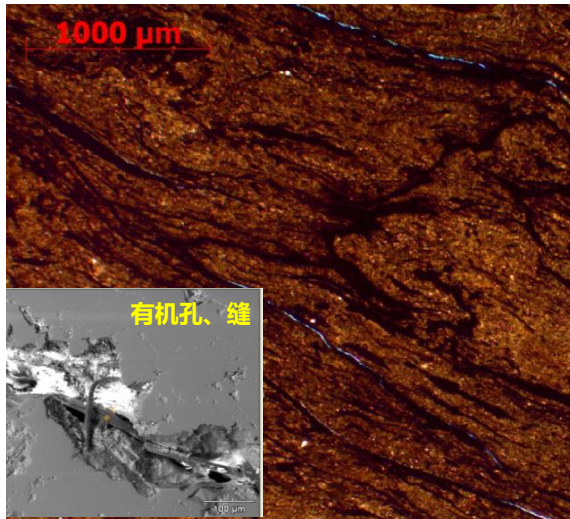
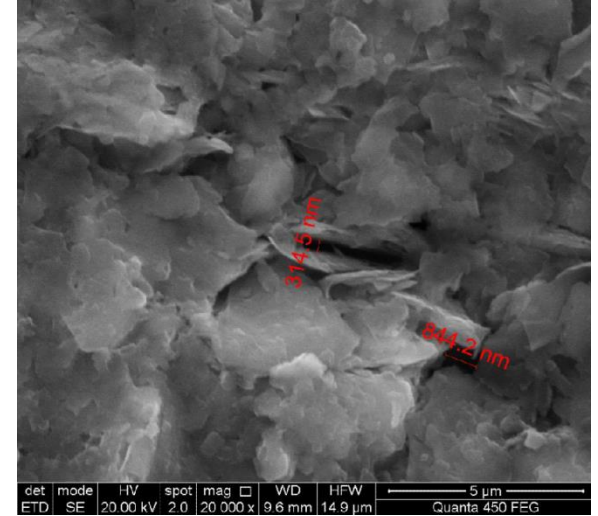
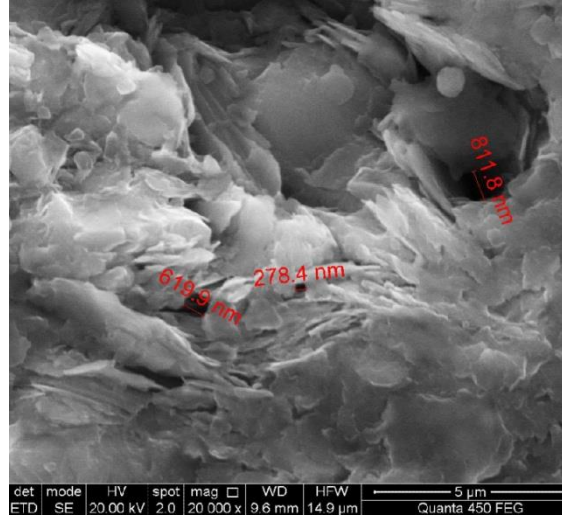
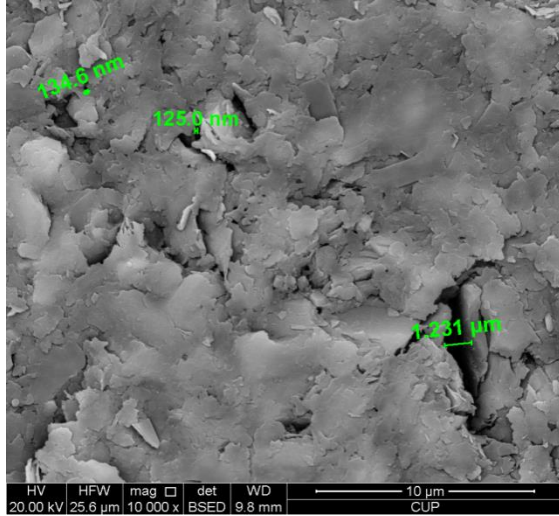
Intragranular dissolved pore

**Cleavage fracture
In Feldspar**



Microstructure Characterization– musrock and shale

Nano pore development, carbonaceous strip development, easy to form diagenetic fracture

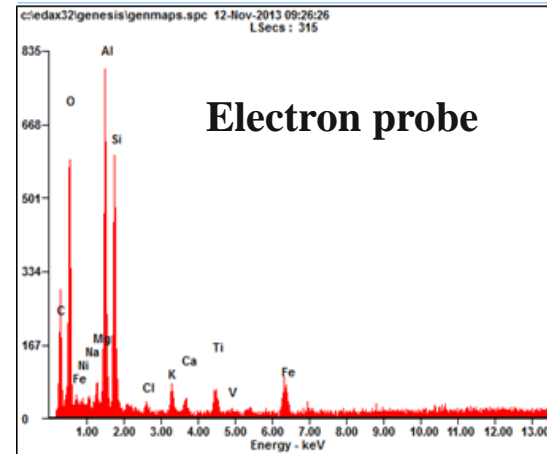
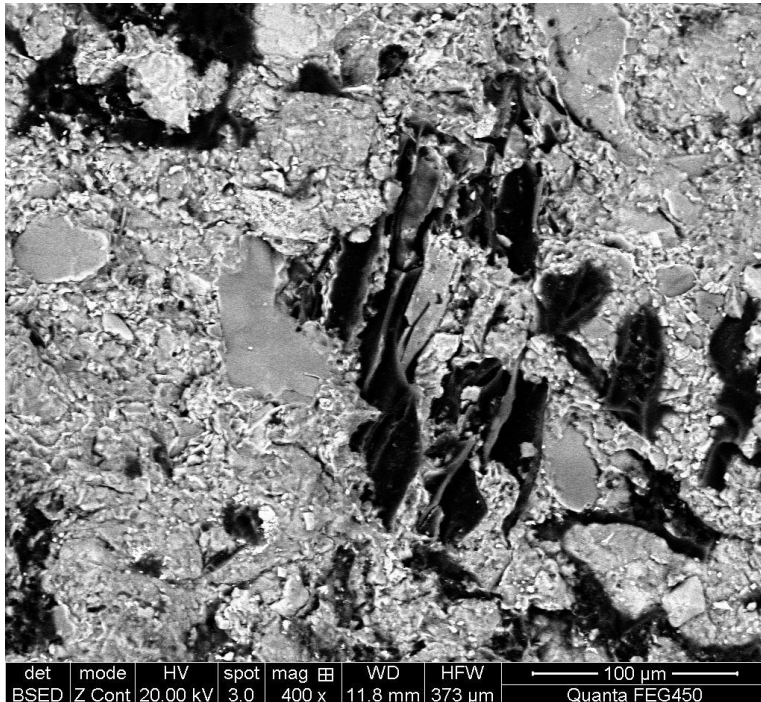


Argillaceous minerals and carbon strip, orientation, diagenetic fracture development

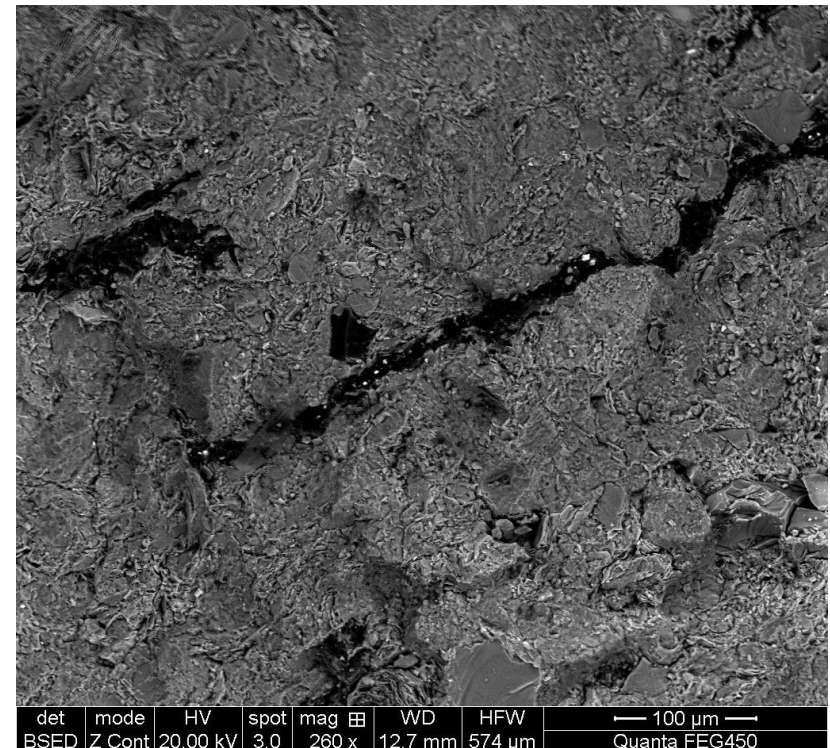
Mineral and clay crystal, development of fracture and solution pore

Argillaceous minerals and silty sand, diagenetic crack, rich in strip carbon

Carbon strip development



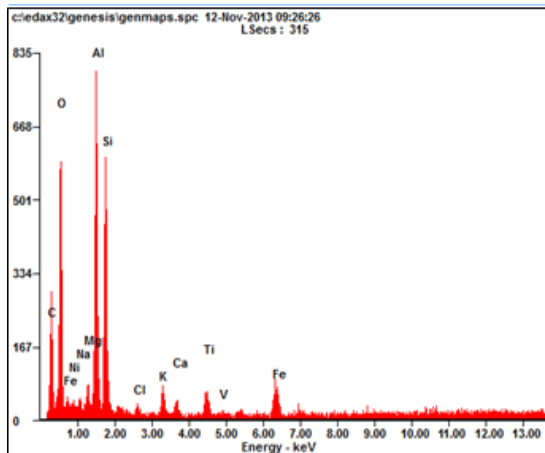
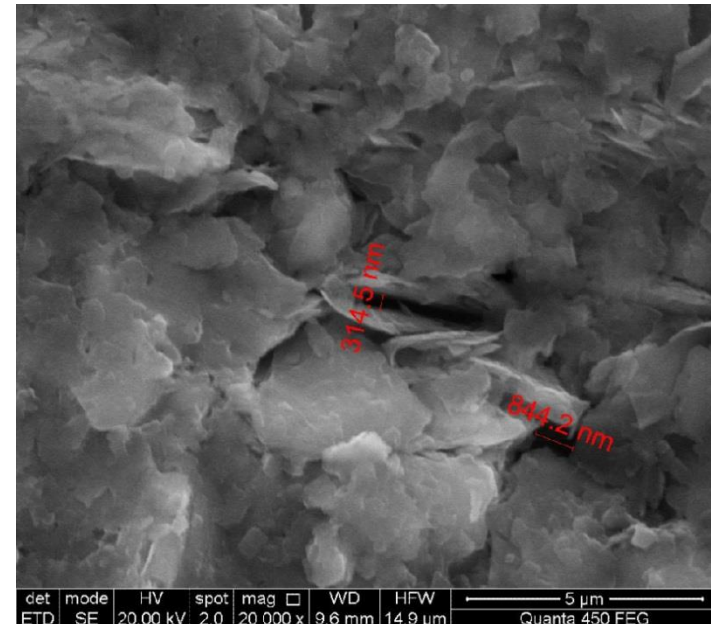
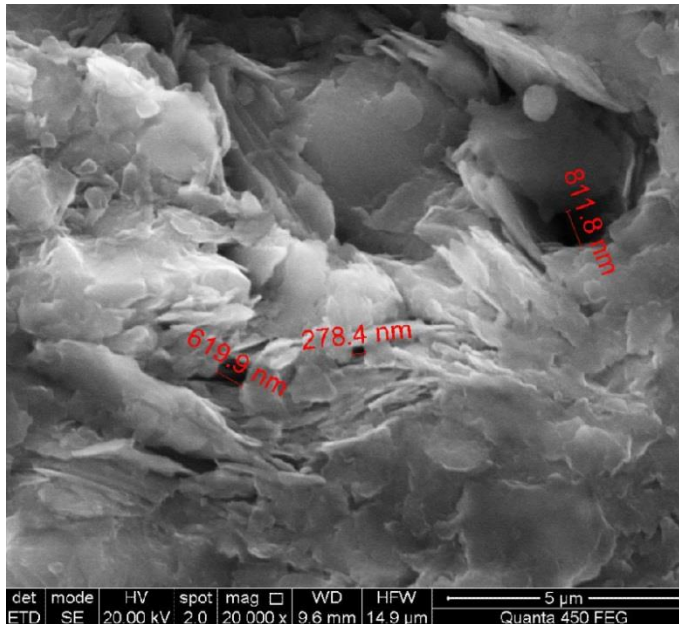
Element [Ⓢ]	Wt% [Ⓢ]	At% [Ⓢ]
<i>CK</i> [Ⓢ]	21.65 [Ⓢ]	33.93 [Ⓢ]
<i>OK</i> [Ⓢ]	34.34 [Ⓢ]	40.41 [Ⓢ]
<i>NiL</i> [Ⓢ]	02.32 [Ⓢ]	00.74 [Ⓢ]
<i>NaK</i> [Ⓢ]	00.75 [Ⓢ]	00.61 [Ⓢ]
<i>MgK</i> [Ⓢ]	01.39 [Ⓢ]	01.07 [Ⓢ]
<i>AlK</i> [Ⓢ]	14.20 [Ⓢ]	09.91 [Ⓢ]
<i>SiK</i> [Ⓢ]	12.45 [Ⓢ]	08.34 [Ⓢ]
<i>ClK</i> [Ⓢ]	00.44 [Ⓢ]	00.23 [Ⓢ]
<i>KK</i> [Ⓢ]	01.72 [Ⓢ]	00.83 [Ⓢ]
<i>CaK</i> [Ⓢ]	01.01 [Ⓢ]	00.47 [Ⓢ]
<i>TiK</i> [Ⓢ]	02.74 [Ⓢ]	01.08 [Ⓢ]
<i>VK</i> [Ⓢ]	00.18 [Ⓢ]	00.07 [Ⓢ]
<i>FeK</i> [Ⓢ]	06.82 [Ⓢ]	02.30 [Ⓢ]
<i>Matrix</i> [Ⓢ]	Correction [Ⓢ]	ZAF [Ⓢ]



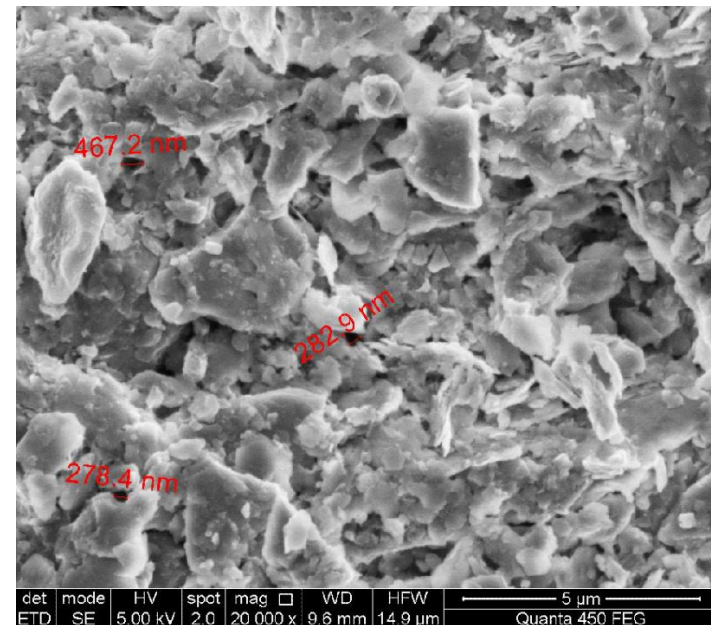
XHF1-6, Gray sandstone, carbonaceous strip

Micro crack growth, carbon deposition and organic matter filling cracks, the content of Si Al is high, good brittleness.

Mudstone composition: illite smectite, illite; Chlorite, kaolinite



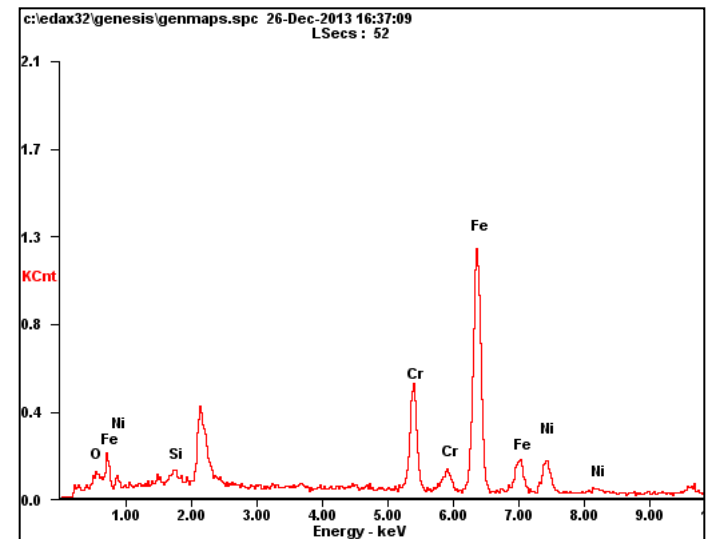
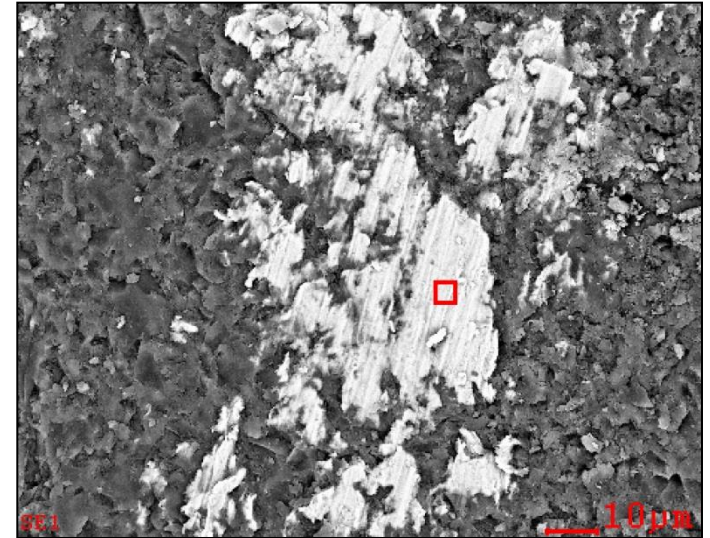
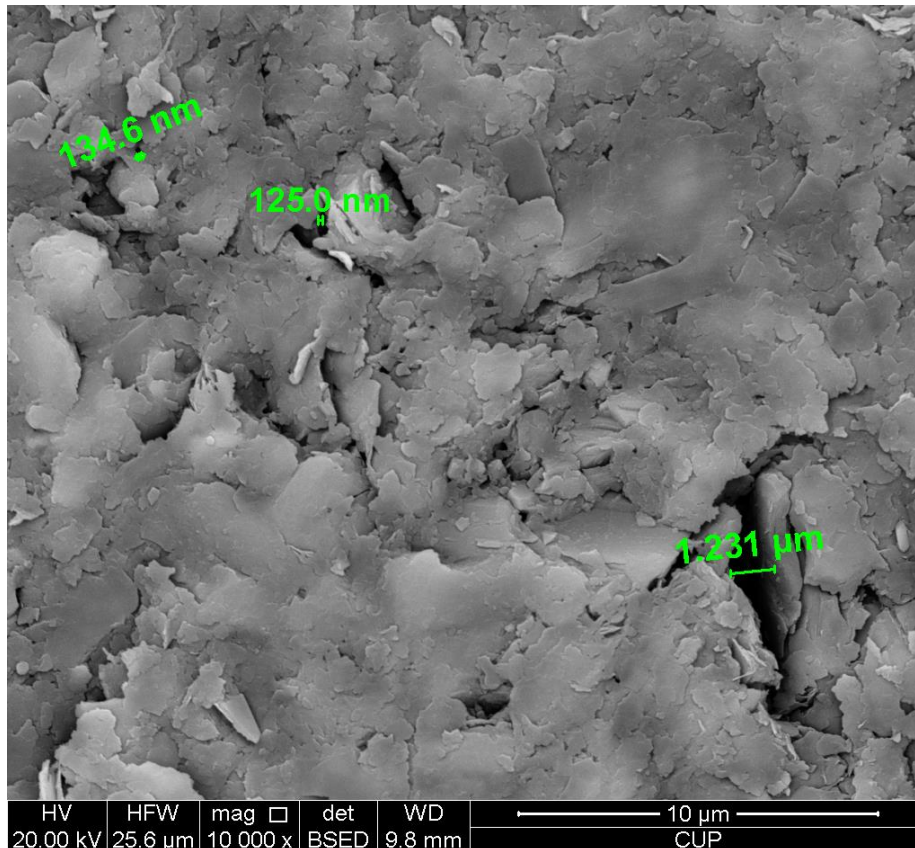
Element	Wt%	At%
CK	21.65	33.93
OK	34.34	40.41
NiL	02.32	00.74
NaK	00.75	00.61
MgK	01.39	01.07
AlK	14.20	09.91
SiK	12.45	08.34
ClK	00.44	00.23
KK	01.72	00.83
CaK	01.01	00.47
TiK	02.74	01.08
VK	00.18	00.07
FeK	06.82	02.30
Matrix	Correction	ZAF



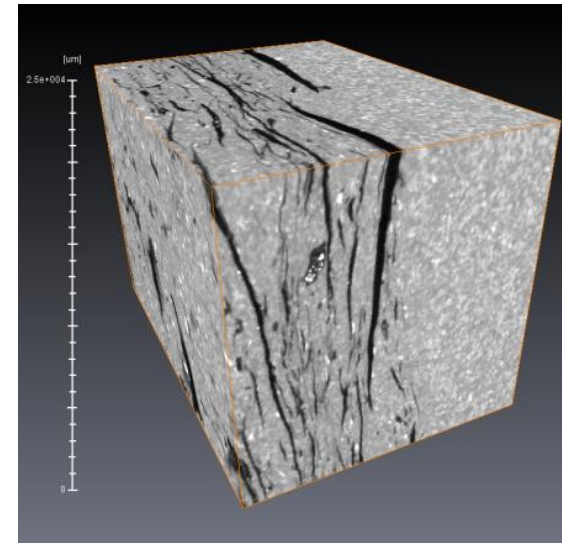
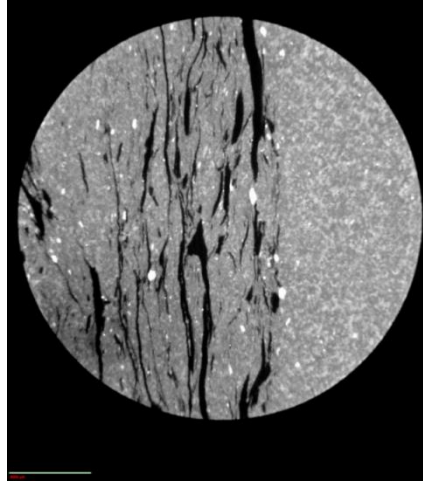
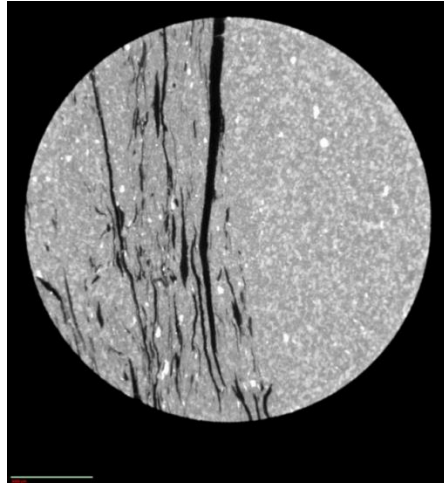
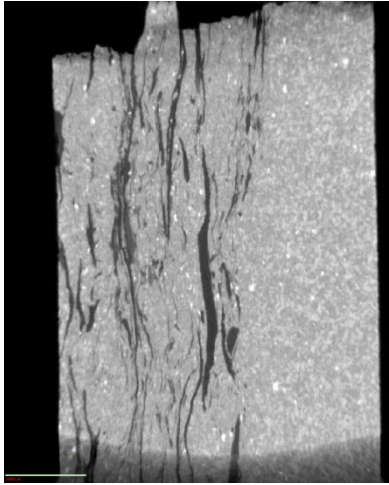
Mudstone composition

- illite smectite, illite
- Chlorite, kaolinite

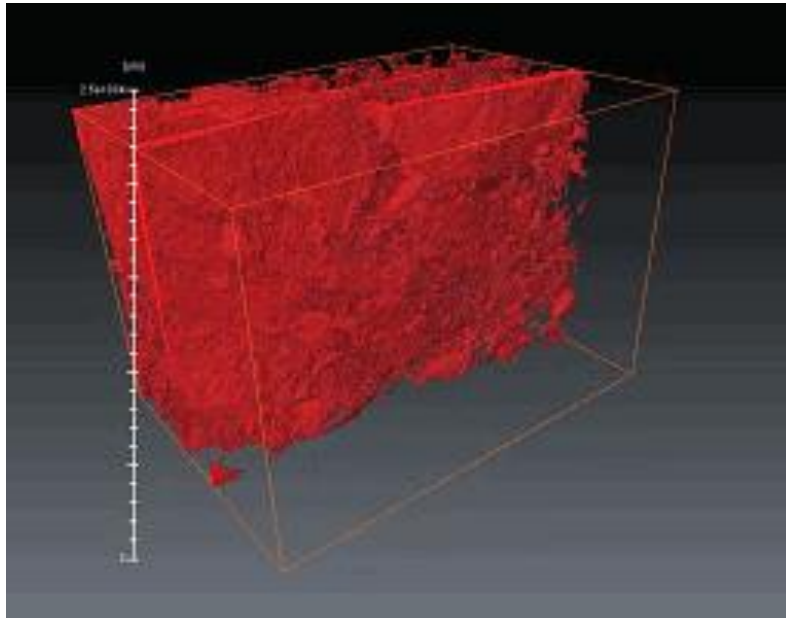
Element	Wt%	At%
OK	01.96	06.39
SiK	01.48	02.75
CrK	16.52	16.61
FeK	65.93	61.70
NiK	14.11	12.56
Matrix	Correction	ZAF



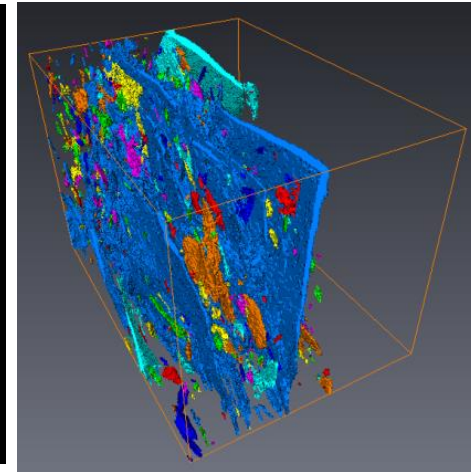
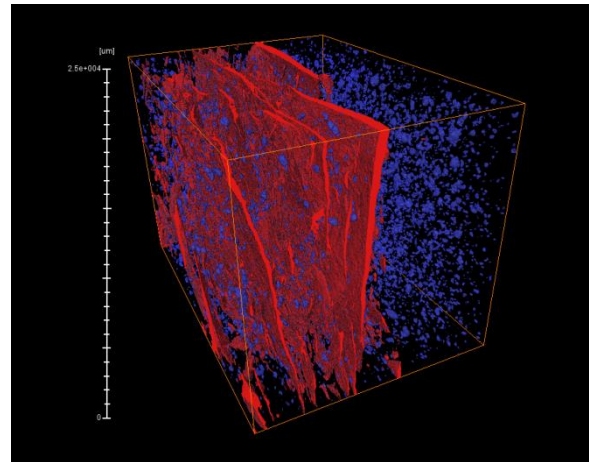
Micro CT scanning Image, grey siltstones carbonaceous filling, tight sandstone



Rock skeleton model

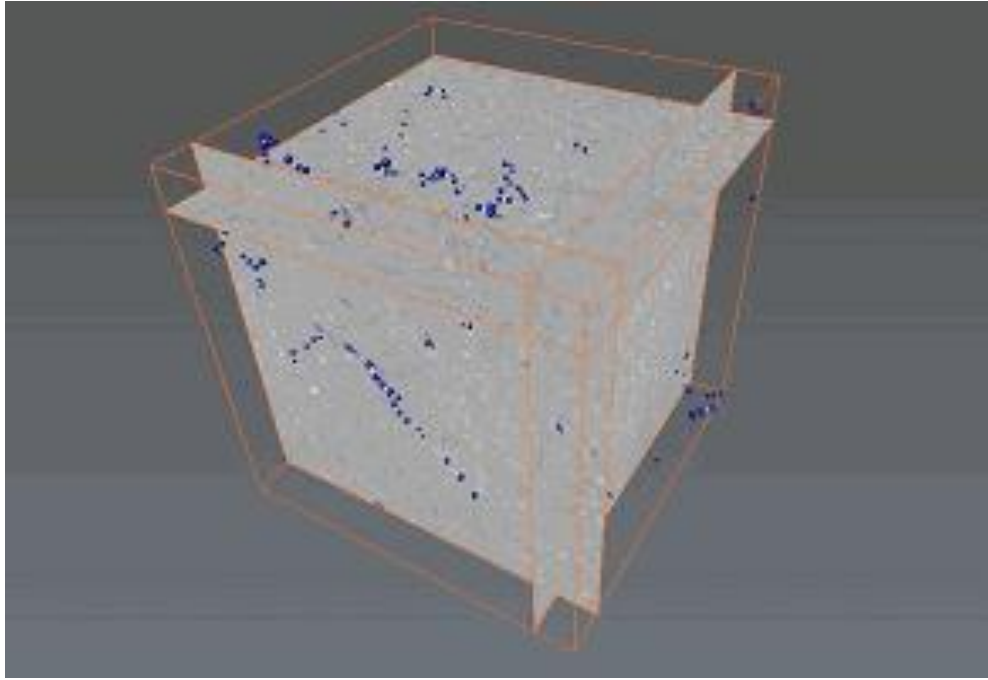


Carbon strip and Pore distribution

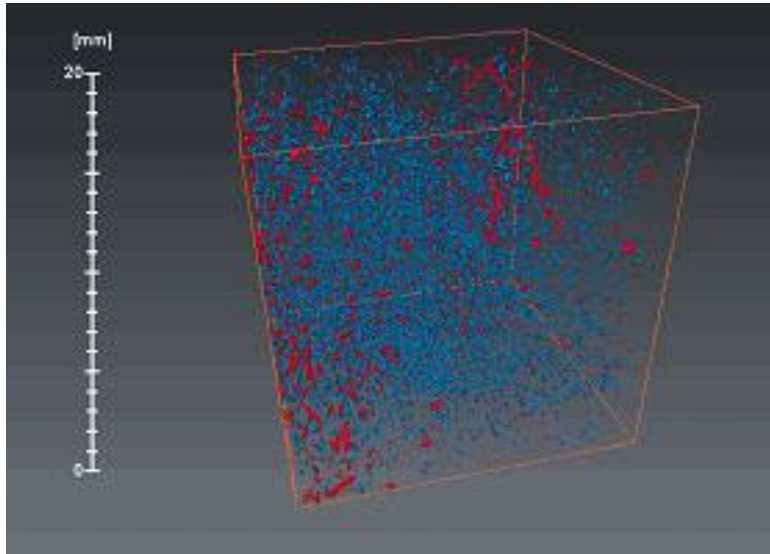


Pore connectivity model

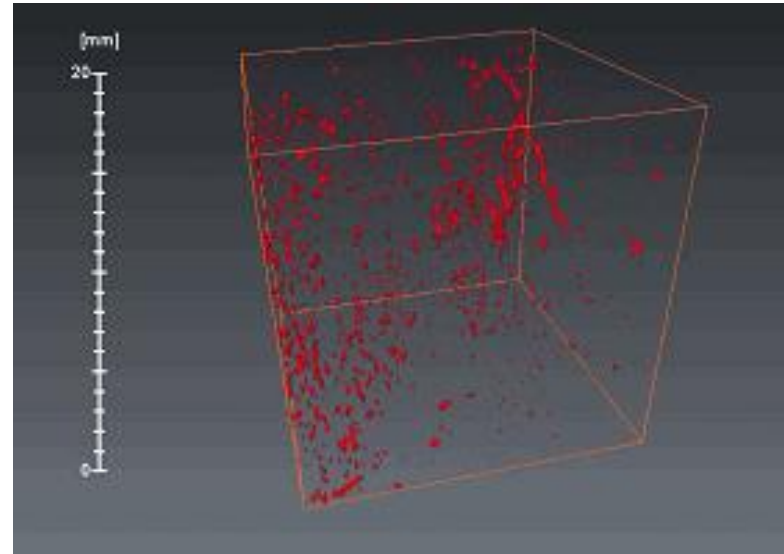
**Micro CT scanning, Fine sandstone, carbon dispersed grey siltstones
tight sandstone and charcoal abundance zone**



Rock skeleton model

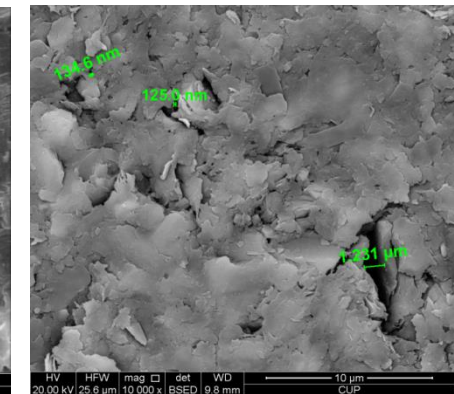
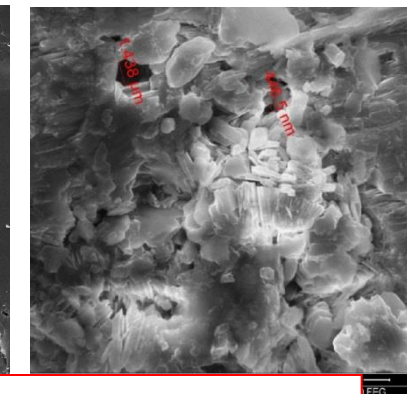
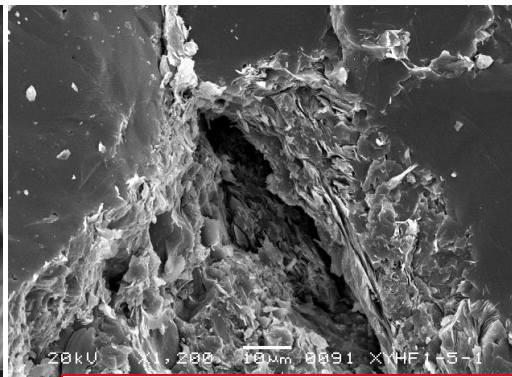
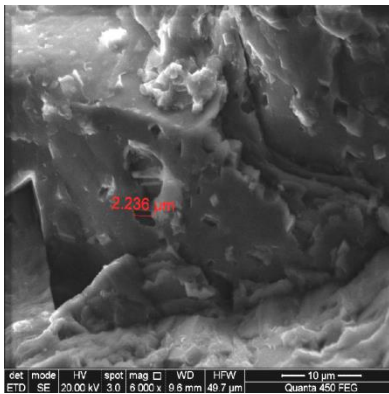


Carbon strip and Pore distribution



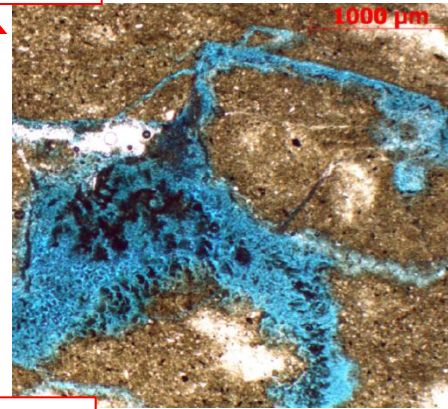
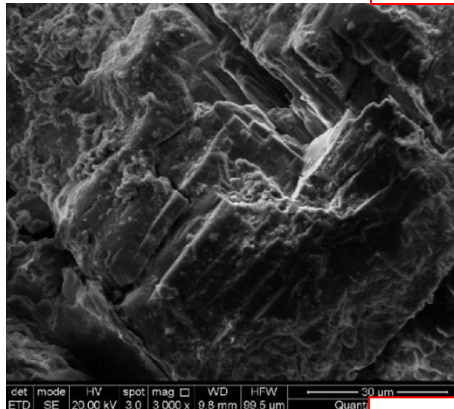
Pore connectivity model

Accumulation

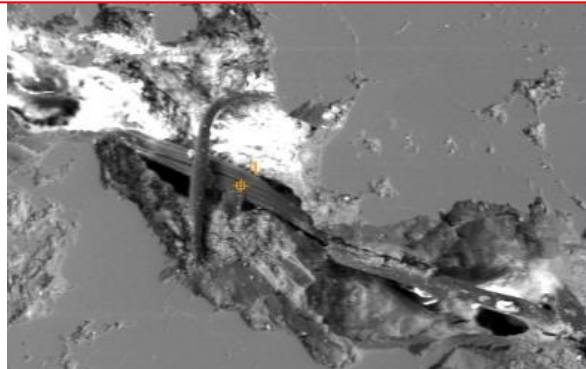


Micro, Nano Pore + Crack Space

Migration

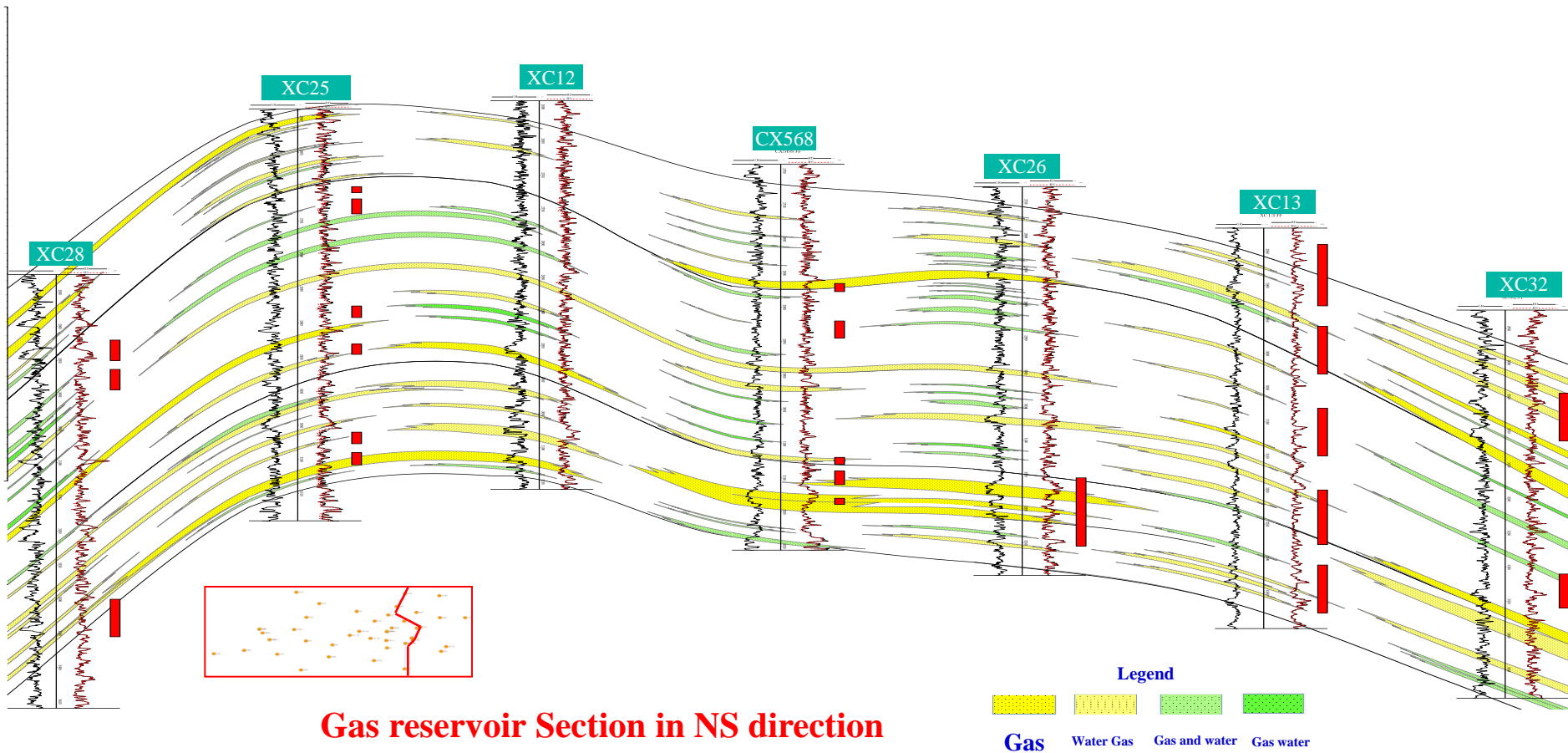


Carbon strip + Fracture network



Carbon strip + Fracture network + micro, nano pore
Composed of generation, migration, accumulation system

Generation



- High content of organic carbon is important, high production
- With the carbon strip are the key, tectonic factor is not obvious
- Reservoir with rich organic matter, fracture control production
- Abnormal high pressure, production with water, tight gas reservoir

Outline

- **Background**
- **Tight sandstone and shale Gas reservoir**
- **Reservoir Microstructure**
- **Conclusions**

Conclusions

- **Lithological association include silted sand and sandy mudstone interbed in the well relatively high production**
- **Pore relative development is the key factors in sandstone reservoir, relatively high porosity development directly related to the productivity in the gas well**
- **High content of organic carbon is important for microstructure and the prerequisite for high production**
- **With the carbon strip are the key factor controlled by tectonic is not obvious**

Acknowledgments

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SINOPEC



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