Reservoir Quality, Hydrocarbon Mobility and Implications for Lacustrine Shale Oil Productivity in the Paleogene Sequence, Bohai Bay Basin*

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Abstract

The Paleogene lacustrine sequences in rift basins in eastern China has been the focal point for exploration of shale oils and tight oils recently, due to the wide spread occurrence of organic-rich black shales, moderate to high maturity levels, association with natural fractures, overpressure zones, or high percentage of brittle minerals. An earlier study identified four potential types of shale oil accumulations: (1) occurring in sandwiched thin shale/sandstone interbeds, (2) in highly fractured shale/mudstones commonly associated with larger faults, (3) in over-pressured shale/mudstones within the evaporates, or (4) in limestone and argillaceous carbonate interbeds within the shale/mudstone sequence.

In this study, we examine the oil resource potentials, reservoir characteristics, and oil chemistry/physical properties of the Es3 and Es4 sections of Eocene-Oligocene Shahejie Formation in the Jiyang Superdepression, Bohai Bay Basin. A litho-stratigraphic comparison with the marine shale sequence in the Devonian-Mississippian Bakken Formation of the Williston Basin reveals critical controls for hydrocarbon mobility and likely shale oil production "sweetspots" within the shale dominated sequences. More importantly, several significant differences between the lacustrine and marine shale systems become apparent. These include (1) the greater heterogeneities in lacustrine sediments and more limited connectivity between source and conventional reservoirs in the distal portions of lacustrine systems; (2) the close proximity to terrestrial source that creates opportunity for higher plant contribution and more waxy oils from lacustrine source rocks in oil window; (3) the relatively narrow but generally higher activation energy range in the kinetics of hydrocarbon generation from type I kerogens in carbonate-rich lacustrine kinetics that have clear implications for kerogen-oil interaction behavior, oil flow characteristics, and gas to oil ratio within the lacustrine system; (4) high temperature thermochemical sulphate reduction that tend to form significant amounts of hydrogen sulphide, with various undesirable effects. We will review the production test results, correlate them with the oil geochemistry and shale reaction kinetics data from available Sinopec shale oil wells, and comment on future directions of lacustrine shale oil exploration in eastern China.

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Sinopec Petroleum Exploration & Production Research Institute

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Pittsburgh， USA

Talk Outline

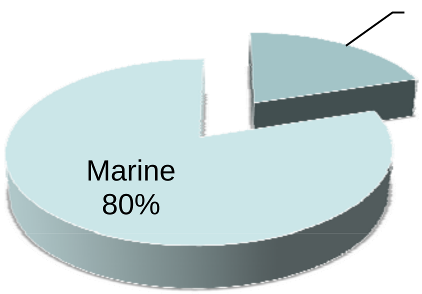
- Lacustrine shale oil resources in China
- Critical controls on hydrocarbon mobility
- Problem areas in lacustrine shale oil reservoir characterization in eastern China

From shale gas to shale oil

- Shale gas production has changed the energy outlook in North America, with significant implications for world energy supply and global energy geopolitics
- Shale oil set off another US oil boom, with estimate that predicts shale oil production in 2020 accounting for one third oil production in US (~1 billion boe or 150 mt)
- What do these developments mean for oil production in China, particularly from the lacustrine shale sequences in eastern China?

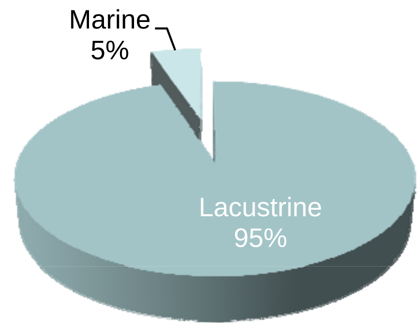
Lacustrine systems in conventional resource-base

Global Resource-Base



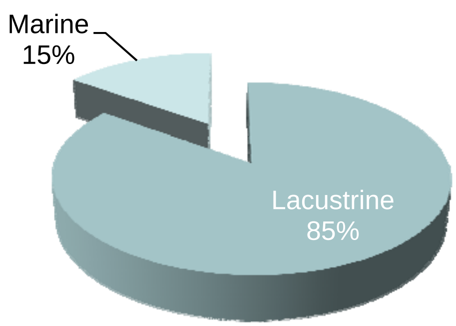
after Bohacs et al., 2000

China



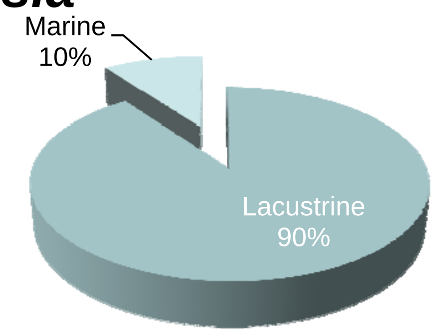
after Katz, 1990

Brazil



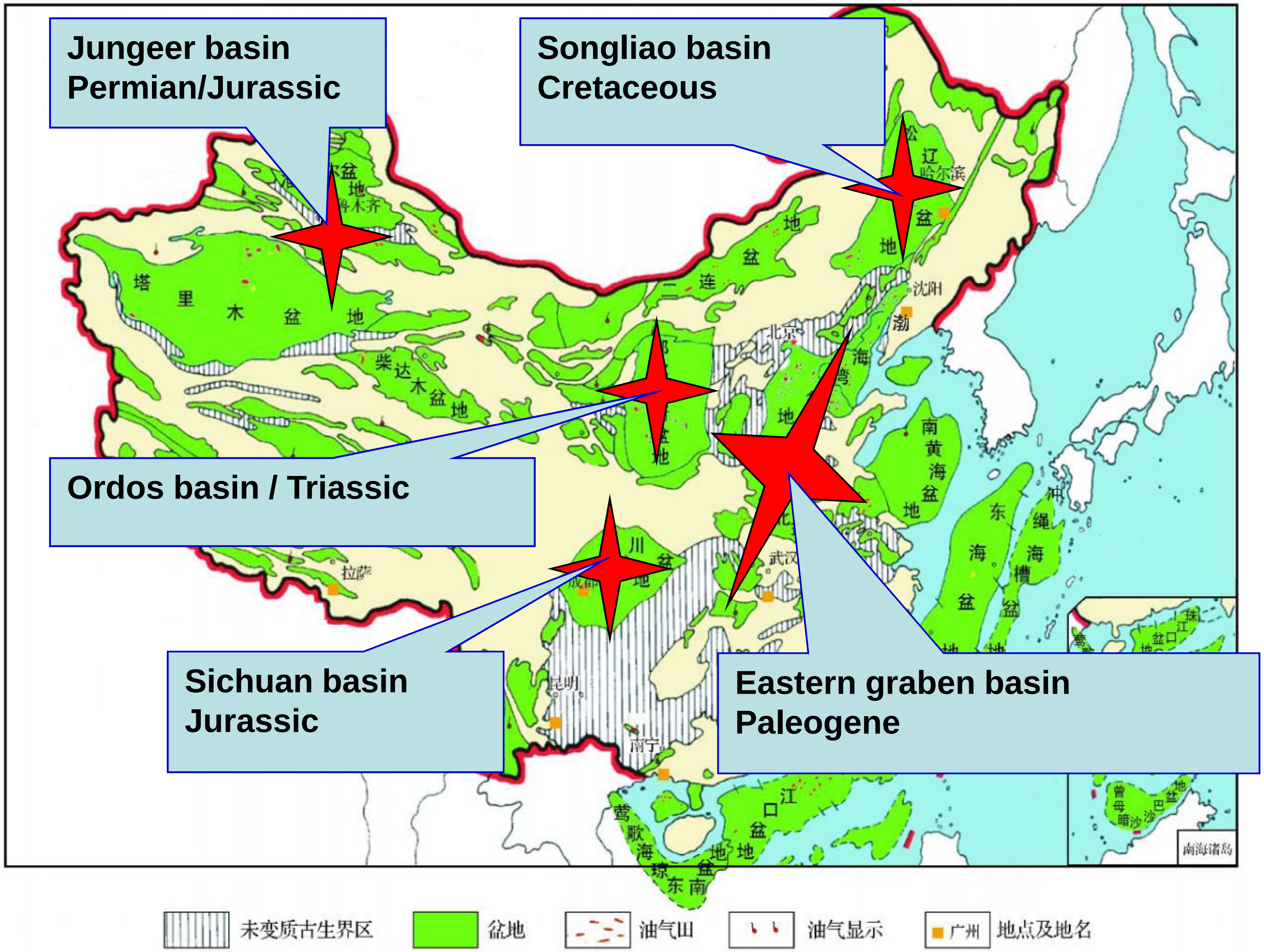
after Katz, 1990

Indonesia



after Katz, 1990

Potential shale oil plays in China



Jin et al. (2012)

Shale oil resource in Chinese basins

(Chinese Ministry of Land & Resources, 2011)

Zhang Dawei (2012)

Unit: billion tons

Region	Strata	P5	P25	P50	P75	P95
Nanyang	Eogene	1.56	1.05	0.62	0.39	0.06
Biyang	Eogene	1.08	0.49	0.29	0.16	0.11
Jiyang	Eogene	19.61	13.74	9.84	6.87	5.06
Dongpu	Eogene	4.01	2.23	1.52	0.97	0.73
Huanghua	Eogene	4.16	2.5	1.14	0.83	0.53
Jizhong	Eogene	2.96	2.58	0.65	0.38	0.28
Santanghu	C-P	1.35	0.95	0.64	0.43	0.27
Tuha	Jurassic	0.77	0.59	0.49	0.39	0.26
Jiuqian	Cretaceous	0.18	0.14	0.12	0.09	0.06
Total resource		35.68	23.23	15.29	10.46	7.44

- It is debatable how reliable the assessment is, knowing the uncertainty in the methodologies and assumptions made
- How much can be turned into reserves is even more questionable

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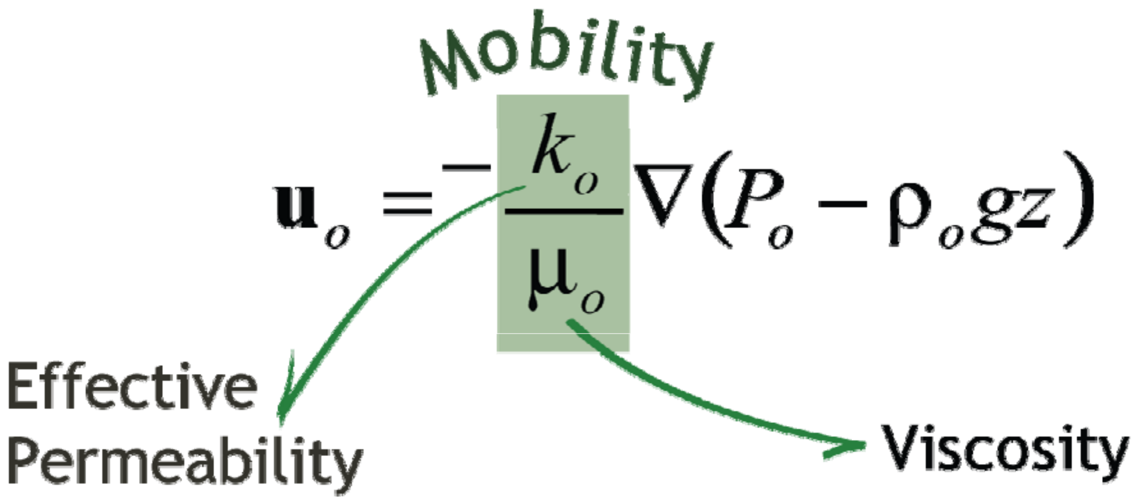
- Critical controls on hydrocarbon mobility
- Problem areas in lacustrine shale oil reservoir characterization in eastern China

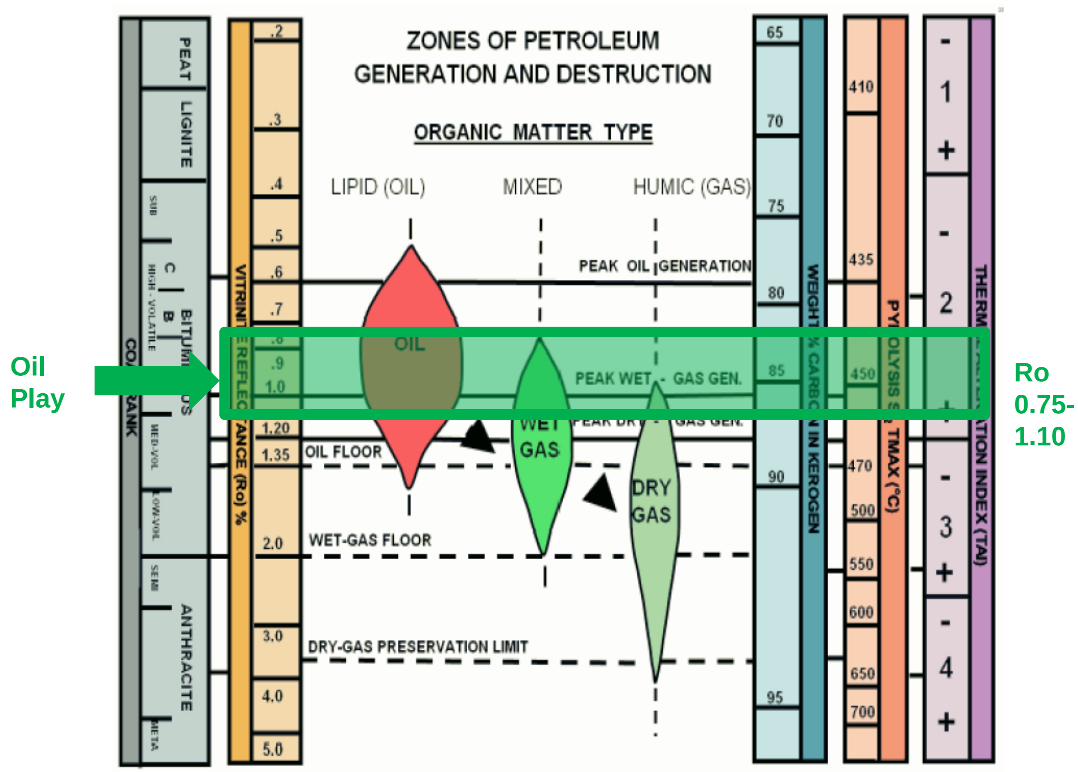
Fluid flow = mobility x driving force



$$\mathbf{u}_o = -\frac{k_o}{\mu_o}\nabla\left(P_o - \rho_o g z\right)$$

- Fluid flow is dependent on a driving force (pressure gradient in a production operation)
- Fluid viscosity at reservoir conditions *(dependent on the fluid phase and composition)*
- Effective rock permeability to the producing fluid

Shale gas and shale oil systems



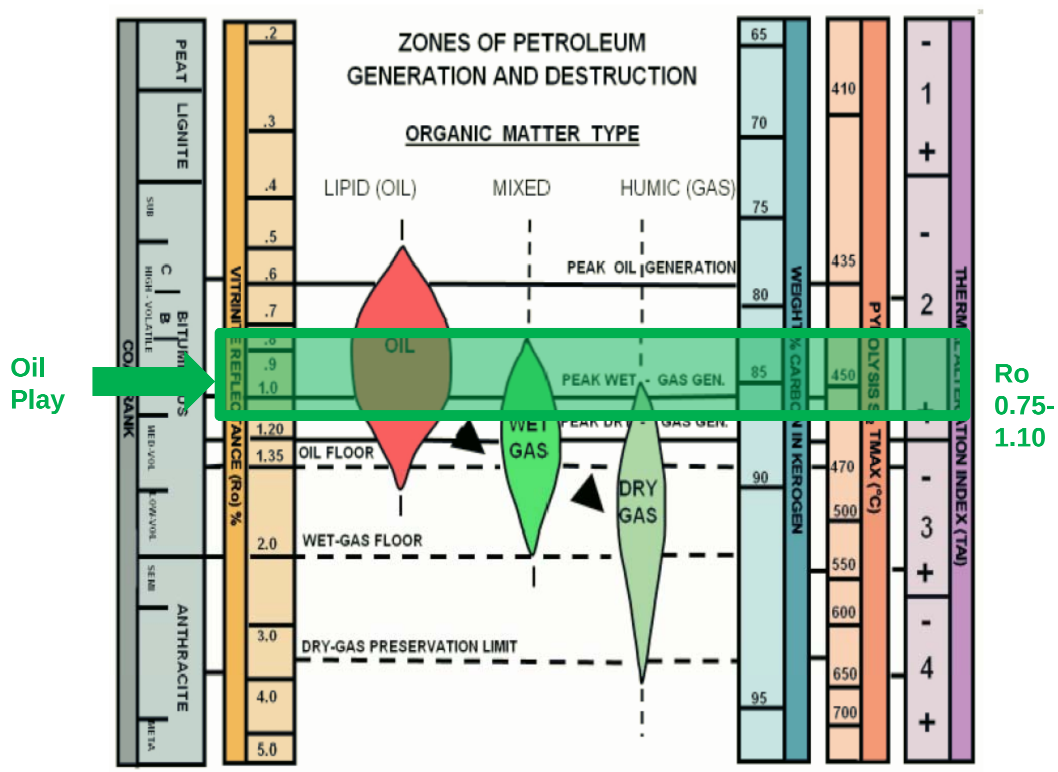
CORRELATION OF VARIOUS MATURATION INDICES AND
ZONES OF PETROLEUM GENERATION AND DESTRUCTION

Dow, 1977

Similarities:

- Maturation enhanced expulsion of pore fluids driven by compaction
- Overlying and underlying rocks with very low permeability
- Overpressure due to potential source rock expulsion rate > transmission rate through adjacent rocks

Shale gas and shale oil systems



CORRELATION OF VARIOUS MATURATION INDICES AND ZONES OF PETROLEUM GENERATION AND DESTRUCTION

Dow, 1977

Differences:

- Shale diagenesis: mixed layer clay minerals-> more brittle illite; silica dissolution and cementation development
- Kerogen maturation: miscible semi-liquids -> immiscible semi-graphite and methane; difference in organic porosity, phase behavior and flow characteristics
- Fluid composition: heavy liquids->light liquids->wet gas-> dry gas
- Overpressure + expulsion induced fractures +subtle structural flexures

Dynamic viscosity of various fluids

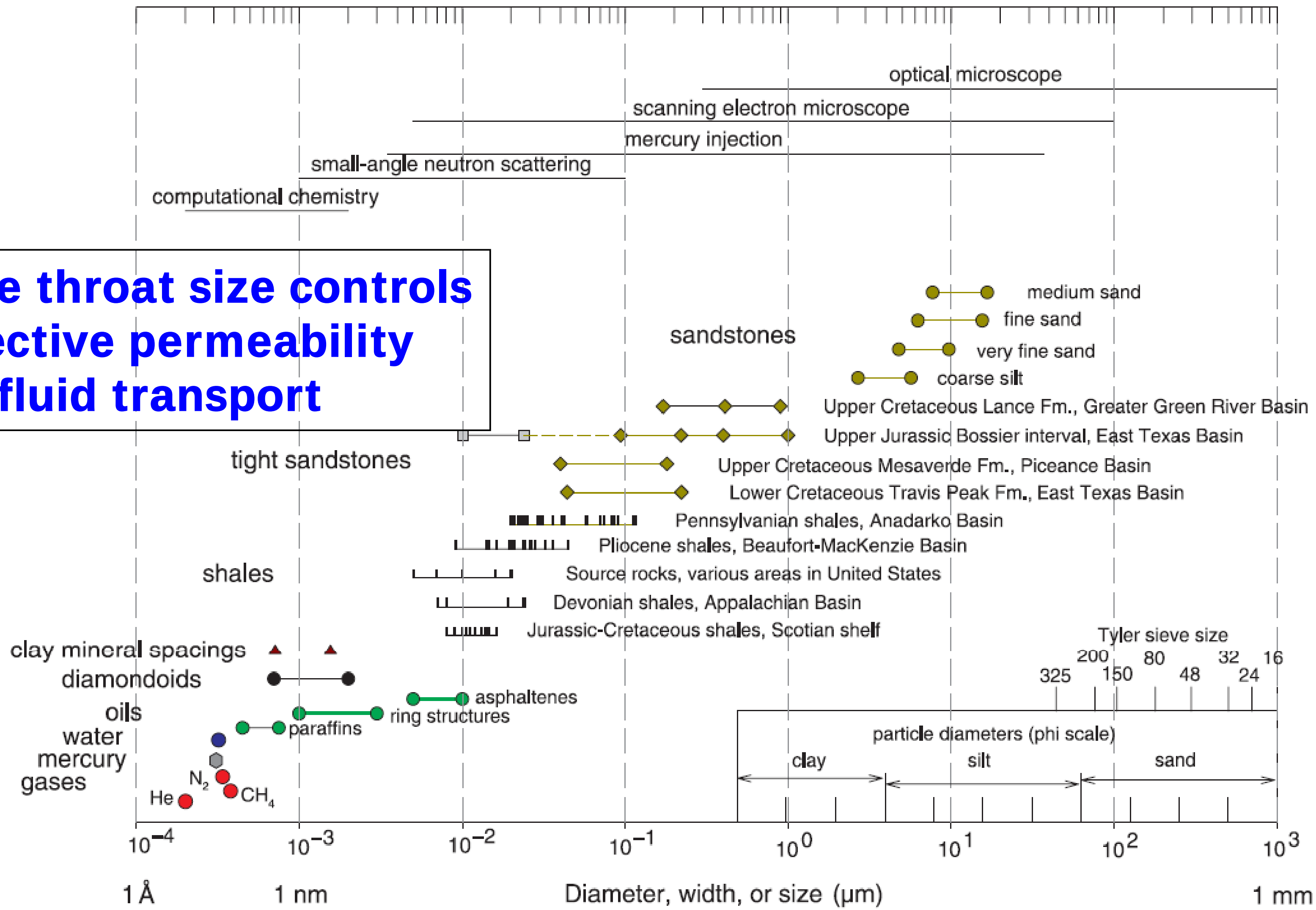
Fluid	Viscosity (cP@20^0 C)
Hydrogen	0.00835
Methane	0.0103
Carbon Dioxide	0.014
Helium	0.0186
Acetone	0.324
Benzene	0.647
Water	1
Kerosene	2.5
Condensate (API =54^0)	0.75
Crude Oil (API =34^0)	7.5
Crude Oil (API=19^0)	1000

As fluid viscosity is critical for fluid mobility, gas and light liquids represent better producers than heavy crudes

http://www.roymech.co.uk/Related/Fluids/Fluids_Viscosities.html

Scales of organic molecules and pore throats in siliciclastic rocks

Pore throat size controls effective permeability for fluid transport



(Nelson, 2009)

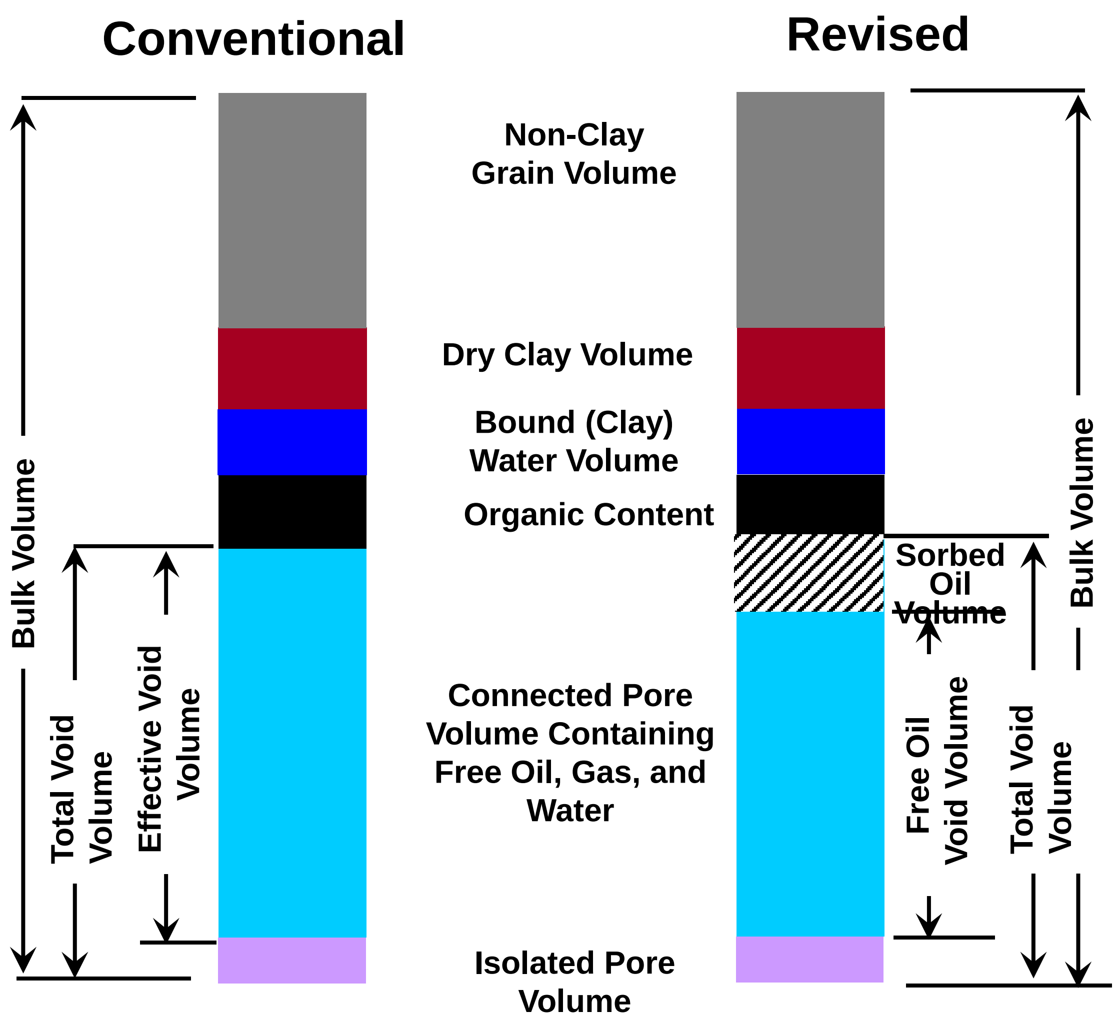
Adsorptive capacity of minerals and kerogen for methane

Lithofacies	Adsorption scf/ton/psi
Quartz	0.029
Carbonate	0.089*
Chlorite	0.128
Illite	0.160
Kerogen	1.293

Shale gas may occur in both free and adsorbed forms, so desorption kinetics may play a role in gas production

Schettler and Parmely, SPE 23422

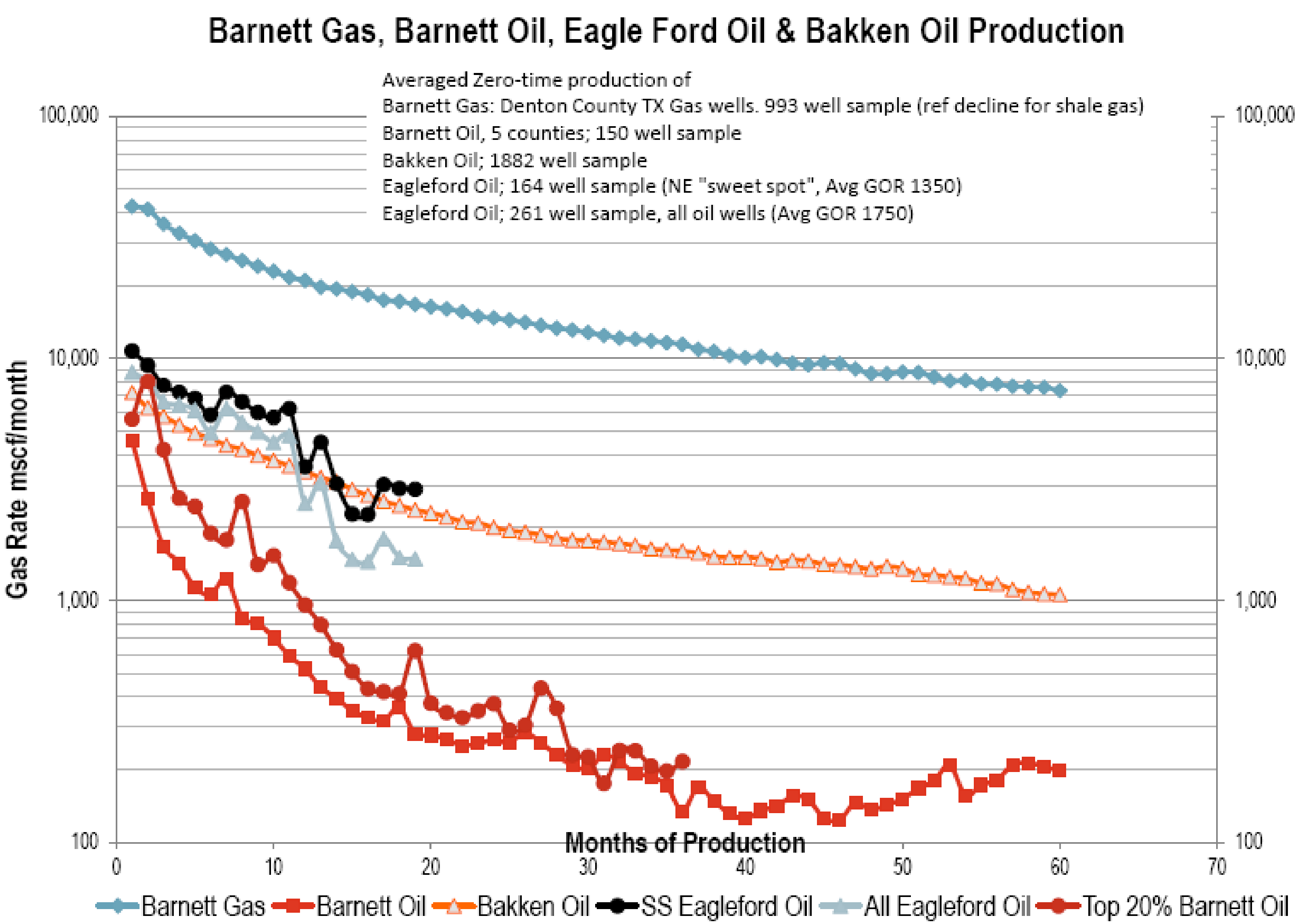
Revised petrophysical model for shale



This revised model needs to be revised again for shale oil reservoirs

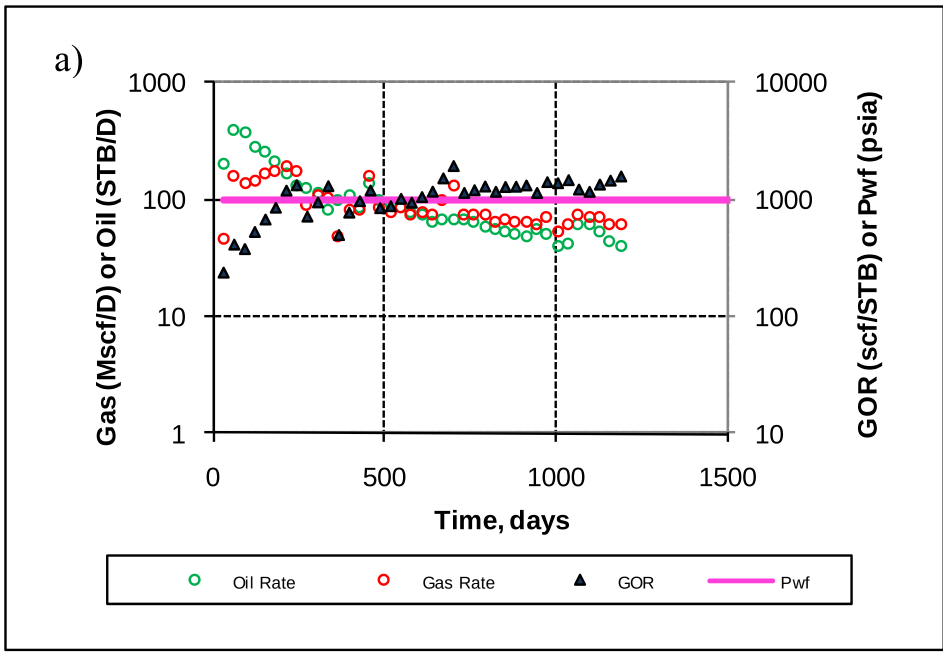
Kerogen-fluid association may change from completely miscible single at low maturity level, to partially miscible in oil window, to separate immiscible phases in gas window, as a function of Ro, GOR & top seal integrity

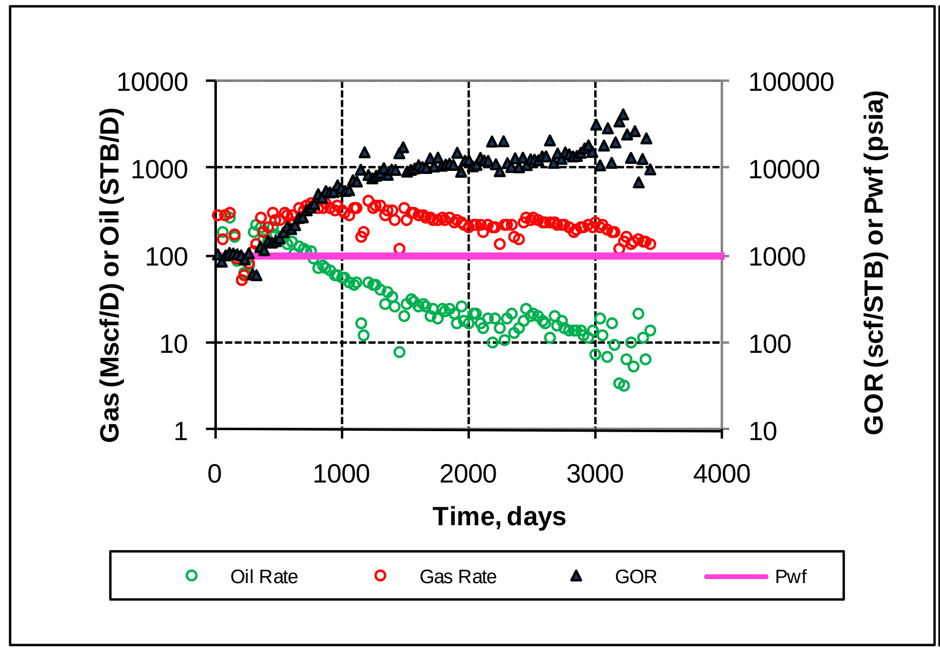
Huang et al. (2012)



Barnett Gas, Barnett Oil, Eagle Ford Oil & Bakken Oil Production
Averaged Zero-time production of
Barnett Gas: Denton County TX Gas wells. 993 well sample (ref decline for shale gas)
Barnett Oil, 5 counties; 150 well sample
Bakken Oil; 1882 well sample
Eagleford Oil; 164 well sample (NE "sweet spot", Avg GOR 1350)
Eagleford Oil; 261 well sample, all oil wells (Avg GOR 1750)
Gas Rate mscf/month
Oil Rate STB/month
100,000
10,000
1,000
100
Months of Production
0
10
20
30
40
50
60
70
Barnett Gas
Barnett Oil
Bakken Oil
SS Eagleford Oil
All Eagleford Oil
Top 20% Barnett Oil

Oil and gas production





Tight Oil: Viewfield Bakken

horizontal wells

Shale Oil: 2WS

vertical well

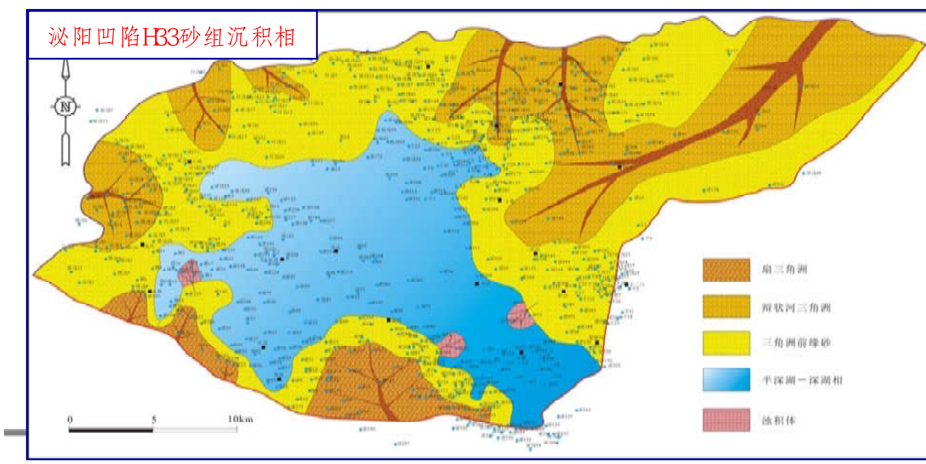
(Clarkson and Pedersen, 2011)

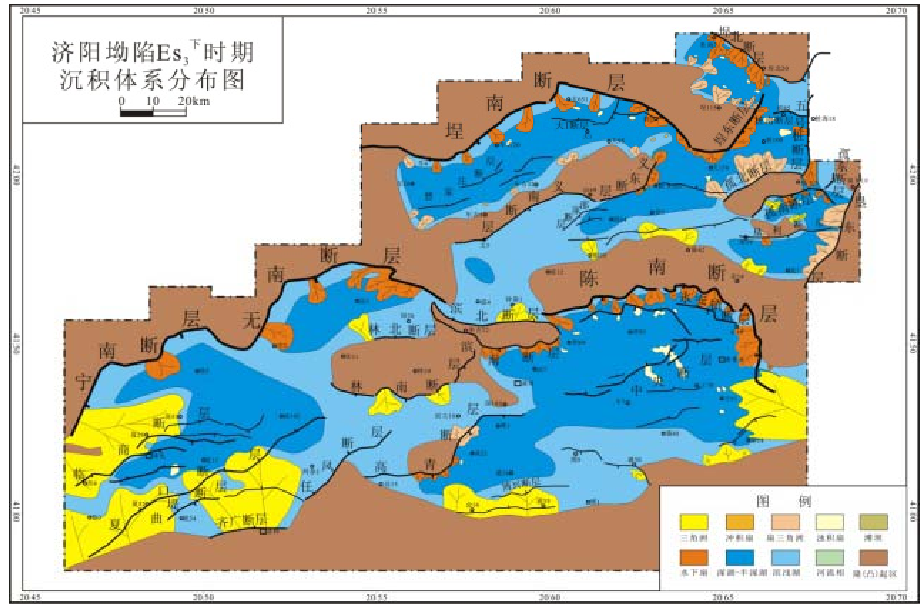
Talk Outline

- Lacustrine shale oil resources in China
- Critical controls on hydrocarbon mobility
- Problem areas in lacustrine shale oil reservoir characterization in eastern China

1. Limited lake area with rapid facies variation, leading to large hetereogeneities

$E_3H_3^3$ facies map in the Biyang Depression

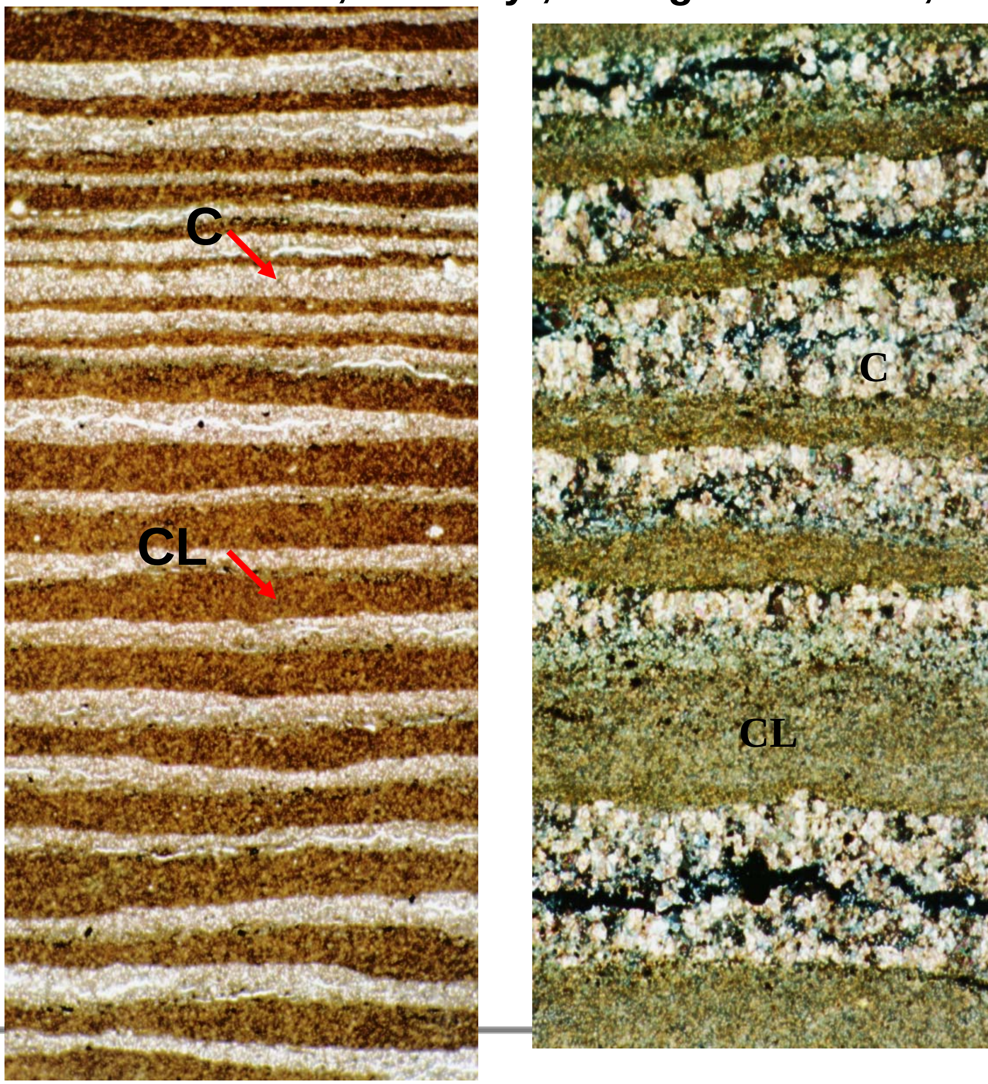




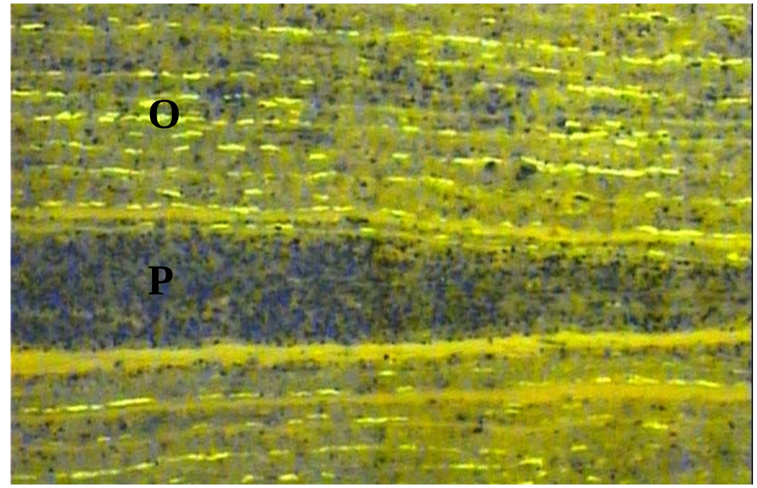
E_2^{3L} facies map in the Dongying depression

Microscopic shale fabrics

C: carbonate; CL: clay ; O: organic matter; P: pyrite **Zhang et al. 2012**

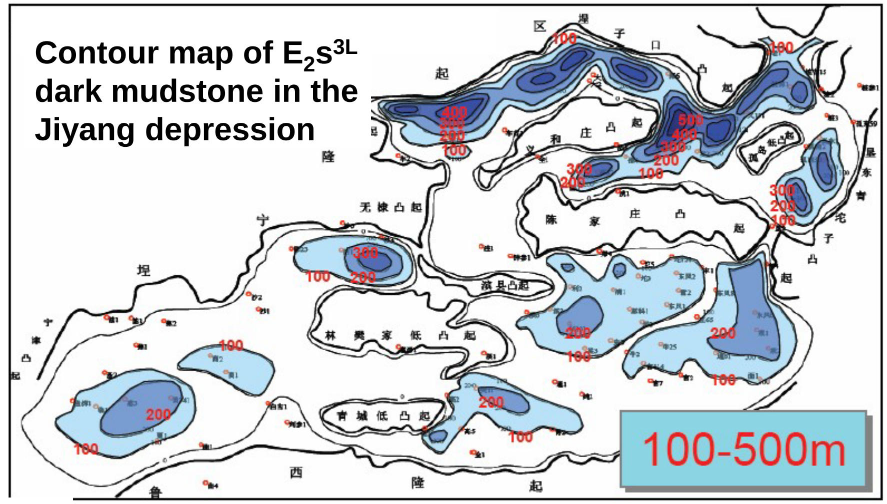


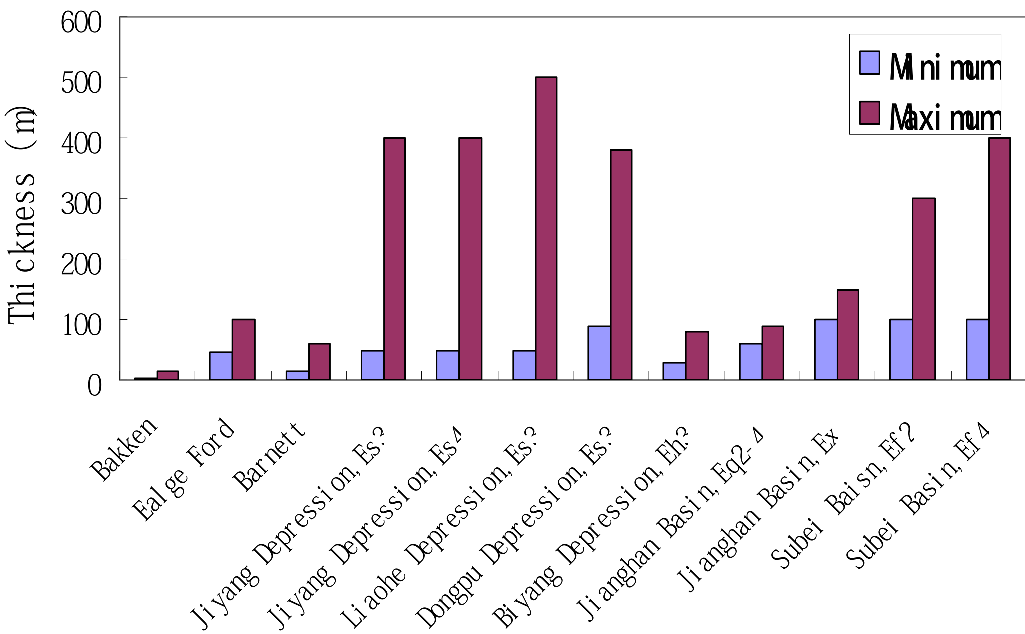
Well Chun-11, 2215m (cross-polarizing light)



Well Chun-372, 2568m (transmitted light)

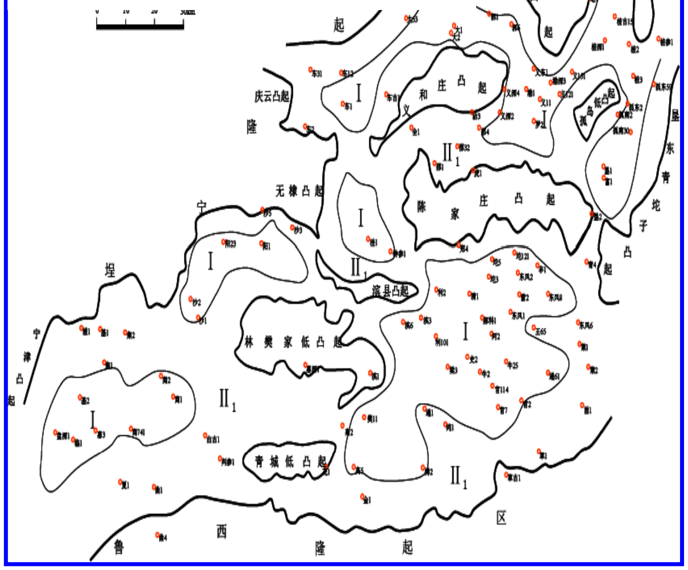
2. Thick shale/mudstone package accompanied by high proportion of immature detritus

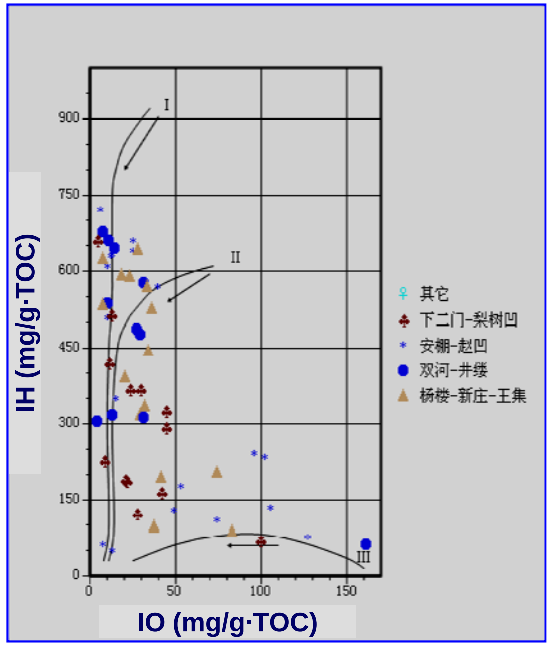


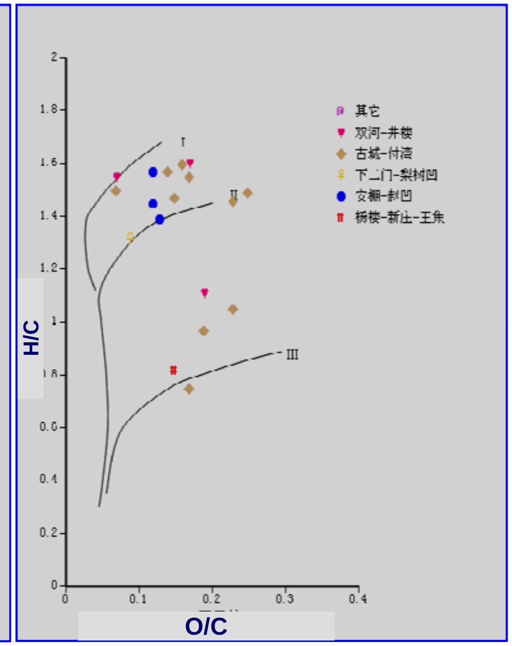


3. Type I and type III kerogens, with drastically different reaction kinetics

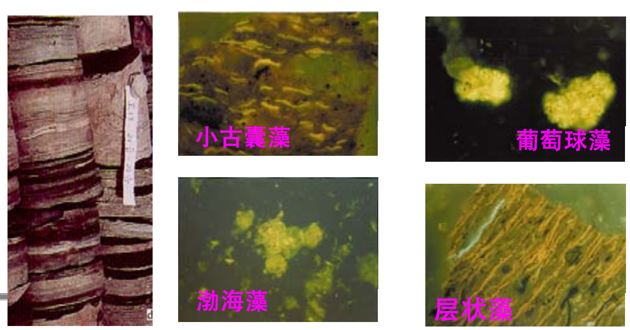
Distribution of E_2s^3(Lwer) organic matter type in Jiyang depression







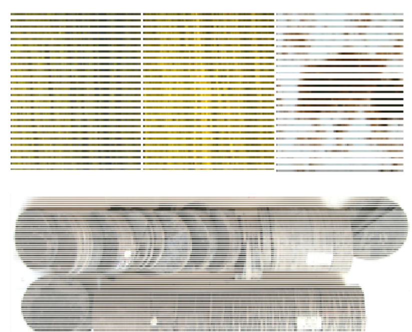
Upper ES4



Ⅰ-Ⅱ1

岩性组合以灰褐色钙质页岩、泥岩为主，富含藻类生物化石，是一套咸水-半咸水湖相沉积

Hypersaline-brackish water algal lamina



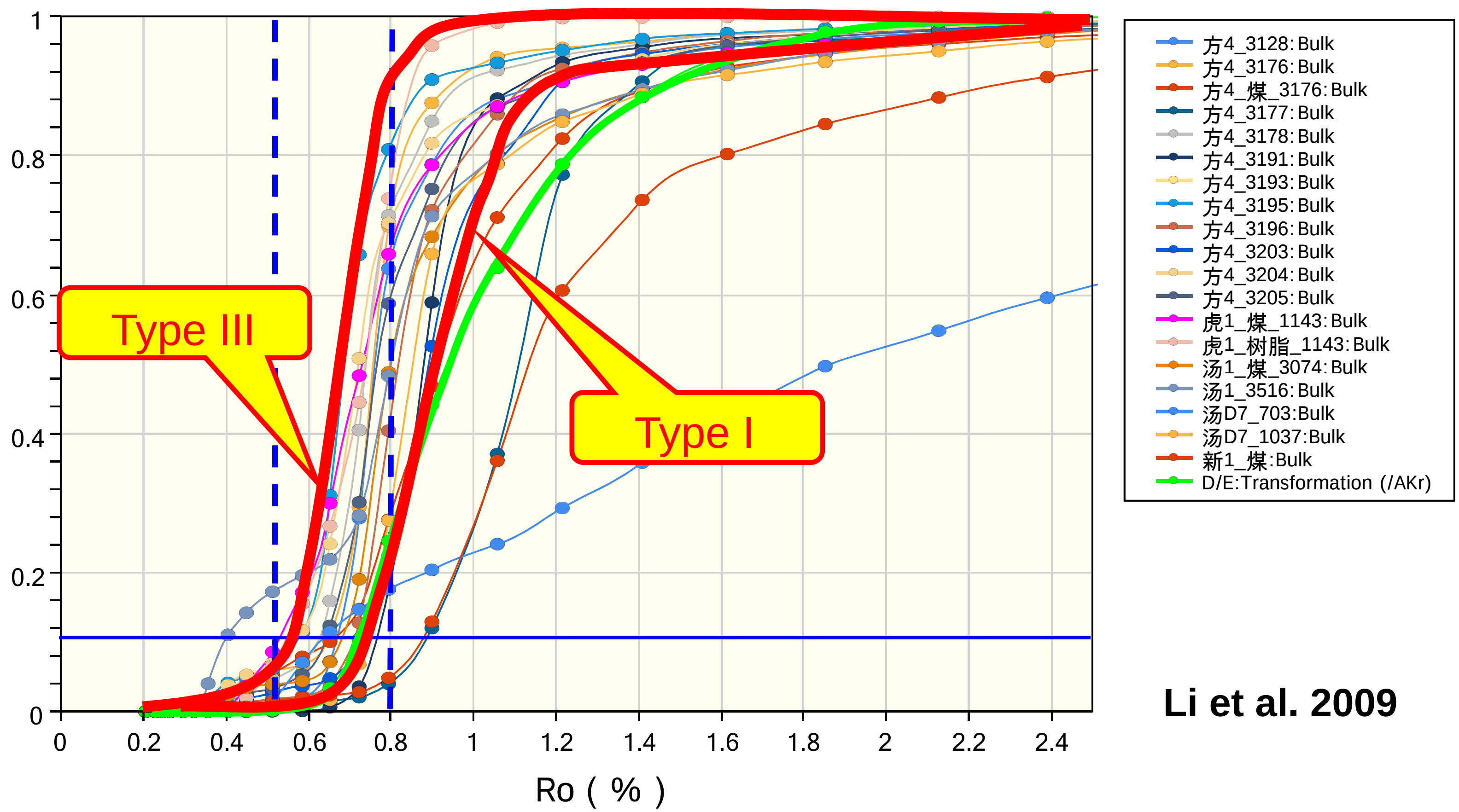
岩性为深灰色泥岩与灰褐色油页岩不等厚互层，夹少量灰色灰岩及白云岩,是一套微咸水-淡水湖相沉积

Ⅰ-Ⅱ1

Lower ES3

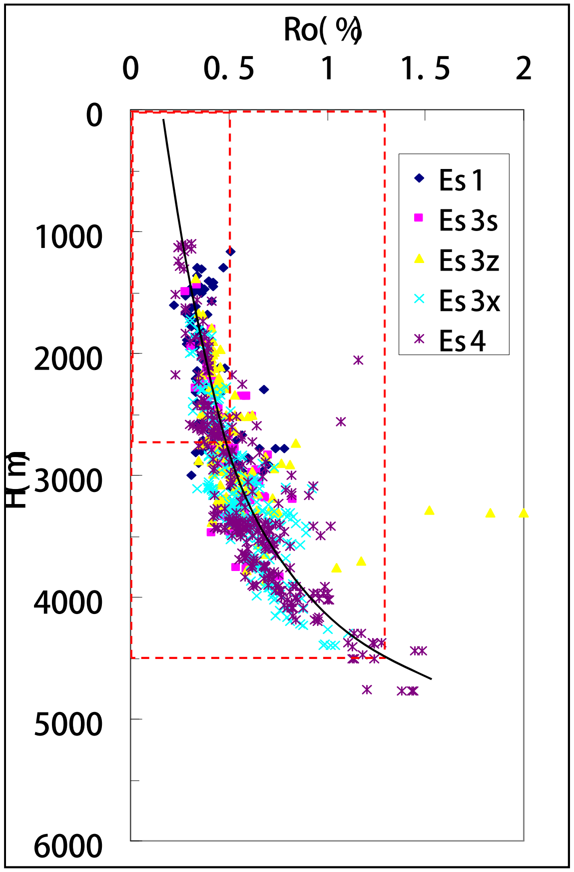
Brackish-fresh water algal laminat

Cumulative conversion rates for different source rock types in NE China



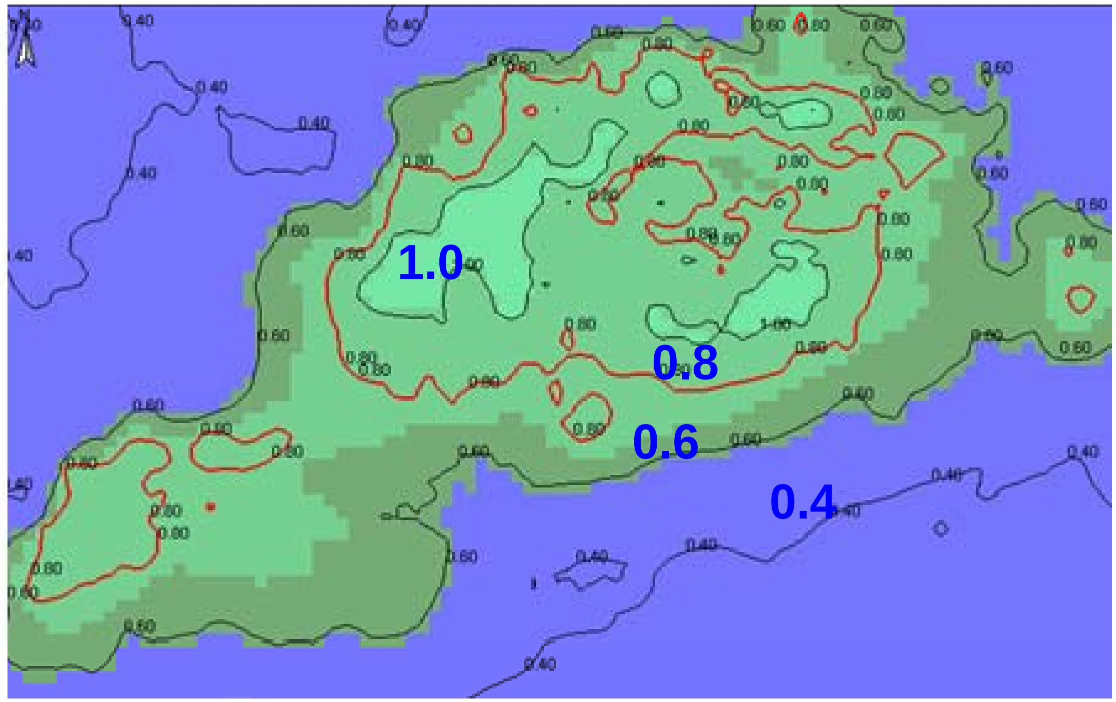
Li et al. 2009

4. Most areas in low maturity to peak oil generation, with high oil retention



Changes in Ro with burial depth in Jiyang Depression

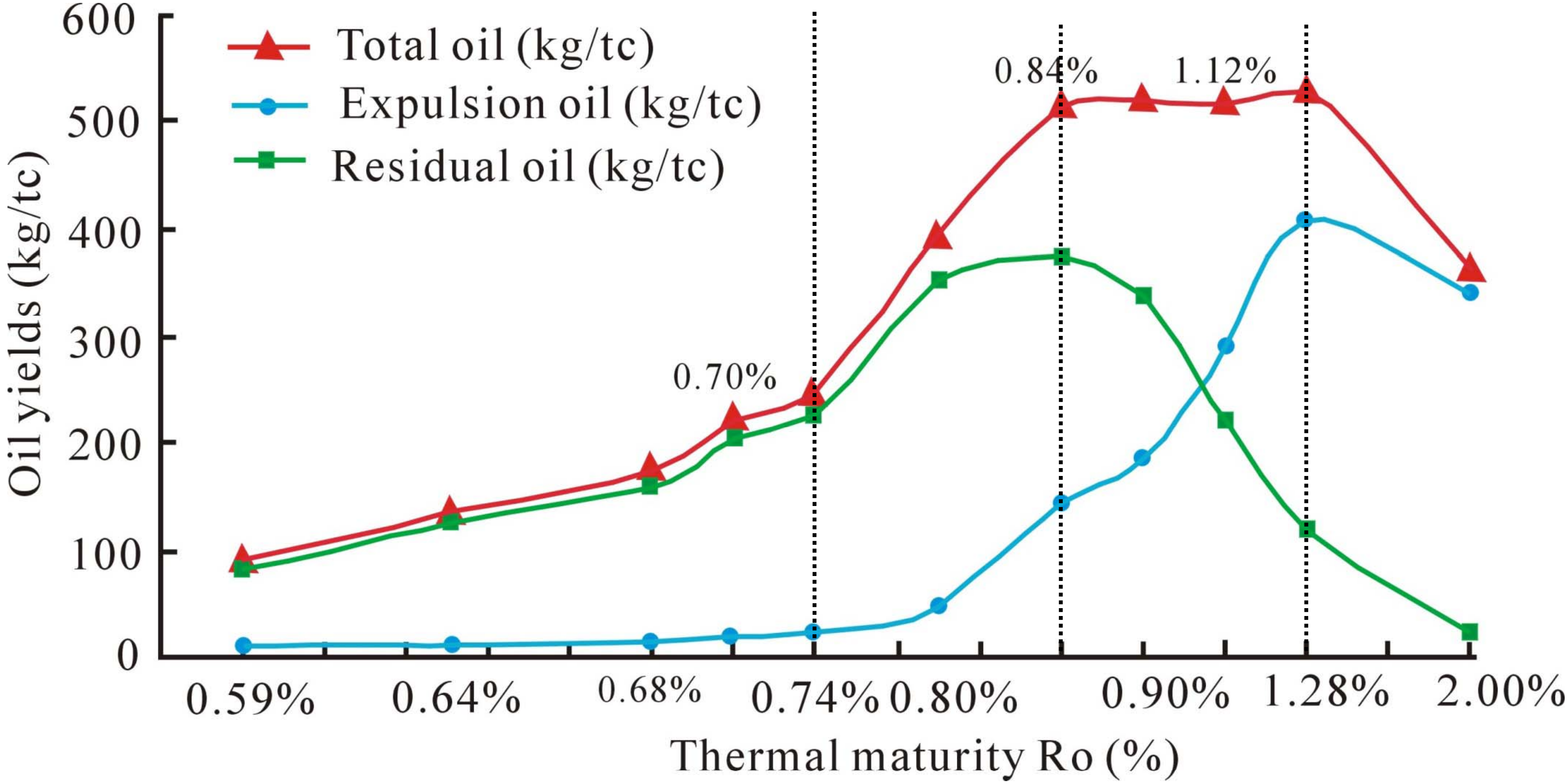
Ro distribution of E_2s^{3L} in Dongying Sag



Modified from Zhang et al. (2012)

Mainly at peak oil period，partly at high maturity in deep sag

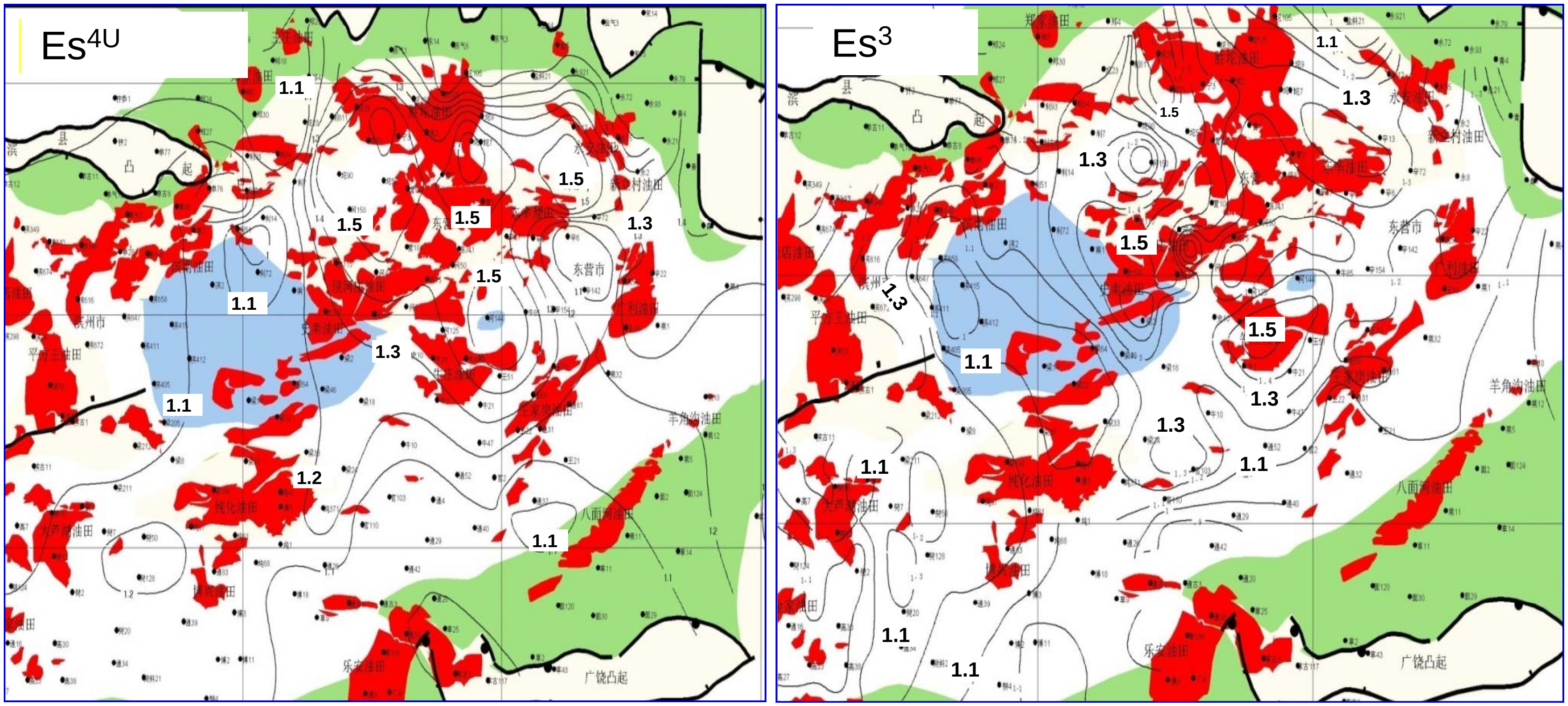
Semi-open system hydrous pyrolysis of a calcareous shale sample



Li Zhiming, 2012

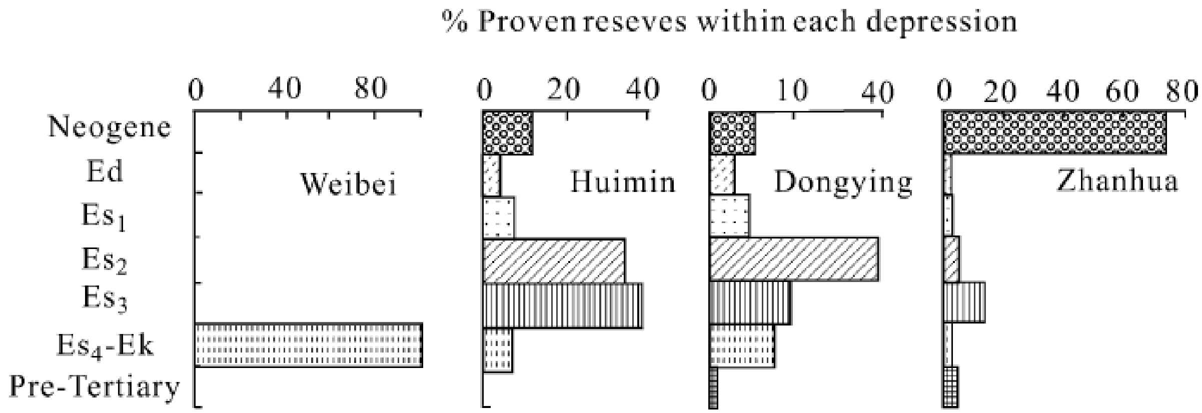
5. Abnormal pressure occurs widely in Dongyong sag

Distribution of pressure gradient in source rocks of Dongying Sag

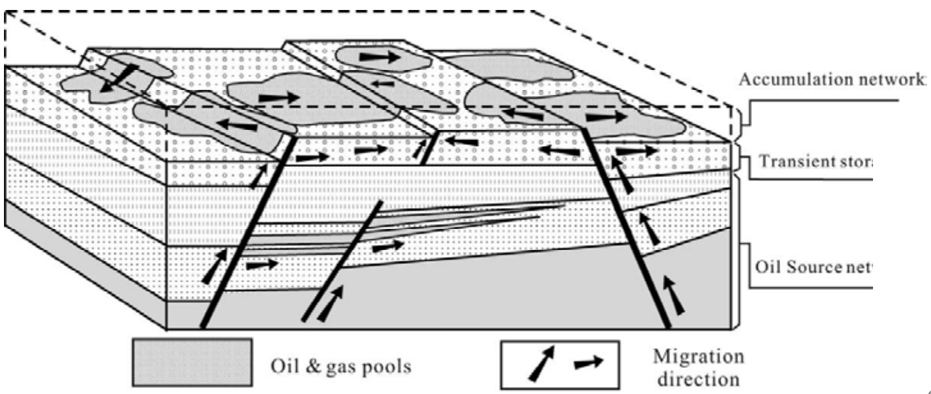


Pressure changes largely from normal to abnaormal high in mud shale of Jiyang Depression. The Highest fracturing coefficient attains to 2.0

Fault-fracture network to breach the top seal is a serious concern in the Zhanhua sag



Fault-fracture mesh petroleum play model



Zhang et al. 2004

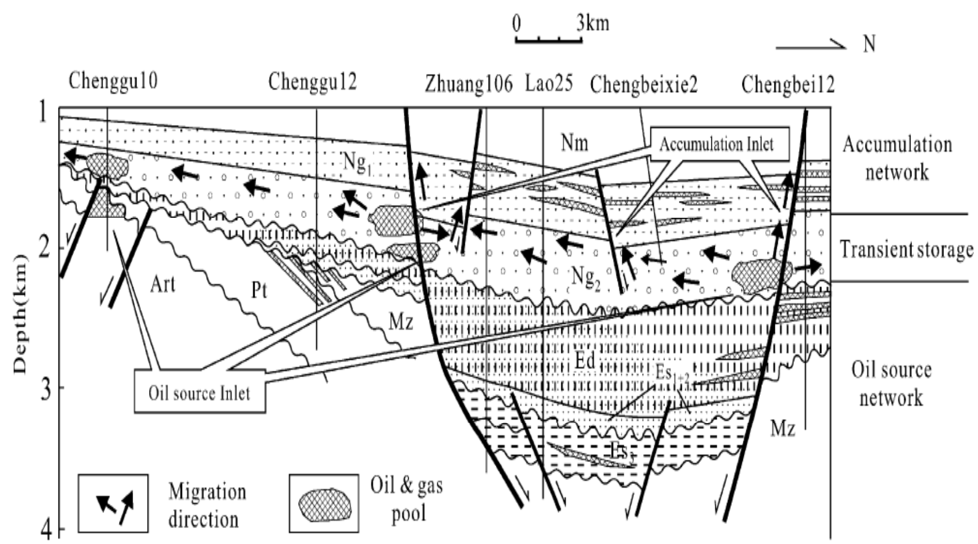
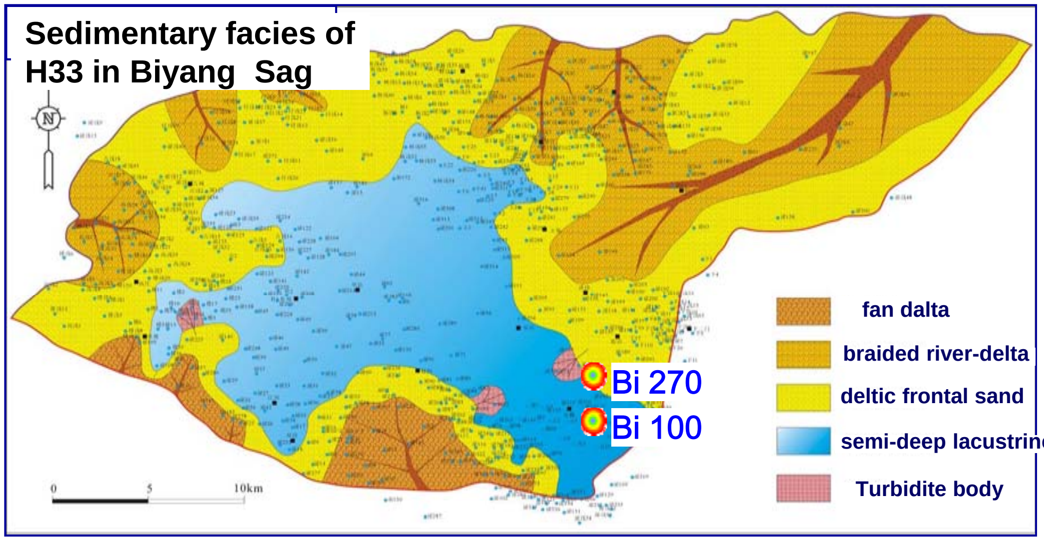


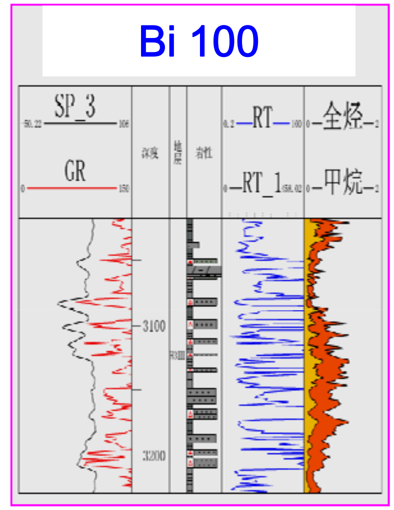
Fig. 10. A S–N cross-section showing the Neogene fault-fracture mesh petroleum plays along the Chengdong Slope, Chengdong oilfield.

6. Matrix porosity-type shale oil play in normal oil window may be characterized by low initial oil yield and rapid rate decline

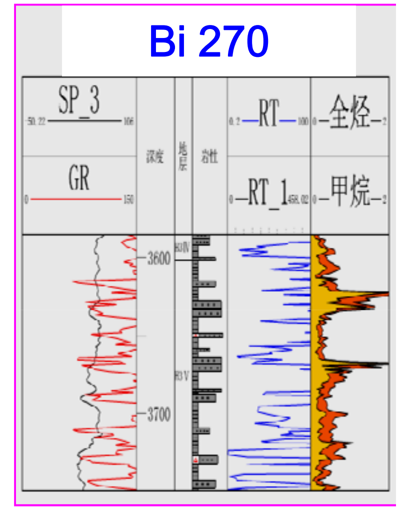
★*Well Bi 100*



Biyang Depression



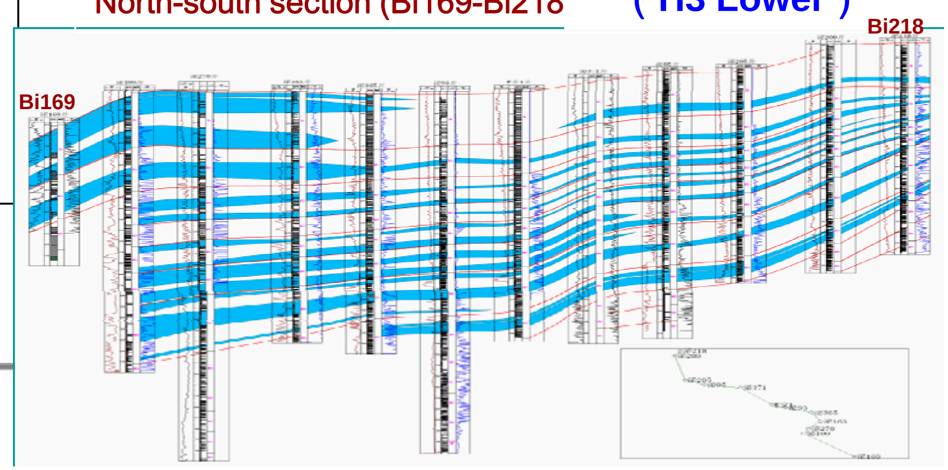
Sand-shale interbed
（H33 bottom）



Mudstone interbedded by sand layer
（H3 Lower）

Sedimentary facies：semi-deep lake – delta front
Lithological combination：sand-shale interbeds
Reservoir space type：micropore、pore
Shale oil reservoir type：sandwich

North-south section (Bi169-Bi218

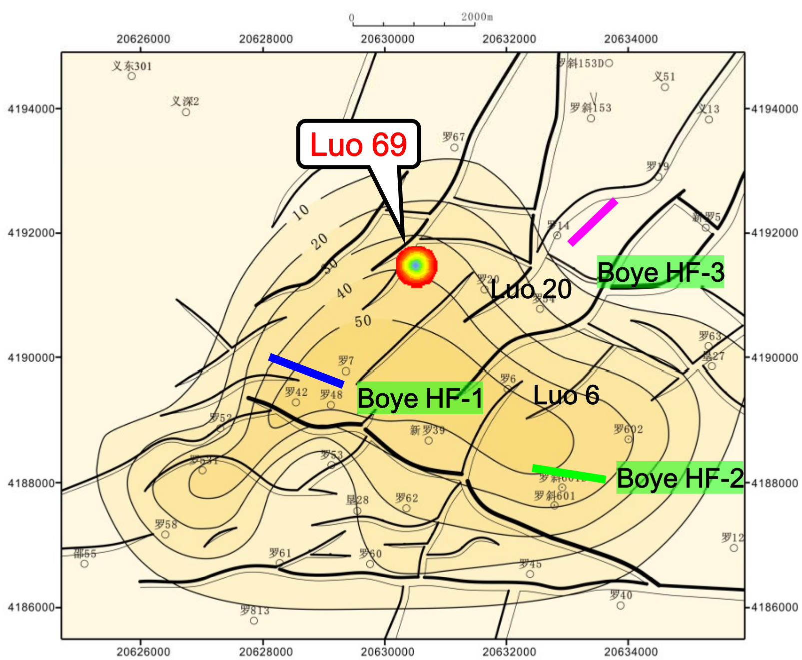


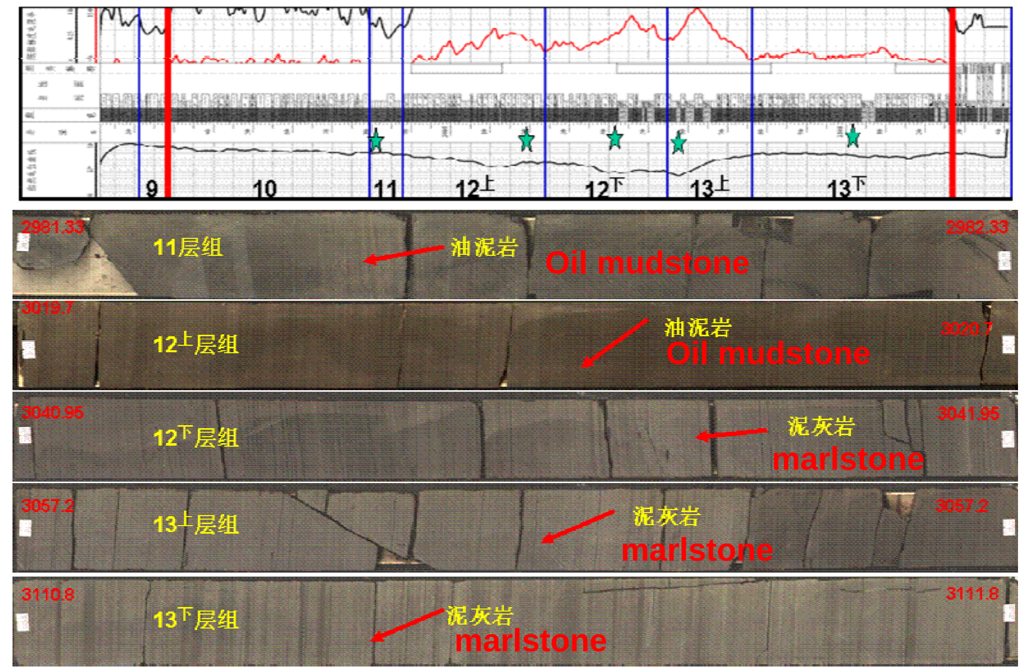
Delta front area as the favorable play

Fracture-type shale oil plays in low maturity area may not be optimal drilling target

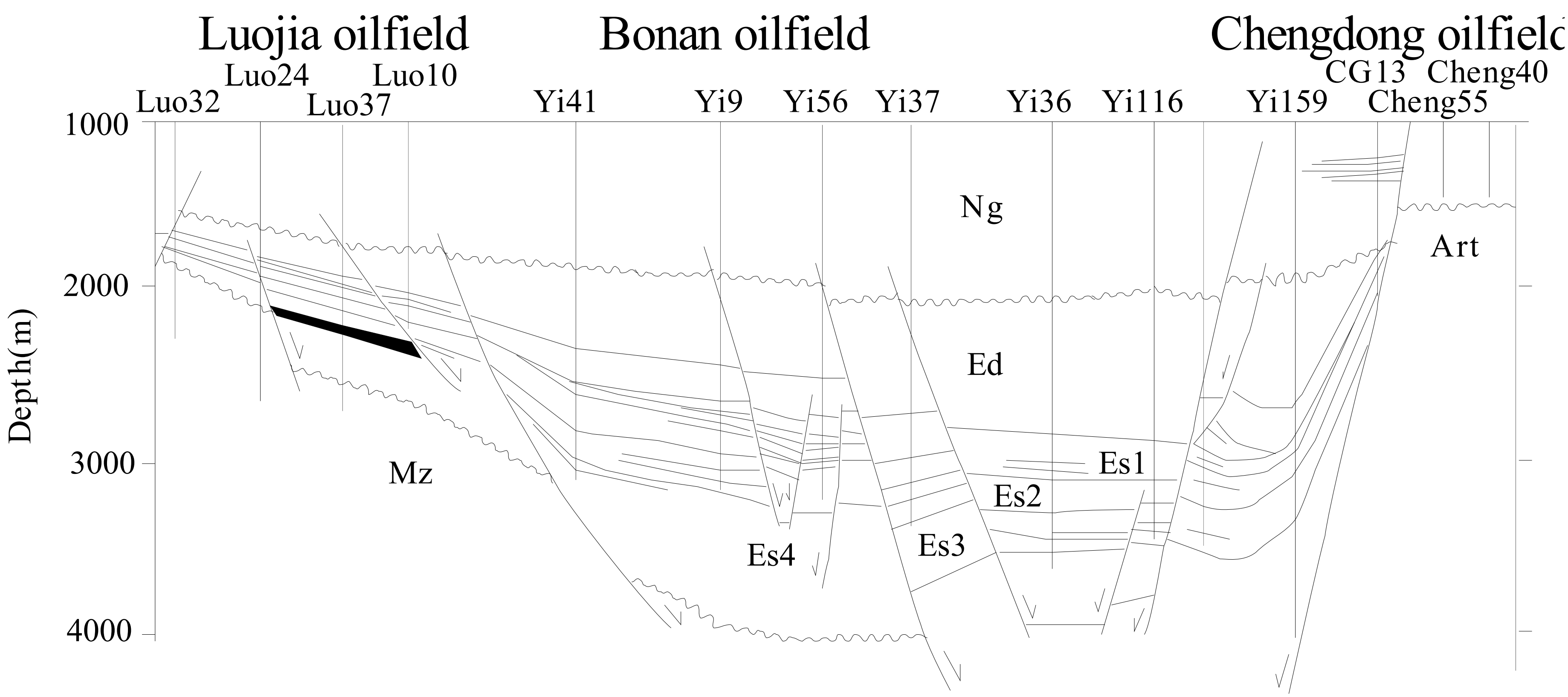
Jiyang Depression

Well distribution of Luo 69 Region

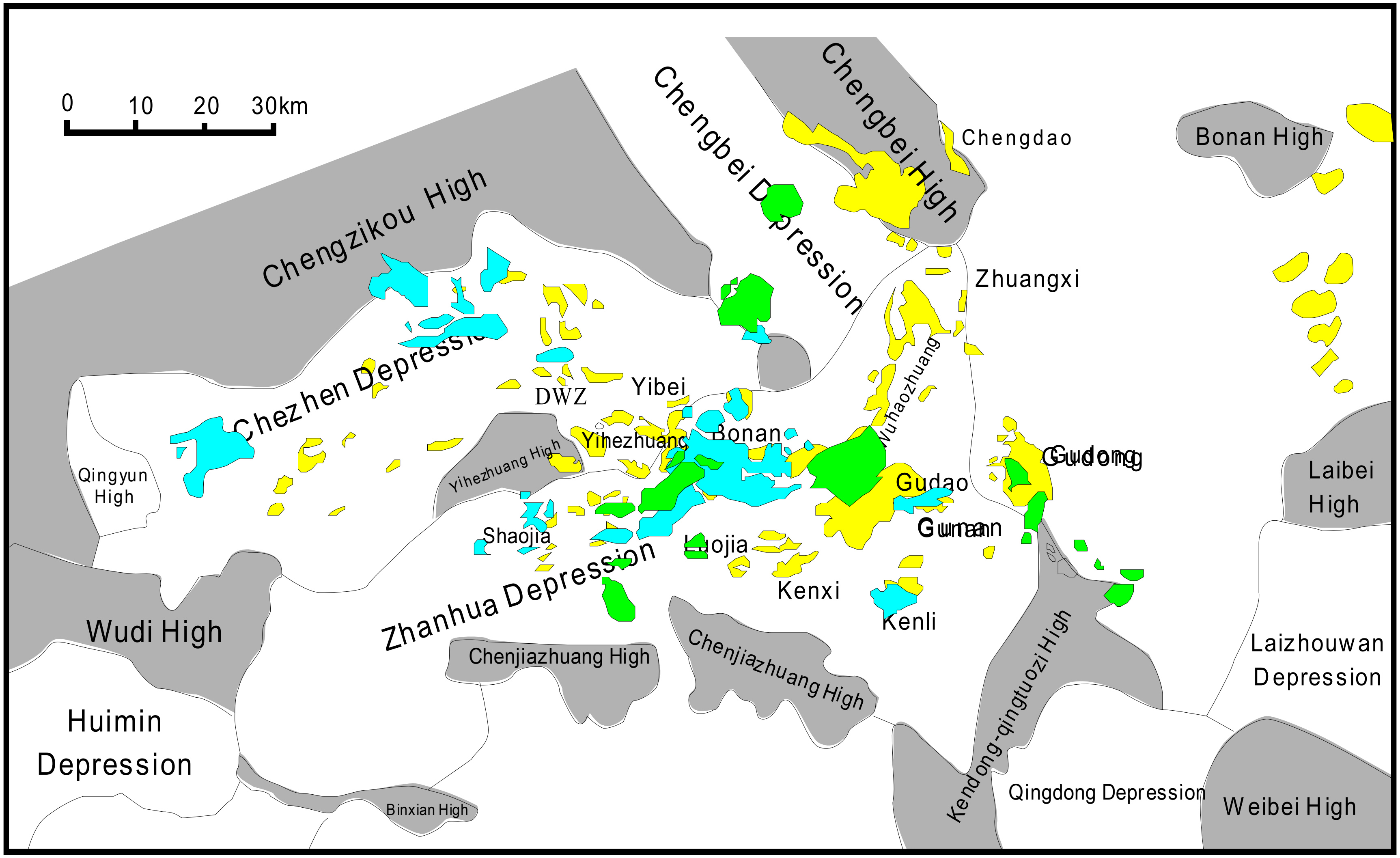




Fracture-type shale oil plays in low maturity area may not be optimal drilling target



Fracture-type shale oil plays in low maturity area may not be optimal drilling target



Normal oil Heavy oil Tight oil

www.pepris.com

Implications for lacustrine shale oil plays

- Areal extent of lacustrine oil plays in rift basins would be limited, – focused on regions where more permanent lake conditions existed with mild faulting to breach the top seal
- Potential thickness of lacustrine oil plays may be quite significant – reservoir attributes will be highly variable over short intervals
- The appropriate silica and carbonate facies exist in lacustrine units to provide the necessary brittleness for reservoir development, but terrestrial detritus may be a complication
- Flow characteristics of oil will differ from marine systems – high wax content, high viscosities and low GOR in generally low maturity region is a concern

Acknowledgments

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