Characteristics and Resource Potential of Lacustrine Shale Oil and Gas in China*

Jin Zhijun¹, Gao Bo², and Wu Xiaoling²

Search and Discovery Article #80359 (2014)**
Posted February 25, 2014

*Adapted from oral presentation presented at AAPG Annual Convention and Exhibition, Pittsburgh, Pennsylvania, May 19-22, 2013
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Abstract

Chinese petroliferous basins contain several organic rich lacustrine shales, including the Upper Cretaceous Qingshankou Formation in the Songliao Basin, Paleogene Shahejie Formation in the Bohai Bay Basin, Triassic Yanchang Formation in the Erdos Basin, Triassic-Jurassic strata in the Sichuan Basin, and Permain and Jurassic in the Zhungeer Basin. In comparison with the marine shales in the USA, lacustrine shales in China are characterized by young geologic age, limited areal extent, large facies variation, variable organic input, low thermal maturity, less brittle mineral, high clay content, and poor diagenesis. Since 2008, China has been actively engaged in lacustrine shale oil and gas exploration. Major breakthroughs have been achieved, successively in the lacustrine shale gas exploration from the Lower Jurassic Ziliujing Formation in the Sichuan Basin and the Triassic Yanchang Formation from the Erdos Basin. Significant progress has been made in the shale oil exploration from the Paleogene in several rift basins in eastern China. This presentation will utilize Sinopec's extensive core data, to address the key geological factors that make the Paleogene shale oil resource in eastern China extremely attractive, and the main technological challenges that impede the large-scale economic exploitation of this resource. Several case studies from the Ordos, Sichuan, and Zhungeer basins will be used to demonstrate the shale gas resource potential and commercial feasibility in the Upper Paleozoic and Mesozoic lacustrine sequences in China.

References Cited


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SINOPEC Research Institute of Exploration & Production

May, 2013
Will China enter a shale gas boom after the US?

What has been and is being done in China?

What are the main challenges ahead?
Outline

- Introduction
- Lacustrine Shale Gas
- Lacustrine Shale Oil
- Conclusions
Shale oil: Indigenous hydrocarbons remaining in thermally mature source rocks and associated non-source interbeds after limited migration.
Distribution of OM-rich lacustrine shale in China

- **Songliao basin**: Cretaceous
- **Junggar basin**: Permian, Jurassic
- **Eastern graben basin**: Paleogene
- **Ordos basin**: Triassic
- **Sichuan basin**: Triassic, Jurassic

- Unmetamorphic Paleozoic area
- Basin
- Oil & gas field
- Showings
- Place name
Basic tectonic characteristics of China

Small craton with extensive orogenic activities

Modified from Renjishun 1999
Multicyclic tectonic & sedimentary evolution leading to accumulation of marine, continental and transitional shales

<table>
<thead>
<tr>
<th>Geologic Age</th>
<th>Junggar Basin</th>
<th>Sichuan Basin</th>
<th>Erdos Basin</th>
<th>Bohai Bay Basin</th>
<th>Songliao Basin</th>
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<tr>
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</table>

Continental deposits

transitional deposits

Marine deposits
The Mesozoic in China is dominated by non-marine deposits, with marine deposits occurring in neo-Tethys domain.

Neo-Tethys-Mid-Cretaceous (98 Ma) paleogeographic map (Skeleton, 2003)
Major differences are observed in tectonic style, diageneces and petroleum potential between the two tectonic domains.
Tectonic profile, Dongying Depression, Bohai Bay Basin

N-S trending profile of Dongying Depression

Jiyang Depression
Sichuan Basin

Tectonic profile of Sichuan Basin
(1) Daily gas flow of 17317 m³ obtained from F HF-1 Well, after acid fracturing of J₁z⁴(2), Fuling region

- Horizontal payzone: J₁z⁴(2)
- Vertical length: 3570 m, horizontal length: 1136.75 m
- March 14, 10-stage fracking, test 1107 m³/d
- May 26, gained gas 17317 m³/d after diversion acidification treatment in 4 segments
2.1 Progress in shale gas exploration, Sichuan Basin

(2) High gas flow from J₁Z₄(2) (Daanzhai) obtained from several wells, Yuanba area

<table>
<thead>
<tr>
<th>Well</th>
<th>Target</th>
<th>Perforation interval (m)</th>
<th>Initial daily output (10³m³)</th>
</tr>
</thead>
<tbody>
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<td>Y5-1</td>
<td>J₁Z₄(2)</td>
<td>42.3</td>
<td>42.3</td>
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<tr>
<td>Y21</td>
<td>J₁Z₄(2)</td>
<td>4035-4110</td>
<td>507</td>
</tr>
<tr>
<td>Y11</td>
<td>J₁Z₄(2)</td>
<td>3880-3940</td>
<td>144.4</td>
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<td>Y101</td>
<td>J₁Z₄(2)</td>
<td>4207-4238</td>
<td>139.7</td>
</tr>
<tr>
<td>Y102</td>
<td>J₁Z₄(2)</td>
<td>3912-3935</td>
<td>237.8</td>
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<tr>
<td>Y9</td>
<td>J₁Z₄(2)</td>
<td>3838-3878</td>
<td>2.6</td>
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<tr>
<td></td>
<td>J₁Z₂</td>
<td>4035-4110</td>
<td>11.5</td>
</tr>
</tbody>
</table>

J₁Z₄ composite stratigraphic column of Y 21 Well

*test section*
2.1 Progress in shale gas exploration, Sichuan Basin

(3) Gas flow from $J_1z^2$(Dongyuemiao) in several wells in Jiannan region

<table>
<thead>
<tr>
<th>Well</th>
<th>Target</th>
<th>Well type</th>
<th>Total Depth (m)</th>
<th>Horizontal length (m)</th>
<th>Stages of fracturing</th>
<th>Initial output ($10^3 m^3/d$)</th>
<th>Present output ($10^3 m^3/d$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>JY 111</td>
<td>$J_1z^2$</td>
<td>vertical</td>
<td>634</td>
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<td></td>
<td>3.9</td>
<td>2.0-3.0</td>
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<td>JY HF-1</td>
<td>$J_1z^2$</td>
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<td>1778</td>
<td>1020</td>
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<td>JY HF-2</td>
<td>$J_1z^2$</td>
<td>horizontal</td>
<td>2888</td>
<td>1000</td>
<td></td>
<td>10</td>
<td>flowback</td>
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</table>
2.1 Progress in shale gas exploration, Sichuan Basin

(4) Shale gas obtained from T₃x⁵, Chuanxi depression

<table>
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<tr>
<th>Well</th>
<th>Target Strata</th>
<th>Well type</th>
<th>Total Depth (m)</th>
<th>Horizontal length (m)</th>
<th>Stages of fracturing</th>
<th>Initial output (10³m³/d)</th>
<th>Present output (10³m³/d)</th>
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<td>T₃x⁵</td>
<td>horizontal</td>
<td>4077</td>
<td>793</td>
<td>7</td>
<td>Flowbacking, 2000m³/d</td>
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<tr>
<td>XY HF-2</td>
<td>T₃x⁵</td>
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<td>4102</td>
<td>815</td>
<td>10</td>
<td>45</td>
<td>21</td>
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</table>

Composite stratigraphic column of XY HF-1 Well

[Composite stratigraphic column diagram]
Two organic-rich shales occur in the Sichuan Basin
- Upper Triassic coal-bearing swampy-lacustrine shales
- Middle-Lower Jurassic semi-deep to deep lacustrine shales
2.2.1 The Triassic shale of Sichuan Basin

**Thick mudstones with high TOC**

- T₃x⁵ dark mudstone isopach in Sichuan Basin

- Sedimentary center is located in West Sichuan Depression

- Total thickness is 100-300 m

- TOC: 1-4%

---

**T₃x composite histogram of Sichuan Basin**

- Sedimentary center is located in West Sichuan Depression
- Total thickness is 100-300 m
- TOC: 1-4%
2.2.1 The Triassic shale of Sichuan Basin

- **Type III kerogen with moderate Ro and high brittleness**

Ro isopach map of $T_3x^5$ dark mudstone in Sichuan Basin

- **Ro 1.0~1.8%**
  - Low clay content, generally <40%
  - Quartz content generally >40%

Carbonate minerals

Clay mineral

Quartz & feldspar
2.2.2 The Jurassic shale of Sichuan Basin

Organic-rich shale deposited in simi-deep to deep lake facies
Organic shale is frequently interbedded by shell limestone
Hydrocarbon content correlate positively with TOC
2.2.2 The Jurassic shale of Sichuan Basin

- Lower Jurassic shale isopach and TOC distribution, Sichuan Basin

- Sedimentation center is located in NE Sichuan Basin
- Dark shale thickness is 120-240m
- TOC: 1.2-2.0%
- High quality source rocks distributed mainly in central Sichuan
2.2.2 The Jurassic shale of Sichuan Basin

◆ Organic type and thermal maturation

◆ Type II karogen dominant
◆ Maturity level: 0.8-1.6% Ro
2.2.2 The Jurassic shale of Sichuan Basin

Reservoir storage space ranges from micropores, nanopores, to microfractures.
Characteristics of Mesozoic shales in Sichuan Basin

Relatively organic-lean with variable organic types, large cumulative shale thickness, and wide range of burial depth
Characteristics of Mesozoic shales in Sichuan Basin

Relatively low in gas and silicate contents
According to Ministry of Land and Resources of PRC (2012):

- **Shale gas recoverable resource**: 25.08 TCM
- **Lacustrine shale gas recoverable resource**: 7.92 TCM, 31.59%
Summary: Lacustrine shale gas systems in Sichuan Basin

Forland basin setting, rapid facies variation, organic-lean, multiple types of storage space, and strong heterogeneity
Outline

- Introduction
- Lacustrine Shale Gas
- Lacustrine Shale Oil
- Conclusions
3.1 Progress in shale oil exploration in eastern China

1st shale oil well in China: Biyang sag, Nanxiang basin


★B HF-1 : 12, 2011-1, 2012, E$_3$H$^3$, 15 Stages fracturing, 8mm glib, oil 22.5m$^3$/d, gas 1072m$^3$/d

Drilling map of Biye HF-1 well
3.1 Progress in shale oil exploration in eastern China

Jiyang Depression, Bohai Bay basin

- X3, lower Es3, oil 35.6t/d, gas 510 m3/d
- X9, Es3, oil 38.5t/d, gas 870 m3/d
- L42, Es3, oil 79.9t/d, gas 7764 m3/d
- M42, Es3, oil 79.9t/d, gas 7764 m3/d
- H54, Es3 natural flow, oil 91.3t/d, gas 2740 m3/d
- X941, lower ES3 oil 6.67t/d, gas 46834 m3/d
- F119, Es4 natural flow, oil 5.9t/d, gas 1480 m3/d
- W76, Middle Es4 oil 21.5t/d
- H88, Es4 pumping, Oil 5.9t/d

Strong oil/gas shows encountered in the shale intervals from 320 exploration wells by the end of 2012.
35 of which produce oil in commercial quantity.
### Jiyang depression of Bohai Bay basin

<table>
<thead>
<tr>
<th>Well</th>
<th>Location</th>
<th>Target Stratum</th>
<th>Well-type</th>
<th>Total Depth (m)</th>
<th>Horizontal Length (m)</th>
<th>Fracturing Stage</th>
<th>Initial oil output (t)</th>
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<tr>
<td>BYP1</td>
<td>Zhanhua</td>
<td>E$_2$s$^3$</td>
<td>horizontal</td>
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<td>1176</td>
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<td>Zhanhua</td>
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<td>Dongying</td>
<td>E$_2$s$^3$(L)</td>
<td>vertical</td>
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<td>Dongying</td>
<td>E$_2$s$^3$(L)</td>
<td>vertical</td>
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<td>8.93</td>
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</table>

**Well Location Map**

**Oil output (t/d)**

3-27  4-1  4-6  4-11  4-16  4-21  4-26  5-1  5-6

BYP1 well’s production after 2nd section was fractured
3.2 Characteristics of Paleogene shale

Depositional environment: mainly deep to semi-deep lacustrine, with rapid facies variation
3.2.1 Paleogene source rock characteristics

(1) Generally in large thickness but quite variable, depending on sedimentary facies

- Black shale thickness > 100m,
  locally > 300m
3.2.1 Paleogene source rock characteristics

(3) Relatively high organic richness

TOC contour map of E_{3s}^{4}(upper) source rock in Jiyang depression

TOC contour map of E_{2s}^{3}(Lower) source rock in Jiyang depression

TOC contour map of E_{2s}^{q} source rock in Jianghan basin
(4) Organic matter dominated by type I and II kerogens, with thermal maturity $< 1.3\%$Ro, mainly in peak oil generation.
3.2.1 Paleogene source rock characteristics

- Average TOC: 1-4%
- Large thickness, over 300 m in places
3.2.1 Paleogene source rock characteristics

- **Ro**: generally $<1.3\%$, can attain to $2\%$ in the deep sag
- **Depth**: commonly $<3500m$, $>3500m$ in deep sag
3.2.2 Paleogene shale reservoir characteristics

(1) Reservoir storage space including micropores, nanopores and microfractures

- **F1 Well, Upper E₂s⁴**, micropore of I/S mixed layer
- **L64, Upper E₂s⁴**, micropore of clay mineral
- **L90, Upper E₂s⁴**, sandy interparticle micropore
- **BY HF-1, E₃h³**, Organic nanopore (X18000)
- **P18, Upper E₂s³**, Intracrystal dissolved hole of calcite
- **W31, Upper E₂s⁴**, dry shrinkage fractures

Abundant microfractures, including shrinkage fracture, interlaminar seam.
Porosity comparison with other shale oil systems
3.2.2 Paleogene Shale Reservoirs Characteristics

(2) Generally enriched in brittle minerals, mainly quartz and carbonate, with clay content < 50%

**Jiyang Depression (E₂s³⁻⁴):**
- **Clay**: 10-40%
- **Quartz**: 20-30%
- **Carbonate**: 20-60%

```
<table>
<thead>
<tr>
<th>Location</th>
<th>Clay Mineral</th>
<th>Quartz</th>
<th>Feldspar</th>
<th>Calcite+Dolomite</th>
<th>Pyrite</th>
<th>Siderite</th>
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- **Clay Mineral**
- **Quartz**
- **Feldspar**
- **Calcite+Dolomite**
- **Pyrite**
- **Siderite**
### 3.3 Paleogene Shale Oil Resources Potential

<table>
<thead>
<tr>
<th>Basin</th>
<th>Area (×10³km²)</th>
<th>Strata</th>
<th>Oil generated (10⁹t)</th>
<th>Oil expelled (10⁹t)</th>
<th>Residual oil (10⁹t)</th>
<th>Conventional Resource volume (10⁹t)</th>
<th>Estimated shale oil resources (10⁹t)</th>
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<tr>
<td>Bohai Bay</td>
<td>195</td>
<td>E₂s</td>
<td>144.68</td>
<td>50.55</td>
<td>94.137</td>
<td>14.893</td>
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<td>Nanxiang</td>
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<td>E₃h</td>
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<td>67.246</td>
<td>83.361</td>
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<td><strong>Total</strong></td>
<td><strong>529.8</strong></td>
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<td><strong>123.995</strong></td>
<td><strong>198.719</strong></td>
<td><strong>27.464</strong></td>
<td><strong>3.974 9.936</strong></td>
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</table>

According to the 3rd round petroleum resources evaluation of China, the total oil generated in Eastern China amounts to about 323 billion tons, while the residual quantity amounts to about 199 billion tons.
Challenges

- Rapid production decline after fracking

Production curve of BYP1 Well after fracturing

The initial production of horizontal well is larger than the vertical well, however, the production of the former declines faster than the latter generally.
Characteristics of lacustrine shale oil system in eastern China

- Rift basin setting
- Young geologic age with low thermal maturity
- High oil viscosity with low mobility
- Relatively poor frackability
- Consequence low initial production rate, rapid production decline
## Physical property of Paleogene shale oil

<table>
<thead>
<tr>
<th>Region</th>
<th>Well</th>
<th>API (ρ420)</th>
<th>Freezing point (°C)</th>
<th>Wax (%)</th>
<th>Polar (%)</th>
<th>Pressure Coefficient</th>
<th>GOR</th>
<th>Viscosity (mPa.s)</th>
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</thead>
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<tr>
<td>Biyang Depression</td>
<td>AS1</td>
<td>30</td>
<td>39</td>
<td>34.21</td>
<td>18.8</td>
<td>0.95</td>
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<td>33.52 15.72 12.06 9.56</td>
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Outline

- Introduction
- Lacustrine Shale Gas
- Lacustrine Shale Oil
- Conclusions
Lacustrine shales in China have large gross thickness, high TOC, different types of reservoirs pore spaces and abundant hydrocarbon shows, so that they have a great shale oil & gas potential.

Drawing on the successful experience of US shale oil and gas, China has made significant progresses in exploration for lacustrine shale oil & gas in the past 3 years.

China is facing great challenges in exploration for lacustrine shale oil & gas, such as prediction of favorable play fairways, shale wellbore stability problems, rapid production decline after fracking.
Sinopec management for research funding and permission to release this work