“Sweet areas (sections)” of continental shale oil in China

YANG Zhi

Research Institute of Petroleum Exploration & Development, PetroChina
Manhattan, Kansas, March, 2019
**Definition: Shale Oil**

- Shale oil refers to oil stored in organic-rich shale, including shale oil with lower $R_o$ and shale condensate oil with higher $R_o$.
- Continuous distribution with no apparent trap limit, and no natural productivity.

<table>
<thead>
<tr>
<th>Tight carbonate oil</th>
<th>Shale oil</th>
<th>Shale condensate oil</th>
<th>Tight sandstone oil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Oil</td>
<td>Oil</td>
<td>Oil</td>
</tr>
<tr>
<td></td>
<td>Oil</td>
<td>Oil</td>
<td>Oil</td>
</tr>
<tr>
<td></td>
<td>Oil</td>
<td>Oil</td>
<td>Oil</td>
</tr>
<tr>
<td></td>
<td>Oil</td>
<td>Oil</td>
<td>Oil</td>
</tr>
</tbody>
</table>

Schematic of formation and distribution of liquid-rich hydrocarbons in shale strata

Two differences from tight oil: ① HC Generation ② HC Migration
4. Conclusions
TWO WHATS?

- What is “sweet area(section)”?  What is resource potential?

**Liquid rich shale in USA**
- 4 major marine basins
- 7.93 billion tons recoverable resources
- 310 million tons production in 2018
- Foreign oil dependence is 35%

**Shale oil in China**
- 3 major continental basins
- 2 billion tons recoverable resources
- 0.1 million tons production in 2018
- Foreign oil dependence is 70%
What are the study areas?

- National Key Basic Research and Development Program (973 Program), China (2014CB239000)(2013-2018)

Fig. 1. Oil-bearing lacustrine shale distribution in the main basins in China.

3 study areas
- Ordos
- Songliao
- Junggar
1. Introduction
2. “Sweet areas (sections)”
3. Resource Potential
4. Conclusions
The target areas (sections) that can be preferentially explored and developed in the oil bearing shale formations under current conditions.

3 key features
- multiple types
- wide age span
- large distribution

3 examples
- Ordos: T₃
- Songliao: K₁
- Junggar: P₂

Fig. 2. Geochemical profile of lacustrine shale in the main basins in China.
The organic matter types I-II, the abundance of the organic matter varies greatly, and the thermal maturity is relatively low with Ro from 0.6 to 1.1%.

Fig. 3. Geochemical parameter cross-plot of continental shale in China.
Table 1 Geochemical parameter statistics of lacustrine shale in the main basins in China

<table>
<thead>
<tr>
<th>No.</th>
<th>Basin</th>
<th>Formation</th>
<th>Sample numbers</th>
<th>Depth (m)</th>
<th>TOC (%)</th>
<th>$S_1$ (mg/g-rock)</th>
<th>$S_2$ (mg/g-rock)</th>
<th>$S_1+S_2$ (mg/g-rock)</th>
<th>Tmax (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Qaidam</td>
<td>N₂(Youshashan)</td>
<td>49</td>
<td>2292-2953</td>
<td>0.09-2.38 (av.0.92)</td>
<td>0.010-0.491 (av.0.121)</td>
<td>0.035-9.927 (av.2.491)</td>
<td>0.046-10.418 (av.2.612)</td>
<td>410-452 (av.430)</td>
</tr>
<tr>
<td>2</td>
<td>Qaidam</td>
<td>N₁(Upper Ganchaigou)</td>
<td>343</td>
<td>2679-3474</td>
<td>0.10-2.68 (av.0.61)</td>
<td>0.004-5.955 av. (0.096)</td>
<td>0.011-12.874 (av.0.751)</td>
<td>0.015-14.660 (av.0.847)</td>
<td>301-565 (av.433)</td>
</tr>
<tr>
<td>3</td>
<td>Qaidam</td>
<td>E₃²(Lower Ganchaigou)</td>
<td>81</td>
<td>3215-3958</td>
<td>0.11-4.32 (av.1.24)</td>
<td>0.006-22.74 (av.2.013)</td>
<td>0.028-41.416 (av.6.492)</td>
<td>0.034-64.157 (av.8.51)</td>
<td>386-457 (av.433)</td>
</tr>
<tr>
<td>4</td>
<td>Bohaibey (Shulu Sag)</td>
<td>E₁₂(Shahejie)</td>
<td>181</td>
<td>2268-4365</td>
<td>0.21-4.13 (av.1.87)</td>
<td>0.01-2.32 (av.0.41)</td>
<td>0.07-57.08 (av.7.31)</td>
<td>0.09-59.4 (av.7.72)</td>
<td>421-460 (av.443)</td>
</tr>
<tr>
<td>5</td>
<td>North Songliao</td>
<td>K₁(Qingshankou)</td>
<td>124</td>
<td>2045-2111</td>
<td>0.88-6.41 (av.2.35)</td>
<td>1.13-6.31 (av.2.59)</td>
<td>3.7-20.43 (av.9.18)</td>
<td>5.24-26.74 (av.11.77)</td>
<td>403-456 (av.443)</td>
</tr>
<tr>
<td>6</td>
<td>South Songliao</td>
<td>K₁(Qingshankou)</td>
<td>232</td>
<td>1048-2612</td>
<td>0.66-6.01 (av.1.73)</td>
<td>0.04-3.11 (av.0.59)</td>
<td>0.38-40.14 (av.6.45)</td>
<td>0.38-40.14 (av.7.04)</td>
<td>436-454 (av.444)</td>
</tr>
<tr>
<td>7</td>
<td>Erlian (Anan Sag)</td>
<td>K₁(Tengri)</td>
<td>401</td>
<td>1390-1635</td>
<td>0.08-4.13 (av.1.13)</td>
<td>0.01-13.91 (av.1.47)</td>
<td>0.04-27.31 (av.5.65)</td>
<td>0.06-31.52 (av.7.13)</td>
<td>409-474 (av.448)</td>
</tr>
<tr>
<td>8</td>
<td>Sichuan</td>
<td>J(Lianggaoshan)</td>
<td>37</td>
<td>1328-2586</td>
<td>0.44-3.86 (av.1.62)</td>
<td>0.08-4.64 (av.1.28)</td>
<td>0.28-12.38 (av.4.19)</td>
<td>0.36-15.51 (av.5.47)</td>
<td>440-465 (av.449)</td>
</tr>
<tr>
<td>9</td>
<td>Sichuan</td>
<td>J(Daanzhai)</td>
<td>44</td>
<td>1167-3211</td>
<td>0.56-3.23 (av.1.31)</td>
<td>0.09-17.75 (av.1.54)</td>
<td>0.42-14.44 (av.3.66)</td>
<td>0.56-28.09 (av.5.20)</td>
<td>438-457 (av.446)</td>
</tr>
<tr>
<td>10</td>
<td>Ordos</td>
<td>T₃(Yanchang)</td>
<td>113</td>
<td>1717-2906</td>
<td>0.52-25.27 (av.6.67)</td>
<td>0.10-8.14 (av.2.45)</td>
<td>0.3-91.38 (av.17.43)</td>
<td>0.4-97.27 (av.19.88)</td>
<td>422-469 (av.451)</td>
</tr>
<tr>
<td>11</td>
<td>Santanghu</td>
<td>P₂(Tiaohu)</td>
<td>52</td>
<td>2123-2960</td>
<td>0.01-10.2 (av.3.10)</td>
<td>0.01-45.44 (av.10.11)</td>
<td>0.01-58 (av.14.59)</td>
<td>0.01-94.39 (av.24.71)</td>
<td>389-479 (av.434)</td>
</tr>
<tr>
<td>12</td>
<td>Santanghu</td>
<td>P₂(Lucaogou)</td>
<td>77</td>
<td>2219-3501</td>
<td>0.57-12.57 (av.4.61)</td>
<td>0.2-10.18 (av.2.43)</td>
<td>0.74-114.71 (av.30.82)</td>
<td>0.94-116.42 (av.32.25)</td>
<td>427-450 (av.441)</td>
</tr>
<tr>
<td>13</td>
<td>Junggar</td>
<td>P₂(Lucaogou)</td>
<td>149</td>
<td>3109-3782</td>
<td>0.03-19.77 (av.2.79)</td>
<td>0.01-2.91 (av.0.30)</td>
<td>0.02-176 (av.14.23)</td>
<td>0.04-176.65 (av.14.54)</td>
<td>424-455 (av.445)</td>
</tr>
</tbody>
</table>
“Sweet areas (sections)"

- Large-scale reservoirs have continuous microscale and nanoscale reservoir spaces, which are the basis for continuous shale oil distribution.

Fig. 4. SEM images of typical continental oil-bearing shale in China.
Case 1: Ordos Basin

Sweet area

- Thickness is greater than 15m
- Ro is greater than 0.9%

Fig. 5. Overlay of the shale thickness and vitrinite reflectance of the Triassic Yanchang Formation in Ordos basin, China.
Case 1: Ordos Basin

Fig. 6. Geochemical depth profile of Triassic Yanchang Formation lacustrine shale in Ordos basin, China.

<table>
<thead>
<tr>
<th>Formation</th>
<th>GR (API)</th>
<th>RT (Ω·m)</th>
<th>Thickness (m)</th>
<th>Lithology</th>
<th>TOC (%)</th>
<th>Pyrite (%)</th>
<th>S₀ (mg/g)</th>
<th>Chloroform bitumen A' (%)</th>
<th>Tₘ₉₅ (°C)</th>
<th>“Sweet section” of shale oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>400</td>
<td>10</td>
<td>150</td>
<td></td>
<td>0</td>
<td>30</td>
<td>40</td>
<td>10</td>
<td>420</td>
<td></td>
</tr>
</tbody>
</table>

Sweet section
● Lower part
Case 1: Ordos Basin

- The TOC content has a positive correlation with the development level of the shale lamellae, and shale oil is extensively present in these lamellar planes or parallel microfractures.

Fig. 7. Microscopic photos under polarized light of lamina and organic matter in the Triassic Yanchang Formation in the Ordos Basin.
Case 2: Songliao Basin

Sweet area

- Thickness is greater than 40m
- Ro is greater than 0.9%

Fig. 8. Overlay of the shale thickness and vitrinite reflectance of the Cretaceous Qingshankou Formation in the Songliao basin, China.
Case 2: Songliao Basin

<table>
<thead>
<tr>
<th>Formation</th>
<th>Lithology</th>
<th>Thickness (m)</th>
<th>TOC (%)</th>
<th>“A” (%)</th>
<th>R₀ (%)</th>
<th>S₁+S₂ (mg/g)</th>
<th>Tₘₐₓ (°C)</th>
<th>HI (mg/g)</th>
<th>Sweet section of shale oil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0</td>
<td>5</td>
<td>6</td>
<td>0.5</td>
<td>1.5</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>420</td>
<td>460</td>
<td>0</td>
<td>700</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Qingshankou Formation</td>
<td>First section</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Second section</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Third section</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sweet section

- Middle and lower part

Fig. 9. Geochemical depth profile of Cretaceous Qingshankou Formation lacustrine shale in the Songliao basin, China.
Case 3: Junggar Basin

Fig. 10. Overlay of the shale thickness and vitrinite reflectance of the Permian Lucaogou Formation in the Jimsar Sag, Junggar basin, China.

Sweet area
- Middle of sag
Case 3: Junggar Basin

**Sweet section**
- P$_2$I$^5$
- P$_2$I$^5$

Fig. 11. Stratigraphic histogram of the Permian Lucaogou Formation lacustrine shale in the Junggar basin, China.
Outline

1. Introduction
2. “Sweet areas (sections)”
3. Resource Potential
4. Conclusions
Medium to high mature shale

- Using SRV, if EUR 2%, about 7 billions shale oil may be recoverable.

**Table 2 Continental shale oil resource potential evaluation of the main basins in China**

<table>
<thead>
<tr>
<th>Basin</th>
<th>Formation</th>
<th>Oil generation (10^8 t)</th>
<th>Oil expulsion (10^8 t)</th>
<th>Oil detention (10^8 t)</th>
<th>Shale oil recoverable (10^8 t)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(10^8t)</td>
<td>(10^8t)</td>
<td>2%</td>
<td>5%</td>
</tr>
<tr>
<td>Songliao</td>
<td>Cretaceous</td>
<td>1100</td>
<td>400</td>
<td>700</td>
<td>14</td>
</tr>
<tr>
<td>Bohai Bay</td>
<td>Paleogene</td>
<td>1400</td>
<td>500</td>
<td>900</td>
<td>18</td>
</tr>
<tr>
<td>Ordos</td>
<td>Triassic</td>
<td>1300</td>
<td>450</td>
<td>750</td>
<td>15</td>
</tr>
<tr>
<td>Junggar</td>
<td>Permian</td>
<td>800</td>
<td>250</td>
<td>550</td>
<td>11</td>
</tr>
<tr>
<td>Sichuan</td>
<td>Jurassic</td>
<td>300</td>
<td>100</td>
<td>200</td>
<td>4</td>
</tr>
<tr>
<td>Qaidam</td>
<td>Paleogene, Neogene</td>
<td>300</td>
<td>100</td>
<td>200</td>
<td>4</td>
</tr>
<tr>
<td>Erlian</td>
<td>Cretaceous</td>
<td>200</td>
<td>50</td>
<td>150</td>
<td>3</td>
</tr>
<tr>
<td>Santanghu</td>
<td>Permian</td>
<td>45</td>
<td>15</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>Jiuquan</td>
<td>Cretaceous</td>
<td>50</td>
<td>15</td>
<td>35</td>
<td>1</td>
</tr>
<tr>
<td>Nanxiang</td>
<td>Paleogene</td>
<td>30</td>
<td>12</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>Subei</td>
<td>Paleogene</td>
<td>115</td>
<td>17</td>
<td>98</td>
<td>2</td>
</tr>
<tr>
<td>Jianghan</td>
<td>Paleogene</td>
<td>82</td>
<td>11</td>
<td>71</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>5722</strong></td>
<td><strong>1920</strong></td>
<td><strong>3702</strong></td>
<td><strong>74</strong></td>
</tr>
</tbody>
</table>
Medium to low mature shale

Fig. 12. Comprehensive evaluation of the favorable pilot area for the Triassic Yanchang Formation shale in Ordos basin in China using ICP technology.

3 key factors
- The scale (area, thickness × TOC)
- Max burial depth
- Present depth

- Area: 12,000 km$^2$
- Thi × TOC: >100
- Ro: <0.8%
- Depth: 700-1700m
- In China, recoverable oil is 40 to 50 billion tons.
• Using technologies such as SRV and ICP, an underground fracture network with “man-made permeability” is constructed, with which continental shale oil may be another revolution of unconventional oil and China the first successful one.

Fig. 13. “Man-made shale oil reservoir” exploitation model.
Outline

1. Introduction
2. “Sweet areas (sections)”
3. Resource Potential
4. Conclusions
Conclusions

- "Sweet areas (sections)" :
  - "Sweet areas" of shale oil with medium-high maturation are mainly located in thick shales with a Ro greater than 0.9%.
  - "Sweet sections" are mainly located in the middle and lower parts of the shale formation.

- Resource Potential:
  - Using SRV, 370 billion tons of geological resources.
  - Using ICP, 40 to 50 billion tons of recoverable part.
  - "Man-made reservoir" is proposed.

Thanks!
yangzhi2009@petrochina.com.cn

Caring For Energy, Caring For You