Shale Oil identification Method Based on Support Vector Machine Classification Technology

Shi YuJiang

PetroChina Changqing Oilfield Branch

August 2019
1. Questions Raised

2. Petrophysical Characteristics

3. Logging Evaluation Method

4. Conclusion
Chang 7 of the Late Triassic in Ordos Basin developed a set of semi-deep lake-deep Lake organic-rich shale deposits. The distribution range of effective source rocks reached 65,000 square kilometers, which laid the material foundation for the Mesozoic large-scale low permeability-tight sandstone reservoirs in the basin. In recent years, while making a major breakthrough in the exploration of dense sandstone adjacent to hydrocarbon source rock, large-scale volume fracturing test oil has been carried out for conventional unexplained shale formations, and some wells have obtained industrial oil flow, showing a certain prospect of exploration.
Influenced by the high radioactivity of organic matter in source rocks, the log response of Chang 73 section is high natural gamma ray, high time difference and high resistance, which makes conventional logging difficult to identify.

Fig. Logging Interpretation Result of Chang 7 Well N148

Oil: 20.40t/d

Fig. Logging Interpretation Result of Chang 7 Well G295

Oil: 24.23t/d
How to identify and evaluate lithology, for unconventional shale oil reservoirs, lithofacies, reservoir property and oil-bearing property, and how to establish targeted rock physics and logging identification and evaluation methods have become an important issue.

Fig. Logging Interpretation Result of C96 Well Chang73
1. Questions raised
2. Petrophysical Characteristics
3. Logging Evaluation Method
4. Conclusion
◆Sediment Combination

Core and outcrop profile observations reveal that there are three types of combination of thin-bedded massive sandstone-shale interbedding, black shale-facies intercalation and thin-bedded parallel bedded sandstone-facies intercalation and collapse in the middle of the lake basin.

Sandstone Interbedding in Chang73 Black Shale of Tongchuan Section

Sedimentary Facies Profile of Well C96 Chang73
Based on the log response and XRD analysis, the shale formation is divided into five lithofacies types, of which the quartz and feldspar content of high/medium gamma siliceous shale is the highest, and it is the favorable lithofacies type.

### Lithofacies Division

#### XRD Whole Rock Mineral Distribution

#### Clay mineral types

#### Table of Mineral Compositions of Different Rocks in Shale Strata

<table>
<thead>
<tr>
<th>Lithofacies Classification</th>
<th>Quartz (%)</th>
<th>Feldspar (%)</th>
<th>Carbonate (%)</th>
<th>Pyrite (%)</th>
<th>Clay mineral (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I : Ultra-high Gamma Silicate Shale</td>
<td>32.7</td>
<td>19.3</td>
<td>5.2</td>
<td>12.6</td>
<td>30.2</td>
</tr>
<tr>
<td>II /V: Medium/High Gamma siliceous shale</td>
<td>52.1</td>
<td>19</td>
<td>9.2</td>
<td>2.1</td>
<td>17.6</td>
</tr>
<tr>
<td>III : High Gamma Clay Shale</td>
<td>26.9</td>
<td>12.5</td>
<td>1.7</td>
<td>3</td>
<td>55.9</td>
</tr>
<tr>
<td>IV : High Gamma Tuffaceous Shale</td>
<td>43.7</td>
<td>9.1</td>
<td>2.5</td>
<td>1.2</td>
<td>43.5</td>
</tr>
</tbody>
</table>
# Lithofacies Classification of Chang7 Shale Oil Strata in Ordos Basin

<table>
<thead>
<tr>
<th>Lithofacies types</th>
<th>Logging curve characteristics</th>
<th>Major mineral components</th>
<th>Reservoir space type</th>
<th>Geochemical characteristics of organic matter</th>
<th>Reservoir quality</th>
</tr>
</thead>
</table>
| Ultra-high Natural Gamma-ray Silicate Shale | • Natural Gamma > 300 API  
  • Uranium content > 8 ppm  
  • Low thorium content  
  • High/Low Resistivity  
  • Low Density, Slow Sound Wave, High School Students  
  • High Silica Content in Elemental Logging  
  • Clay content 20-40% | Quartz, feldspar, clay, pyrite, siderite, mica, organic matter | • Intergranular pore  
  • Intergranular pore dissolution  
  • Intergranular pore of clay minerals  
  • Intragranular dissolved pore (feldspar, quartz)  
  • Internal pore of organic matter  
  • Microfissures  
  • Intergranular pore | • TOC Excellent High > 8%  
  • Maturity  
  • Type I kerogen  
  • Layered, lenticular and reticulate distribution  
  • Organoporous agenesis  
  • Microfracture development | The overall quality of this kind of shale reservoir is poor. |
| High natural gamma siliceous shale     | • Natural gamma 150 API-300 API  
  • Uranium content 3-8 ppm  
  • Low thorium content  
  • High/Medium Resistivity  
  • Relative Low Density, Low Neutron, Slow Acoustic Wave  
  • High Silica Content in Elemental Logging  
  • Clay content is less than 30% | Quartz, feldspar, clay, pyrite, siderite, mica, organic matter | • Intergranular pore  
  • Intergranular pore dissolution  
  • Intergranular pore of clay minerals  
  • Intragranular dissolved pore (feldspar, quartz)  
  • Internal pore of organic matter  
  • Microfissures  
  • Intergranular pore | • TOC medium 2-8%  
  • Maturity  
  • Type I kerogen  
  • Layered, lenticular and reticulate distribution  
  • Organic pore development  
  • Microfracture development | The quality of this kind of shale reservoir is good. |
| High Natural Gamma Clay Shale          | • Natural gamma 150 API-300 API  
  • Uranium content 3-8 ppm  
  • Low thorium content  
  • High/Medium Resistivity  
  • Low Density, Slow Sound Wave, High School Students  
  • Low Silica Content in Elemental Logging  
  • Clay content is more than 40% | Quartz, feldspar, clay, pyrite, siderite, mica, organic matter | • Intergranular pore  
  • Intergranular pore dissolution  
  • Intergranular pore of clay minerals  
  • Intragranular dissolved pore (feldspar, quartz)  
  • Internal pore of organic matter  
  • Microfissures  
  • Intergranular pore | • TOC is 4-10% higher  
  • Maturity  
  • Type I kerogen  
  • Layered, lenticular and reticulate distribution  
  • Organoporous agenesis  
  • Microfracture development | The overall quality of this kind of shale reservoir is poor. |
| High Natural Gamma Tuffaceous Shale    | • Natural gamma 150 API-300 API  
  • Low uranium content  
  • Thorium content > 14 ppm  
  • Low Resistivity  
  • Low Density, Slow Sound Wave, High School Students  
  • High Silica Content in Elemental Logging  
  • Clay content is more than 40% | Quartz, feldspar, clay, pyrite, siderite, mica, organic matter | • Intergranular pore  
  • Intergranular pore dissolution  
  • Intergranular pore of clay minerals  
  • Intragranular dissolved pore (feldspar, quartz)  
  • Internal pore of organic matter  
  • Microfissures  
  • Intergranular pore | • Low TOC < 2%  
  • Maturity  
  • Type I kerogen  
  • Layered, lenticular and reticulate distribution  
  • Organoporous agenesis  
  • Microfissure undeveloped | The overall quality of this kind of shale reservoir is poor. |
| Natural gamma-ray siliceous shale      | • Natural gamma < 150 API  
  • Low uranium content  
  • Low thorium content  
  • High/Medium Resistivity  
  • Relative Low Density, Slow Acoustic Wave and Low Neutron  
  • High Silica Content in Elemental Logging  
  • Clay content is less than 25% | Quartz, feldspar, clay, pyrite, siderite, mica, organic matter | • Intergranular pore  
  • Intergranular pore dissolution  
  • Intergranular pore of clay minerals  
  • Intragranular dissolved pore (feldspar, quartz)  
  • Internal pore of organic matter  
  • Microfissures  
  • Intergranular pore | • TOC is relatively low < 4%  
  • Maturity  
  • Type I kerogen  
  • Layered, lenticular and reticulate distribution  
  • Organic pore development  
  • Microfracture development | The overall quality of this kind of shale reservoir is good. |
MINERAL COMPOSITION OF MIDDLE/HIGH GAMMA SILICONIC SHALE

B36 well digital core QEMSCAN scan mineral results

Mineral Composition of Clay Shale with High Natural Gamma

<table>
<thead>
<tr>
<th>Mineral Name</th>
<th>Vol%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>47.95</td>
</tr>
<tr>
<td>Albite</td>
<td>14.78</td>
</tr>
<tr>
<td>Illite</td>
<td>12.41</td>
</tr>
<tr>
<td>K-Feldspar</td>
<td>6.72</td>
</tr>
<tr>
<td>Dolomite</td>
<td>5.25</td>
</tr>
<tr>
<td>Muscovite</td>
<td>3.06</td>
</tr>
<tr>
<td>Chlorite</td>
<td>2.31</td>
</tr>
<tr>
<td>Pores</td>
<td>1.81</td>
</tr>
<tr>
<td>Biotite</td>
<td>1.60</td>
</tr>
<tr>
<td>Calcite</td>
<td>1.51</td>
</tr>
<tr>
<td>Siderite</td>
<td>0.64</td>
</tr>
<tr>
<td>Siderite</td>
<td>0.63</td>
</tr>
<tr>
<td>Rutile</td>
<td>0.36</td>
</tr>
<tr>
<td>Apatite</td>
<td>0.27</td>
</tr>
<tr>
<td>Smectite</td>
<td>0.20</td>
</tr>
<tr>
<td>Pyrite</td>
<td>0.17</td>
</tr>
<tr>
<td>Pyrophylite</td>
<td>0.12</td>
</tr>
<tr>
<td>Ankerite</td>
<td>0.04</td>
</tr>
<tr>
<td>Paragonite</td>
<td>0.04</td>
</tr>
<tr>
<td>Unclassified</td>
<td>0.03</td>
</tr>
<tr>
<td>Andesine</td>
<td>0.03</td>
</tr>
<tr>
<td>Zircon</td>
<td>0.02</td>
</tr>
<tr>
<td>Al Oxide</td>
<td>0.01</td>
</tr>
<tr>
<td>Glaucnite</td>
<td>0.01</td>
</tr>
<tr>
<td>Gypsum/Anhydrite</td>
<td>0.01</td>
</tr>
</tbody>
</table>

F28 well digital core QEMSCAN scan mineral results
Pore characteristics

The results of high-resolution scanning electron image analysis show that intergranular pore, intragranular solution pore, organic pore and micro-fissure coexist in Chang 7 source rock, but the abundance, distribution and pore connectivity of different types of pore are quite different.
Microcracks
Bedding microcracks
Microcracks
Microcracks
Microcracks
Dissolution pore
Dissolution pore
Microfissures in Organic Matter
Organic matter pore
**Characteristics of pore and throat**

The experimental results of high pressure mercury injection show that the pore and throat in shale oil are nanometer scale, and the median pore throat size is several to hundreds of nanometer intervals.
### Physical Characteristics

I: Ultra-high gamma siliceous shale: core porosity is below 5%, permeability (pressure attenuation permeability) is basically below 100 Nadasi.

II/V: high/medium gamma siliceous shale: core porosity is mainly between 3-7%, permeability (pulse attenuation permeability 5000psi) is basically in hundreds to thousands of Nadasi, the highest 0.017 mda.

III: high gamma clay shale: core porosity is less than 4.5%, permeability (pressure attenuation permeability) is less than 100 Nadasi.

IV: High gamma tuffaceous shale: core porosity is 4.1-10.2%, and permeability (pressure attenuation permeability) averages 53 Nadasi.
The pore-permeability relationship of core analysis is not obvious, and the pore-permeability relationship and pore structure of reservoir are complex.
**Oil-bearing Characteristics**

By means of high resolution distillation experiment, the content of fluid components in different temperature ranges was measured, and the content of movable oil, water and bound fluid was evaluated.
Ultra-high gamma siliceous shale: water saturation is mostly 30-60%.

High/medium gamma siliceous shale: good oil-bearing, low water saturation as a whole, mostly less than 40%.

High gamma clay shale: high water saturation, basically above 60%.

High gamma ash shale: high water saturation, basically above 60%.
1. Questions raised
2. Petrophysical Characteristics
3. Logging Evaluation Method
4. Conclusion
3. Logging Evaluation Method

- **Lithofacies division by logging**

Through core observation, thin section, XRD, lithology scanning logging and FMI image characteristics, shale oil facies can be comprehensively divided.

Comparison of lithologic scanning processing results with XRD, electrical imaging, core photograph and thin section analysis results in Well B36
Division of lithofacies by electric imaging logging

Through high resolution processing of electrical imaging logging, the recognition accuracy of thin sand strips embedded in high radioactive source rocks is improved.

Field outcrop profile of interbedded sandstone and source rock
Classification of Lithofacies by Conventional+Spectral Logging

Classification chart of lithofacies logging for Chang73 shale oil formation
Combined with fine lithofacies classification, the medium gamma siliceous shale mainly exists in sandstone shale interbedded, while the high gamma siliceous shale mainly develops in black shale with a certain thickness.

**Shale oil interbedded with sandstone and shale**

**Thick Layered Silica-Rich Hidden Reservoir in Black Shale**
Quantitative Evaluation of Rock and Mineral Components

- Multimineral model

Physical Model of Rock Volume

- **Kerogen**
- **Por**
- **Quartz** + **Feldspar**
- **Calcite** + **Dolomite**
- **Illite**

Response equation:

\[
\rho_b = \rho_1 V_1 + \rho_2 V_2 + \rho_i V_i + \rho_m V_m
\]

\[
\Delta t = \Delta t_1 V_1 + \Delta t_2 V_2 + \Delta t_i V_i + \Delta t_m V_m
\]

\[
CNL = CNL_1 V_1 + CNL_2 V_2 + CNL_i V_i + CNL_m V_m
\]

\[
1 = V_1 + V_2 + V_i + V_m
\]

Important feature: Kerogen as part of rock volume model

Determining the skeleton values of rocks and minerals by different intersection diagrams
Determination of skeleton value of mineral components

Different mineral components will cause greater sensitivity to the corresponding curves. For example, illite will have a greater impact on Gr value. The Gr skeleton value of the mineral in the model is adjusted by calculating illite content and the ratio of GR prediction curve to GR measured curve.


Intersection Diagram of Lithologic Porosity

For the slope of the connection between skeleton point and water point, its value is a reflection of the lithological characteristics of each rock skeleton, which has nothing to do with porosity, but only with lithology.

\[
M = \frac{\Delta t_f - \Delta t}{\rho_b - \rho_f} \times 0.03 = \frac{\Delta t_f - \Delta t_{ma}}{\rho_{ma} - \rho_f} \times 0.03
\]

\[
N = \frac{CNL_f - CNL}{\rho_b - \rho_f} = \frac{CNL_f - CNL_{ma}}{\rho_{ma} - \rho_f}
\]

The parameters M and N, which mainly reflect lithology, are calculated by three porosity curves. On this basis, the M-N intersection diagram is made to determine lithology and calculate shale content.
Lithology determinations:
The mineral composition of rocks can be determined according to the position of the data points on the intersection map.

Calculate shale content:
(1) Firstly, a straight line through limestone and dolomite is defined.
(2) Secondly, the skeleton parameters of porosity curve of pure mudstone point in the study area are defined, the location of M-N intersection map is determined, and the distance from pure mudstone point to the straight line La is calculated.
(3) Calculate the distance from any curve data point to the line Lb;
(4) Calculating shale content $V_{sh} = \frac{Lb}{La}$.
Fig. Shale Oil Lithology and Porosity Intersection, Method for Determining Shale Content in Well Y32
The argillaceous content calculated by crossplot method is consistent with the core lithology, and the core is described as gray-black siltstone.
According to the thin section analysis of well L57, feldspar sandstone is developed in this section, and the sandstone has good oil-bearing property.
Fig. G295 well logging interpretation results

oil: 20.49t/d
The support vector machine (SVM) is actually a kind of perception model, which belongs to a classification algorithm, which can establish a classification model for unknown samples according to the sample data and classification indicators that have been formed. The mean idea of the algorithm: first find multiple superplanes that can be classified to separate the data, and optimize all the data points (especially those closer to the hyperplane) to the maximum extent away from the hyperplane, to achieve a better classification effect on unknown samples.
By analyzing and studying gamma, resistivity and pe value and porosity overlap graph difference as input parameters of the SVM prediction model, the shale oil reservoir verified by oil testing are used as a known sample, and the SVM prediction model is trained to achieve a prediction accuracy of 92.5%.

SVM Prediction accuracy (well Cheng96)
According to the characteristics of shale oil reservoir, such as thin thickness, small pore size and fine pore roar, the acquisition parameters of nuclear magnetic resonance logging are optimized, the number of main measurement echoes is reduced, the repetition times of short waiting time are increased, and the accuracy of small pore measurement is improved.

Comparison of acquisition parameters and effects of nuclear magnetic logging for Chang73 shale oil in Well B42
By comparing the experimental T2 spectrum of NMR with the T2 spectrum of NMR logging, the T2 time corresponding to the large difference of cumulative porosity crossover can roughly be used as the cut-off value of NMR free fluids.

\[ T2_{\text{cutoff}} = 10.4 \text{ms} \]
Reservoir classification criteria for NMR pore structure logging and corresponding T2 spectral characteristics:

- **The first type of reservoir**: the proportion of pore larger than 40 ms is the largest, and the main type is macropore.
- **The second type of reservoirs** are mainly medium and large pore less than 40 ms.
- **The third types of reservoirs**: small pores less than 4ms are dominant.
Study on Source Rock Evaluation and Source-Reservoir Allocation Relation

- Overlapping of Resistivity and Porosity Curves
  \[ \Delta \log R = \log \frac{R}{R_{\text{基线}}} + K \cdot (\Delta t - \Delta t_{\text{基线}}) \]
  \[ TOC = (\Delta \log R) \cdot 10^{2.297-0.1688 \cdot LOM} \]

- Multivariate Statistical Regression Method
  \[ TOC = 56.44-0.049 \times AC-17.05 \times DEN+0.037 \times GR \]

Classification and Evaluation Criteria of Source Rocks

<table>
<thead>
<tr>
<th>Classification</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>mudstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOC,%</td>
<td>&gt;10</td>
<td>6~10</td>
<td>2~6</td>
<td>&lt;2</td>
</tr>
<tr>
<td>GR, API</td>
<td>&gt;230</td>
<td>180~230</td>
<td>130~180</td>
<td>&lt;130</td>
</tr>
<tr>
<td>DEN, g/cm³</td>
<td>&lt;2.2</td>
<td>2.2~2.35</td>
<td>2.35~2.5</td>
<td>&gt;2.5</td>
</tr>
<tr>
<td>AC, us/m</td>
<td>&gt;300</td>
<td>270~300</td>
<td>250~270</td>
<td>&lt;250</td>
</tr>
</tbody>
</table>
By studying the relationship between source and reservoir allocation, it is clear that the relatively low TOC section in organic-rich shale should be selected for the sweet spot section of shale oil.

Fig. Logging Interpretation Result of C96 Well Chang73

 relativel
y low

TOC

segme
nt

oil: 10.97t/d
wet: 5.4m³/d
◆ Shale oil sweet spot evaluation

The oil-bearing property of shale oil reservoir is the result of the interaction of reservoir quality and organic matter quality. A comprehensive evaluation chart of shale oil based on reservoir quality and organic matter quality is established, which lays a foundation for the optimization of shale oil sweet spot area.

**Reservoir quality:** \( RQ_I_R = F(\phi, Aniso, p, wclay) \)

**Quality of source rocks:** \( RQ_I_S = F(RT, DTCO) \)

Intersection of Shale Oil Reservoir Quality and Organic Quality
1. Questions Raised
2. Petrophysical Characteristics
3. Logging Evaluation Method
4. Conclusion
4. CONCLUSION

- Based on core observation, thin section analysis, XRD, geochemical, TRA physical properties, NMR and mercury injection experiments, nano-CT scanning and other petrophysical experimental techniques, the lithology, mineral composition, reservoir physical properties, reservoir space type, pore throat size distribution and oil-bearing characteristics of Chang73 shale formation in Ordos Basin are revealed, and the shale oil and its reservoir characteristics clearly defined.

- Through core calibration logging data (conventional and special logging), a new logging interpretation model for Chang73 formation is established, including multi-mineral model, porosity and permeability model, organic carbon content calculation model, etc. The mineral content calculation method of rock-porosity crossplot and classification technology based on support vector machine are innovatively formed. The method of shale reservoir identification and the classification chart based on the quality of reservoir and organic matter were established, which laid the foundation for the optimization of dessert for shale oil exploration.
Thank you!