The key reservoir characterization technology in strategic discovery of a giant ancient carbonate gas field in Sichuan Basin, China

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Outline

• The discovery of a giant ancient carbonate gas field
• The key reservoir petrophysical evaluation technology for the deep giant ancient vug-fracture carbonate gas field
  – Key Technology 1: "3-highs" special minerals identification and quantitative evaluation for complex carbonate reservoir
  – Key Technology 2: Effectiveness of fracture and pore space evaluation for complex inhomegeneity carbonate reservoir
  – Key Technology 3: Fluid identification evaluation for vug-fracture carbonate reservoir
• E&P achievements
The Sichuan Basin is located in southwestern China and covers an area of approximately $18 \times 10^4$ km$^2$. It is one of a major petroliferous basin in China.
1. History of oil & gas exploration in Sinian-Cambrian, Sichuan Basin

- **Year 1964 – The discovery stage**

  Taking large ground structure as prospecting target, the first mono-block large gas field, Weiyuan Sinian gas field, was discovered (with proved gas reserves of 400 thousand million m$^3$). After more than 40 years of multiple rounds of exploration, no big discovery was made in the area.

- **1965-1990: Regional exploration stage**

  Around the east & west ends of the paleo-uplift, 5 exploration wells were drilled, water was produced in 4 wells, and 18.5 thousand m$^3$ of gas was produced in Well Nvji1 of Sinian stratigraphy.

- **1991-1999: Continuous exploration stage**

  11 exploration wells drilled in the slope of the paleo-uplift, 3 wells get commercial gas flow in Ziyang, Anping1 gets gas of 2000 m$^3$ and Gaoke1 gets gas of 7000 m$^3$ in Anyue.

- **2000-2005: Weiyuan structure drilling stage**

  Mainly targeting at Cambrian stratigraphy, 5 wells were drilled and all produced water.
2006-2010: Breakthrough stage of risk exploration

In the slope zones near the axial Leshan-Longnvsi paleo-uplift, which is also modern large structural high sections, Gaoshi1 and Moxi8 were drilled, and major breakthroughs were got in Sinian Dengying Formation and Cambrian Longwangmiao Formation.
Integrated petrophysical analysis composite log of well Moxi 8

- 3 gas zone interpreted by logs with total pay thickness 60 m and average porosity 6.1 p.u.
- The accumulative test production from zone 2 is $190.68 \times 10^4$ m³/day.

Historical breakthrough of Cambrian Longwangmiao Formation of Moxi8

Field test picture of Longwangmiao Formation for Well Moxi8(2012)
2011-2016 Efficient stereoscopic exploration & development stage

- 3 main production layers: Second member and Forth member of Sinian Dengying formation, and Cambrian Longwangmiao Formation;
- Anyue giant gas field of Longwangmiao Fm is proved in 3 yrs with the proved gas reserves of 440,383 million m3;
- Overall controlling for exploration area of 7500 km2 in Gaoshiti-Moxi block of Sinian & Cambrian stratigraphy in Central Sichuan;
- The cumulative proved gas reserves reaches 810200 million m3, and the proved, probable and possible reserves exceeds 1.5 trillion m3.
- Over 10 billion m3 of production for gas development has built up.

The prospect map of Cambrian Longwangmiao Formation

The prospect map of Sinian Dengying formation
2. Favorable geological conditions for the formation of the giant ancient carbonate gas field

(1) During late damian - early Cambrian the large paleo-taphrogenic trough & hydrocarbon generation center was developed in the area with abundant gas resources.

- 3 sets of high-quality source rock of Cambrian Qiongzhusi Formation, Maidiping Formation and Third Member of Dengying Formation were developed in the paleo-taphrogenic trough, the source rock thickness, organic matter abundance, and gas generation intensity were 2-4 times for that in the platform. The total gas resources reach 410-500 million m$^3$.

- Taphrogenic trough: source rock thickness ranging 300-500m, TOC > 2%, and gas generation intensity ranging 8-18 billion m$^3$/km$^2$.
- Adjacent regions: source rock thickness ranging 100-150m, TOC averaging 1%, and gas generation intensity ranging 2-4 billion m$^3$/km$^2$.

Distribution of source rock thickness of the lower Cambrian

Distribution of gas generation intensity of the lower Cambrian
The widespread distribution for fracture-vug type dolomite reservoirs of Dengying Formation and Longwangmiao Formation

- **Dengying Formation:** the distribution of the dune-beach body is along platform margin showing U shape with an area of 30000 km²

- **Longwangmiao Formation:** the distribution of the upper-beach body is along carbonate buildup during Tongwan stage with an area of 80000 km²

Lithofacies paleogeography for Forth member of Sinian Dengying formation in Upper Yangtze craton

Lithofacies paleogeography for Cambrian Longwangmiao Formation in Upper Yangtze craton
The formation of Anyue giant gas field is the result of the time-space effective allocation of the oil & gas evolution and the “4 Paleo” accumulation elements which is focusing on the paleo-taphrogenic trough.

“4 Paleo” accumulation elements: Early stage paleo-uplift controlled by paleo-taphrogenic trough in craton, paleo lithologic-stratigraphic trap, paleo dune-beach body reservoirs jointly provide effective space for gas storage and accumulation.

- The distribution of hydrocarbon generation center was controlled by paleo-taphrogenic trough, which lays foundation of gas resources for the formation of the large gas field.
- The large-scale distribution for paleo dune-beach body reservoirs provides effective space for gas storage.
- Large-scale paleo lithologic-stratigraphic trap provides a place for gas accumulation.
- Inherited development of the superimposed paleo-uplift provide tectonic background for the evolution of the large gas field.

![Diagram of Anyue block and Paleo-trap](image-url)
The reservoir characteristics and evaluation challenges of Longwangmiao and Dengying formation:

- Various in kind of sedimentary microfacies;
- Complicated lithology, complex rock fabric, high content of special minerals;
- Multi-stage diagenesis and tectonization, Polytype of pore space, heavy inhomogeneity;
- Low porosity and low permeability, hard to predict producibility.
Key Technology 1:”3-highs” special minerals identification and quantitative evaluation for complex carbonate reservoir

- Developed the “high silica, high pyrite, high pyrobitumen” identification method by calibrating the LithoScanner logs with core.

Characteristics of Silicalite:

Triple-com logs: high resistivity, low gamma ray, mirror image between sonic and neutron logs in proper scale;
Electric Imaging Log: Tight, massive feature;

Mineral Identification Chart:
Key Technology 1: “3-highest” special minerals identification and quantitative evaluation for complex carbonate reservoir

- Developed the “high silica, high pyrite, high pyrobitumen” identification method by calibrating the LithoScanner logs with core.

Characteristics of Pyrite:

- Triple-com logs: low resistivity, low gamma ray, high density
- Electric Imaging Log: Dark, banded feature;

Mineral Identification Chart:
Key Technology 1: “3-highs” special minerals identification and quantitative evaluation for complex carbonate reservoir

- **Pyrobitumen affection for reservoir properties and log identification method**
  - **Porosity**: increasing porosity in a range of 0.25~3.02%, averaged helium gas core porosity increased by 1.29% (27% higher).
  - **Permeability**: increased permeability in a range of 0.0025~0.092mD, averaged core perm. Increased by 0.0374mD (68.5% higher).
  - **Pore structure**: improved the pore throat distribution, more for macro-pore throat, less for micro-pore throat.

To identify Pyrobitumen by using compressional-resistivity and shear slowness cross plot.

![Graph showing compressional-shear slowness correlation from core data.](image-url)

![Graph showing stress vs. depth.](image-url)
Pyrobitumenous reservoir petrophysical evaluation

Pyrobitumen identification and porosity correction plot of well Moxi 29

<table>
<thead>
<tr>
<th>Natural</th>
<th>Porosity before correction</th>
<th>Oil</th>
<th>Gas</th>
<th>Water</th>
<th>Formation</th>
<th>Test result: 10.45 × 10^4 m^3/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</table>

Corrected porosity: 3.3%
Porosity from log: 5.3%

Prodicibility prediction with non-corrected porosity (RQ: 0.76)
Predicted productivity: 50 ~ 100 × 10^4 m^3/day

Prodicibility prediction with corrected porosity (RQ: 0.61)
Predicted productivity: 10 ~ 50 × 10^4 m^3/day

Better correlation between reservoir petrophysical properties and test result
Key Technology 2: Effectiveness of fracture and pore space evaluation for complex inhomogeneity carbonate reservoir

- Reservoir classification method by using NMR measurement
- Fracture effectiveness evaluation
- Pore and vug connectivity evaluation

### T2 (saturated sample) and porosity distribution

<table>
<thead>
<tr>
<th>Type</th>
<th>T2</th>
<th>Macro pore (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>3 peaks</td>
<td>&gt;60</td>
</tr>
<tr>
<td>II</td>
<td>3 peaks</td>
<td>50~60</td>
</tr>
<tr>
<td>III</td>
<td>3 peaks</td>
<td>20~50</td>
</tr>
<tr>
<td>IV</td>
<td>Uni-peak</td>
<td>&lt;20</td>
</tr>
</tbody>
</table>

- The porosity-Permeability correlation controlled by pore structure

- Longwangmiao Reservoir Classification with core NMR data
Key Technology 2: Effectiveness of fracture and pore space evaluation for complex inhomogeneity carbonate reservoir

Well Moxi202-Well Moxi17-Well Moxi205 reservoir classification cross-section by CMR

- Well Moxi 202: Test result 30.32x10^4 m^3/day
- Well Moxi 17: Test result 53.2x10^4 m^3/day
- Well Moxi 205: Test result 116.87x10^4 m^3/day

Production is higher with more macro porosity in the reservoir
Key Technology 2: Effectiveness of fracture and pore space evaluation for complex inhomegeneity carbonate reservoir

➢ Fracture effectiveness evaluation method

Log response pattern and identification chart for fracture attitude

<table>
<thead>
<tr>
<th>Chinese Name</th>
<th>Fracture Name</th>
<th>Color</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>溶蚀增强高导缝</td>
<td>Solution Enhanced Conductive Fracture</td>
<td>Red</td>
<td>ECF</td>
</tr>
<tr>
<td>连续高导缝</td>
<td>Continuous Conductive Fracture</td>
<td>DarkViolet</td>
<td>CCF</td>
</tr>
<tr>
<td>不连续高导缝</td>
<td>Discontinued Conductive Fracture</td>
<td>Cadetblue1</td>
<td>DCF</td>
</tr>
</tbody>
</table>

Basic log response pattern

- Low angle fracture
- Skew angle fracture
- High angle fracture

Solution enhanced conductive fracture (ECF)  Continuous conductive fracture (CCF)  Discontinous conductive fracture (DCF)
Key Technology 2: Effectiveness of fracture and pore space evaluation for complex inhomogeneity carbonate reservoir

➢ Fracture effectiveness evaluation method

SonicScanner-FMI joint fracture effectiveness evaluation-Fracture anisotropic property modeling

Fracture effectiveness evaluation

Effective fractures developed, test result: $1.67 \times 10^4$ m$^3$/day
Key Technology 2: Effectiveness of fracture and pore space evaluation for complex inhomegeneity carbonate reservoir

➢ Fracture effectiveness evaluation method

Fracture effectiveness evaluation with Fast-Slow flextural wave dispersion plot from SonicScanner
Key Technology 2: Effectiveness of fracture and pore space evaluation for complex inhomegeneity carbonate reservoir

- Pore and vug connectivity evaluation

Well gaoshi 102

Core 5135.70-5135.89m
Core depth+3.3m=image depth

Effective fracture and pore space identification from threshold picking calibrated by core data

Well gaoshi 102

Core 5136.25-5136.46m
Core depth+3.2m=image depth

Well Moxi 108

Core 5296.57-5296.77m
Core depth+0.8m=image depth

Bortex pore connectivity analysis

Conductivity Ratio(Formation/Matrix)

Effective fracture or pore space
**Key Technology 3: Fluid identification evaluation for vug-fracture carbonate reservoir**

- **Fluid identification method by ADT**

  - **Fluid identification chart from permittivity - porosity**

  - Low water filled porosity and permittivity, test result is gas $115.62 \times 10^4$ m$^3$/day produced.

  - High water filled porosity and permittivity, test result is water 72 m$^3$/day produced.

<table>
<thead>
<tr>
<th>Effective Porosity</th>
<th>Permittivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas</td>
<td>High</td>
</tr>
<tr>
<td>Water</td>
<td>Low</td>
</tr>
</tbody>
</table>
Key Technology 3: Fluid identification evaluation for vug-fracture carbonate reservoir

- MDT fluid identification and gas reservoir characteristics analysis

- In well Moxi 52, MDT identified successfully multiple high pressure water zones

- Saturn 3D radial probe were successfully deployed at GaoShiTie block, improved the operation efficiency of fluid analyzing in tight formation significantly
The reservoir interpretation and fluid identification coincidence rate has been improved with the application and development of key petrophysical evaluation technology in Sichuan Basin.

**Well Moxi 009-X1**
- Reservoir: 4 zones identified with 233.6 m reservoir thickness and 4.4 p.u porosity
- Test result: gas 263.47x10^4 m³/day produced

**Coincidence rate of log interpretation:**
- Reservoir: Dengying formation 94%, Longwangmiao 95-100%.
- Fluid: Dengying 97%, Longwangmiao 94-100%.
- Results: Dengying 1%, Longwang miao 90-100%.

**Bar Chart of log interpretation Coincidence rate**

- Reservoir
- Fluid
- Results
- 100% coincidence rate
● **Test Result**: 20 wells drilled in exploration stage, 19 wells completed and tested, 18 wells produced, with gas production $1466.34 \times 10^4$ m$^3$/day, 9 wells with gas production over 1 m m$^3$/day; 31 wells drilled in development stage, 30 wells completed, with gas production $4506.53 \times 10^4$ m$^3$/day, average gas production is $150.22 \times 10^4$ m$^3$/day/well, 28 wells with gas production over 1 m m$^3$/day;

● **Production result**: 11B m$^3$ gas producibility from Longwangmiao formation was completed and put into operation in Nov., 2016. 44 wells were put into operation, 42 wells are producing with production $2600 \times 10^4$ m$^3$/day, the cumulative production is about 23.3B m$^3$.

The development map of Longwangmiao gas field in Moxi Block  The production curve of longwangmiao gas field in Moxi block
A robust and comprehensive petrophysical description of lithology, porosity, pore geometry, permeability, rock types, fractures and sonic anisotropy is presented, by utilizing Schlumberger’s latest technologies on Techlog and Petrel. A new understanding of carbonate reservoir heterogeneity is established.
THANKS!