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Mesozoic and Cenozoic thermal history and source rock thermal evolution of the Baiyinchagan sag, Erlian Basin, Northern China

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A B S T R A C T

The hydrocarbon-bearing Baiyinchagan sag is located in the west of the Erlian Basin in the Inner Mongolia, Northern China. Its potential source rocks include the Lower Cretaceous Aershan, Tenggeer and Duhongmu 1 Formations. The former two formations are major source rocks. They are dominated by dark mudstone with the largest thickness of 560-600 m, and mainly distributed in the western sub-sag.

In this study, temperature data from three wells used to calculate the present-day geothermal gradient in the sag, and used 144 vitrinite reflectance measurements from 35 wells together with seven apatite fission track data from seven wells to reconstruct the Mesozoic and Cenozoic thermal history. The results show that the present-day geothermal gradient is 35.1 °C/km. In the Early Cretaceous, the geothermal gradient was 40.0–42.1 °C/km during the early deposition of the Aershan Formation (135–110 Ma), and then increased to 49.9–56.4 °C/km at the end deposition of the Saihantala Formation (100–95 Ma). The geothermal gradient decreased to a present-day value of 32.0–35.4 °C/km.

Using this model of thermal history, combined with the source rock geochemistry, the maturation histories of three source rock intervals, including the Aershan, Tenggeer and Duhongmu 1 Formations, were modeled. The modeled results suggest that source rock maturation was controlled by palaeogeothermal gradient, and that source rocks in the eastern sub-sag have not reached hydrocarbon generation threshold (0.5% Ro). In the western sub-sag, Aershan Formation source rocks reached a high maturity (1.0% < Ro < 1.3%) with greater hydrocarbon generation potential, and the Tenggeer Formation is mid-mature (0.7% < Ro < 1.0%). The Duhongmu 1 Formation possesses the least hydrocarbon generation potential (0.5% < Ro < 0.7%) at the present day.

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1. Introduction

The thermal history of a sedimentary basin controls source rock maturation evolution (Qiu et al., 2010a, b, 2012a; Sahu et al., 2013; Zuo et al., 2010, 2011, 2015) and hydrocarbon generation and expulsion history (Pang et al., 2004, 2012; Kosakowski et al., 2013; Zuo et al., 2010, 2011), and therefore petroleum resource assessment (Zuo et al., 2010). It also provides information for basin formation mechanism and tectono-thermal evolution (Rudnick et al., 1998; Hu et al., 2001; Marechal and Jaupart, 2004; Qiu et al., 2012b; Zuo et al., 2013a; Qiu et al., 2014).

China is one of the biggest petroleum consumption countries, and more than half of the crude oil (more than 14 × 108 bbl) depends on import by 2014. The production of the Chinese traditional large oilfields, including Daqing Oilfield, Shengli Oilfield, Zhongyuan Oilfield, is beginning to decrease, which seriously restricts the economic development in China. To address this issue, China has enhanced resource surveys in the Mesozoic rift basins on land, such as the Erlian Basin (about 10.0 × 104 km²), Yinggeng-Ejinqui Basin (about 10.4 × 104 km²), Hailaer Basin (about 7.1 × 104 km²) in the Inner Mongolia (Fig. 1a), which show a great promise for petroleum resources. Exploration has validated certain petroleum resources in these Mesozoic rift basins. The petroleum reserves are proved to exceed 70 × 108 bbl in the Hailaer Basin so far, and the Erlian and Hailaer Basins have reached millions of tons of annual production.

The Baiyinchagan sag, located in the western margin of the Chuanjing depression, has one of the greatest oil and gas exploration potential in the Erlian Basin. Moreover, the oil and gas has been found only in the Baiyinchagan sag for the Chuanjing depression (Chen et al., 2014). Oil and gas shows were discovered in the Baiyinchagan sag in the early 1980s; commercial oil and gas flow was found in 1994. More than 150 wells have so far been
drilled. Oil and gas shows and commercial discoveries have been made in the West Daerqi, Daireqi, Sanghe, Wengte, Xilinhaolai and Guer areas, and the Daerqi, Sanghe and Xilinhaolai oilfields with reserves of more than $35 \times 10^6$ bbl. More than $560 \times 10^6$ bbl of oil reserves has so far been found in the Baiyinchagan sag and exploration is continuing.

However, there are still some problems restricting oil and gas exploration in the Baiyinchagan sag. Petroleum resources appear to be clustered in the Sanghe and Aolun in the western sub-sag. While there have been no commercial oil and gas discoveries in the eastern and Zhamu sub-sags whose exploration potential is uncertain. The thermal history of the Baiyinchagan sag has been little documented which restricts understanding of the source rock maturation history and oil and gas distribution were discussed.

In this paper, the Mesozoic and Cenozoic thermal history of the Baiyinchagan sag was modeled based on the vitrinite reflectance ($R_v$) and apatite fission track (AFT) data. Based on the thermal history, the source rock maturation history was then modeled, and the relationship between source rock maturation history and oil and gas distribution were discussed.

2. Geological setting

The Baiyinchagan sag (longitude 107°30’ to 109°10’; latitude 41°50’ to 42°30’) is a second-order structural unit in the Chuanjing depression, Erlian Basin (Fig. 1a). The Erlian Basin is a Mesozoic rift basin, developing on the Inner Mongolia-Daxinganling Hercynian fold basement (Yu, 1990; Ren et al., 2000; Cui et al., 2011; Li et al., 2012). It located in central-northern Inner Mongolia, China. It is surrounded by the Daxinganling to the east, the Wulatehouqi to the west, the Yin Mountains to the south, the China-Mongolian border to the north. The Erlian Basin, consisting of 1000 km (east to west), 20–220 km (south to north), an area of $10 \times 10^4$ km$^2$, is one of the largest onshore sedimentary basins in China. The Erlian Basin consists of five depressions and an uplift, and forty-five sags and twenty-one uplifts.

The Erlian Basin has experienced five phase of tectonism since the Mesozoic (Yu, 1990; Cui et al., 2011; Li et al., 2012). These phases are (1) a crustal uplift stage during the Triassic, including regional crustal uplift, missing the Triassic sedimentary, and strong volcanic activity accompanied by acidic magma intrusion; (2) an initial rifting stage during the Jurassic, with a lot of heat dissipation within the crust, mantle uplift shrinkage and tensile rupture gradually expanded in the Early-middle Jurassic, forming NNE-NE trending tensional rifts with deposition of 300–1000 m mudstone, sandstone, conglomerate and coal; Late Jurassic, the Erlian Basin N–W trending extensional strengthened in respond to the Pacific plate subduction to the Asian continent, volcanism frequently along the NE-NNE trending faults, and developing a set of volcanic and volaniclastic rocks; (3) an intense rifting phase...
during the early-middle period of the Early Cretaceous, NW-SE trending tensional effect rapidly increasing, developing larger NNE-NE trending rifts than ones in the Jurassic, depositing 300–500 m sandstone, gravel-like sandstone and mudstone during the early period of the Early Cretaceous, and 500–3000 m mudstone in lacustrine environments during the middle period of the Early Cretaceous.

**Fig. 2.** Stratigraphic column map [modified from Wang (2006), Guo et al. (2012), Deng (2013)]. Φ—porosity, %; K—permeability, md; TOC—total organic carbon, %; S1+S2—Potential of generating hydrocarbon, mg/g; "A"HCl-Chloroform bitumen "A", %; HI—Hydrogen index, mg/g; n—Number of samples.
Cretaceous; (4) a transition stage from synrift to postrift during the late period of the Early Cretaceous, the basin beginning to thermal subsidence, lake shrinking, and depositing 200–700 m typical molasses in fluvial and swamp environments; (5) an ex- trusion and uplift stage from the Late Cretaceous to the present day, depositing in the fluvial environments, with relatively thin sediments.

Potential source rocks of the Erlian Basin include the Lower-middle Jurassic, Lower Cretaceous Aershan, Tenggeer and Du- hongmu Formations. The Lower-middle Jurassic source rocks de- velop the local area with high maturity, generally more than 2.0%. The Duhongmu Formation source rocks are good quality, but with low maturity, generally less than 0.7%. By contrast, the Aershan 2 and Tenggeer Formations are main source rocks in the Erlian Basin. Their total organic content (TOC) ranges from 1.36% to 2.77%; the chloroform bitumen “A” [the whole-rock samples were powdered to 100 mesh after surface cleaning, and subsequently extracted with chloroform. This extract is referred to as chloroform bitumen “A” (Li et al. 2000)] ranges from 0.073% to 1.900%; the S1+S2 values range from 2.06 mg/g to 11.72 mg/g; and the organic matter is mainly type II kerogen (Yu, 1990; Hao and Lin, 2006).

The Baiyinchagan sag trends NEE and is 150 km (east to west) and 15–28 km (south to north), with an area of 3200 km². The sag is a Mesozoic rift developed on Hercynian folded basement and can be divided into nine structural units based on basement relief, interpreted fault systems and tectonic evolution (Zhang et al., 2003; Li et al., 2007): the Tala fault belt, western sub-sag, Baiyinwengte uplift, southern slope, northern slope, Maohu low uplift, Gashun slope, eastern sub-sag and eastern uplift (Fig. 1a). The sedimentary fill consists of the Early Cretaceous Aershan, Tenggeer, Duhongmu, Saihantala Formations, the Late Cretaceous Erliandabusu Formation and the overlying Cenozoic succession (Figs. 1b, and Fig. 2). The Aershan Formation, 253–1219 m, com- prises coarse clastic strata and sandy conglomerates deposited in the alluvial fan and shallow lacustrine environments, overlain by lacustrine mudstones and interbedded sandstones which serve as main source rocks (Wang, 2006; Dang, 2013). The Tenggeer Forma- tion, 91–828 m, consists of mudstones, dolomitic mudstone, interbedded sandstone and conglomerate deposited in the braided delta and shallow lacustrine, including both source and reservoir rocks (Wang, 2006; Dang, 2013). The Duhongmu 1 Formation, 120–833 m, consists of siltstone, dark mudstone and shale de- posited in the lacustrine environments, and comprises a third set of the source rocks (Wang, 2006; Dang, 2013). The Duhongmu 2 and 3 Formations, 103–716 m, is dominated by the dark thick mudstone and shale deposited in the lacustrine, acting as good regional cap rocks (Guo et al., 2012). The Saihantala Formation, 0–300 m, consists of mudstone, sandstone and conglomerate de- posited in the fluvial environments (Guo et al., 2012).

The Baiyinchagan sag has experienced three phases of tecton- ism since the Early Cretaceous in response to the Yanshan and Himalayan movements (Zhang et al., 2003; Wang, 2006; Li et al., 2007; Guo et al., 2012; Dang, 2013). These phases are (1) a rift stage from 135 Ma to 103 Ma (deposition of the Aershan Formation to the Duhongmu 1 Formation), characterized by intense faulting. (2) A transition stage from synrift to postrift occurred from 103 Ma to 95 Ma (deposition of the Duhongmu 2 Formation to the Saihantala Formation), characterized by weak faulting and wide lake basin; and (3) postrift and uplifting stages from 95 Ma to the present day (from the Late Cretaceous to the present day). The strata were relatively thin deposited in the fluvial environment (Wang, 2006).

The Aershan 2 and Tenggeer Formations include major source rock intervals (Wang, 2006; Dang, 2013). The TOC of the Tenggeer Formation ranges from 0.42% to 5.50% (average: 1.77%); the chloroform bitumen “A” ranges from 0.0017% to 5.0673% (average: 0.2257%); the Rock-Eval S1+S2 values range from 0.04 mg/g to 13.27 mg/g (average: 3.40 mg/g); the hydrogen index (HI) values range from 27.6 mg/g to 534.1 mg/g (average: 260.3 mg/g); and the organic matter is also mainly type II kerogen (Fig. 3). These values suggest that the Tenggeer Formation is a good source rock (Table 1). Its burial depth is 1500–3500 m in the western sub-sag, 2500 m in the central of the Sanghe and Aolun sub-sags, and reaches a maximum of 3500 m in the Zhamu sub-sag. In the eastern sub-sag, its maximum burial depth is less than 1500 m (Fig. 4a). The Aershan 2 Formation source rocks are dominated by dark mudstone with the largest thickness of 560 m. Its TOC ranges from 0.45% to 1.62% (average: 1.13%); the chloroform bitumen “A” ranges from 0.0014% to 0.1389% (average: 0.0409%); the Rock-Eval S1+S2 values range from 0.13 to 4.69 mg/g (average: 2.55 mg/g) (Wang, 2006; Dang, 2013); the HI values range from 22.1 mg/g to 836.6 mg/g (average: 138.7 mg/g); and the organic matter is mainly type II kerogen (Fig. 3). It burial depth is 2000–4500 m in the western sub-sag and reaches 3500–4500 m in the Sanghe, Aolun and Zhamu sub-sags, while in the eastern sub-sag, its maximum burial depth is less than 1500 m (Fig. 4b). The above values suggest that the Aershan 2 Formation is a medium source

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Evaluation criteria of the Chinese continental basins (Huang, 1984).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source rock level</td>
<td>Good source rock</td>
</tr>
<tr>
<td>Sedimentary facies</td>
<td>Semi-deep lacustrine</td>
</tr>
<tr>
<td>Lithology</td>
<td>Grey black mudstone</td>
</tr>
<tr>
<td>TOC(%)</td>
<td>&gt; 1.0</td>
</tr>
<tr>
<td>“A”(mg/g)</td>
<td>&gt; 0.1</td>
</tr>
<tr>
<td>S1+S2(mg/g)</td>
<td>&gt; 0.5</td>
</tr>
<tr>
<td>H(C10%H)</td>
<td>&gt; 500</td>
</tr>
</tbody>
</table>

Fig. 3. The types of organic matter for the Tenggeer and Aershan 2 Formations source rocks. Espitalie diagram; Tmax−Peak temperature of pyrolysis; HI−Hydrogen index.
rock (Table 1). In all, these values suggest that the Aershan and Tengger Formations in the western sub-sag have major hydrocarbon generation potential.

3. Methods and general parameters

3.1. Methods of thermal history reconstruction

$R_o$ and AFT are two commonly used indicators in the thermal history reconstruction of sedimentary basins. AFT data were measured in the College of Earth Sciences, Jilin University. The apatite grain is prepared into epoxy section with polishing treatment after being selected from the sandstone samples. The grain is etched in 6.6% HNO$_3$ solution for 30 s at 25°C. Then the section covered by low-Uranium muscovite and the standard Uranium glass is irradiated in the reactor to show the parameters. $R_o$ data were measured from the dark mudstone samples by the Zhongyuan Oilfield, China Petroleum & Chemical Corp. (SINOPEC).

Apatite fission-track analysis is useful in understanding the geothermal history of host rocks because apatite fission-track age (AFTA) is a reflection of the time over which tracks have been retained in the apatite and the amount of annealing (length reduction) that has occurred (Green et al., 1989). The AFTA is mainly a function of track annealing in response to increasing temperatures between approximately 65 and 120 °C (Green et al., 1986; Ghorl et al., 2005; Menzies et al., 2007; Mora et al., 2010). The distribution of conserved track lengths showed a progressive broadening as the degree of annealing increases, and track lengths reflect the style of cooling (Green et al., 1986). When combined with vitrinite reflectance data, AFTA data constrain palaeo temperatures and identify periods of cooling from peak temperature. Vitrinite reflectance data provide control over a wider palaeo temperature range, especially when the AFTs are totally annealed (Ghorl et al. 2005). In such a situation, AFTA data constrain minimum palaeo temperature estimates (Green et al., 1989).

3.2. General parameters

3.2.1. Thermal indicators

144 vitrinite reflectance data from 35 wells (Fig. 5) and 7 apatite fission track data from 7 wells (Table 2, Fig. 6) were measured in the Baiyinchagan sag, and 5 typical wells were chosen to reconstruct thermal history.

3.2.2. Basic geological parameters

Geological parameters include lithological data, the present-day and palaeo surface temperatures, the thermal gradient and heat flow, and stratigraphic data. Lithological data include the...
thermal conductivity, heat production rate, rock density, initial porosity, and compaction factor. The thermal physical parameters adopt results of the adjacent Chagan sag (Zuo et al., 2015) due to the lack of these data in this area. The other lithological data were obtained from the Zhongyuan Oilfield, China Petroleum & Chemical Corp. (SINOPEC). The burial histories of the study wells were reconstructed using the Sclater, Chrisie (1980) compaction model. The present-day and palaeo surface temperatures in the field, China Petroleum & Chemical Corp. (SINOPEC). The burial histories of the study wells were reconstructed using the Sclater, Chrisie (1980) compaction model. The present-day and palaeo surface temperatures in the model were set to 9 °C over geologic time.

3.3. Constraints

3.3.1. Present-day geothermal gradient and terrestrial heat flow

Logging temperature from wells BC1, D1, D2, D4, B6, B7, W1 (Fig. 7, well positions are shown in the Fig. 1a) and formation-testing temperature data from wells X3, X2, X3 (Table 3, well position shown in the Fig. 1a) were collected. The geothermal gradient values range from 14.9 to 30.5 °C/km, with an average value of 22.9 °C/km, by the fitting method based on the logging temperature data, which is significantly smaller than other sags of the Erlian Basin and adjacent basins. The average thermal gradient in the Erlian Basin is 35.0 °C/km (Ren, 1998); in the Chagan sag of the Yingen-ejinaqi Basin, the average is 33.6 °C/km (Zuo et al., 2013b); and in the Hailaer Basin, 30.0 °C/km (Cui et al., 2007).

The geothermal gradient values do not reflect the present-day geothermal field in the Baiyinchagan sag. This is because the logging temperature in general measures the borehole temperature just after drilling, when formation temperatures can be influenced by frictional heat generated during drilling and by heat exchanged with the drilling mud. Hence there can be differences between the measured temperature and the actual formation temperature. However, the formation-testing temperature is obtained by measuring the oil reservoir temperature after well completion and shut-in for several days, or after long-term shut-in. Long-term shut-in allows temperature equilibrium between fluids in the well and the formation.

The geothermal gradient in the Baiyinchagan sag was calculated from formation-testing temperatures at wells X3, X2 and X35 and values range from 34.7 to 35.7 °C/km, with an average value of 35.1 °C/km. The average heat flow in the Baiyinchagan sag was calculated to be 75.5 mW/m² (Table 3).

3.3.2. Erosion events, unconformities and erosion amount of the main geological periods

In the Early Cretaceous, there were two significant regional unconformities (between the Duohongmu 1 Formation and Duohongmu 2 Formation, and between the Sanhaitala Formation and Erlandabusu Formation) in the Baiyinchagan sag due to the 3rd episode of the Yanshan movement (135–95 Ma). The unconformity between the Duohongmu 1 Formation and Duohongmu 2 Formation is an apparent angular unconformity, but the unconformity between the Sanhaitala Formation and Erlandabusu Formation is a disconformity accompanied by intense erosion.

Table 2

Apatite fission track measurements from the samples of the Baiyinchagan sag.

<table>
<thead>
<tr>
<th>Well No.</th>
<th>Depth (m)</th>
<th>Stratigraphy</th>
<th>n</th>
<th>p&lt;sub&gt;f&lt;/sub&gt; (10&lt;sup&gt;5&lt;/sup&gt;/cm²) (N&lt;sub&gt;f&lt;/sub&gt;)</th>
<th>p&lt;sub&gt;r&lt;/sub&gt; (10&lt;sup&gt;5&lt;/sup&gt;/cm²) (N&lt;sub&gt;r&lt;/sub&gt;)</th>
<th>p&lt;sub&gt;a&lt;/sub&gt; (10&lt;sup&gt;7&lt;/sup&gt;/cm²) (N&lt;sub&gt;a&lt;/sub&gt;)</th>
<th>P (χ²) (%)</th>
<th>Age (Ma) (± 1σ)</th>
<th>L (μm ± 1σ) (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D3</td>
<td>0</td>
<td>K,bs</td>
<td>20</td>
<td>13.803</td>
<td>33.064</td>
<td>14.547</td>
<td>0.01</td>
<td>99.1</td>
<td>10.1 ± 3.1</td>
</tr>
<tr>
<td>X2</td>
<td>2259.0</td>
<td>K,ba</td>
<td>564</td>
<td>7.475</td>
<td>36.065</td>
<td>14.664</td>
<td>0.00</td>
<td>93.1</td>
<td>8.0 ± 2.2</td>
</tr>
<tr>
<td>D1</td>
<td>1011.0</td>
<td>K,pt</td>
<td>564</td>
<td>6.097</td>
<td>15.591</td>
<td>14.781</td>
<td>0.13</td>
<td>101.5</td>
<td>8.3 ± 2.1</td>
</tr>
<tr>
<td>W2</td>
<td>1305.0</td>
<td>K,pt</td>
<td>289</td>
<td>9.822</td>
<td>38.546</td>
<td>14.898</td>
<td>0.00</td>
<td>123.2</td>
<td>9.7 ± 2.1</td>
</tr>
<tr>
<td>C2</td>
<td>9811.2</td>
<td>K,ba</td>
<td>1148</td>
<td>7.475</td>
<td>36.065</td>
<td>14.664</td>
<td>0.00</td>
<td>93.1</td>
<td>8.0 ± 2.2</td>
</tr>
<tr>
<td>C3</td>
<td>1124.0</td>
<td>K,pt</td>
<td>289</td>
<td>6.097</td>
<td>15.591</td>
<td>14.781</td>
<td>0.13</td>
<td>101.5</td>
<td>8.3 ± 2.1</td>
</tr>
</tbody>
</table>

<sup>i</sup>p<sub>f</sub>=spontaneous track density; p<sub>r</sub>=fossil track density; p<sub>a</sub>=induced track density; n=number of grains. All track densities are 10<sup>5</sup>/cm², N<sub>f</sub>=number of spontaneous and induced tracks, respectively. N<sub>a</sub>=number of fossil tracks. Number of tracks counted or measured is shown in parentheses of length. L=mean track length; N=number of counted or measured tracks. Uncertainties are quoted at σ. Ages calculated using a z of 3221 ± 16 for dosemeter glass CNS for apatite. The λ<sub>s</sub> is 1.5×10<sup>−10</sup>/yr and γ=0.5 in this measurement. P (χ²)=chi-square probability, which is a measure of probability that individual grains counted in a sample are from a single population. Ages were determined using average age when values of P (χ²)<5%, which are generally taken to indicate that multiple age populations are present. However, ages were determined using assembled age with the values of P (χ²)>5%. Mean track lengths are corrected for length bias (Laslett et al., 1992).

The magnitude and amount of erosion in the Baiyinchagan sag must be reconstructed in order to study burial history, thermal history and source rock maturation. Palaeo thermal indicators such as \( R_o \) and mudstone acoustic travel times are commonly used for this purpose. Maximum palaeo temperatures can be inferred from \( R_o \) measurements (Hu et al., 1999). \( R_o \) data suggest that the sag underwent maximum palaeo temperatures during deposition of the Saihantala Formation (100–95 Ma). Thus, it is appropriate to use the thermal indicators to reconstruct the erosion amount at the end deposition of the Saihantala Formation (100–95 Ma).

There is a significant difference between mudstone acoustic travel time of the Duhongmu 1 and 2 Formation (Fig. 8), indicating differential compaction for the two units and uplift between the two formations. Therefore, mudstone acoustic travel time can be used to reconstruct the erosion amount between the Duhongmu 1 and 2 Formations. The results show that the sag underwent large-scale erosion at the end deposition of the Duhongmu 1 Formation and the Saihantala Formation; erosion magnitudes were 800–1410 m and 760–1110 m, respectively (Table 4).

### 3.4. Results of thermal history

#### 3.4.1. Analytical results of thermal indicator

All the \( R_o \) data were distributed in the Early Cretaceous. The \( R_o \)-depth relation indicated a low to over maturation level of source rock (Fig. 5), and \( R_o \) data have a strong linear relationship with depth, indicating that source rock thermal evolution was controlled as \( R_o \) and mudstone acoustic travel times are commonly used for this purpose. Maximum palaeo temperatures can be inferred from \( R_o \) measurements (Hu et al., 1999). \( R_o \) data suggest that the sag underwent maximum palaeo temperatures during deposition of the Saihantala Formation (100–95 Ma). Thus, it is appropriate to use the thermal indicators to reconstruct the erosion amount at the end deposition of the Saihantala Formation (100–95 Ma).

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### Table 3

Geothermal gradient and terrestrial heat flow of the Baiyinchagan sag.

<table>
<thead>
<tr>
<th>Well</th>
<th>Depth (m)</th>
<th>Temperature (°C)</th>
<th>Thermal Gradient (°C/km)</th>
<th>Average thermal gradient (°C/km)</th>
<th>Thermal conductivity (W/m K)</th>
<th>Heat flow (mW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X32</td>
<td>2130.00</td>
<td>81.37</td>
<td>34.3</td>
<td>35.0</td>
<td>2.15</td>
<td>75.3</td>
</tr>
<tr>
<td></td>
<td>1930.00</td>
<td>76.22</td>
<td>35.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1730.00</td>
<td>69.45</td>
<td>35.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1530.00</td>
<td>62.28</td>
<td>35.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X35</td>
<td>1809.00</td>
<td>73.00</td>
<td>35.8</td>
<td>35.7</td>
<td></td>
<td>76.8</td>
</tr>
<tr>
<td></td>
<td>1833.00</td>
<td>73.60</td>
<td>35.6</td>
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<td></td>
</tr>
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<td>X31</td>
<td>2002.30</td>
<td>77.75</td>
<td>34.7</td>
<td>34.7</td>
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<td>79.13</td>
<td>34.8</td>
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by the same geothermal field. The surface $R_o$ datum greater than 0.3% (Fig. 5) suggests that thermal evolution of the source rocks in this area was controlled by the palaeo geothermal fields.

AFTAs of wells D3, X2, D1 and C9 with the stratigraphic thermal information are less than their stratigraphic ages, and can be used to construct the thermal history of the sag. The apatite fission track ages from the other 3 wells with the provenance information are greater than their stratigraphic ages, and were not used to construct the thermal history of the sag (Table 2). Track lengths for all the seven wells range from 7.7 ± 2.4 μm to 10.1 ± 3.1 μm, and are less than the original fission track length of 16.3 μm. This indicates that the strata have undergone significant annealing, and the track lengths exhibit a bi- or multi-peak distribution (Fig. 6). These observations indicate that the Baiyinchagan sag has undergone more than one phase of large-scale uplift and erosion in the Cretaceous.

### 3.4.2. Results of thermal history

The burial, thermal and hydrocarbon generation histories for five wells are modeled using the kinetic model of Sweeney and Burnham (1990) and BasinMod software provided by Platte River Associates Inc. Fig. 9 gives the burial and thermal histories of well BC1. The modeled results show the Baiyinchagan sag experienced...
4. Tectonic subsidence analysis

Tectonic subsidence history can offer some information on the geodynamic evolution of the basin. Steckler and Watts (1980) and Van Hinte (1978) have previously described the technique of subsidence analysis. The tectonic subsidence in the Baiyinchagan sag was reconstructed in our study using the Falvey and Middleton (1981) model and the Sclater and Chrisie (1980) compaction model. Considering wells C9 and D49 were not drilled the Aershan Formation, and in order to unify the starting time, tectonic subsidence of all the wells was reconstructed from the deposition of the Tengger Formation to the present day.

The tectonic subsidence of the Baiyinchagan sag in the Cretaceous was characterized by an initial synrift subsidence followed by a subsequent long-term thermal subsidence (Fig. 10). The synrift stage included the 1st rapid rifting subsidence (R1) during 110 to approximately 107 Ma, the 1st eroded section on the regional unconformity at the top of the Duhongmu 1 Formation (E1) during 107 to approximately 100 Ma, the 2nd rapid rifting subsidence (R2) during 100 Ma to approximately 97 Ma and the 2nd eroded section the regional unconformity at the top of the Saihantala Formation (E2) during 97 to approximately 95 Ma. The rifting ceased in the Baiyinchagan sag and the sag began its postrift thermal subsidence and weak tectonic uplift stage (T1) during 95Ma to the present day (Fig. 10).

Tectonic subsidence history for different wells is consistent with the general trend, but the tectonic subsidence amount varies greatly. The tectonic subsidence amount of the well C9, located in the northern edge of the Sanghe sub-sag, is the smallest among the wells, and is only 526 m at the present day. For the well D49 which is located in the center of the Aolun sub-sag, it has the greatest tectonic subsidence amount among the wells, reaching up to 1400 m at the present day (Fig. 10).

The different tectonic subsidence resulted in different thermal and source rock maturation histories in different structural zones of the sag.

5. Source rock maturation

The maturation histories of source rocks are basis for hydrocarbon kitchen evolution and hydrocarbon accumulation (Zuo et al., 2011). The maturation histories of the typical wells, pseudo-wells and source rock horizons were modeled using the BasinMod 1D and Basinview softwares provided by Platte River Associates Inc. The isopach maps for each stratum and stratigraphic data were obtained from the Zhongyuan Oilfield, China Petroleum & Chemical Corp. (SINOPEC). The maturities at the base of the source rock interval at four geologic stages [the end deposition of the Duhongmu 1 Formation (103 Ma), of the Duhongmu 3 Formation (100 Ma), of the Saihantala Formation (95 Ma), and present day (0 Ma)] were calculated. Here, due to the type II kerogen was mainly developed in this sag, the value of Ro used to indicate the maturation of source rocks and the stage of maturation history was classified as follows:

1. Immature: \( R_o < 0.5\% \)
2. Early mature: \( 0.5\% < R_o < 0.7\% \)
3. Middle mature: \( 0.7\% < R_o < 1.0\% \)
4. Late mature: \( 1.0\% < R_o < 1.3\% \)
5. Main gas stage: \( 1.3\% < R_o < 2.0\% \)
6. Dry-gas stage: \( R_o > 2.0\% \)
5.1. Maturation histories of the typical wells and pseudo-wells

5.1.1. The western sub-sag

As there are no wells in the central part of the Sanghe and Zhamu sub-sags, pseudo-wells were built using seismic data to model the maturation evolution in these areas. The modeled results show that source rock maturation in the Sanghe, Aolun and Zhamu sub-sags reached maximum values at the end deposition of the Saihantala Formation, and Aershan Formation source rocks in the three sub-sags reached an over mature stage (R_o > 1.3%) (Fig. 12). However, there are differences in the maturation evolutions of the Tenggeer and Duhongmu 1 Formations among the Sanghe, Aolun and Zhamu sub-sags. In the Sanghe sub-sag, the Tenggeer Formation source rocks entered the hydrocarbon generation peak during deposition of the Saihantala Formation (1.0% < R_o < 1.3%), and the low part of the Tenggeer Formation reached over mature stage (R_o > 1.3%) at the end deposition of the Saihantala Formation; the Duhongmu 1 Formation source rocks entered the hydrocarbon generation threshold during deposition of the Saihantala Formation (0.5% R_o), and most of the source rocks reached over mid-mature stage (0.7% < R_o < 1.0%) at the end deposition of the Saihantala Formation (Fig. 12a). In the Aolun sub-sag, the maturation evolution of the Tenggeer Formation was the same as the source rocks in the Sanghe sub-sag. However, the maturation evolution degree of the Duhongmu 1 Formation in the area was higher than that in the Sanghe sub-sag, and reaching mid-high mature stage (0.7% < R_o < 1.3%) (Fig. 12b). In the Zhamu sub-sag, the maturation evolution degree of the most of the Tenggeer Formation source rocks reached high-over mature stage (1.0% < R_o < 2.0%), and the top of the source rock only reached middle mature stage (0.7% < R_o < 1.0%). The maturation evolution degree of the Duhongmu 1 Formation reached low-middle mature stage (0.5% < R_o < 1.0%) (Fig. 12c). As seen from the above, the Tenggeer and Aershan Formations have reached a mid-over mature stage (0.7% < R_o < 2.0%) at the present day, and most of the source rocks have experienced hydrocarbon generation peak, so the Tenggeer and Aershan Formations have a great hydrocarbon generation potential. However, most of the Duhongmu 1 Formation source rocks only have reached a low-middle mature stage (0.5% < R_o < 1.0%) with a minor hydrocarbon generation potential.

5.1.2. The eastern sub-sag

Considering no wells in the eastern sub-sag, pseudo-well was utilized to carry out simulation. The modeled result shows that all the three sets of source rocks have not reached hydrocarbon generation threshold (0.5% R_o) at the present day (Fig. 12d), indicating no prospecting potential in this area.

5.2. Maturation evolution of the main source rock horizons

Here, the maturation evolution of the Tenggeer and Aershan Formations source rocks were chosen to model in the western sub-sag, for the formations have a great hydrocarbon generation potential based on the above study results.

5.2.1. Maturation history of the Tenggeer Formation

The maturation modeling shows that the top of the Tenggeer Formation didn’t reached hydrocarbon generation threshold (0.5% R_o) at the end deposition of the Duhongmu 1 Formation. The source rock reached hydrocarbon generation threshold (0.5% R_o) in the central of the Zhamu and Aolun sub-sags at the end deposition of the Duhongmu 3 Formation. During the late of deposition of the Saihantala Formation, maturation increased rapidly and most of the source rocks reached high mature stage (1.0% < R_o < 1.3%) in the western sub-sag, and the central of the three sub-sags reached over mature stage (R_o > 1.3%). From the Late Cretaceous to the present day, the maturation didn’t increase in the area (Fig. 13).

5.2.2. Maturation history of the Aershan Formation

The maturation modeling shows that the top of the Aershan Formation entered hydrocarbon generation threshold (0.5% R_o) and that the source rocks reached middle mature stage (0.7% < R_o < 1.0%) in the central of the Zhamu sub-sag at the end deposition of the Duhongmu 1 Formation. During deposition of the Duhongmu 3 Formation, the maturation increasing in the Zhamu and Aolun sub-sags was greater than that in the Sanghe sub-sag, and most of the source rocks in the Zhamu and Aolun sub-sags reached middle mature stage (0.7% < R_o < 1.0%). Moreover, the source rocks in the central of the Zhamu sub-sag reached high mature stage (1.0% < R_o < 1.3%). During the late of deposition of the Saihantala Formation, maturation increased rapidly and most of the source rocks reached high mature stage (1.0% < R_o < 1.3%) in the western sub-sag zone, moreover, the source...
rocks reached over mature stage ($R_o > 1.3\%$) in the Sanghe, Aolun and Zhamu sub-sags. From the Late Cretaceous to the present day, the maturation didn’t increase in the area (Fig. 14).

6. Discussions

6.1. Coupling relationship of basin thermal history with tectonic evolution

High thermal state in the Cretaceous for the Baiyinchagan sag is consistent with the Mesozoic rift basin of northern China. The geothermal gradient in the Cretaceous for the Erlian Basin is 50–60 °C/km (Zhao et al., 1998); the Hailaer Basin, 35–58 °C/km (Liu, 1992; Chen et al., 2004; Cui et al., 2007); the Chagan sag of the Yingen-ejinaqi Basin, 50.0–58.0 °C/km (Zuo et al., 2013b); the Jiuxi and Huahai Basins, 38–42 °C/km (Ren et al., 2000); the Jiudong Basin, 35–42 °C/km (Ren, 1998). So what causes the high thermal state in the Early Cretaceous of the Baiyinchagan sag?

Regionally, the thermal state in the Baiyinchagan sag is closely related to subduction of Kula-Pacific plate under the Eurasia plate. From 130 Ma to 100 Ma before the present day (the Early Cretaceous), the Kula-Pacific plate at about 30° angle dived and inserted into mantle of the Eurasia plate at depth of 400–600 km (Maruyama, 1994; Xiao et al., 2001), and corresponding giant seismic anomaly belts were discovered below the south mountain of the Siberian Platform at depth of 300–400 km and 700 km. When the Pacific plate inserted into the mantle of the Eurasia plate, viscosity of the mantle was decreased and activity of the mantle was enhanced. Meanwhile, the new generating sinistral strike-slip faults in the eastern edge of the Kula-Pacific plate and the Eurasia plate provided a channel for upwelling of the low viscosity mantle. A large amount of mantle heat pumped into the shallow lithosphere and formed high geothermal state in the Early Cretaceous. From the Late Cretaceous, the Erlian Basin began its thermal subsidence stage, and its geothermal gradient decreased gradually.

During the Early Cretaceous, the Baiyinchagan sag experienced the 1st rapid rifting subsidence (R1) during 110 to approximately 107 Ma in respond to the 3rd episode of the Yanshan movement, and the rifting was enhanced and the crust began to be thinned.

Fig. 13. Maturation level of the top of the Tenggeer Formation. The contour interval is 0.1%. The modeled area is shown in Fig. 1a.
during this period, while thermal energy in the deep earth was easily released to the shallow layer, resulting in geothermal gradient increasing rapidly. At the end of the deposition of the Duhongmu 1 Formation (approximately 107 Ma), the geothermal gradient reached to the 1st peak in this sag, with the maximum value of 44°C/km (Fig. 11), corresponding to the heat flow was 95 mW/m² [the rock thermal conductivity adopt 2.15 W/m K on basis of the adjacent Chagan sag (Zuo et al., 2015) due to the lack of these data in this area]. During the late period of the Early Cretaceous, the Baiyinchagan sag experienced the 2nd rapid rifting subsidence (R2), while the crustal vertical movement caused the Saihantala Formation to be denudated 760–1110 m, when lithosphere was thinned again, and the geothermal gradient began to increase rapidly again. At the end of the deposition of the Saihantala Formation (approximately 95 Ma), the geothermal gradient reached to the 2nd peak in this sag, with the maximum value of 52°C/km (Fig. 11), corresponding to the heat flow was 112 mW/m² (the rock thermal conductivity adopt the above value). The twice heat flow peak values were similar to the ones of the modern continental rift, such as the Begall rift with a heat flow value of 99 mW/m² (Morgan, 1982). Therefore, the Baiyinchagan sag experienced strong rifting in the Early Cretaceous.

From the Late Cretaceous to the present, the Baiyinchagan sag began its thermal subsidence stage in respond to the 4th episode of the Yanshan movement and Himalayan movement (Zhang et al., 2003), and geothermal gradient decreased gradually (Fig. 11). Therefore, the thermal history results are consistent with the tectonic evolution in the Baiyinchagan sag.

6.2. Relationship between thermal history and maturation evolution of source rocks

Maturation evolution reveals that source rocks reached their maximum values at the end deposition of the Saihantala Formation. It is thus indicated that maturation evolution in the Baiyinchagan sag shows a significant control by the high thermal state in the Early Cretaceous, which is conducive to hydrocarbon generation. The palaeo hydrocarbon generation threshold in the Baiyinchagan sag is 1915 m, and the hydrocarbon generation peak corresponds to 3355 m. This is shallower than the area with a low
6.3. Petroleum exploration prospects in the Baiyinchagan sag

The Baiyinchagan sag is a small continental rift basin, with a limited hydrocarbon generation capacity and undergone strong rifting movement in the Early Cretaceous followed by a subsequent long-term uplift and erosion from the Late Cretaceous to the present day. Therefore, oil and gas which was generated during the deposition of the Saihantala Formation (main hydrocarbon generation) suffered a certain amount of damage from the Late Cretaceous to the present day.

But the lithologic and structural traps of the Aershan 2 and Tenggeer Formations had formed before the period of main hydrocarbon generation, and mudstone of the Duohongmu 1 and 2 Formations acted as regional cap rocks, as well as the reverse faults were developed in the western sub-sag. Their factors control the oil and gas secondary migration and spatial distribution. Therefore, although some reservoirs suffered a certain amount of damage later period, lithologic, structural residual and composite reservoirs still could be found in the deep strata, mainly including Aershan 2 and Tenggeer Formations, such as the sandstone reservoirs in the Aershan 2 Formation of the wells D49, D56 in the Daerqi area and wells X41, X46 in the Xilinhaolai area. The heavy oil reservoirs formed in the shallow Duhongmu 1 Formation by adjusting deep reservoirs, such as wells BD1 and X24.

Anyhow, the Baiyinchagan sag still has certain oil and gas exploration prospect, and lithologic reservoirs around the Sanghe and Aolun subsags in the deep strata, as well as composite structural and lithologic reservoirs in the slope belt of the Sanghe and Aolun subsags in the shallow strata will be favorable areas for further exploration.

7. Conclusions

(1) The geothermal gradient gradually increased from 40.0–42.1 °C/km in the early deposition of the Aershan Formation to 49.9–56.4 °C/km during deposition of the Saihantala Formation in the Early Cretaceous. From the Late Cretaceous to the present day, the geothermal gradient decreased to 32.0–35.4 °C/km at the present day.

(2) Maturation evolution of the source rocks in the Baiyinchagan sag shows a critical control by palaeo geothermal gradient. All the three sets of source rocks reached their maximum values at the end deposition of the Saihantala Formation. The maturation evolution in the western and eastern sub-sags exhibits great differences. The three sets of source rocks in the eastern sub-sag have not reached hydrocarbon generation threshold (0.5% Ro). However, in the western sub-sag, the Aershan Formation exhibits the greatest hydrocarbon generation potential, reaching a high mature stage (1.0% < Ro < 1.3%); the Tenggeer Formation follows, reaching a middle mature stage (0.7% < Ro < 1.0%); and the Duohongmu 1 Formation possesses the least hydrocarbon generation potential, only in a low mature stage (0.5% < Ro < 0.7%).

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References


Uncited references

(Ketcham et al., 2007)
Cordillera of Colombia interpreted from fission-track results and structural relationships: implications for petroleum systems. AAPG Bull. 94, 1543–1580.