Lithofacies palaeogeography as a guide to petroleum exploration

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Abstract Lithofacies palaeogeography as a guide to petroleum exploration is a very important topic. By using the following five exploration examples, this paper discusses the guide of lithofacies palaeogeography or of sedimentary facies to petroleum exploration. These examples include the dolostone of the Lower Ordovician Majiagou Formation 5 in the Ordos area, the Donghe Sandstone of the Upper Devonian and Lower Carboniferous in the Tarim Basin, the reef of the Upper Permian Changxing Formation in the Sichuan Basin, the oolitic bank of the Lower Triassic Feixianguan Formation in the Sichuan Basin, and the lacustrine delta sediments and gravity flow sediments of the Middle and Upper Triassic Yanchang Formation in the Ordos Basin.

Key words lithofacies palaeogeography, sedimentary facies, petroleum exploration, guide

In 1948, a famous Chinese geologist, Xie Jiarong, published an article, *Palaeogeography as a guide to mineral exploration* (Hsieh, 1948). This was the first time that a Chinese geologist openly proposed this important viewpoint. It specified that the relationship between palaeogeography and mineral deposits exploration was not a usual, but a directive relationship. In his article, Xie emphatically explained how palaeogeography could guide mineral deposits exploration regarding the coal, bauxite, sedimentary phosphate deposits, sedimentary iron deposits, and sedimentary copper deposits. The famous Huainan Coal Field was discovered by Xie who utilized the theory of palaeogeography as a guide to exploration. In his article, the palaeogeography mainly referred to lithofacies palaeogeography. However, due to historical limitations, Xie didn’t mention oil and gas.

Using the following five examples, this paper discusses how lithofacies palaeogeography and sedimentary facies guide petroleum exploration.

1 Lithofacies palaeogeography of the Lower Ordovician Majiagou Formation 5 in the Ordos area and the Jingbian Gas Field

1.1 Introduction

The Ordos area is located in North China. It is limited by the east of the Helan Mountains, by the west of the Luliang Mountains, by the south of the Yinshan Mountains, and by the north of the Qinling Mountains. It crosses over the Shaanxi Province, Gansu Province, Ningxia Autonomous Region, Shanxi Province, and Inner Mongolia Autonomous Region. The total area is about 320,000 km².

The Ordovician is exposed at the western, southern, and eastern margins of the Ordos area. In the inner area, the Ordovician is deeply buried under ground. The strati-
graphic division and correlation of the Ordovician in the Ordos are shown in Table 1.

In the famous Jingbian Gas Field, the natural gas production stratum is the Lower Ordovician Majiagou Formation 5.

1.2 To design an exploration well in Jingbian–Pianguan Restricted Sea

In 1980, in Study report of the Ordovician lithofacies palaeogeography in Shaanxi–Gansu–Ningxia area, Feng Zengzhao et al. suggested that “we should design an exploration well in the central area of Jingbian–Pianguan Restricted Sea to probe the secret of this virgin land”. The Jingbian–Pianguan Restricted Sea was a restricted area of carbonate sedimentation in the Early Ordovician, in which penecontemporaneous mud-sized to silt-sized crystalline dolostone and gypsum were well developed. The virgin land means that at that time there were no petroleum exploration wells in that area. This was the initial proposal for petroleum exploration of the Lower Paleozoic carbonate strata in this area.

In 1983, a polished copy of the study report The Ordovician Lithofacies Palaeogeography of the Shaanxi–Gansu–Ningxia–Nei Monggol–Shanxi region, was published in the Geological Review, vol. 29, no.1. The exploration suggestion proposed by Feng Zengzhao et al. attracted the peer’s attention in China.

In 1985, commercial amounts of gas were discovered in the exploration well in Jingbian area, which broke through the oil and gas valve of the virgin land of the Lower Paleozoic in the Ordos area. Since then, the oil and gas exploration of this area entered a climax phase.

1.3 Lithofacies palaeogeography of the Majiagou Age 5

In 1990, 1991 and 1998, Feng Zengzhao et al. successively published the monographs Lithofacies Palaeogeography of Early Paleozoic of North China Platform, Lithofacies Palaeogeography of Early Paleozoic of Ordos, and Stratigraphy Petrology Lithofacies Palaeogeography of Ordovician in Ordos. These studies timely and effectively promoted petroleum exploration in the Ordos area, especially in Jingbian area. Figure 1 is the lithofacies palaeogeographic map of the Early Ordovician Majiagou Age 5 in the Ordos area.

From Figure 1, we can see:

<table>
<thead>
<tr>
<th>System</th>
<th>Series</th>
<th>Southwestern area</th>
<th>Central and eastern area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carboniferous</td>
<td></td>
<td>Benxi Formation</td>
<td>Benxi Formation</td>
</tr>
<tr>
<td>Upper</td>
<td></td>
<td>Beiguoshan Formation</td>
<td></td>
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<tr>
<td>Middle</td>
<td></td>
<td>Sheshan Formation, Gongwusu Formation, Lashizhong Formation, Wulalik Formation</td>
<td>Pingliang Formation</td>
</tr>
<tr>
<td>Ordovician</td>
<td>Lower</td>
<td>Kelimoli Formation</td>
<td>Majiagou Formation 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Majiagou Group</td>
<td>Majiagou Formation 5</td>
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<tr>
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<td></td>
<td>Majiagou Formation 4</td>
<td>Majiagou Formation 4</td>
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<td>Majiagou Formation 3</td>
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<td>Majiagou Formation 2</td>
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<td>Majiagou Formation 1</td>
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<td></td>
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<td>Liangjiashan Formation</td>
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<td></td>
<td></td>
<td>Yeli Formation</td>
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<tr>
<td>Cambrian</td>
<td>Upper</td>
<td>Fengshan Formation</td>
<td></td>
</tr>
</tbody>
</table>
There were three lands, *i.e.*, the Alxa Land, Yimeng Land and Qingyang Land.

There were three dolostone flats, *i.e.*, the West Dolostone Flat, North Dolostone Flat, and East Dolostone Flat. In these dolostone flats, the content of penecontemporaneous mud-sized to silt-sized crystalline dolostones was $\geq 50\%$, or $\geq 90\%$.

There were one gypsum-bearing lake and two gyp-
sum lakes, *i.e.*, the Central Gypsum-bearing Lake, Mizhi Gypsum Lake, and Linfen Gypsum Lake. In the gypsum-bearing lake, the content of gypsum was 29%–10%. In the gypsum lake, the content of gypsum was ≥30%. Penecontemporaneous dolostones were mainly deposited in the gypsum-bearing lake and in the gypsum lake. These lakes also belonged to the dolostone flat. There were one salt-bearing lake and one salt lake, *i.e.*, the Shaan 24 Halite-bearing Lake and Yu 9 Halite Lake. In the halite-bearing lake, the content of halite was 29%–10%. In the salt lake, the content of halite was ≥30%. Actually, the penecontemporaneous dolostones were mainly deposited in the halite-bearing lake and in the halite lake. These lakes still belonged to the dolostone flat. There were two banks, *i.e.*, the Li 1 Limemud Grain Bank and Longxian Limemud Grain Bank. In the limemud grain banks, the content of grains was ≥30%, and the limemud filled in the intergranular space. There were two embryonic banks, *i.e.*, the Zhuozishan Limemud Grain Embryonic Bank and E 6 Limemud Grain Embryonic Bank. In the limemud embryonic banks, the content of grains was 19%–10%, and the limemud filled in the intergranular space. There were two open seas, *i.e.*, the South Open Sea and West Open Sea. In these open seas, the content of limestone was ≥50%. Also, there was an interflat sea, *i.e.*, the North Interflat Sea. In this interflat sea, the content of penecontemporaneous dolostone was <50%, the main rock was limestone. The dolostone flats, gypsum-bearing lakes, gypsum lakes, halite-bearing lakes, halite lakes and interflat sea, all belonged to the domain of Jingbian–Pianguan Restricted Sea.

1.4 Treasure flat

In the dolostone flat of Majiagou Formation 5, the mud-sized to silt-sized crystalline dolostones, especially gypsum-bearing dolostones, are the main reservoir rocks in Jingbian Gas Field (Fig. 2).

The natural gas in the Jingbian Gas Field mainly came from these dolostones in dolostone flat. The dolostone flat is a treasure flat!

During the past twenty years, the studies of lithofacies palaeogeography and other academic fields (such as palaeokarst water) greatly promoted the progression of gas exploration of the Majiagou Formation 5 in Jingbian area. As a result, the natural gas reserve of Jingbian Gas Field was increased more than a thousand hundred million cubic meters, which expanded the scale of the Jingbian Gas Field. This was an important exploration breakthrough of the Lower Paleozoic in Ordos.

2 Sedimentary facies of the Donghe Sandstone of the Upper Devonian–Lower Carboniferous in the Tarim Basin and discovery of the Hadexun Oilfield

2.1 Introduction

The Hadexun Oilfield is located in the northern Tarim Basin (Fig. 3). It is one of the largest oil fields in the Tarim Basin with oil reserves of more than a hundred million tons. The annual oil production of the Hadexun Oilfield is more than three million tons.

The Donghe Sandstone of the Upper Devonian–Lower Carboniferous is the reservoir for the Hadexun Oilfield. The sedimentary facies and evolution of the rule of the Donghe Sandstone provided the most important guide for exploration of the Hadexun Oilfield.

2.2 Stratigraphy and distribution of the Donghe Sandstone

In the northern Tarim Basin, the Upper Devonian–Lower Carboniferous can be divided into the Bachu Formation, Kalashayi Formation and Xiaohaizi Formation, and can be further divided into nine lithologic members (Table 2).

The Donghe Sandstone is a transgressive basal sandstone that was deposited from the Late Devonian to the Early Carboniferous when sea level rose. It is mainly a beach facies sandstone. In the entire Tarim Basin, the Donghe Sandstone is a sedimentary body across the geologic time boundaries. The late Late Devonian sediments occurred in the west of the basin, the early Early Carboniferous sediments are found in the east of the basin. The transgressive overlap developed from west to east. In the Hadexun area, the Donghe Sandstone Member can be correlated with the Lower Mudstone Member and the Bioclastic Limestone Member in the inner basin. See Table 2 and Figure 4.

2.3 The pinch-out zone of the Donghe Sandstone and discovery of the Hadexun Oilfield

The Donghe Sandstone filled in and evened up the palaeogeomorphic landscape of the underlying strata. The thickness of the Donghe Sandstone increased at a steep slope and decreased at a gentle slope. When meeting islands or erosion areas, the sandstone was pinched out.
The pinch-out line of the Donghe Sandstone was an overlapping line. The overlying stratum was the Lower Mudstone. These two lithological members create a perfect reservoir–cap combination, *i.e.*, the underlying Donghe Sandstone Member as reservoir rock, and the overlapping Lower Mudstone Member as cap rock. From north to south, the length of this pinch-out line is about 100 km, the width is 10–30 km. The Hadexun Oilfield was discovered...
Fig. 3 Location of the Hadexun Oilfield.

Table 2 Division and correlation of the Devonian and Carboniferous in the Tarim Basin

<table>
<thead>
<tr>
<th>System</th>
<th>Series</th>
<th>Formation</th>
<th>Member</th>
<th>Manjiaer Depression</th>
<th>Bachu Uplift</th>
<th>Tazhong Uplift</th>
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<td></td>
<td></td>
<td></td>
<td>South area</td>
<td>Hadexun</td>
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<tr>
<td>Carboniferous</td>
<td>Upper</td>
<td>Xiaoahaizi</td>
<td>Limestone</td>
<td>Limestone</td>
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<td></td>
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<td></td>
<td>Bearing Limestone</td>
<td>Bearing Limestone</td>
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<td>Siltstone-Mudstone</td>
<td>Siltstone-Mudstone</td>
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<td>Upper Mudstone</td>
<td>Upper Mudstone</td>
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<td>Standard Limestone</td>
<td>Standard Limestone</td>
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<td>Middle Mudstone</td>
<td>Middle Mudstone</td>
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<td></td>
<td>Bioclastic Limestone</td>
<td>Bioclastic Limestone</td>
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<td></td>
<td></td>
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<td>Lower Mudstone</td>
<td>Lower Mudstone</td>
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<td></td>
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<td></td>
<td>Donghe Sandstone</td>
<td>Donghe Sandstone</td>
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<tr>
<td>Devonian</td>
<td>Upper</td>
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</table>
in this pinch-out line.

The in-depth study of sedimentary facies of the Donghe Sandstone guided the discovery of the Hadexun Oilfield. Along with the exploration, new discoveries of sizable oil and gas reservoirs are expected in the future.

3 Lithofacies palaeogeography of the Upper Permian Changxing Formation in the Sichuan Basin and the exploration of reef gas reservoirs

3.1 Tortuous exploration history

The gas reservoir in reefs of the Upper Permian Changxing Formation is the most important marine carbonate gas reservoir in the Sichuan Basin.

In 1964, the Bureau of Petroleum Administration of Sichuan discovered an anomaly in dolostone of the Upper Permian Changxing Formation, however, they didn’t recognize reef facies within the formation.

In 1983, at an outcrop near Huayingshan in eastern Sichuan, the reef facies of the Changxing Formation was discovered (Qiang et al., 1985). In the same year, in Well Shibao 1, a natural gas reservoir was discovered in the reef facies of the Changxing Formation (Zhao, 1987). In the Sichuan Basin, this was the first natural gas reservoir in the reef facies of the Upper Permian Changxing Formation.

Up to the late 1980s, more than twenty reefs and four gas reservoirs were discovered in the Changxing Formation, both in outcrops and in wells.

At that time, geologists thought that these reefs are patch reefs scattered on the carbonate platform, their origin and distribution was not well understood. Therefore, it was impossible to propose a suitable exploration plan for the reef reservoirs. This trapped reef reservoir exploration of the Changxing Formation into a difficult position, i.e., “never found a reef in a designed well, but stumbled upon a reef in an undesigned well.”

Another reason led geologists into the predicament was that the exploration wells should be designed on the higher position of an anticline because of the low viscosity and easy flow of natural gas. This misleading idea led all the exploration wells to fail.

This difficult situation persisted until the late 1990s.

3.2 Out of difficult situation and achieving breakthrough

In 1990s, the Bureau of Petroleum Administration of Sichuan set up a national science and technology project as the 9th five-year plan. Via the studies of outcrop section, well profile, seismic section, thin section, and other laboratory analysis and tests, utilizing over-all analysis and comprehensive judgement, geologists discovered and confirmed that the Kaijiang–Liangping area in eastern Sichuan is an area of deep water sedimentary rocks. These rocks include chert, siliceous mudstone, mud-sized crystalline limestone, and carbonaceous shale, which all belong to the Dalong Formation that was deposited during the same period as the Changxing Formation but in quite different facies. This area was initially called the “Kaijiang–Liangping Trough”, but now it is called the “Kaijiang–Liangping Basin”. Geologists also recognized that reefs favorably developed in the transition zone between deep water facies and carbonate platform facies, i.e., the
platform marginal facies. In eastern Sichuan, reefs of the Changxing Formation mainly developed in the platform margin facies. They were not patch reefs scattered on the platform. In eastern Sichuan, all of the discovered reef gas reservoirs in the Changxing Formation were deposited in the platform margin facies zone. This is a most important new understanding of lithofacies palaeogeography (Wang et al., 1998, 2000). See Figures 5 and 6.

This new understanding of lithofacies palaeogeography totally changed wrong exploration strategies previously used in the reef gas reservoir in the Changxing Formation. Since then, instead of designing exploration wells

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**Fig. 5** Lithofacies palaeogeographic map of the Late Permian Changxing Age in the Sichuan Basin.

**Fig. 6** Profile of lithofacies palaeogeography of the Lower Permian Changxing Formation in the Sichuan Basin.
In high position of an anticline, the exploration targets were concentrated on the platform margin facies around the Kaijiang–Liangping Basin. In this way, natural gas reservoir exploration in the reefs of the Changxing Formation in eastern Sichuan was out of a difficult situation and achieved an important breakthrough, and found many large and medium-sized reef gas reservoirs successively, such as the gas reservoirs of Maoba reef, Dawan reef, Puguang reef, Qilibei reef, Huanglongchang reef, Tiandong reef, Yun'an reef, Tieshan reef, and Longgang reef.

4 Lithofacies palaeogeography of the Lower Triassic Feixianguan Formation in the Sichuan Basin and the exploration of oolitic bank gas reservoirs

In the Sichuan Basin, the history of gas exploration of the oolitic banks of the Lower Triassic Feixianguan Formation was comparable with that of the reef exploration in the Upper Permian Changxing Formation.

In 1963, the Bureau of Petroleum Administration of Sichuan discovered a gas reservoir in the oolitic bank of the Feixianguan Formation on the Shiyougou structure in eastern Sichuan. After that, several gas reservoirs were discovered in the Feixianguan Formation on other structures successively. However, because of a lack of understanding of the genesis and distribution of the oolitic bank dolostone, therefore the gas exploration in oolitic bank of the Feixianguan Formation in the eastern Sichuan Basin was slumping for a long duration.

In late 1990s, the Bureau of Petroleum Administration of Sichuan set up a national science and technology project for the 9th five-year plan to study the sedimentary facies and lithofacies palaeogeography of the Upper Permian and the Lower Triassic. This study found that the Kaijiang–Liangping Basin persisted through the Late Permian Changxing Age and the Early Triassic Feixianguan Age. On the eastern and the western sides of the Kaijiang–Liangping Basin, the oolitic banks and related gas reservoirs were perfectly developed. See Figure 7.

That is to say, in the transitional zone between the Kai-
5 Sedimentary facies of the Middle-Upper Triassic Yanchang Formation in the Ordos Basin: A great breakthrough of petroleum exploration

5.1 Introduction

The Ordos Basin is located in northern China. It crosses over the Shaanxi Province, Gansu Province, Ningxia Autonomous Region, Inner Mongolia Autonomous Region, and Shanxi Province. The total area of the Ordos Basin is about 250,000 km². The Ordos Basin has a stable basement, simple structure and gently tilted strata. It is one of the largest sedimentary basins in China (Fig. 8).

In the Ordos Basin, there existed the Middle–Upper Triassic Yanchang Formation with thickness of more than a thousand meters, in which the sedimentary facies of alluvial plain, delta plain, delta front, shore lake, shallow lake, semi-deep lake, deep lake and gravity flow sediments were developed. The Yanchang Formation is an important production stratum for oil, natural gas and coal (Yang et al., 2002).

The Middle–Upper Triassic Yanchang Formation can be divided into 5 lithologic members and 10 oil-bearing intervals (Table 3). According to data from more than one hundred wells drilled into the Yanchang Formation and information from outcrop sections along the periphery of the basin, combining the long time working experience in the Changqing Oilfield, the sedimentary facies maps of all oil-bearing intervals in the Yanchang Formation were composed. Herein, four typical sedimentary facies maps of Chang 10, Chang 8, Chang 7 and Chang 6 were selected, to discuss the characteristics of sedimentary facies of these four intervals and their guidance to petroleum exploration.

5.2 Sedimentary facies of Interval Chang 10

In the sedimentary period of Interval Chang 10, the alluvial plain facies and delta plain facies were well developed, the lake (mainly shore lake) area was relatively small. In the Ordos Basin, this was the initial developing period for the lacustrine basin of the Yanchang Formation (Fig. 9).

The alluvial plain was only developed in the western area, the boundary between the alluvial plain and delta plain was in the area of Jiyan–Qingcheng. The shoreline of the lake was located in the area of Zhengning–Wuqi–Zhidan–Fuxian. The long axis direction of the lacustrine basin was NW–SE. The depocenter was located in the area of Zhidan–Fuxian. The thickness ratio of sandstone to stratum is <20%. The mudstone contains aquatic fossils, for example, in the Liulin section of Tongchuan, abundant Ostracoda fossils were discovered in the mudstone of Interval Chang 10.

In the sedimentary period of Interval Chang 10, abundant sediments were from the northwest, west, and southwest provenances with a rapid sedimentary rate. In the west and southwest provenance sedimentary area of Huanxian–Qingcheng, the thickness ratio of sandstone to stratum is >50%; in some isolated areas, the thickness ratio is >80%. In the course of pushing sediments forwards, the grain size gradually became fine, at the same time, the content of sandstone gradually decreased. In the area of Dingbian–Wuqi–Zhiden–Fuxian, the thickness ratio of sandstone to stratum reduced to 30%. In the northwest provenance sedimentary area, the Yanchi delta plain extended to the area of Yanchi–Dingbian. The deltas that were controlled by the west and southwest provenance influenced the area of Wuqi–Zhangcha. The Huangling delta front that was created by the south provenance extended northward to the north of Huangling. Relatively speaking, the influence of the northeast provenance was weak. In Jingbian–Ansai delta plain, the thickness ratio of sandstone to stratum is between 30%–40%. The rocks are mainly medi-
um-grained to coarse-grained sandstones, the sandbodies reach the area of Zhidan–Ansai.

5.3 Sedimentary facies of Interval Chang 8

The sedimentary periods of Interval Chang 9 and Interval Chang 8 were the early period of lacustrine transgression of the Yanchang Age.

The sedimentary facies map of Interval Chang 9 is omitted.

In the sedimentary period of Interval Chang 8, the lake area was broad, however, the depth of lake water was shallow. The shore lake facies, shallow lake facies, delta front facies and delta plain facies were developed (Fig. 10).

At this time, the supply of sedimentary materials was abundant, the overflowing sediments gradually filled and evened up the floor of the lake. Thus, the lake bottom was rather gentle and smooth, and the lake area was broad and shallow. Therefore, there were no semi-deep lake and deep lake. The western shoreline of the lake was located in the area of Huanxian–Zhenyuan–Jingchuan, the eastern shoreline was located in the area of Hengshan–Qinjian. The boundary between the shore lake facies and the shall-
ow lake facies was located in the area of Zhengning–Huachi–Dingbian–Ansai.

In shore lake facies, coal seams, root clay and vertical worm borings are common. This indicates that this area is the swing zone of shoreline migration.

In shallow lake facies, signs of intermittent exposure are missing, however, aquatic fossils are well developed and horizontal beddings are common. The central area of the lake was located in the area of Wuqi–Zhidan–Fuxian. The thickness ratio of sandstone to stratum is <20%; mudstone is dominant.

In the sedimentary period of Interval Chang 8, the delta facies that was controlled by each provenance was perfectly developed. In the Yanchang Formation, this was a major constructive period of delta sediments. The rocks were medium grain sandstone and fine grain sandstone. The thickness ratio of sandstone to stratum was between 30%–50%. Due to the gentle lake bottom, the delta sandbodies frequently altered their moving path with various divergence and convergence, and therefore created a dendritic shape.

5.4 Sedimentary facies of Interval Chang 7

In the sedimentary period of Interval Chang 7, the lake area nearly covered the entire lake basin of the Yanchang Formation in the Ordos Basin, lacustrine transgression of the Yanchang Age reached the maximum. The deep lake facies and semi-deep lake facies were well developed. In addition, the gravity flow sediments were developed in deep lake and semi-deep lake facies. In the western peripheral area, alluvial fan and alluvial plain facies were developed as well (Fig. 11).

Compared to the facies of earlier sedimentary periods of the Yanchang Formation, the framework of sedimentary facies of Interval Chang 7 was changed obviously.

(1) The lake area exceeded 100,000 km², which almost covered the entire basin. The area of deep lake and semi-deep lake was nearly 60,000 km², the hydrocarbon source rocks (dark mudstone and oil shale) were well developed.

(2) The depocenter migrated westwards from the previous area of Wuqi–Zhidan–Fuxian–Huangling to the area of Huachi–Qincheng–Heshui–Zhengning. In this sedi-
Fig. 9 Sedimentary facies of Interval Chang 10 of the Yanchang Formation in the Ordos Basin.

In the sedimentary central area, the gravity flow sediments were well developed.

(3) The topography of lake floor was asymmetrical. A long and gentle slope with broadly stretched facies was on the northeastern side, a steep slope with narrowly distributed facies was on the southwestern side. The width of shore lake facies and shallow lake facies was 150 km wide at the northeastern side approximately, but was only 20–60 km at the southeastern side.

(4) Delta sediments were not well-developed. The delta sandbodies were small with shortly stretched distance. The thickness ratio of sandstone to stratum is 30% in general, the grains size is relatively fine, the rocks are fine-grained sandstone and siltstone.

(5) The gravity flow sandbodies in deep lake clearly displayed the phenomena of “broken root”.

5.5 Sedimentary facies of Interval Chang 6

In the sedimentary period of Inteval Chang 6, the lake area, comparing with that of Interval Chang 7, was greatly reduced.

It indicates that the largest lacustrine transgression had passed and the lacustrine regression began. The western shoreline was located in the area of Yinjiacheng–Zheny-
Fig. 10  Sedimentary facies of Interval Chang 8 of the Yanchang Formation in the Ordos Basin.

Yuan–Jingchuan. The eastern shoreline was located in the area of Jingbian–Ansai. The semi-deep lake facies and deep lake facies retreated to the area of Huachi–Zhengning–Huangling (Fig. 12).

In the semi-deep lake and the deep lake, the gravity flow sandbodies were well developed. It was an important feature of Interval Chang 6.

The delta sandbodies were well developed. It was another important feature of Interval Chang 6.

The Jingbian–Ansai delta that was controlled by the northeastern provenance presented a significant construction. The thickness ratio of sandstone to stratum reached up to 70%, most sandstones are medium-grained and fine-grained sandstones. The thickness of a single sand bed is large, its distribution is stable, and its extension distance is over 200 km. Therefore, the huge delta sandbody complex was established, the front margin of sandbodies extended to the area of semi-deep lake and deep lake.

In comparison, the delta sandbodies that were controlled by the western, southwestern, and southern provenances had small dimension with the short extended distance (usually <80 km). For the major sandbody, the thickness ratio of sandstone to stratum is between 30%–35%. The thickness of a single sandstone bed is small, the
fine-grained sandstone is dominant.

In the area of semi-deep lake facies and deep lake facies, gravity flow sandbodies were well developed, and clastic sediments were mainly from the west and southwest. Because the topography of the lake floor at the western and the southwestern sides was relatively steep, and because the palaeoearthquakes occurred frequently, loose clastic grains slumped downwards along the slope and accumulated either at the base of the slope or on the floor of the lake, and formed gravity flow sandbodies. Therefore, these gravity flow sandbodies demonstrated “broken root” phenomena. For the gravity flow sandbodies, the thickness ratio of sandstone to stratum is between 30%–60%, in some areas, this ratio can reach up to 70%. The rocks are fine-grained sandstone and siltstone. The sandbodies were distributed along the boundary of facies, the lengthening of them can stretch to 150 km and the broadening of them is between 15–70 km. These sandbodies cover an area of 8,000 km². They are a set of large scale sandbody complex of gravity flow sediments.

On the other hand, in the northeastern side of the lake basin, the lake floor was gentle. The Jingbian–Ansai delta had abundant clastic sediments, as a result, the sandbody swiftly moved forwards with a long stretch. Therefore, in the deep lake area, the gravity flow sandbodies were distributed along the delta front, and there were no “broken root” phenomena.

5.6 Sedimentary facies of Intervals Chang 5 to Chang 1

In the sedimentary period of Intervals Chang 4+5, the lake area was continually shrunken and the depth of water became shallow. The area of deep lake and semi-deep lake were further reduced. In some areas, wetland occurred. The mudstone was well developed. The magnitude of delta sediments was obviously decreased. For the major sandbodies, the thickness ratio of sandstone to stratum is 30%–40% in general, the primary rocks are fine-grained sandstone and siltstone. Most gravity flow sandbodies are in lenticular shape with small thickness.

In the sedimentary periods of Intervals Chang 3 and Chang 2, the lake area further decreased, the area of deep lake and semi-deep lake vanished, and the only surviving lake facies was shore lake facies and shallow lake facies. The delta plain facies was also well developed. The size of the delta sandbody became small. For the major sandbody, the thickness ratio of sandstone to stratum is <30% in general.

In the sedimentary period of Interval Chang 1, the entire lake basin became wetland; only in some location, a few small scale lakes still remained. In the end of the Yanchang Age, the unified lake basin in the Ordos area basically vanished.

The sedimentary facies maps of Intervals Chang 4+5, Chang 3, Chang 2 and Chang 1 are all omitted.

5.7 Sedimentary facies and petroleum exploration

The in-depth study of the Upper Triassic Yanchang Formation in the Ordos Basin provides a good foundation and guidance to oil and gas exploration. The relationship between sedimentary facies and petroleum exploration can be summarized into three aspects.

First, hydrocarbon source rocks are excellent. In Interval Chang 7, the deep lake facies and semi-deep lake facies were widely distributed. The thickness of dark mudstone and oil shale reached up to 30–80 meters. They are excellent hydrocarbon source rocks. In addition, the oil shale in Interval Chang 9, and the mudstone in Intervals Chang 8 and Chang 4+5 also had the ability to generate hydrocarbon. These high quality hydrocarbon source rocks are the material foundation for the giant oil fields in the Yanchang Formation.

Second, reservoir sandbodies are positioned in multiple intervals. The sandbodies of Intervals Chang 6 and Chang 8 were located either above or beneath the hydrocarbon source rocks of Interval Chang 7. Because of their favorable locations, these sandbodies were the first ones to obtain source oil from Interval Chang 7 and formed a large size oil reservoir. At the same time, in the center of the lake basin, gravity flow sandbodies of Intervals Chang 7 and Chang 6 are also favorable reservoir units (Yang et al., 2006; Deng et al., 2010; Fu et al., 2010). In addition, the sandbodies in other intervals could also become reservoir units. This is to say, in the Yanchang Formation of the Ordos, there were multiple intervals with reservoir sandbodies of various origins. They intersected with each other in space and created the framework of “full basin sandbodies”, which provided the most beneficial reservoir space for oil migration and accumulation.

Third, the cap rocks are widely distributed. In Interval Chang 4+5, the shallow lake facies mudstone interbedded with siltstone and fine-grained sandstone were the best regional cap rocks in the basin. Furthermore, the Intervals Chang 3, Chang 2, and Chang 1 were also moderately good regional cap rocks.

Overall, “Excellent source rocks, multiple intervals of reservoir sandbodies, and widely distributed cap rocks” constitute the favorable conditions for the formation of
Fig. 11 Sedimentary facies of Interval Chang 7 of the Yanchang Formation in the Ordos Basin.

high quality hydrocarbon accumulations.

Utilizing lithofacies palaeogeography and sedimentary facies of the Yanchang Formation in the Middle and Upper Triassic as a guide, geologists discovered several oil fields of hundred million tons scale and thousand million tons scale successively. These oil fields are Shaanbei Oilfield, Xifeng Oilfield, Jiyuan Oilfield, and Huaqing Oilfield (Fig. 8). Due to these discoveries, the Ordos Basin became one of the most important energy centers in China (Deng et al., 2011).

In the above, utilizing five examples, i.e., the dolostone of the Lower Ordovician Majiagou Formation 5 in the Ordos area, the Donghe Sandstone of the Upper Devonian and the Lower Carboniferous in the Tarim Basin, reef of the Upper Permian Changxing Formation in the Sichuan Basin, oolitic bank of the Lower Triassic Feixianguan For-
These five examples touch upon five different geologic periods (Ordovician, Devonian, Carboniferous, Permian, and Triassic), three famous Chinese oil and gas regions (Ordos area, Tarim Basin, and Sichuan Basin), three carbonate rock oil and gas fields, two clastic rock oil and gas fields, four marine oil and gas fields, and one lacustrine oil and gas field. They are typical examples.

Certainly, we have to point out that, although this paper emphatically discussed lithofacies palaeogeography or sedimentary facies as a guide to petroleum exploration, however, we do not exclude other geological disciplines to make contributions for petroleum exploration.
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References


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