



Pre-Jurassic paleogeomorphology restoration and favorable conditions for oil accumulation of the Zhouchang area, Ordos Basin, China

Xia Wang^{1,2} · Guomin Fu¹ · Bojiang Fan² · Xiuchan Liu²

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Abstract

The Zhouchang area, where the oil is mainly accumulated in Mesozoic sandstone reservoirs, is located in the Ordos Basin, China. Paleogeomorphology plays an important role in the oil accumulation of the Jurassic Yan'an Formation. Previous studies on paleogeomorphology propose that Lower Jurassic oil reservoirs are distributed in the higher units, such as the paleoslope, which is now proved to be not completely accurate in this study. The paper mainly focuses on paleogeomorphology restoration, favorable oil accumulation conditions, oil accumulation patterns, and favorable area prediction. Based on the stratigraphic division of the Lower Jurassic strata, the pre-Jurassic paleogeomorphology is precisely restored using the moldic method and is divided into secondary units. Furthermore, the controlling effects of the pre-Jurassic paleogeomorphology on oil accumulation are discussed. Results indicate that the paleogeomorphology can be divided into paleochannel, paleoslope, and paleohighland in the study area. The proved oil is distributed not only in the paleoslope but also in the lower paleochannel, which is different from previous study conclusions. Paleochannel sandbodies provide a conducive pathway and storage space for oil migration and accumulation, and the sandbodies in the paleoslope area are considered as favorable reservoir strata. Paleogeomorphology-controlled microamplitude structures are suitable traps for oil preservation. Two patterns for oil accumulation in 2D are newly established: paleochannel-braided channel-delta plain pattern and paleoslope-braided channel-delta plain pattern. The pattern for oil accumulation in 3D is also created for the first time. Through the studies above, four favorable areas for oil accumulation in Zhouchang area are predicted.

Keywords Oil accumulation pattern · Paleogeomorphology restoration · Pre-Jurassic · Sandstone reservoir

Introduction

Paleogeomorphology results from the combination of tectonic deformation, differential compaction, sedimentary filling, weathering, and denudation (Aloui et al. 2012; Pángaro et al. 2016). Paleogeomorphology form the foundation of sedimentary systems. Moreover, it imposes key controls on the accumulation and distribution of sedimentary facies and affects the facies-controlling reservoir properties (Yandoka et al. 2015). Paleogeomorphology not only affects the development of paleokarstification in carbonate rocks but also the differentiation of sediments in sandstone rocks (Han et al. 2019; Zhu et al. 2019). Different paleogeomorphic units have some controlling effect on the reservoir characteristics. Therefore, paleogeomorphology is closely related to hydrocarbon accumulation and plays an important role in the prediction of hydrocarbon distribution.

✉ Xia Wang
oukawang@yau.edu.cn

Guomin Fu
guominfu2000@163.com

Bojiang Fan
2632890647@qq.com

Xiuchan Liu
372005458@qq.com

¹ School of Earth Science and Resources, Chang'an University, Xi'an 710054, China

² School of Petroleum Engineering and Environmental Engineering, Yan'an University, Yan'an 716000, China

The relationship between paleogeomorphology and hydrocarbon accumulation was discussed for the first time by Thornbury in 1954. Since then, researches on paleogeomorphology have been increasingly conducted (Antonioli et al. 2011; Christopher et al. 2005; Parham et al. 2019; Tony 2000). Although paleogeomorphology research began relatively late in China, numerous studies have been conducted, especially in recent years. Among these researches, the pre-Jurassic paleogeomorphology restoration of the Ordos Basin and the relationship between the paleogeomorphology and oil reservoirs are research hot spots. Common methods used in paleogeomorphology restoration are the moldic method, the residual thickness method, the back-stripping method, the error simulation method, the sequence stratigraphy method, and other relevant methods (Zhao et al. 2020). Among these methods, the moldic method is a mature and the most widely used method. In previous researches, paleogeomorphology was divided into paleohighlands, paleoslopes, paleochannels, remnant ridges, and remnant earthen mounds (Han et al. 2019). Zhu et al. (2019) well-identified not only the first-order paleochannels with downcutting depths of more than 200 m but also the third-order paleochannels with downcutting depths of less than 100 m. Their results indicated that the accumulation and distribution of the Lower Jurassic oil reservoirs were evidently controlled by the pre-Jurassic paleogeomorphology. Moreover, they demonstrated that the oil reservoirs were distributed in higher units adjacent to paleohighlands, such as paleoslopes. Accordingly, in practice, the paleogeomorphic units with relatively high terrains are the primary exploration targets of the Low Jurassic oil reservoirs. These results have important guiding significance for the exploration of Jurassic oil reservoirs. However, the areas investigated in the aforementioned studies are usually large, the drilled wells are inadequate, and the paleogeomorphology depiction is too macro. In particular, the description of paleogeomorphic units is too simple and unrefined, making the accurate determination of the location of the small but fertile Jurassic oil reservoirs challenging. Therefore, restoring the pre-Jurassic paleogeomorphology with high precision is necessary. Moreover, the favorable accumulation conditions of the oil reservoirs controlled by paleochannels have not been clearly clarified yet. In addition, suitable patterns for oil accumulation in case of this type of oil reservoir have not been established. All these points restrict the perfection of the paleogeomorphology theory.

This study aims to (1) stratify strata and restore the pre-Jurassic paleogeomorphology, (2) divide pre-Jurassic paleogeomorphic units and discuss their characteristics, (3) elucidate favorable conditions for oil accumulation, (4) establish oil accumulation patterns, and (5) predict favorable regions for oil accumulation. This study are helpful for oil exploration and development in the future.

Geological setting

The Ordos Basin in China (Fig. 1a) is a large multicycle superimposed basin with an area of approximately 37×10^4 km² (Yang et al. 2005). Its crystalline basement was likely formed during the Archean to the Early Proterozoic (Yang et al. 2012). During the Middle–Late Proterozoic, the basin experienced steady uplift, subsidence and weak tectonic activities (Yang et al. 2005). During the late Paleozoic, the sedimentary facies of the Ordos Basin changed from marine to terrestrial and the filling surface of the basin was likely flattened due to intense weathering and denudation. During the Mesozoic, the Ordos Basin underwent two tectonic cycles: the Triassic Indosinian Orogeny and the Jurassic–Cretaceous Yanshanian Orogeny. These orogenies shaped the present six structural units: western fold-thrust belt, Yimeng uplift, Tianhuan depression, Yishan slope, Weibei uplift, and Jinxi fault-fold belt (Ji et al. 2010). Influenced by the two orogeny events, the whole basin was uplifted and some strata were eroded, forming the rugged paleogeomorphology with many rivers, hills, ravines, and gullies (Yang et al. 2012). The Ordos Basin is richly endowed with hydrocarbon resources and characterized by poor reservoir properties, complex oil–water distribution, and strong heterogeneity (Fu et al. 2019).

The Zhouchang area is located in the middle of the Yishan slope, Ordos Basin (Fig. 1b). The Upper Triassic Yanchang Formation is an important Mesozoic oil-bearing sequence with well-preserved feldspar sandstone reservoirs and widely developed lake–delta sedimentary system (Qiu et al. 2015). The Yanchang Formation can be divided into 10 oil-bearing members, namely, Chang 1–10 members from top to bottom (Yang et al. 2012) (Fig. 1c). Among them, the Chang 1 member contacts unconformably with the overlying Fuxian Formation. During the Lower Jurassic Fuxian period, the basin was uplifted by the late Indosinian Orogeny (Liu et al. 2008, 2012). The sediments of the Fuxian Formation are mainly developed on an uneven surface of unconformity due to the denudation and downcutting of the Yanchang Formation. They are characterized by thick, coarse clastic quartz sandstone facies associations that are interpreted to have been formed via fluvial-filling sedimentary conditions (Liu et al. 2012). However, the denudation surface has not been completely filled in the study area, and the early sedimentation of the Yan'an Formation was obviously controlled by a rugged paleogeomorphology. The Yan'an Formation is one of the majorly exploited formations hosting numerous sandstone reservoirs in the Jurassic. According to marker beds and lithological associations, the Yan'an Formation can be divided into ten members, namely, Yan 1–10 from

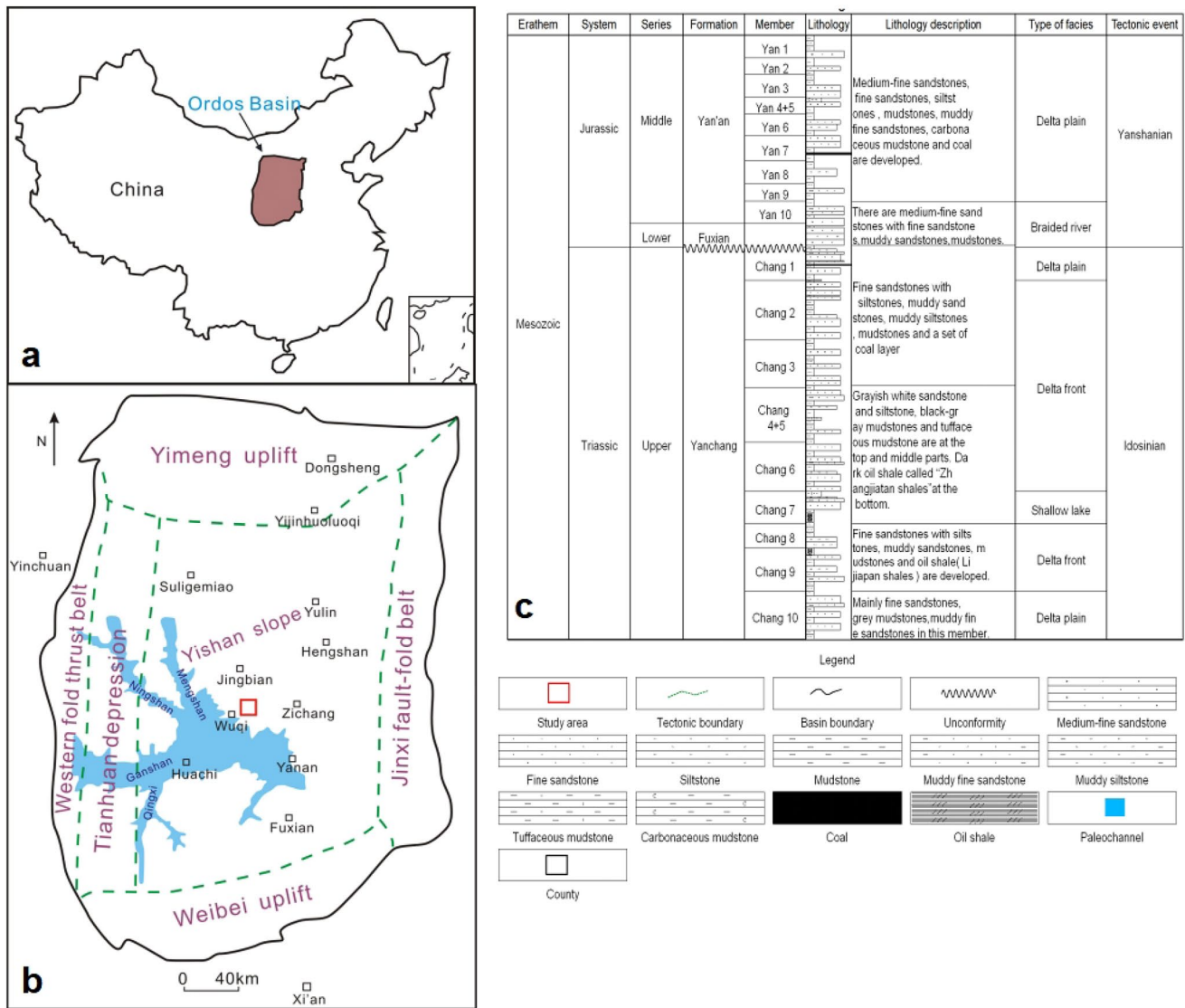


Fig. 1 Location of Zhouchang area, Ordos Basin, Northwest China. a Location of the Ordos Basin in China. b Tectonic location of the study area. c Stratigraphic division for the Lower Jurassic and Upper Triassic

top to bottom. Among them, the Yan 10 member is the main oil-bearing layer of the Yan'an Formation and has been extensively studied for the characteristics including its sedimentary environment, reservoir characteristics, and hydrocarbon accumulation. The Yan 10 member is mainly composed of channel-filling sediments, and its stratum thickness varies with the extent of river downcutting. From the late Yan 10 member stage, a fluvial-lacustrine delta compensation sedimentary system emerged in this area, mudstone swamps were widely developed, and a series of coal-bearing clastic rock strata was possibly formed. Finally, the Yan 9 member was completely filled and the top surface was flattened (Liu et al. 2012).

Paleogeomorphology restoration

Logging data and production data from 415 oil wells in Zhouchang area were collected. Data of core analysis from drill cores were also collected. The data with obvious abnormalities were removed. It is believed that the carefully selected data provide sufficient assurance to this study.

Method

As mentioned above, the top surface of the Yanchang Formation is uneven due to erosion, i.e., an unconformity

surface, and it is filled and flattened by overlying sedimentary strata. Larger scale denudation occurred at the place, where the paleogeomorphology was higher with thinner overlying strata (Zhu et al. 2019). In other words, a negative correlation exists between the filling thickness and paleogeomorphology. The filling thickness from the unconformity surface to the filled and flattened surface (also called as isochronous surface) can indirectly reflect the undulating pre-Jurassic paleogeomorphology. Paleogeomorphology is lower when the sedimentary stratum is thicker, and vice versa (Han et al. 2019). Based on this principle, we can use the moldic method to restore the paleogeomorphology. The shape of the paleogeomorphology would be well-mirrored through the thickness distribution of the overlying strata on the unconformity surface using the moldic method.

In addition, we have known that the top surface of the Yan 9 member is an isochronous surface. The stratum thickness from the unconformity surface to the isochronous surface, i.e., the total stratum thickness (H) of the Yan 9 member (H_1), the Yan 10 member (H_2), and the Fuxian Formation (H_3), is calculated as $H = H_1 + H_2 + H_3$ and then converted into a contour map using the geologic graphics software GeoMap3.6 (Fig. 2). The pre-Jurassic paleogeomorphology in the Zhouchang area, Ordos Basin, is restored through the mirror-image relationship of the moldic method.

Several basic steps must be completed before the restoration of the pre-Jurassic paleogeomorphology. The strata of the Yan 9 member, Yan 10 member, and Fuxian Formation must be recognized accurately according to marker beds with the help of well-logging data. The top layer of the Yan 9 member is mudstone with a typical stable distribution, a certain thickness, and obvious logging characteristics (high sonic log [DT], low deep induction logging resistivity [RILD], high caliper [CAL], and high gamma ray [GR]). This mudstone is selected as the upper marker bed. The top rock of the Yan10 member is of the same lithology and has similar logging responses as those of the Yan 9 member,

and it is selected as the middle marker bed. The unconformity surface between the Fuxian Formation and Yanchang Formation is a tectonic movement surface that resulted from basin uplift and erosion caused by the late Indosinian Orogeny. The sedimentary rocks beneath the unconformity surface are mudstones characterized by high GR and high spontaneous potential (SP). By contrast, the sedimentary rocks overlying the unconformity surface are sandstones characterized by low GR and low SP. Therefore, there is an obvious “step” in the well-logging curves. The unconformity surface is selected as the lower marker bed. With these easy identifications of the marker beds in the well-logging curves, we complete the stratigraphic division and comparison and obtain the stratum thicknesses of the Yan 9 member, Yan 10 member, and Fuxian Formation.

Results

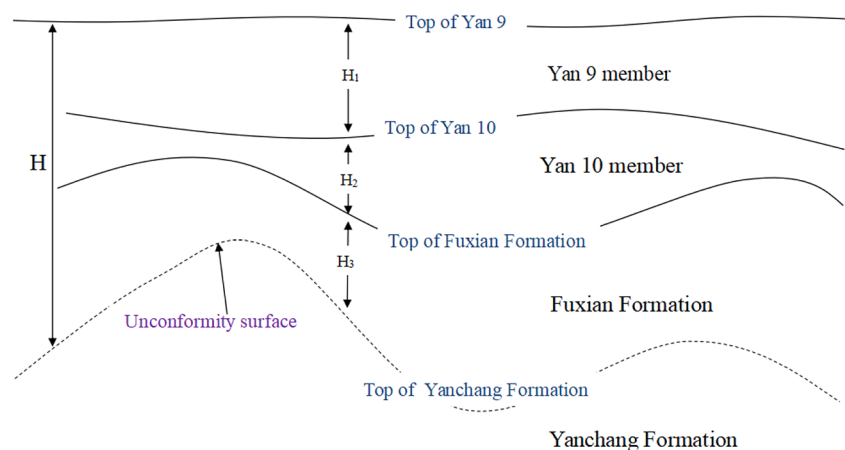
Stratum thickness features

In the study area, the stratum thickness of the Yan 9 member (H_1) ranges from 30.2 m to 42.8 m, whereas that of the Yan 10 member (H_2) is in the range of from 38.4 to 79.9 m. Therefore, the Yan 9 member is more stable than the Yan 10 member. The stratum thickness of the Fuxian Formation (H_3) varies in a wider range from 12.3 to 84.8 m. The total stratum thickness (H) of the Yan 9 member, Yan 10 member, and Fuxian Formation, ranging from 99.5 to 218.0 m, gradually increases from northeast to southwest direction. The thick strata in the southwest of this study area feature the development of sandbodies (Fig. 3). Accordingly, the contour map of the total stratum thickness (H) is generated (Fig. 4).

Paleogeomorphic units

Based on the total stratum thickness (H), we divide the paleogeomorphology of the study area into different

Fig. 2 Schematic diagram of the moldic method



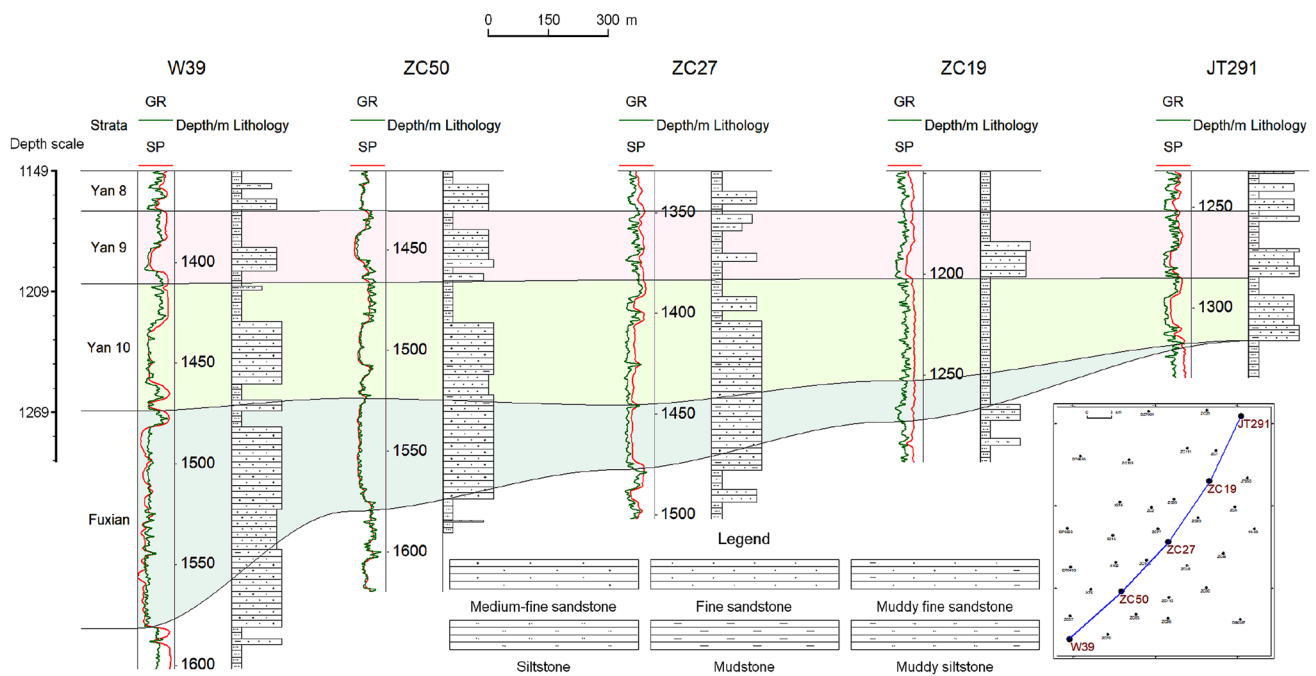


Fig. 3 Characteristics of GR and SP logging responses and the thickness variation of the Lower Jurassic strata in the study area

units (Table 1). Three paleogeomorphic units are identified: paleochannel, paleoslope, and paleohighland (Fig. 4), which are divided more accurately than previous research in this area. The characteristics of each unit are as follows.

(a) Paleochannel

The paleochannel is the lowest paleogeomorphic unit. It is extended in the north–south direction and is distributed in the south and west of the study area. The total stratum thickness (H) is more than 150 m. The paleochannel with downcutting depth of > 115 m may have branched from the Mengshan paleochannel. The sedimentary stratum is mainly characterized by a clear dualistic structure with coarse–fine-grained sediments from bottom to top. In this unit, the lower strata comprise light-gray sandstones and grayish white medium–coarse gravel-bearing sandstones, while the upper strata comprise dark gray mudstones. The sandstones are thick and massive. The 115–185-m-thick filling sandstones in the paleochannel have high-quality petrophysical properties and they serve as both reservoir strata and migration pathways (Table 2).

(b) Paleoslope

The paleoslope is a relatively high paleogeomorphic unit with a certain gradient around the paleohighland and extends nearly northeast–southwest direction. The paleoslope covers a relatively large area, and the total stratum thickness (H) varies from 90 to 150 m. Light-gray medium–fine sandstones with muddy siltstones and mudstones are mainly developed in this unit. Compared with that of the paleochannel, the sandstone thicknesses in the paleoslope clearly decrease.

The sandbodies in the paleoslope with high porosity and high permeability and the dark gray mudstones in the updip direction provide reservoir space and traps for oil accumulation, respectively. The oil generated by the source rocks at the lower part of the Yanchang Formation migrated upward along the downcutting paleochannel and partly accumulated in the paleoslope area (Table 2).

(c) Paleohighland

The paleohighland is the highest paleogeomorphic unit with a limited areal extent in the northeast of the study area. In this area, the total stratum thickness (H) is less than 90 m, and the terrain is relatively flat. This unit predominantly comprises gray siltstones and dark gray mudstones. The drilling data revealed that sediments of the Fuxian Formation are absent in the actual stratum sequence, because the paleohighland suffered from long-term weathering and denudation over the Fuxian sedimentary period (Table 2).

Distribution characteristics of oil reservoirs

Oil production data shows that oil is mainly distributed in the Yan 10 member. The plane distribution characteristics of the oil reservoirs of the Yan 10 member are as follows: (a) the oil reservoirs have a scattered distribution in plane view, with most oil reservoirs being distributed in the upper parts of the nose-like structures, which extend from the northeast to the southwest direction of the study area and (b) 93% of the oil reservoirs are distributed in the paleoslope, and 7% are distributed in the paleochannel (Table 3 and Fig. 4).

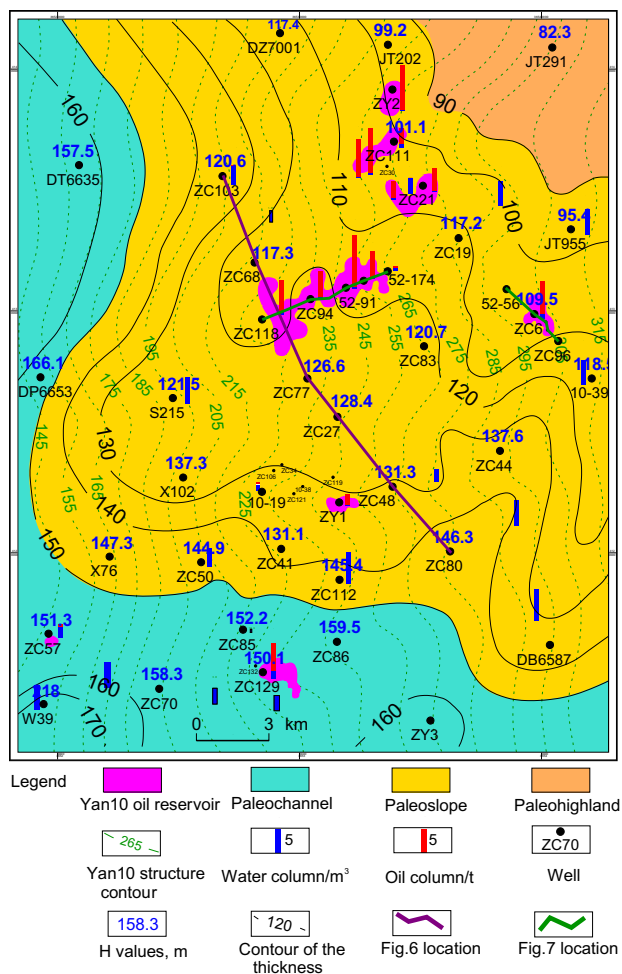


Fig. 4 Overlapping map of the paleogeomorphology, the structure contour, and the oil distribution of the Yan 10 member in the study area

Table 1 Thickness index for the classification of the paleogeomorphic units in the study area

Palaeogeomorphic units	Total thickness <i>H</i> (m)
Paleochannel	$H \geq 150$
Paleoslope	$90 < H < 150$
Paleohighland	$H \leq 90$

Discussion on favorable conditions for oil accumulation

Based on the comprehensive analysis of the source–rock features, reservoir characteristics, migration pathways, and trap conditions (Table 4), we summarize the conditions for oil accumulation in the Jurassic Yan 10 reservoirs

as sufficient oil sources, high-quality reservoirs, excellent traps, and predominant migration pathways.

Source–reservoir–cap combination

An effective source–reservoir–cap combination is important for oil accumulation. Previous regional studies argue that the sufficient oil could not be obtained from the Jurassic source rocks because of their inadequate thickness and low maturity and that the oil immigrated mainly from the Yanchang Formation (Hu et al. 2019; Ye et al. 2019). The mudstones of the lower part of the Yanchang Formation are well-developed with a certain oil-generation capacity. Notably, the organic-rich black shale rocks of the Chang 7 member are widely distributed, with the maximum thickness of more than 50 m. The total organic carbon contents range from 2.87 to 24.86% (average 14%), indicating high organic abundance. The values of vitrinite reflectance (R_o) for the shale rocks are from 0.65 to 1.15%, with a mean of 0.87%, showing relatively high maturity of organic matter (Xu et al. 2019). These high-quality source rocks are able to provide sufficient oil sources for the Ordos Basin. The study area is adjacent to the hydrocarbon generation center of the Chang 7 member and, therefore, has sufficient oil sources (Ye et al. 2019).

During the Yan 10 sedimentary period, large-scale thick sandbodies in the braided channel are important reservoirs for oil accumulation. The Yan10 member is obviously affected by the pre-Jurassic paleogeomorphology. Channel-filling sedimentation occurs on the basis of the paleogeomorphology, the braided channel is widely developed, and large-scale thick sandbodies in the braided channel serve as important reservoirs for oil accumulation. The thicknesses of the sandbodies in the paleohighland range from 0 to 20 m, mostly from 20 to 35 m in the paleoslope, and may reach up to 50 m in the paleochannel area. The sandstones, mainly composed of coarse-grained quartz, are superimposed longitudinally and interconnected in plane. Their porosities are mainly concentrated in the range of 14–20%, and their permeabilities mainly range from 1.0 to $200 \times 10^{-3} \mu\text{m}^2$ (Fig. 5). In general, the sandstones with high-quality physical properties are favorable oil accumulation reservoirs.

From the late Yan 10 period, fluvial deposits gradated to delta deposits (Liu et al. 2008). There are fine-grained sediments consisting of siltstones, argillaceous sandstones, and mudstones on the top of the Yan 10 member in the study area. During the Yan 9 period, argillaceous sediments consisting of mudstones and carbonaceous mudstones formed in the swamp. These fine-grained and argillaceous sediments, with thicknesses predominantly greater than 10 m and a maximum of 43.6 m, featured wide and stable distribution, dense lithology, and low permeability (a few with more than

Table 2 Characteristics of the paleogeomorphic units in the study area

Palaeogeomorphic units	Terrain	Stratigraphy	Total thickness <i>H</i> (m)	Lithology
Paleochannel	Lowest	Yan 9, Yan 10, Fuxian	150.1–218.0 (197.5)	Light gray and grayish white medium–coarse gravel-bearing sandstones, sandstones, mudstones
Paleoslope	Relatively high	Yan 9, Yan 10, Fuxian	95.4–147.3 (135.0)	Medium–fine sandstones with muddy siltstones, mudstones
Paleohighland	Highest	Yan 9, Yan 10	56.2–87.3 (77.4)	Siltstones, dark mudstones
Min–max (mean)				

Table 3 Oil production of the Yan 10 reservoirs in different paleogeomorphic units

Well blocks	Member	Palaeogeomorphic units	Production well number	Oil-bearing area (m ²)	Daily production of single well (t)	Total oil production (t)	Water content (%)	Total water production (t)
ZC57	Yan 10	Paleochannel	4	0.17	0.43	770.26	88.0	5665.53
ZC129	Yan 10	Paleochannel	20	1.31	3.89	35,800.51	53.9	41,891
ZY1	Yan 10	Paleoslope	10	0.58	1.81	23,244.40	56.2	29,866
ZC94	Yan 10	Paleoslope	60	7.00	8.29	299,285.11	23.6	92,455.41
ZC6	Yan 10	Paleoslope	15	1.11	4.63	10,930.36	82.6	52,024.84
ZC21	Yan 10	Paleoslope	14	1.95	5.20	35,776.46	30.7	15,832
ZC111	Yan 10	Paleoslope	16	1.58	8.50	55,485.32	46.8	48,778.34
ZY2	Yan 10	Paleoslope	10	1.00	12.97	64,472.21	9.9	7070.65

$0.01 \times 10^{-3} \mu\text{m}^2$). They work together as high-quality cap rocks of the Yan 10 oil reservoirs (Fig. 6).

Migration and preservation

The synergistic effect of the unconformity surface and the superimposed sandbodies contributed toward the formation of oil reservoirs. The unconformity developed between the Fuxian Formation and the underlying Yanchang Formation acted as a favorable site for the overpressure release from the latter formation (Wang et al. 2019). The oil generated in the Chang 7 member may have migrated upward to the top of the Yanchang Formation mainly through the pathways of structural fractures (Liu et al. 2008; Wang et al. 2011; Zhao et al. 2020) and then arrived into the superimposed and interconnected sandbodies of the Fuxian Formation and Yan 10 member. Some oil may have migrated along the sandbodies vertically or laterally. Some of the oil may have accumulated in the Yan 10 reservoirs (Ye et al. 2019). The downcutting paleochannels greatly shortened the distance between the oil source and oil reservoirs. The superimposed and interconnected sandbodies in the paleochannel provided favorable migration pathways for oil accumulation (Zhao et al. 2020).

The reservoir traps of the Yan 10 member comprise lithologic traps and structural traps of differential compaction (Liu et al. 2008). There is a certain correlation between the different compaction structures and distribution of the main sand belt. According to the overlapping map of the paleogeomorphology of the study area, structural contour of the top of the Yan 10, and oil reservoir distribution (Fig. 4), the Yan10 oil reservoirs are mostly distributed in the sandstones with high thickness values, high-quality properties, and relative structural highs in the paleoslope and paleochannel areas. For example, the oil reservoirs at the ZC 94 and ZC 129 well blocks, where the sandstone to mudstone ratio is large and just at the high point of the structures. Therefore, the local structural highs are likely the result of lithologic differential compaction and are controlled by the paleogeomorphology. The reservoir profile of the Yan10 member indicates that lenticular sandbodies are surrounded by impermeable mudstones and the traps are composed of lithologic traps and differential compaction structure traps (Fig. 7). The oil reservoirs of this type are characterized by good oil–water separation.

In summary, the organic-rich black shale rocks of the Chang 7 member of Yanchang Formation provide sufficient oil sources for the study area. The large-scale thick sandbodies

Table 4 Controlling factors of oil accumulation of Jurassic reservoirs in different paleogeomorphic units in the study area

Palaeo-geomorphic units	Well blocks	Member	Source rocks	Reservoir lithology	Reservoir properties		Cap rocks	Migration pathways	Trap conditions
					Porosity (%)	Permeability ($10^{-3} \mu\text{m}^2$)			
Paleochannel	ZC57, ZC129	Yan 10	Chang 7 shale rocks	Fine sandstone	14.28–18.00 (15.66)	9.119–100.924 (27.76)	The swamp mudstones of Yan 9 delta plain	Structural fractures of Yanchang formation, superimposed and interconnected sand bodies of Yan10 member and Fuxian formation	Lithology and differential compaction structure
Paleoslope	ZY1, ZC94, ZC6, ZC21, ZC111, ZY2	Yan 10	Chang 7 shale rocks	Fine sandstone	13.00–21.53 (16.43)	3.983–582.371 (62.920)	The swamp mudstones and carbonaceous mudstones of Yan 9 delta plain as well as the argillaceous sandstones and mudstones on the top of Yan10 member	Structural fractures of Yanchang formation, superimposed and interconnected sand bodies of Fuxian formation	Lithology and differential compaction structure

Min–max (mean)

with high-quality physical properties in the braided channel provide good reservoir space for oil accumulation of Yan 10. The fine-grained and argillaceous sediments of Yan 9 member and Yan 10 member work together as high-quality cap rocks of the Yan 10 oil reservoirs. The downcutting paleochannels greatly shorten the distance between the oil source and oil reservoirs. The superimposed and interconnected sandbodies in the paleochannel provided favorable migration pathways for oil accumulation. The local structural highs resulted from lithologic differential compaction are suitable traps for oil preservation. The synergistic effect of source rocks, reservoirs, cap rocks, migration pathways and traps is the basic condition for the formation of the paleogeomorphic reservoirs.

Oil accumulation patterns

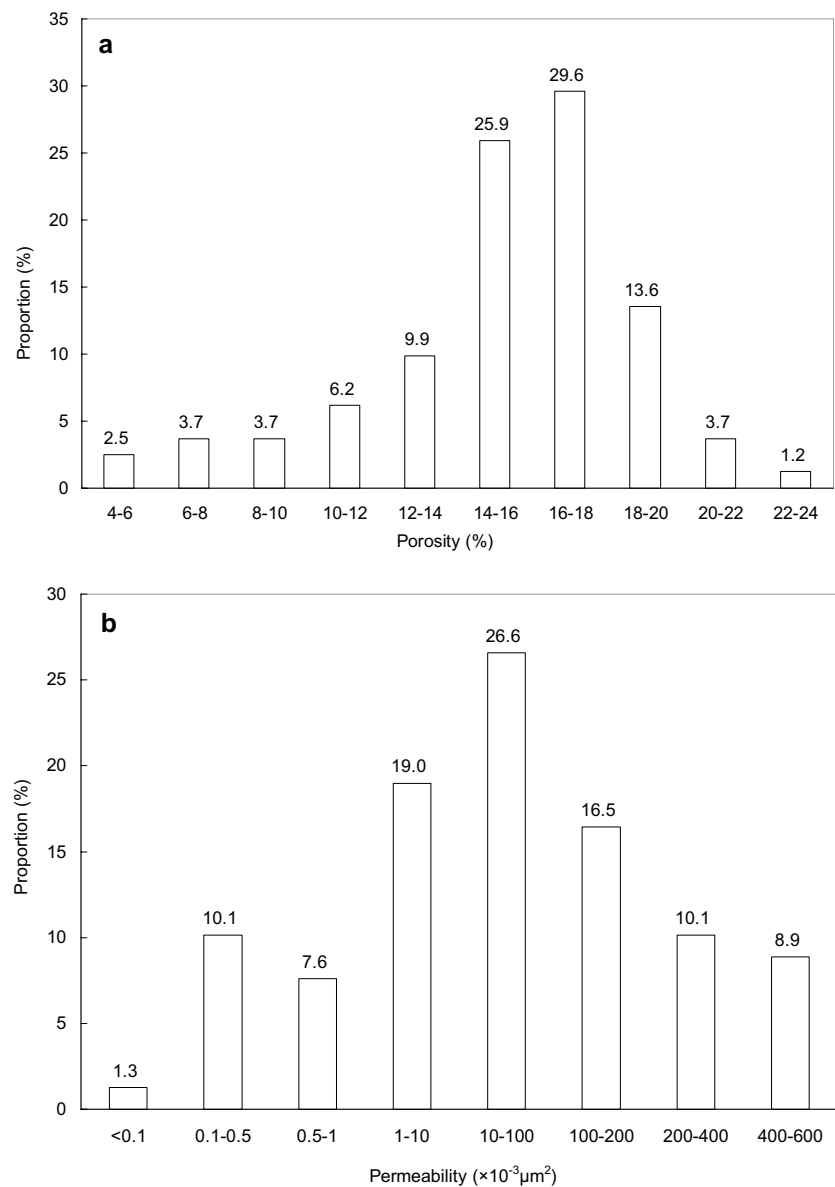
According to the plane distribution of the proved oil reservoirs of the Yan 10 member in the study area and in combination of other factors, such as the sedimentary environment,

structure, reservoir, migration pathway, and the paleogeomorphology, this paper newly established two oil accumulation patterns in 2D: the paleoslope-braided channel-delta plain pattern and the paleochannel-braided channel-delta plain pattern. The pattern for oil accumulation in 3D is also established for the first time.

Paleoslope-braided channel-delta plain pattern

The oil reservoirs of the paleoslope-braided channel-delta plain pattern are distributed in the paleoslope (Fig. 8). The braided-channel sandbodies of the Fuxian Formation act as oil migration pathways. The swamp mudstones and carbonaceous mudstones of the Yan 9 delta plain and the argillaceous sandstones and mudstones on the top of the Yan 10 member act as cap rocks. On the paleoslope, the sedimentary environment of the Yan 10 member changed frequently in lateral directions, i.e., the sandstones converted into mudstones frequently. The sandbodies of the Yan 10 member likely played a dual role in oil migration and oil

Fig. 5 Distribution histogram of the physical properties of the sandstone reservoirs in the Yan10 member (132 samples). **a** Porosity: concentrated in the range of 14–20%. **b** Permeability: concentrated in the range of $1\text{--}200 \times 10^{-3} \mu\text{m}^2$



preservation. Oil reservoirs of this pattern, such as the oil reservoir of the ZC94 well block, are characterized by an active edge and bottom water.

Paleochannel-braided channel-delta plain pattern

The oil reservoirs of the paleochannel-braided channel-delta plain pattern are distributed in the paleochannel of the pre-Jurassic paleogeomorphology (Fig. 8). The braided-channel sandbodies of the Fuxian Formation act as the oil migration pathways. The braided channel sandbodies of the Yan 10 member act as the main reservoirs, and the overlying delta plain swamp mudstones of the Yan 9 member act as cap rocks. The small differential compaction structures facilitate oil accumulation.

In the ZC129 well block, for example, the downcutting paleochannel may have shortened the distance between the oil source rocks of the Chang 7 member and the Yan 10 permeable sandstones. Thus, the resistance to oil migration was greatly reduced, migration pathways between the oil source rocks and oil reservoirs were created, and the oil migrated upward through the paleochannel and finally accumulated in the top layer of the Yan 10 member.

The paleochannel-braided channel-delta plain pattern newly established in this study can perfect the theory of oil accumulation of paleogeomorphic oil reservoirs, and can guide oil exploration in paleochannels in future. Oil exploration cannot no longer only focus on paleoslopes.

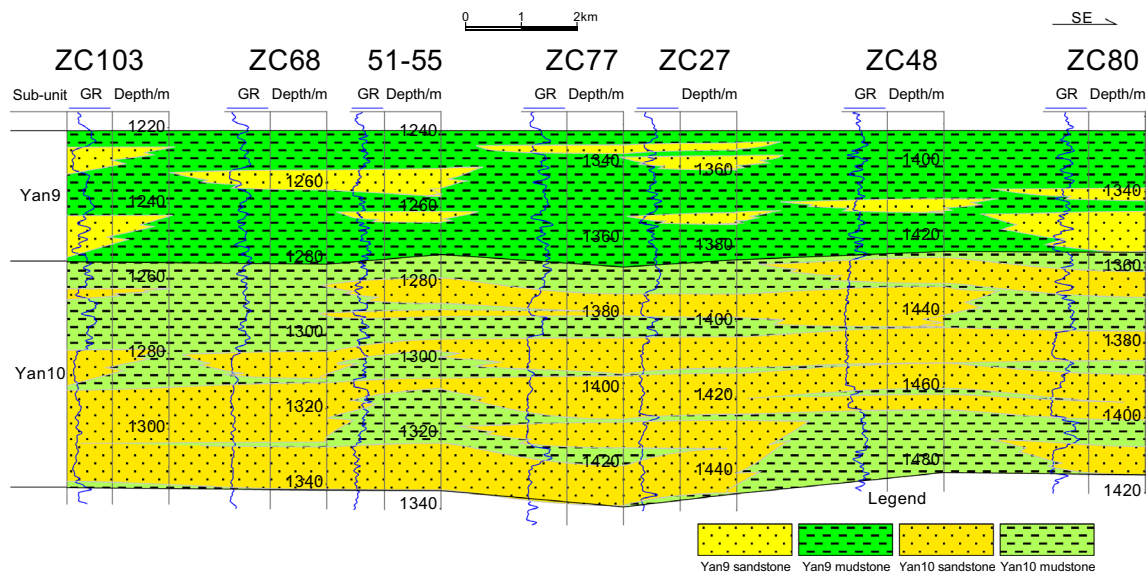


Fig. 6 NW–SE trending profile showing the lithology of the Yan 9 and Yan 10 members (profile position is shown in Fig. 4)

Favorable area prediction

Prediction principle

Based on the above analysis of favorable conditions for oil accumulation patterns of Yan 10 member, according to the "four key factors of reservoir formation: paleogeomorphic background, tectonic dominance, sandbody control and cap-rock closure", the following principles are proposed for the prediction of favorable areas.

(1) Paleogeomorphic background: both the paleoslope unit and the paleochannel unit are possible areas for oil accumulation of Yan 10 member, but the highland unit is not.

(2) Tectonic dominance: nose-like structures formed by regional structural movements or differential compaction in the later stage are the favorable directional areas for oil migration and accumulation of Yan 10 member.

(3) Sandbody control: the thick sandbodies with good physical properties on the main sandbelts of the braided channel are favorable reservoirs for oil accumulation of Yan 10 member in the study area.

(4) Cap-rock closure: based on the analysis on the cap rocks of the oil reservoirs discovered in Yan 10 member, the area with mudstone thickness values larger than 15 m and mudstone permeability less than $0.01 \times 10^{-3} \mu\text{m}^2$ is a favorable region for oil preservation.

Therefore, the main sandbelts of the braided channel in the paleoslope or paleochannel with the local small amplitude nose-like structure and thick mudstones at the top are considered as favorable area for oil reservoir accumulation.

Prediction results

A total of four favorable areas are chosen in the study area, namely, favorable area I, II, III, and IV (Fig. 9). The favorable area I is about 2.76 km^2 , which is located in the paleoslope unit with the sandstone thickness of the main sandbelt larger than 20 m. There are mudstones with thickness larger than 20 m acting as cap rocks in the upward dip direction of the reservoir. Nose-like structure is developed in the north. One well, ZC30 well, has been drilled, and evidences of hydrocarbon are found. The favorable area II is about 7.64 km^2 , and it is located in the paleoslope unit with the sandstone thickness of the main sandbelt larger than 25 m. There are mudstones with thickness larger than 15 m acting as cap rocks. Nose-like structure is developed nearby. Six wells have been drilled, and evidences of hydrocarbon are found in every well. The oil testing production of 10–19 well is 1.36 t/day. The favorable area III is about 1.25 km^2 . It is located in the paleochannel unit with the sandstone thickness larger than 30 m. There are mudstones with thickness larger than 15 m acting as cap rocks in the upward dip direction of the reservoir. A nose-like structure is developed nearby. A well, ZC132 well, has been drilled, and evidences of hydrocarbon are found. The favorable area IV is on the southeast of the proved ZC57 well block. Its area is about 1.96 km^2 , and it is located in the paleochannel unit with the sandstone thickness larger than 30 m. There are mudstones with thickness larger than 20 m acting as cap rocks in the upward dip direction of the reservoir. A nose-like structure is developed nearby. No well has been drilled now.

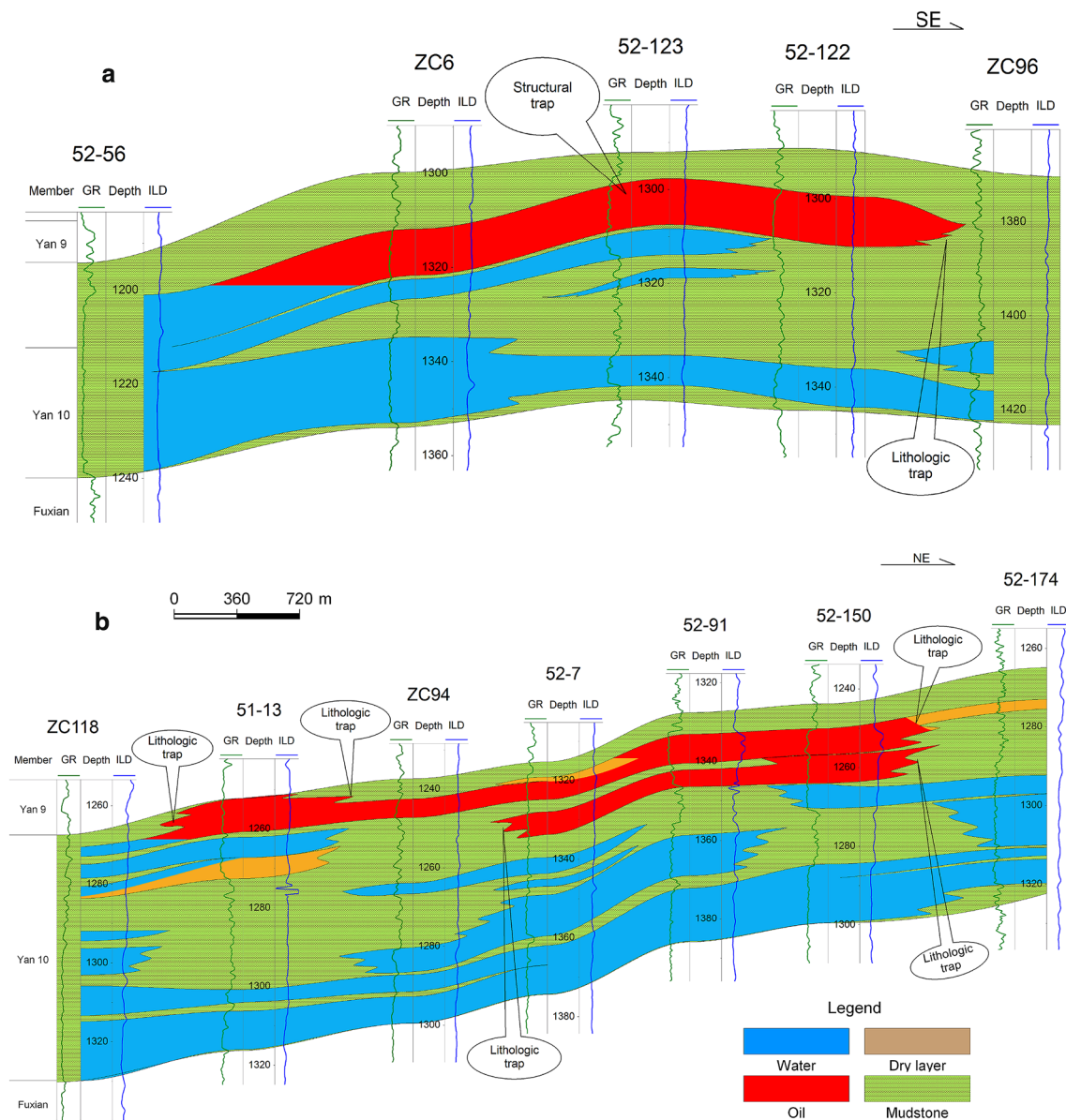
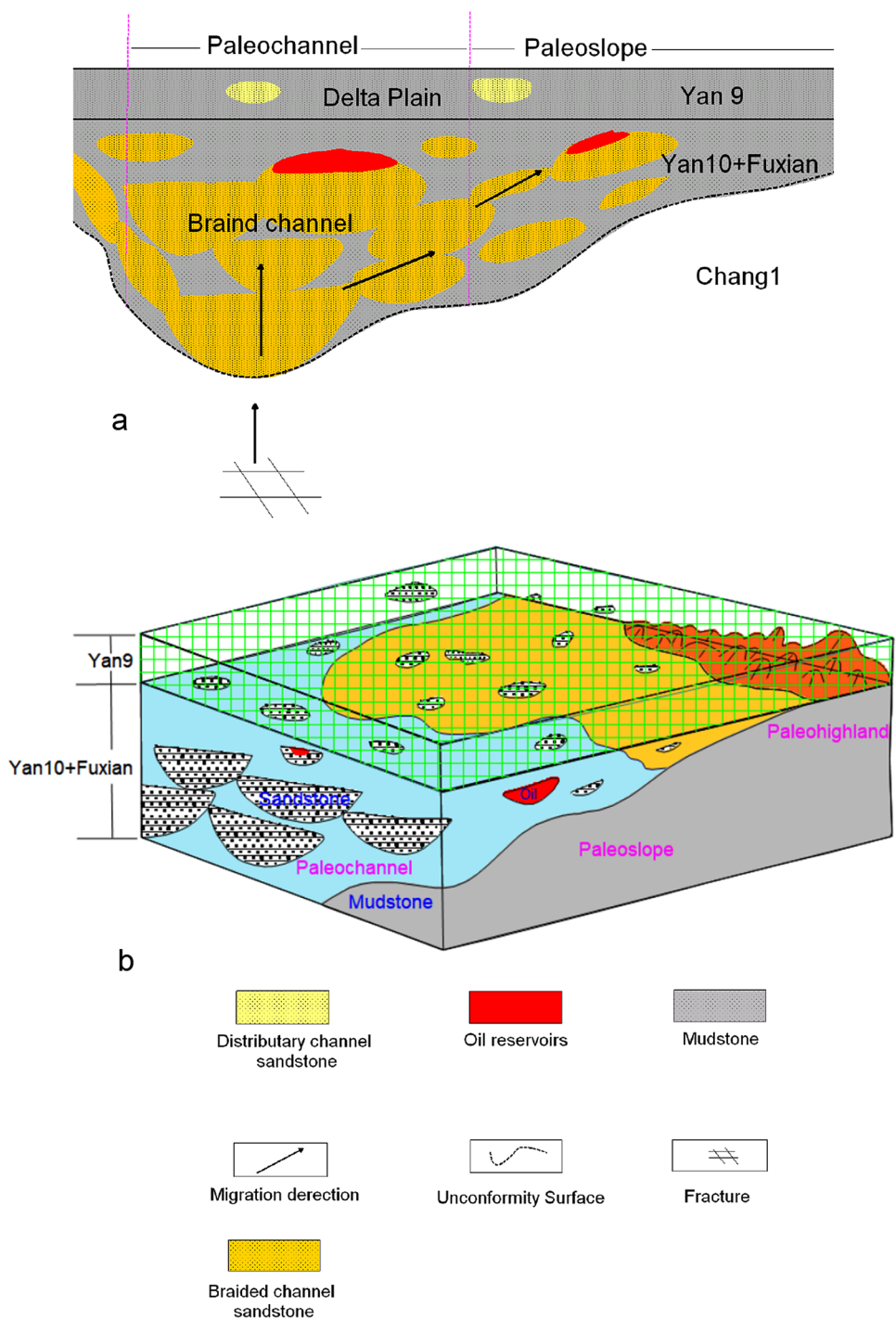


Fig. 7 Reservoir profiles showing the trap conditions of the Yan 10 member (profile position is shown in Fig. 4)

Conclusions

1. The stratigraphic division of the Lower Jurassic strata is performed in the investigated Zhouchang area, Ordos Basin. The stratum thicknesses of the Yan 10 member and the Fuxian Formation both vary in a wide range, whereas that of the Yan 9 member is more stable. The pre-Jurassic paleogeomorphology is restored using the moldic method. There are three paleogeomorphic units in the study area: paleochannel, paleoslope, and paleo-highland. The pre-Jurassic strata likely dip from the northeast to the southwest direction of the study area. Different from previous research conclusions, the proved
- oil reservoirs of the Yan 10 member are located not only in the higher paleoslope but also in the lower paleochannel.
2. Oil accumulation is controlled by the pre-Jurassic paleogeomorphology. Paleochannel sandbodies act as conducive pathways and storage space for oil migration and accumulation, respectively. The sandbodies in the paleoslope area are considered to be favorable reservoirs for oil, and the microamplitude structures and lithological traps controlled by paleogeomorphology favor hydrocarbon preservation.
3. Two oil accumulation patterns are newly established: the paleochannel-braided channel-delta plain pattern and

Fig. 8 Schematic diagram of oil accumulation patterns of the Lower Jurassic Formation in the Zhouchang area. **a** 2D model **b** 3D model



the paleoslope-braided channel-delta plain pattern. The latter is the major pattern in the study area.

4. Based on the key factors of paleogeomorphic background, tectonic dominance, sandbody control and cap-

rock closure, four favorable regions, i.e., favorable area I, II, III, and IV, for oil accumulation in the study area are predicted, which are target zones for future oil explorations of Yan 10 member.

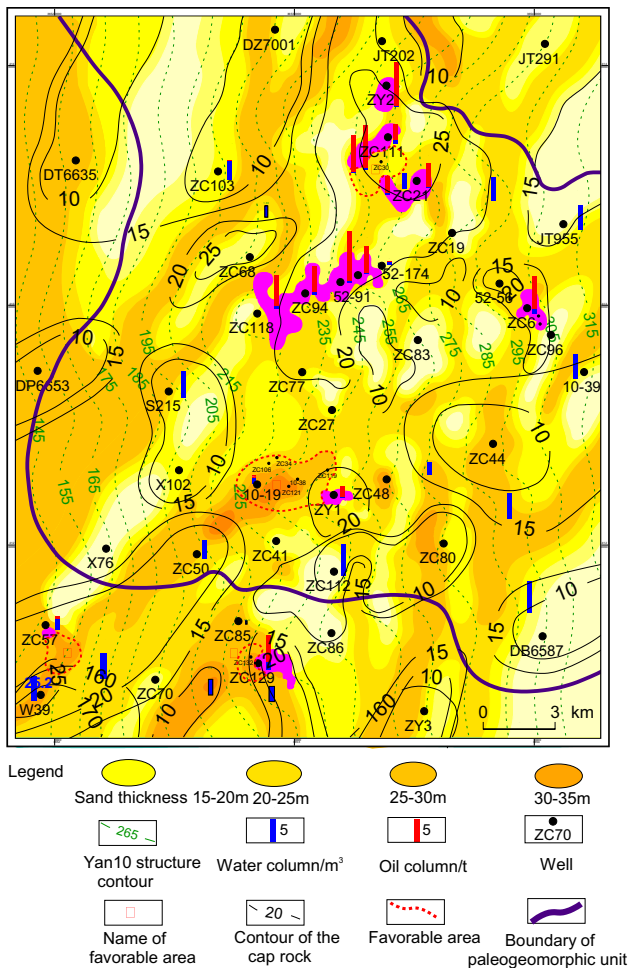


Fig. 9 Favorable areas of oil enrichment from the Yan 10 member in the study area

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Data availability statement The data sets analyzed during the current study are available from the corresponding author on a reasonable request.

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