Factors Controlling Hydrocarbon Accumulation in Jurassic Reservoirs in The Southwest Ordos Basin, NW China

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Abstract: The sedimentary, paleogeomorphological and reservoir characteristics of the Jurassic Yan'an Formation in the southwestern Ordos Basin, northwest China, were studied by means of casting thin sections, scanning electron microscopy, inclusion analysis and identification of low-amplitude structures. A model for reservoir formation is established, and the controlling effects of sedimentary facies, paleotopography, low-amplitude structures and formation water on oil reservoirs are revealed. There are significant differences in the sedimentary characteristics, structural morphology and paleowater characteristics between the reservoirs above the Yan 10 Member and those in the Yan 9 to Yan 7 members. The Yan 10 Member contains fluvial sediments, whereas the Yan 9 to Yan 7 members contain delta-plain anastomosing-river deposits. The distribution of high-permeability reservoir is controlled by pre-Jurassic paleogeomorphology and sedimentary facies, Some of these facies exhibit high porosity and high permeability in a low-permeability background. The main hydrocarbon accumulation period was during the late Early Cretaceous, filling was continuous, and the charging strength altered from weak to strong and then from strong to weak. The Yan 10 reservoir is mainly controlled by the paleogeomorphology: hydrocarbons migrated upward at high speed through the unconformity surface, and accumulated in the favorable traps formed by paleogeomorphic structural units, such as gentle slopes or channel island. Furthermore, groundwater alternation in these areas is relatively stagnant, providing good reservoir preservation conditions. The reservoirs in the Yan 9 and higher members are controlled by the sedimentary facies, low-amplitude structure and paleowater characteristics, Hydrocarbons migrated through the three-dimensional delivery system, influenced by favorable sedimentary facies and high-salinity groundwater, then accumulated in the favorable low-amplitude structural traps that formed during the hydrocarbon production period.

Keywords: southwestern Ordos Basin; Jurassic Yan'an Formation; inclusion analysis; low-amplitude structure; hydrocarbon accumulation

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1 Introduction

The Jurassic Yan'an Formation reservoir was one of the earliest discovered reservoirs in Ordos Basin, and may even be the first reported oil layer in the world(Yang et al., 2002; Guo et al., 2008). As early as the Han Dynasty in China, the historian Ban Gu recorded in the "Book of Han" that "Gao Nu, the Wei river, is rich and flammable", Gaonu is now Yan'an city, the Wei river is a tributary of Yanhe River(Yu, 2016). After the discovery of Maling Oilfield in Qingyang County of Gansu Province in 1970s, the exploration of Yan'an Formation attracted a great deal of attention (Huang et al., 1980; Wang et al., 1991). After nearly 30 years of research and exploration, many Jurassic reservoirs (such as Wuqi, Fanjiachuan and Huachi reservoirs) have been discovered, which have become the main exploration strata of the Mesozoic succession in the Ordos Basin (Yang et al., 1984, 2002; He et al., 2003). The Jurassic reservoirs possess good reservoir physical properties, small reservoir size, high abundance of reserves, high single-well production and low saturation pressure. These features are of great significance for economically beneficial exploration under the background of a low oil price (Yang et al., 1984, 2002; Zhang et al., 2001; He et al., 2003; Fu et al., 2013).

With increasing petroleum exploration in the Ordos Basin, the exploration saturation in the basin has steadily increased, and the target of exploration has gradually shifted to the basin margin. In recent years, a series of new

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discoveries have been made in the Jurassic Yan'an Formation in the Pengyang area, southwest Ordos Basin. Many exploratory wells were drilled in the Huanxian, Pengyang, Yanwu, Mengba and Xiaoxian areas, where industrial oil flows were obtained, leading to discovery of the Pengyang and Yanwu oil fields and reinforcing the status of this area as an important exploration reserve zone (Liu et al., 2010; Yang et al, 2012; Yu et al., 2013; Lan et al., 2014; Ye et al., 2018). The formation conditions of Jurassic reservoirs in the southwest of the basin were complex, and the reservoir distribution is controlled by many factors, such as paleogeomorphology (Huang et al., 1981; Yang et al., 1984; Guo et al., 2008; Ding et al., 2008; zhu et al., 2010; Yuan et al., 2013; Mao et al., 2013), low-amplitude structures (Guo et al., 2001; Li et al., 2013; Yu et al., 2013;Xu et al., 2015; Chai et al., 2018, 2019) and lithology (Yang et al., 2002; Song et al., 2003; Zhao et al 2016; Ye et al., 2018). The area exhibits rapid phase transitions, complex oil–water relationships, an unclear oil–water interface and development of low-resistivity reservoirs, leading to difficulty in reservoir identification and a lack of clarity on the factors controlling reservoir formation and distribution (Hu et al., 2002). Little research has been conducted on the main factors affecting reservoir formation in this area. To guide further oil and gas exploration and development, it is necessary to determine the distribution of sand bodies, the pore structure of reservoirs and the factors controlling oil and gas accumulation in Jurassic reservoirs in the study area.

2 Geological Settings

The research area is located in the southwest Ordos Basin, northwest China. The study area extends to north to Duhoutan, south to Mengba, west to Pengyang and east to Maling, covering an area of about 1.0×10^4 km^2. The area includes four administrative regions: Pengyang, Huan, Zhenyuan and Maling counties. The region can be divided into three tectonic units: the southwest Yishan Slope, the Tianhuan Depression and the western margin thrust belt(Fig. 1), which is structurally complex (Zhang et al., 2018). As a result of river erosion and tectonic uplift during the Jurassic Period, the stratigraphic sequence is not complete and there is substantial variation in the sedimentary succession across the area. Most of the strata above the Chang 3 Member of the Yanchang Formation are missing, and denudation has affected down to the Chang 6 Member of the Yanchang Formation. The Yan 1 to Yan 3 members of the Yan'an Formation were affected by denudation, and the total thickness of the Yan 6 to Yan 9 members is about 80–160 m. The Yan 10 member and Yan 9 to Yan 7 members of the Jurassic Yan'an Formation are the main target layers of this study. Details of the sedimentary thickness and lithologic characteristics of each reservoir group are provided in Table 1. Stratigraphic correlation has demonstrated that the Yan'an Formation is missing or partially missing in the western part of the study area. A complete sequence of the Yan 7 to Yan 9 members is present in the central and eastern part of the area, and the Yan 10 Member was deposited in the northeastern part of the study area. Regional stratigraphic correlation shows that marker layers B1, B2 and B3 (which are mainly coal seams 2–4 m thick) are the main marker beds for stratigraphic division and correlation of the Jurassic Yan'an Formation in the study area（He et al., 2013; Chen et al., 2013）.

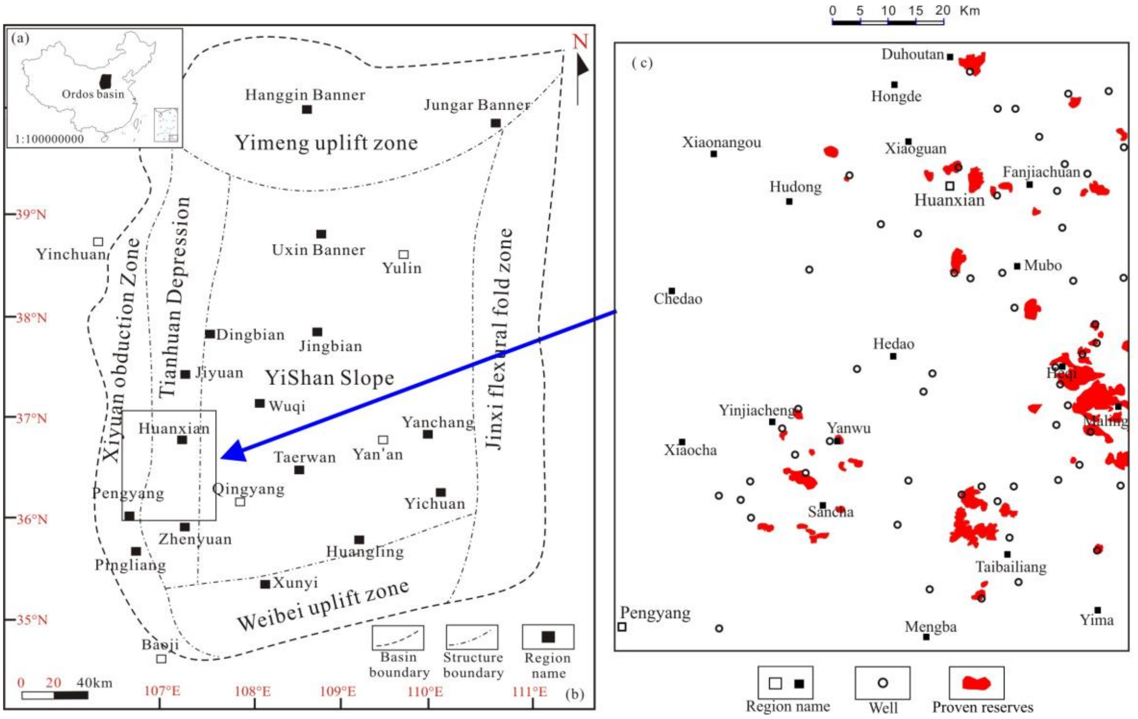

Fig. 1. Location map and structural elements of study area in the Ordos basin, NW China (China basemap after China National Bureau of Surveying and Mapping Geographical Information).
(a) Index map showing the general location of the Ordos Basin in China; (b) Tectonic elements of the study area; (c) Locations of wells and reservoirs.

Table 1 Stratigraphy and lithology of Upper Triassic and Lower Jurassic in Ordos Basin

Epoch	Fomation	Subsection	Thickness (m)	lithology	marker bed
	Zhiluo		200-400	Grayish-white glutenite	
		Yan1-Yan3	strata missing		
		Yan4+5	20-35		
Lower Jurassic		Yan6	20-35		B3
	Yan'an	Yan7	20-40		
		Yan8	20-40	Grayish-white sandstone and Deep Gray mudstone interbedded, Rich in fossil plants, ostracods and Gastropod fossil	B2
		Yan9	20-50		
		Yan10			B1
		chang1	Most strata missing		
		chang2			
Upper Triassic	Yanchang	chang3	100-120 (some strata missing)	Development of gray-black mudstone siltstone in middle and upper part, Development of siltstone with black mudstone and Sand grain bedding and small cross bedding in the lower part	K6

3 Sedimentary and Reservoir Characteristics

3.1 Sedimentary characteristics

The Ordos Basin was affected by the Indosinian Orogeny at the end of the Triassic Period and the whole basin was unevenly uplifted (Xu et al., 1985; Yang et al., 2002). The uplift resulted in extensive erosion, long-term weathering and leaching of the Triassic strata to form a landscape consisting of crisscrossing river valleys, highlands, residual hills and ancient terraces. The deposition and distribution of the lower Yan 10 Member and Fuxian Formation were largely controlled by the paleogeomorphology and tectonic setting.

The basin began to subside in the Yan 9 period. Rapid lake transgression, quick accumulation of deltaic deposits, and rapid infilling of the topography took place. During the Yan 8 period, deltaic sedimentation reached its peak. The area of the lake basin reached its maximum during the Yan 7 to Yan 6 interval, at this time, deltaic sedimentation began to wane, because of undercompensation. During the Yan 4 + 5 period, the basin was uplifted further, the lake basin and delta deposits shrank, and the plains gradually became swamp (Guo et al., 2001).

From analysis of core data for the Jurassic reservoirs in more than 40 exploration and evaluation wells in the study area, the main reservoir of the units Yan'an Formation, the Yan 10 member and Yan 9 to Yan 7 members, exhibits marked variation in sedimentary characteristics. The Yan 10 Member is mainly composed of feldspathic quartz sandstone, feldspathic lithic sandstone and lithic sandstone. This unit largely consists of fluvial deposits (Fig. 2a), mainly sandy gravel, with coarse-grained, thick-bedded sandstone(Fig. 2b). The fine-grained sediments are mostly siltstone, silty mudstone and carbonaceous mudstone(Fig. 2c) and exhibit cross-bedding (Fig. 2d), containing carbonized fossil stems or carbonaceous debris（Fig. 2e）. Bioturbation is rare in the fine-grained sediments, reflecting a high-turbidity fluvial sedimentary environment(Liu et al., 1980). Delta-plain braided-river deposits are developed in the Yan 9 and higher members. The dominant lithology is feldspathic lithic sandstone and lithic feldspathic sandstone. These sandstones are coarse-, medium- and fine-grained, normally graded, and exhibit wedge-shaped cross-bedding, tabular cross-bedding, trough cross-bedding and parallelbedding(Fig. 2f.g). The fine-grained sediments are mostly silty mudstone, muddy siltstone and carbonaceous mudstone. Coal seams, which are generally 1–4 m thick, are developed. Carbonized plant stem remains or carbonaceous fragments are present, and vertical burrowing is common(Fig. 2h), reflecting the terrestrial swamp sedimentary environment and luxuriant vegetation(Chu et al., 2013).

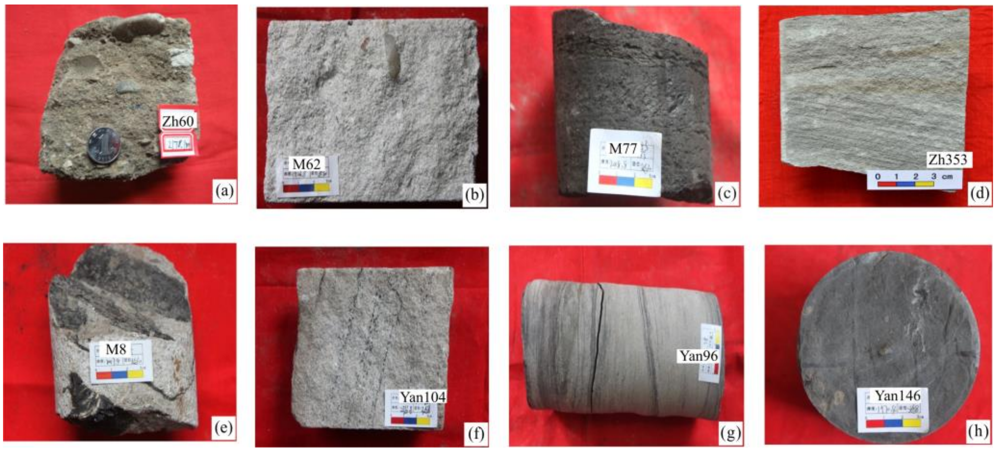

Fig. 2. Photographs showing the sedimentary structural characteristics of cores.
(a) Zh60, Yan10, bottom conglomerate sedimentation; (b) M62, Yan10, middle coarse sandstone of block structure;(c) M77, Yan10, carbon mudstone; (d) Zh353, Yan10, tabular cross bedding; (e) M8, Yan10, Carbonated plant fossil stem; (f) Y104, Yan8, parallel bedding; (g) Y96, Yan9, normal grain sequence ripple cross bedding; (h) Y146, Yan8, plant debris and biological vertical drilling.

The Yan 10 Member mainly developed fluvial deposits with braided river characteristics, These deposits contain channel subfacies (incorporating channel lag deposit and channel bar microfacies) and overbank deposit subfacies (incorporating floodplain and side bar microfacies). Braided rivers are characterized by frequent channel and sand-bar migration; thus, development of the channel bar facies is an indicator of the existence of an ancient river (liu et al., 1980). High velocity sedimentary structures, such as trough cross-bedding, wedge-shaped cross-bedding, tabular cross-bedding and parallel bedding, can be seen on a single well geogram （Fig.3）. Graded bedding is not obvious and there is no biological remains. The gamma-ray log curves are mainly box-shaped. The floodplain contains thin deposits of fine-grained sediment, dominantly gray-black or black silty mudstone, with ripples and horizontal bedding. Carbonized plant stems and trace fossils are rare. Poingt bar deposits are developed in the edge of the channel, but they are much less developed and eroded than meandering rivers. The resistivity log curves are characterized by a medium to low toothed protuberance,, and the gamma-ray log curves are usually box-shaped with a lower amplitude

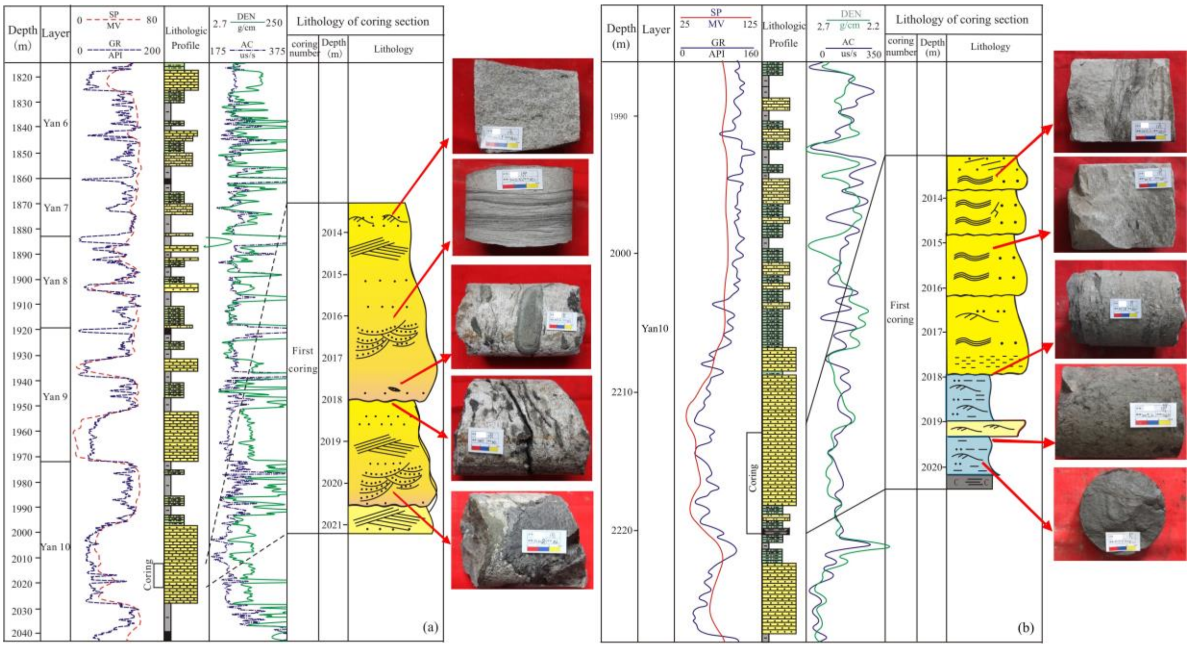

Fig. 3. Sedimentary facies map of single well in Yan'an formation, Yan10 member.
(a) Mu8, Yan10, channel bar facies; (b) M77, Yan10, floodplain facies.

The distribution of sedimentary facies in the Yan 10 stage of the study area was controlled by the pre-Jurassic paleogeomorphology. The channel lag subfacies mainly occur in the northeast Gan-shaan primary ancient River valley, the Qingxi secondary ancient river valley, the Zhenbei branch river valley, and in the Yanwu branch ditch, west of Yinjiacheng town. The floodplain subfacies is found in the gentle zone between the river bed and the highlands. In addition, channel bars developed in a limited area determined by the paleotopography (Shi et al., 2002, 2003; Song et al., 2003; Zhao et al., 2005; Guo et al., 2008). The Gan-Shaan ancient river in the north of the study area has a sand body to total rock ratio of more than 85% and a paleoflow direction from west to east. In the Yanwu branch ditch, west of Yinjiacheng, the ratio of sand body thickness to total rock thickness is relatively low, and the channel width is about 2–6 km（Fig. 4）.

At the end of the Yan 10 stage, the topography of the basin gradually became flatter, the climate gradually became warm and humid and the vegetation was luxuriant. The lake basin was a vast expanse of water during flood periods; during the dry season, the river meandered and scattered lakes occurred throughout the Ordos Basin（Ye et al., 2014）. With this background, delta-plain anastomosing-river deposits developed in the Yan 9 and stratigraphically higher layers. In addition, sedimentary microfacies such as distributary channels, back swamps, natural barrier and crevasse splay can be identified in the study area(Fig.5a, b,c, d), with distributary channel and river overflow marsh microfacies being the most common. The sedimentary environments of the Yan 9 to Yan 7 members were inherited from the previous member, and the scale of the deposition was enhanced. The river channel was directed northeast in southern Huanxian County, east–west in the vicinity of Huanxian County, and southeast in northern Huanxian county. From the Yan 9 to Yan 7 period, the channel migrated little, and and sedimentation was greatest during the Yan 7 period.

Nearly 40% of the study area is occupied by channel microfacies, which is oriented NE-SW. The channel is narrow, banded distribution, and frequently bifurcates. The width of the channel is about 3–6 km. The flood plain is well developed and covers a wide area, and the channel is arranged within the flood-plain microfacies(Fig. 6). The development of sand bodies was controlled by the sedimentary facies, and the sand-body distribution is consistent with that of anastomosing-river channels.

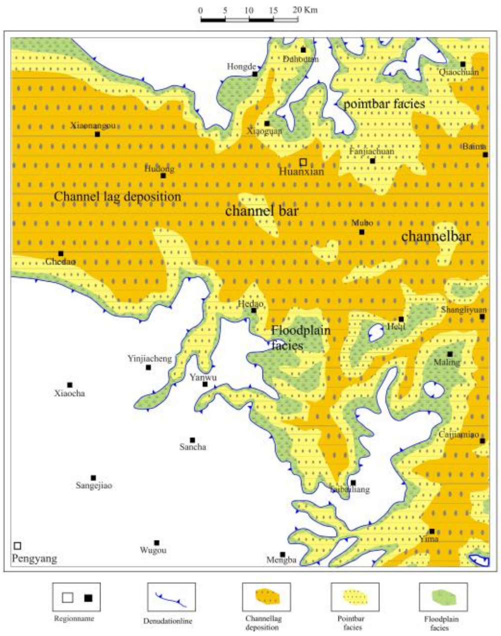

Fig. 4. The distribution of Jurassic Yan10 and Fuxian sedimentary facies diagram.

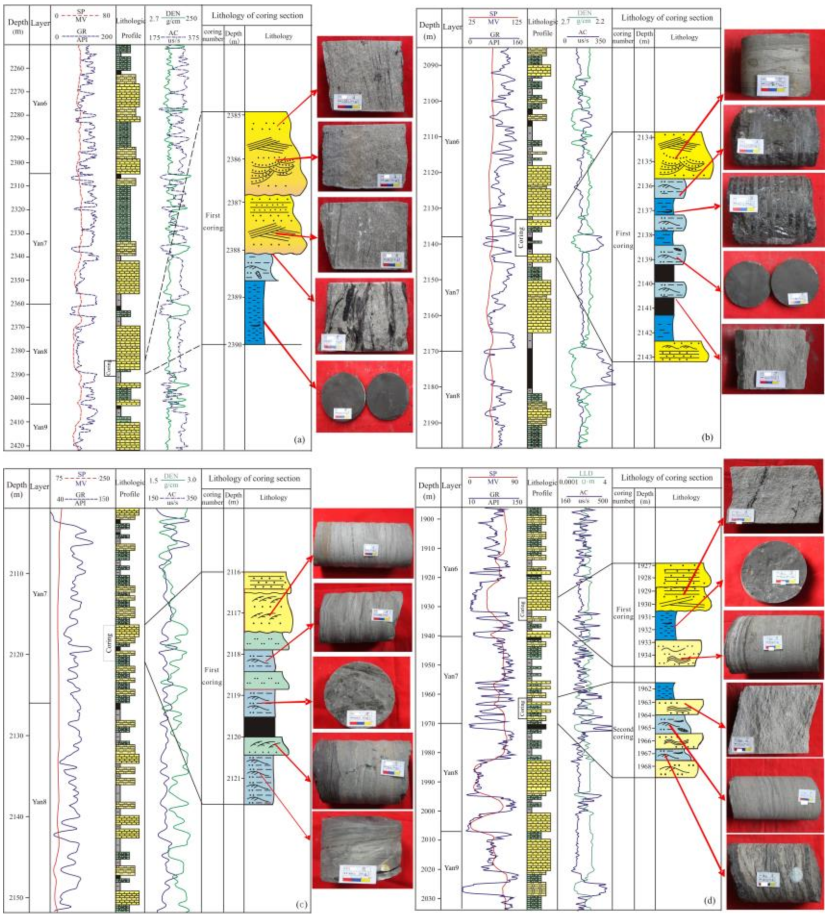

Fig. 5. Sedimentary facies map of single well in Yan'an formation, Yan9 and higher member.
(a) Hu33, Yan8, distributary channels microfacies; (b) Y214, Yan7, back swamps microfacies; (c) Y117, Yan7, natural barrier microfacies; (d) Y162, Yan6 and Yan7, crevasse splay microfacies.

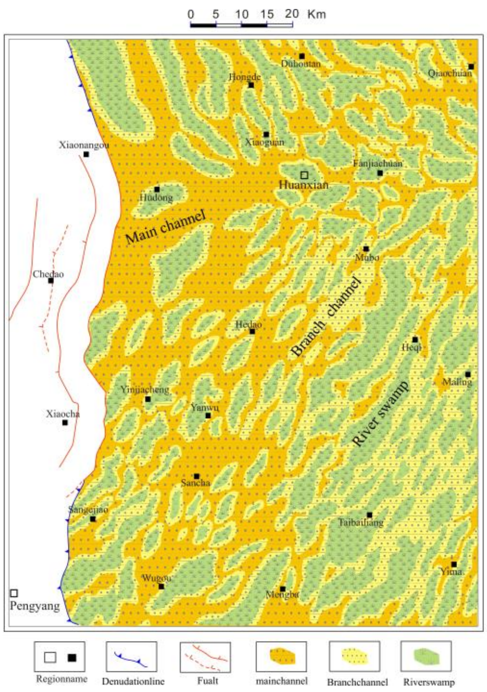

Fig. 6. The distribution of Jurassic Yan9 to Yan7 sedimentary facies diagram.

3.2 Reservoir characteristics

The results of casting thin section and scanning electron microscope analysis indicate that the main pore types of the Yan'an Formation in the study area are intergranular pores, feldspar dissolution pores, lithic dissolution pores and intergranular pores(Fig. 7). Of these, intergranular pores and dissolution pores are the main reservoir spaces, with intergranular pores accounting for 64% of the total rock porosity. The dissolution pores were mainly formed as a result of dissolution of unstable components in feldspar and debris; these pores are irregular in both size and shape. Dissolution pores account for 24.9% of the total rock porosity in the Yan'an Formation reservoirs, of which feldspar dissolution pores are the most abundant (12% of total porosity), and lithic dissolution pores are of secondary importance (6% of total porosity). Intergranular pores are relatively small, accounting for only 6% of the total porosity, and are 0.5–15.0 μm in size. The average surface porosity of the sandstone reservoir is 7.6%. The main pore and throat combinations are mesopores with medium–coarse throats and fine pores with micro-throats, which are characteristic of high-quality reservoirs with low permeability (Yang et al., 2016; Yang et al., 2017).

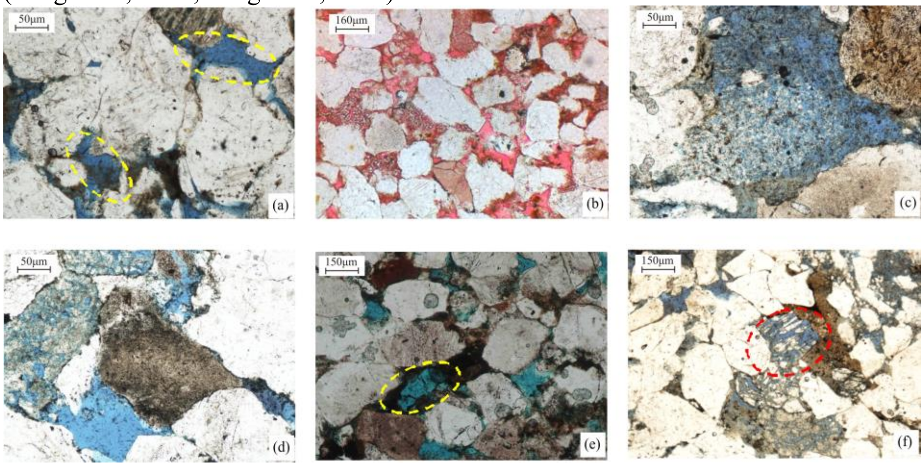

Fig. 7. Photomicrographs of Pore type occurrence of cast sheet in study area.

(a) M130, Yan10, Intergranular pore and intergranular solution pore; (b) L44, Yan8, Intergranular pore; (c) M33, Yan10, Feldspar dissolution pore; (d) H33, Yan9, detritus dissolution pore; (e) Y153, Yan10, mould pore; (f) M33, Yan10, kaolinite intercrystalline pore.

Statistical analysis of core analysis data for nearly 80 wells in the study area has demonstrated that the Jurassic reservoirs are characterized by high porosity and high permeability, and high-quality reservoirs are present. Reservoir porosity is 6.8%–22.3%, average 14.7%; permeability is 0.3–521 mD, average 34.2 mD(Fig. 8). The porosity of the Jurassic reservoirs is mainly affected by the grain size and sorting of the sandstone: the larger the grain size, the greater the porosity; the better the sorting, the greater the porosity (Scherer M et al., 1987; Zhang et al., 2008;Liu et al., 2015). There is a good positive correlation between porosity and permeability(Fig. 9), indicating that reservoir permeability is controlled by pore and throat size and by pore structure (Houseknecht, et al., 1987; Mc Creesh et al., 1991; Liu et al., 2013).

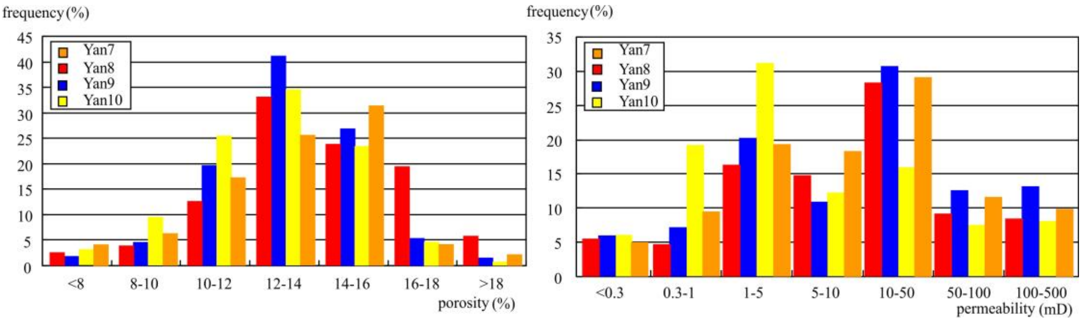

Fig. 8. Distribution Frequency map of porosity and permeability of sandstone reservoir in Yan'an formation of Jurassic in study area.

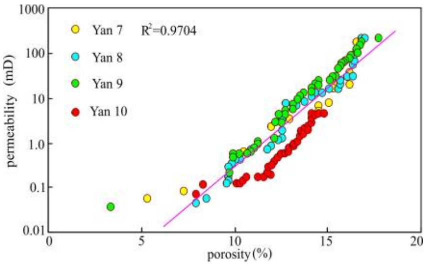

Fig. 9. Scatter plot of porosity and permeability of sandstone reservoirs in Yan'an formation of Jurassic in study area.

The distribution of Jurassic high permeability reservoirs is affected by sedimentary characteristics, and different factors influenced the Yan 10 and Yan 9 to Yan 7 members. The high-permeability reservoir of Yan 10 member is mainly controlled by pre-Jurassic paleogeomorphology, because different paleogeomorphological units have different pore types, particle sizes and interstitial material. The primary and secondary ancient river and terrace are mostly filled with favorable interstitial material. In these units, intergranular pores and dissolution pores are developed, the plane porosity is high and the porosity and permeability are good. In contrast, the slope, branch ditch and tertiary ancient river are slightly worse than the main channel and terrace(Tab. 2). The high-permeability reservoir in the Yan 9 and higher members are mainly controlled by sedimentary facies, and good intergranular pores are preserved in the main channel, where the average porosity, permeability and surface porosity are relatively high (Tab. 3).

Table 2 Contrast table of reservoir characteristics of Yan10 member in Yan'an Formation

paleogeomorphic Unit	Pore factors（%）			Size factors（%）			interstitial material factors（%）				porosity（%）	permeability（mD）
	intergranular pore	dissolution pore	plane porosity	coarse sand	coarse sand	fine sand	hydromica	kaolinite	silicic	ankerite		
Gan-Shaan primary ancient river	7.46	1.98	9.74	34.6	51.2	10.2	1.81	1.84	3.85	0.23	14.6	11.4
Qingxi secondary ancient river	2.57	3.03	6.60	34.4	48.7	15.1	4.55	4.03	2.74	1.14	14.1	10.8
Zhenbei tertiary ancient river	0.95	1.65	4.70	10.3	63	25.6	8.4	1.21	1.6	2.1	13.5	9.08
terrace	4.38	2.95	8.71	20.1	58.9	18.1	1.83	3.21	4.76	0.2	14.5	23.7
slope belt	4.19	1.72	6.49	0	31.5	58.6	3.47	1.97	3.12	3.72	13.5	2.74
Yanwu branch ditch	6.45	1.50	10.23	9.4	62.1	27.2	3.16	1.45	2.08	1.81	13.8	10.2

Table 3 Contrast table of reservoir characteristics of Yan 7 - Yan 9 member in Yan'an Formation

layer	Sedimentary zone	intergranular pore (%)	dissolution pore(%)	plane porosity(%)	porosity (%)	Permeability (mD)
Yan9	Main channel	5.37	2.18	8.12	15.1	42.6
	channel flank	3.92	2.79	7.75	14.3	28.6
Yan8	Main channel	4.55	7.47	17.8	15.3	59.4
	channel flank	4.25	6.16	11.8	13.8	19.6
Yan7	Main channel	5.14	6.87	18.2	15.2	56.7
	channel flank	4.13	5.84	12.4	13.6	18.2

4 Oil Accumulation

4.1 Oil source analysis

During deposition of the Triassic Yanchang Formation in the Ordos Basin, the area of the lake basin expanded and the water body deepened, resulting in formation of a wide range of semi-deep lacustrine to deep lacustrine sedimentary environments, and propagation of zooplankton, benthic algae and a large number of aquatic animals (Yang et al., 2016, 2017; Wu et al., 2016; Cui et al., 2017). At this time, thick lacustrine dark muddy sediments were developed. The Chang 7 Member of the Triassic Yanchang Formation, which contains black organic-rich shale and thick-bedded black mudstone, is the main source rock for Mesozoic oil in the Ordos Basin.

Regional drilling results show that the Chang 7 dark mudstones in the study area are favorable hydrocarbon source rocks. Geochemical analysis of Chang 7 dark mudstone samples indicates that the Chang 7 dark mudstone has good organic matter abundance, an average total organic carbon content of 5.7%, an average hydrocarbon generation potential of 3.75 mg/g, a favorable organic matter type, I–II1 type kerogen and an average vitrinite reflectance of 0.81%. These results indicate that the Chang 7 Member is an effective, mature source rock(Zhang et al., 2008; Zhao et al., 2012; Yang et al., 2016, 2017; Han et al., 2018).

Comparison of the crude oil biomarker compounds of Jurassic crude oil and the quality source chromatogram of steroidal and terpene biomarkers of source rocks (Hughes et al., 1995; Chakhmakhchev et al., 1997) indicated that the dark mudstone of the Chang 7 Member that formed in a deep and semi-deep lake environment was the oil source for the Jurassic Yan'an Formation (Zhao et al., 2011, 2012, 2014, 2015; Liu et al., 2015).

4.2 Migration pathway

The Indosinian Orogeny at the end of the Triassic uplifted the basin as a whole, and the top of the Yanchang

Formation experienced strong weathering and fluvial erosion, forming a landscape with a wide range of rivers, gullies and hills(Guo et al., 2008). The Lower Jurassic Yan'an and Fuxian formations were deposited on this topography. These deposits filled the low points in the pre-existing landscape, and are in unconformable contact with the underlying Triassic Yanchang Formation.

Fluvial filling took place during the Fuxian to Yan 10 sedimentary period, quasi-plain deposits developed during the Yan 10 sedimentary period, and marsh and lake sediments were formed during the Yan 9 to Yan 1 interval. Therefore, the thicknesses and lithologic changes of the Fuxian Formation and the Yan 10 Member record the pre-Jurassic paleogeomorphology in this area. Because of the down-cutting effect of the Yan 10–Fuxian ancient river valley on the underlying strata, most areas cut down to Chang 3 member of the Yanchang formation, and in some areas even up to Chang 6 member in Yanchang formation. This downcutting greatly shortened the distance between the high-permeability sandstone of the Yan 10 Member and the source–reservoir in the Yanchang Formation, and reduced the resistance to vertical migration of the oil and gas upward from the lower part to a large extent. Thus, oil could have been rapidly transported from the Yanchang Formation source rock to the Yan'an Formation. The unconformity surface below the valley was an important migration channel in the study area. Three types of unconformity occur in the study area: microangular unconformities, parallel unconformities and erosive unconformities. Microangular unconformities are mainly developed to the west of the Huanxian and Mengba area; parallel and erosive unconformities mainly occur in the east of the Huanxian to Mengba area. The shape of the erosion surface follows the Jurassic paleogeomorphology(Fig. 10).

The sedimentary conditions resulted in good development of sand bodies in the Yan'an Formation in the study area. The physical properties of these sand bodies are good, and their longitudinal superposition means that they are easy to connect with each other, forming good channels for oil migration. Sand body correlation shows that high-permeability sand layers occur in the Yan 10 and Yan 9 members in the study area; these sand layers provided favorable channels for oil migration. The characteristics of oil migration upward through high-permeability sand bodies are illustrated in Figure 11.

Fractures play an important role in oil and gas migration and fluid percolation. This is of great significance in formation of oil reservoirs. Fractures can both divert and provide the dominant channel for petroleum migration, and also simplify petroleum migration (Niu et al., 2016). The study area is adjacent to the western margin thrust belt of the Ordos Basin. After the Indosinian Orogeny, the area was affected by subduction of the South China

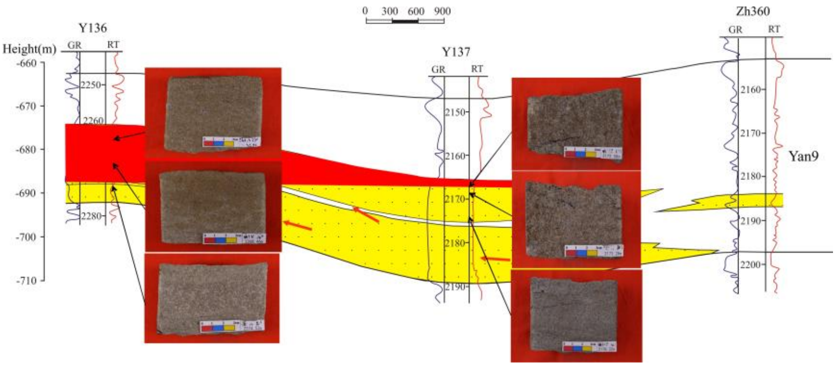

Fig. 11. The sand body profile of the Yan 9 Member in the study area.

Plate and the strata in the western margin were squeezed and deformed, resulting in extensive fracturing in the basin. A large number of high-angle fractures are developed in the Yan'an Formation in the study area, which have been visualized by means of field surveys, core observations and electrical imaging logging. Traces of oil migration can be clearly seen on fracture surfaces(Fig. 12). In the study area, most of the oil wells in the Yan'an Formation coincide with zones of fracture development, indicating that the reservoir is fracture-controlled. As a result of the presence of unconformities, hypertonic sand bodies and fracture systems, a complex three-dimensional transport system formed in the Yan'an Formation.

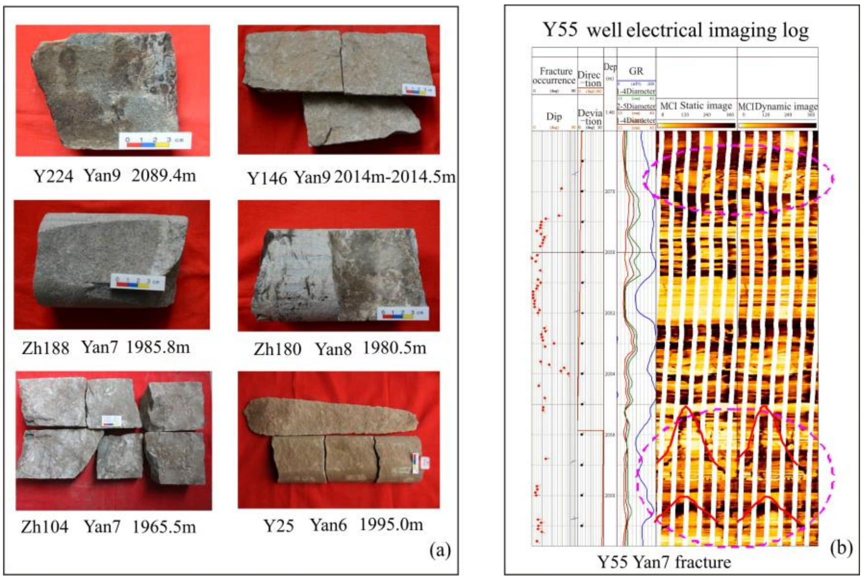

Fig. 12. Sandstone core fractures and electrical imaging logging in Yan'an formation in study area.
(a) Fracture in core observation; (b) Fractures identified by electrical imaging logging.

4.3 Hydrocarbon accumulation period

Secondary inclusions formed in the process of hydrocarbon migration and enrichment record information on the physical and chemical conditions during petroleum migration and oil formation, and provide direct evidence for hydrocarbon migration. In recent years, the composition of single inclusions has been obtained by using laser Raman spectroscopy and other methods, from which great progress has been made in the study of hydrocarbon migration(Zhao et al., 2016; Fu et al., 2017; Yao et al., 2018). Identification of hydrocarbon accumulation times from the homogenization temperature of fluid inclusions has been widely used in the study of oil and gas accumulation in the Mesozoic Yanchang Formation of the Ordos Basin (Liu et al., 1997;Chen et al., 2000). During formation of inclusions in sedimentary rocks, the inclusions develop their own characteristic distribution and composition. The core problem of the study is to confirm the origin and properties of inclusions. Correct understanding of the origin, properties and stages of inclusions is of direct significance for research on hydrocarbon sources, generation and evolution(Tao et al., 2004). To determine the consistency of the source and timing of inclusion formation, samples containing gas–liquid inclusions were obtained from secondary enlarged quartz edges, quartz grain fractures and micro-fractures in Jurassic sandstone reservoirs.

The inclusions are nearly round or oval in shape, mostly distributed in a beaded shape, and partly irregular in shape(Fig. 13). The main physical phases within inclusions are three kinds of gaseous hydrocarbons + liquid hydrocarbon + a small amount of brine, gaseous hydrocarbon + liquid hydrocarbon and pure liquid hydrocarbon. Inclusions are mainly visible in secondary concrescence of quartz edge and dissolution pores, are distributed like beads along fissures, and were captured and formed in the process of fluid migration after fissure formation. Under the fluorescence microscope (Fig. 14), yellow fluorescent oil inclusions and light blue oil bitumen can be seen, which indicates that oil filling was continuous.

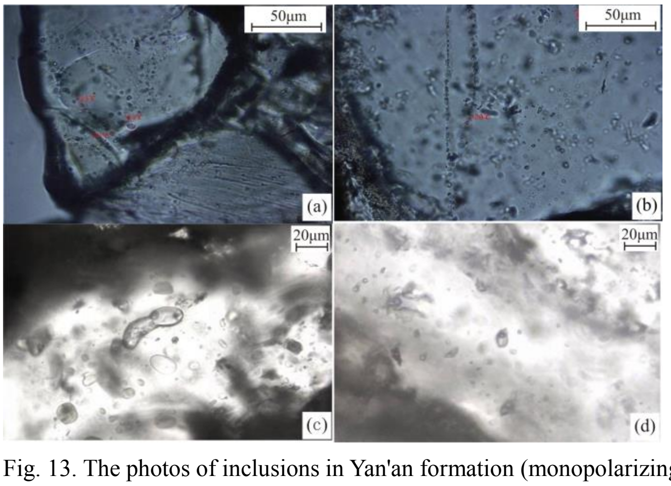

Fig. 13. The photos of inclusions in Yan'an formation (monopolarizing) in study area.
(a) H33, Yan8, 2387.8m, Inclusions in the secondary concrescence of quartz edge; (b) Y127, Yan9, 1893.5m, Inclusions distributed like beads along fissures; (c) H67, Yan8, 1787.1m, Inclusions in dissolution pores; (d) Zh60, Yan10, 2182.6m, Inclusions in the secondary concrescence of quartz edge.

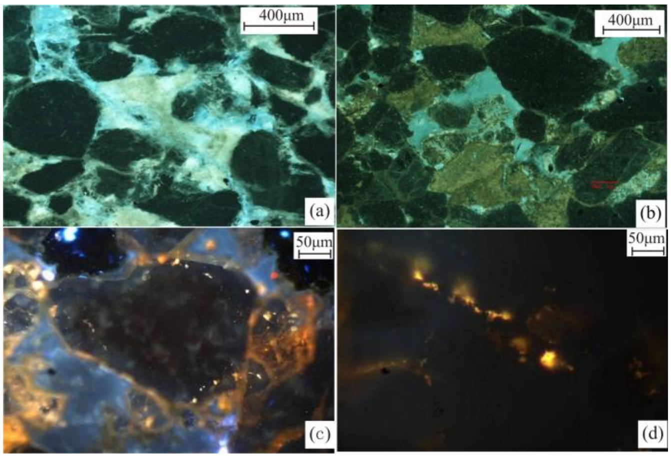

Fig. 14. The photos of inclusions in Yan'an formation (fluorescence) in study area.
(a) Y137, Yan9, 2173.4m, light blue oil bitumen under the fluorescence microscope; (b) Y27, Yan7, 2065.4m, light blue oil bitumen under the fluorescence; (c) Y116, Yan9, 1933.1m, yellow fluorescent oil inclusions under the fluorescence; (d) Zh180, Yan8, 1968.7m, fluorescent oil inclusions distributed like beads.

The Raman spectra of hydrocarbon inclusions can be divided into five types: saturated hydrocarbon; alkane bitumen; bitumen; fluorescent and methane types. The first three types are most commonly used for petroleum inclusions. The most obvious Raman characteristic of petroleum saturated alkanes are a series of strong Raman effects in the 2700–2970 cm^{-1} region; the second most obvious characteristic is that there are ring "breathing" Raman characteristic peaks and isomeric skeleton Raman characteristic peaks in the region less than 1700 cm−1(Zhang et al., 2004, 2009, 2010).

From analysis of Raman spectra, the saturated alkanes in inclusions are mainly composed of isoalkanes, and the ring groups of alkanes also exhibit a strong Raman effect. These results are characteristic of highly saturated hydrocarbon inclusions(Fig. 15). These results indicate that the content of organic components in inclusions is high, and specific stages of hydrocarbon migration can be identified on the basis of the degree of the difference of the levels of organic components in inclusions(Zhang et al., 2006). The total content of organic components of each inclusion can reflect the characteristics of hydrocarbon migration; a high content of organic components reflects capture of inclusions during the peak period of hydrocarbon migration. The Raman effect in the Huanxian region in the northern part of the study area is slower than that in the south, indicating that the saturated hydrocarbon content is lower than the southern region, that the timing of capture may have been earlier in the north than in the south, and that there were several oil and gas migration and accumulation events in the study area.

The homogenization temperature of fluid inclusions is the main basis for understanding the fluid paleo-temperature and reconstructing the paleogeothermal history of the basin. A total of 23 thin-section samples of inclusions were selected in this study for analysis and testing, and 334 points were measured in salt-water inclusions associated with oil–water inclusions. The results (Fig. 16) show that the homogeneous temperature distribution of inclusions is in the range 80–150°C and the highest peak value is 110–120°C, indicating that the migration of Jurassic crude oil in this area was a continuous filling process, and the charging strength altered from weak to strong and then from strong to weak. However, there are some differences between the north and south of the study area. The northern area yields two homogeneous temperature peaks at 80–90°C and 110–120°C; in contrast, the southern region has peaks at 100–120°C and 130–140°C. This finding indicates that reservoir formation may have been earlier in the northern part of the study area than in the south, and there were two stages of reservoir formation in the northern part of the study area.

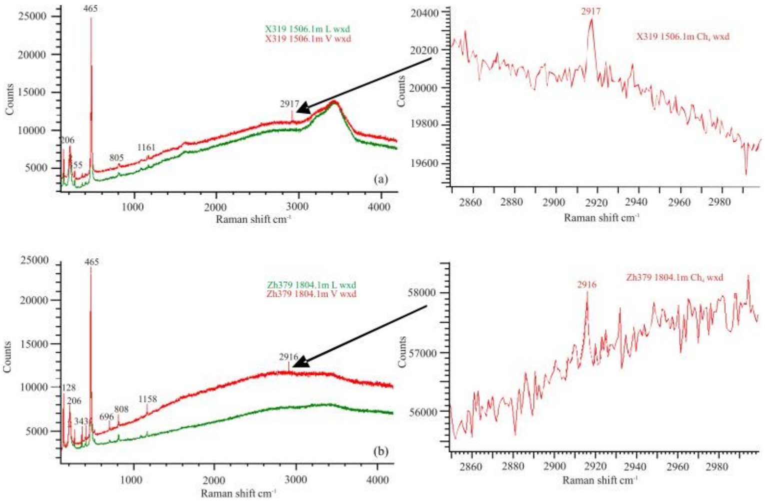

Fig. 15. Raman diagram of inclusions of Jurassic Yan'an formation in study area.
(a) X319, Y10, 1506m, Highly saturated hydrocarbon inclusions; (b) Zh379, Y9, 1804.1m, Highly saturated hydrocarbon inclusions.

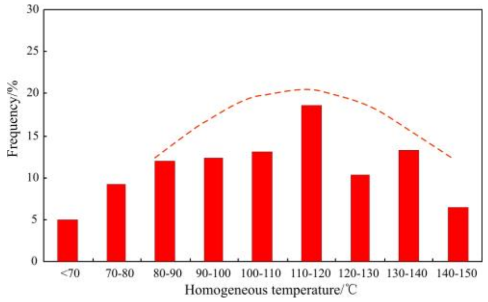

Fig. 16. Histogram of homogeneous temperature distribution of inclusions of Jurassic Yan'an formation in study area.

Combining the tectonic evolution history with the oil–water inclusion host minerals, homogeneous temperature and diagenetic evolution, a paleogeothermal gradient of 3.68°C/100m and a modern surface temperature of 15°C for the Ordos Basin were calculated (Ren et al., 2017). It is concluded that the oil filling time in the study area was early Late Jurassic to Early Cretaceous and Early Cretaceous to Late Cretaceous, with substantial hydrocarbon filling during the Early Cretaceous(Fig. 17). Oil charging was continuous during this time interval. Hydrocarbon filling occurred earlier in the northern part of the study area than in the south. The timing of hydrocarbon accumulation was closely related to the formation and evolution of the Tianhuan Depression.

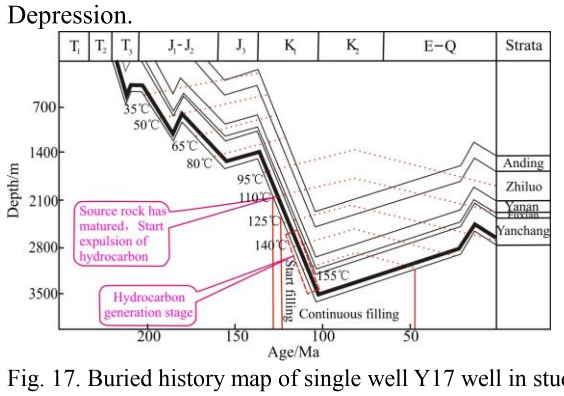

Fig. 17. Buried history map of single well Y17 well in study area.

4.4 Factors controlling oil accumulation in the Yan 10 reservoir

Reservoir enrichment of the Jurassic Fuxian Formation and the Yan 10 Member of the Yan'an Formation was affected by factors such as the pre-Jurassic paleogeomorphology, oil migration channels, structure of the top surface of the formation, and groundwater changes. Of these factors, the pre-Jurassic paleogeomorphology was the main controlling factor of reservoir formation, and low-amplitude structures (i.e. geological bodies with relatively flat structure and a closure range of only 10–20 m) had some controlling effect on the reservoirs. Oil wells in the Fuxian Formation and the Yan 10 Member generally occur in the paleogeomorphological slope and the channel island(Fig. 18). The sediments of the overlying Fuxian Formation and the Yan 10 Member readily formed draped and compacted structures, providing a good trap configuration for formation of paleogeomorphic reservoirs.

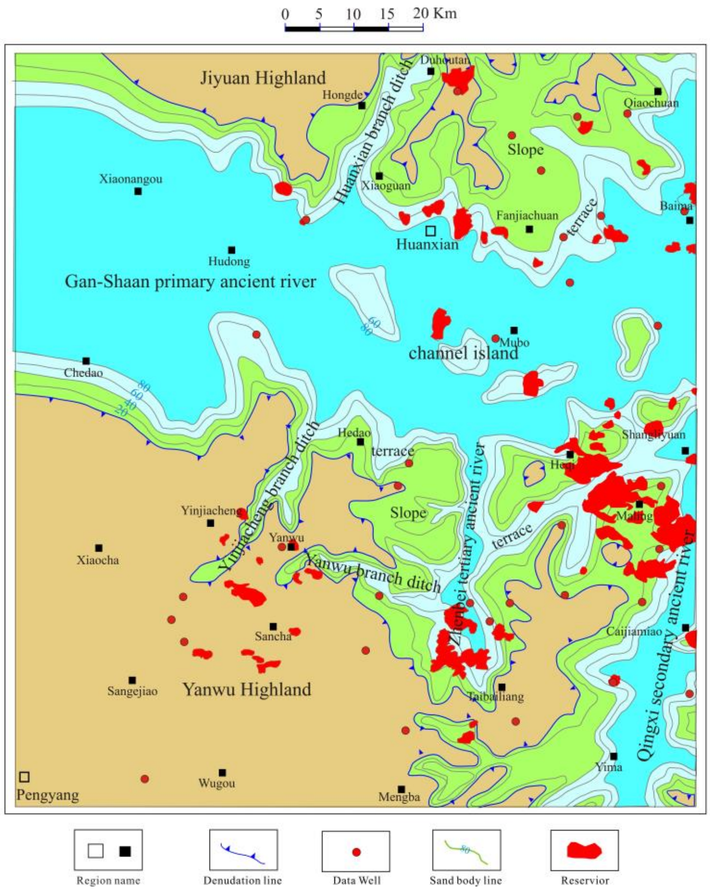

Fig. 18. The paleogeomorphology and reservoir distribution map of Jurassic Yan'an formation in study area.

(1)The source of the ancient river is a favorable location for reservoir formation. Exploration has confirmed that paleo-river cutting and denudation was stronger nearer the source of the river. The oil generated by the source rocks of the Yanchang Formation migrated upward through fractures in the formation. As the oil migrated to the deep paleovalley of the Jurassic, it moved upward along the unconformity above the ancient valley as a result of the pressure release, and gathered to form a reservoir in the drape structure on the paleoslope. In contrast, petroleum could be transported upward through the high-permeability sand body of the Fuxian Formation and the Yan 10 Member of the Yan'an Formation, forming an oil reservoir at the drape structure of the channel island; alternatively, because of the difference in lithology and the influence of low-amplitude structural traps, oil reservoirs formed at the nose structures of the channel sand body.

(2) The gently sloping region of the paleoslope is the main reservoir area. From the plane distance between the exploration well at the slope and the exploration well at the highland edge and the depth gradient between the wells, the slope angle of the paleoslope in the study area was calculated by trigonometry. The western part of the study area is close to the source of the ancient river. In this region, the speed of the river was fast, the difference in altitude between the two banks was great, the slope formed was steep and the slope angle was larger than 70°, which is equivalent to the two sides of the cliff near the vertical. In contrast, in the eastern region, the flow velocity of the river was slower and the river may have been transformed from a meandering to a braided river, resulting in formation of multi-level slope terraces. The slope angle is also lower, generally less than 40°. Reservoirs are well developed in the gently sloping area, and most of the Yan 10 paleogeomorphic reservoirs are located in this core region.

Groundwater is relatively stagnant above the paleogeomorphic slope in the Ordos Basin, which is beneficial for reservoir preservation; however, there are marked groundwater changes in the paleovalley and the reservoir preservation conditions are poor (Guo,et al., 2001). To sum up, the paleoslope zone and the channel island possess preferential conditions for oil or gas capture, have good preservation conditions, and are favorable areas for reservoir formation.

4.5 Factors controlling oil accumulation in the Yan9 and higher members reservoirs

(1) Favorable sedimentary facies promote preferential accumulation of oil

The control of sedimentary facies on hydrocarbon accumulation is essentially the control of sedimentary facies on sand body type and the porosity and permeability characteristics. The distributary channel of the delta plain during deposition of the Yan 9 Member and stratigraphically higher units was mainly composed of well-sorted medium- and fine-grained sandstone, the grain psephicity was mainly subangular to subrounded, and the structural maturity was high. The porosity and permeability of reservoirs in the middle of distributary channels are 10%–18% and 1–50 mD, respectively. These physical properties are better than those of the reservoirs at the channel edge. Thus, the middle of the channel was a good place for oil enrichment in the Jurassic Yan'an Formation, and the reservoirs are mainly located in the middle of the distributary channel.

(2) Low-amplitude structures play an important role in reservoir control

There are a large number of low-amplitude uplift structures in the eastern and western slopes of the Tianhuan Depression in the Ordos Basin. In the Yanchang Formation, the large low-amplitude uplift structures along the east–west were mainly controlled by the paleotopography of the basement, whereas the local uplift structures in the Yanchang and Yan'an formations were mainly controlled by fault-related folds and differential compaction and had a complex origin. These large, low-amplitude nose structures provided the tectonic setting for oil accumulation, so the local uplift structures and nearby non-structural traps are favorable places for oil accumulation(Li et al., 2013).

Restoration of the paleotopography at the top of the Yan 9 Member of the Yan'an Formation has been carried out. The TJ9-Tk4 seismic marker layer represents the sequence between the bottom boundary of the Cretaceous Huanhe Formation and the base of the Yan 9 Member. Variations in the thickness of this marker bed reflect the paleostructural form of the top of the Yan 9 Member of the Yan'an Formation in the Early and Middle Cretaceous (during deposition of the Huanhe Formation) (Fig. 19, a). In the Early and Middle Cretaceous, the paleotopography at the top of the Yan 9 Member was higher in the east and lower in the west, and the shape of the Tianhuan Depression in the west was basically formed. There is a relatively poor correlation between the occurrence of industrial wells in Jurassic strata and the paleotectonics. Considering the present-day morphology of seismic reflector TJ9 (Fig. 19, b), industrial wells in Jurassic strata are drilled mostly in the higher parts of the structure, indicating that the low-amplitude structural traps and nasal uplift zones of the reflector are favorable places for oil accumulation in this area.

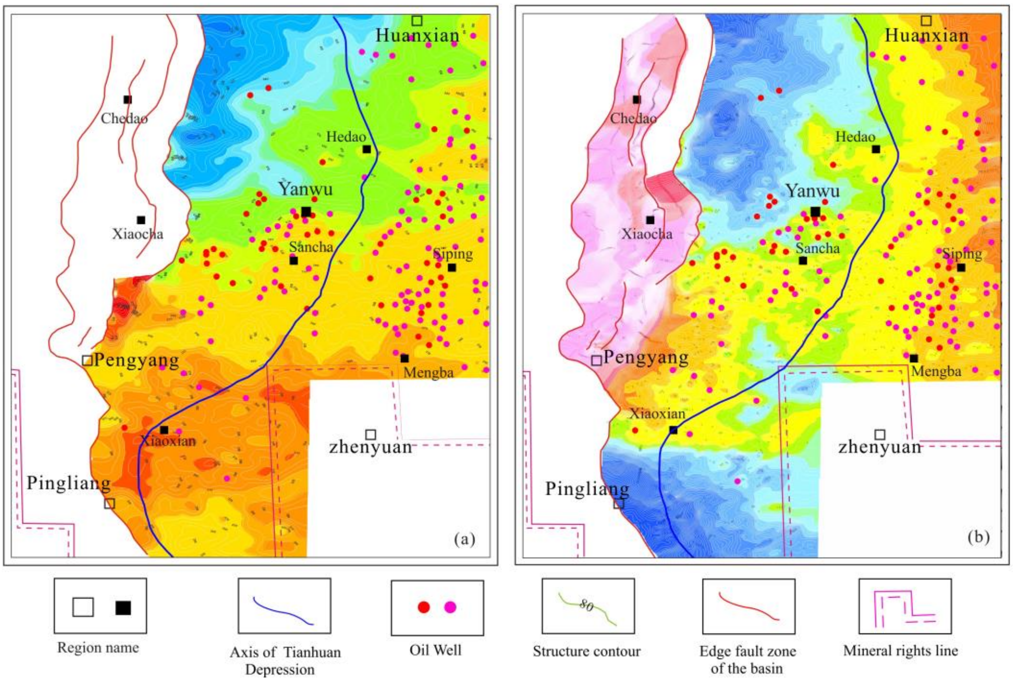

Fig. 19. The paleo-modern tectonic map in Yan'an formation Yan9 member, Jurassic.

(a) The paleostructural form of the top of the Yan 9 Member of the Yan'an Formation in the Early and Middle Cretaceous (during deposition of the Huanhe Formation) ; (b) The present-day structural form of the top of the Yan 9 Member of the Yan'an Formation.

The reservoirs in the study area are highly correlated with the present tectonic and pre-Jurassic paleostructural forms.In the Late Jurassic to Early Cretaceous main hydrocarbon expulsion period, the low-amplitude structures were formed, which provided the main locations for oil capture. The oil migrated to the higher part of the structure in the southwest, and gathered in the low tectonic zone. Subsequently, the study area underwent multi-stage tectonic compression and transformation caused by the Yanshan and Himalayan orogenies, and the influence of differential compaction and paleogeomorphology produced the present tectonic pattern. The present structural pattern exhibits low-amplitude structures in the east and west wings of the Tianhuan Depression, and residual uplifts exist in the south-central part of the axis.

As the tectonic movements of later periods resulted in structural changes to the region, the oil migrated again and gathered in a more favorable tectonic area, forming the present tectonic traps and the oil-bearing area of the nose structures.

(3) Reservoirs are preserved well by high-salinity groundwater.

The alternation of groundwater flow is another important factor in oil and gas reservoir formation (Hitchon et al., 1990; Grasby et al., 2012; Wu et al., 2017). The Jurassic river during the Yan 10 period played an important role in controlling the distribution of formation water in the overlying strata, and the distribution of formation water had some effect on oil accumulation.

From analysis of formation water data from 150 exploration and evaluation wells, the hydrochemical characteristics of the Jurassic Yan 9 Member and stratigraphically higher layers in the north, southeast and northwest of the study area are obviously zoned. The Surin's water type was identified to contain $CaCl_2$, $MgCl_2$, Na_2SO_4 and Na_2HCO_3. The concentrations of Na^+ + K^+ ions and Ca^{2+} ions are lower in the north than in the south, and highest in the southeast. The whole of the southeast exhibits high levels of total dissolved solids (TDS) and Mg^{2+} ions, and the southwest is characterized by high levels of SO_4^{2-} and HCO_3^- ions and high pH values (Table 4).

Table 4 Statistical table for water analysis of Jurassic Yan'an formation in study area

Region	K^++Na^+ (mg/l)	Ca^{2+} (mg/l)	Mg^{2+} (mg/l)	CL^- (mg/l)	$SO4^{2-}$ (mg/l)	$CO3^{2-}$ (mg/l)	$HCO3^-$ (mg/l)	TDS (mg/l)	Surin classification	ph	Na^+/Cl^-	$2SO4^{2-}/Cl^-$*100	sample (block)
North	14672	1424	455	22932	4461	20	482	44449	$Ca_{(Mg)}{}_{Cl2}$, Na_2SO_4	6.28	1.16	35.7	52
Southwest	19015	1529	466	23906	**5249**	446	**587**	50802	$CaCl_2$, Na_2SO_4, Na_2HCO_3	6.97	1.73	45.6	88
Southeast	**27068**	3126	824	**47311**	2096	158	285	**80846**	$CaCl_2$, $_{Na2SO4}$	6.19	1.01	13.0	42

The levels of Cl− ions are significantly lower in the Yan 9 member than in the Yan 10 Member, but the overall level was still high (average 31000 mg/l). The levels of Cl^- ions are low in the central and western parts of the study area, and high in the southeast and north. The distribution of Cl^- ions is similar to that of the Gan-Shaan ancient river. This is because chlorine ions have strong mobility and do not form insoluble compounds, are not adsorbed by colloids, and are not adsorbed by organisms. The main sources are organic, inorganic and atmospheric precipitation（Margi F et al., 2009; Dmitry et al., 2017). Therefore, the Yan 10 period, during which the Gan-shaan ancient river was the phreatic layer, may have affected the distribution of Cl^- ions in formation water of the Jurassic Yan 9 Member and stratigraphically higher units (Fig. 20).

As a result of the high concentrations of Cl^- ions and potassium salt in the study area, the overall mineralization degree is higher in the Yan'an Formation (average 58 g/L). Salt concentrations below 25 g/L occur only in San Cha, Hu Dong and Xiao Guan, reflecting the good preservation conditions of the paleowater in general in this area. The Yan 9 and stratigraphically higher oil reservoirs are located in the area with high salinity (>40 g/L, i.e. seawater salinity; Fig. 21), indicating that the high-salinity region of the study area is a favorable zone for oil or gas preservation（Xue et al., 2018).

The formation conditions of the Jurassic reservoirs in the study area were complex, with several main controlling factors. The enrichment of the Fuxian and Yan 10 reservoirs was partly controlled by the source rocks or sedimentary microfacies, but also by the paleogeomorphic conditions and the accumulation of oil in favorable traps in the channel island and slope. The reservoirs of the Yan 9 Member and higher strata were controlled by low-amplitude structures, the distribution of favorable facies and paleo-water characteristics. As a result of the presence of a network of fractures, oil flowed through the unconformity surface at high speed, and accumulated in favorable traps through high-permeability sand bodies and fractures (Fig. 22).

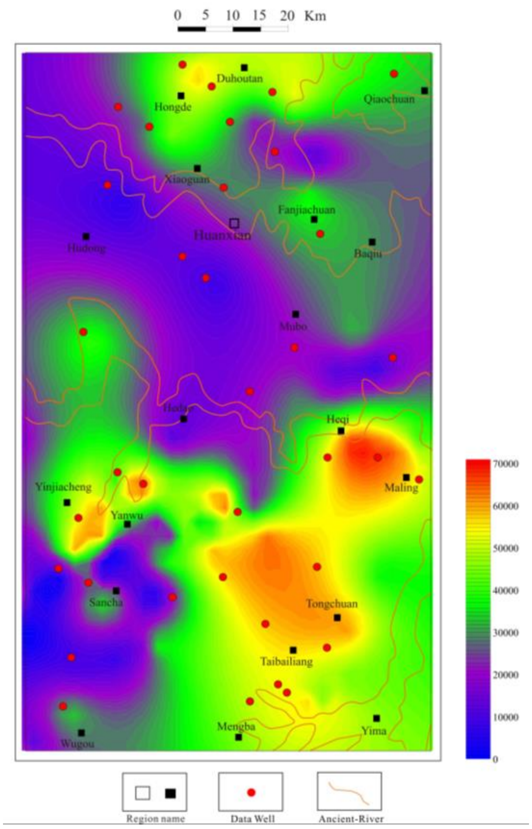

Fig. 20. The distribution map of chloride ions in formation water in Yan9 and above layers in Yan'an formation of Jurassic in study area.

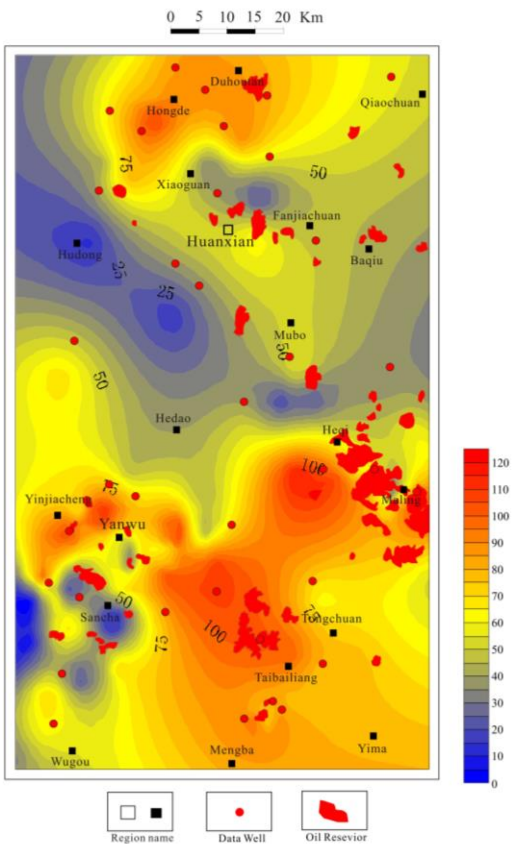

Fig. 21. The distribution map of formation water salinity in Yan'an formation of Jurassic in study area.

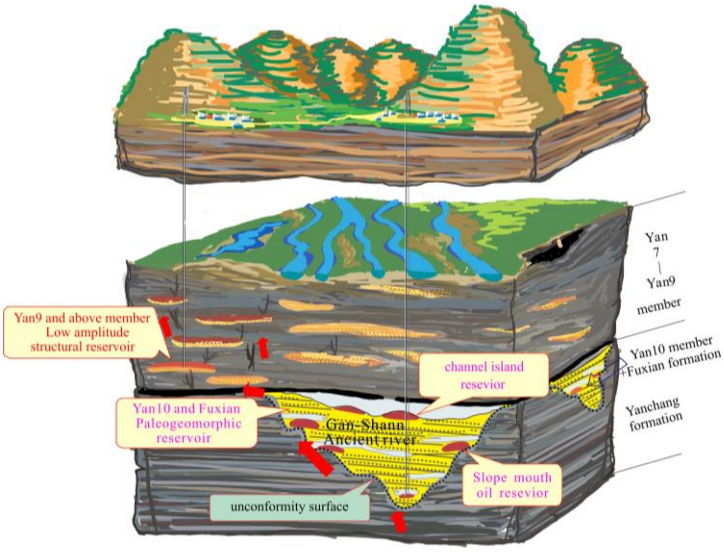

Fig. 22. The reservoir model in Yan'an formation of Jurassic in study area.

5 Conclusions

(1) Study of drill cores and identification of marker beds in multiple wells has demonstrated that the Yan 10 and Fuxian reservoirs contain fluvial facies, and the Yan 9 to Yan 7 members consist of delta-plain braided-river sediments. These sediments form a set of good reservoir sand bodies, which have high porosity and high permeability in a low-permeability background, and form a high-quality reservoir.

(2) The hydrocarbons were derived from the high-quality source rock of the Chang 7 Member of the Yanchang Formation. The unconformity surface between the Yanchang Formation and the Yan'an Formation, high-permeability sand bodies and fractures constituted a comprehensive transportation system. Together, these provided the hydrocarbon source and a high-speed pathway for oil accumulation in the Yan'an Formation.

(3) The homogenization temperature of inclusions and Raman spectroscopy showed that the Jurassic reservoir in the study area experienced continuous filling, and charging strength from weak to strong and then from strong to weak. Filling occurred in the Early Cretaceous and continued until the end of the Late Cretaceous. The timing of hydrocarbon accumulation was closely related to the formation and evolution of the Tianhuan Depression.

(4) The pre-Jurassic paleogeomorphology not only controlled the distribution of the Fuxian Formation and the Yan 10 sedimentary facies belt, but also laid the foundation for formation of the drape structure. The slope mouth and terrace on the gently sloping area of the slope and channel island are favorable regions for exploration of Yan'an Formation reservoirs. Furthermore, the groundwater in the area above the paleogeomorphic slope is relatively stagnant, which is highly favorable for reservoir preservation. Therefore, the pre-Jurassic paleogeomorphology played an important role in formation of the Fuxian and Yan 10 reservoirs.

(5) The reservoirs of the Yan 9 Member and stratigraphically higher units are controlled by the distribution of favorable sedimentary facies such as distributary channels. Oil was transported through the unconformity surface, fractures and connected sand bodies, and hydrocarbon preservation was favored by high-salinity groundwater. The favorable low-amplitude structural traps that formed during the hydrocarbon production period are rich and integrated reservoirs.

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