Research Article

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Late Triassic–Early Jurassic paleogeomorphic characteristics and hydrocarbon potential of the Ordos Basin, China, a case of study of the Jiyuan area

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Abstract: Paleogeomorphology is the surface morphology formed by the deposition of strata in the basin in historical period, which is greatly affected by the regional tectonic movement; however, the effect of basin paleogeomorphology on reservoir has been underexplored. This study documents the basin paleogeomorphic terrain features and their implications for the depositional processes and oil migration and accumulation in the Jiyuan area of the Ordos Basin. Stratigraphic classification is achieved through well logging data analysis. A seismic fine interpretation of the Triassic–Jurassic paleogeomorphology is conducted. Typical drilling core observations were utilized in a well section analysis of the strata at the top of the Yanchang formation sedimentary facies characteristics. Studies have shown that the Chang 1 subsection on top of the Triassic Yanchang formation in the Jiyuan area was eroded by an ancient Jurassic river, and the residual strata are primarily distributed in the Dingbian and Jiyuan plateaus. The Chang 1 reservoir in the Jiyuan area is dominated by a delta distributary channel sand body. The reservoir is concentrated in a high reservoir sand body structure position, and is controlled by a combination of structural and rock characteristics. This study suggests that the Indosinian movement in the late Triassic caused the entire basin to uplift and denude, and the strata at the top of the Yanchang

formation suffered from weathering and river erosion. The residual strata in the upper part of the Yanchang formation are controlled by the late Triassic–early Jurassic paleogeomorphology.

Keywords: Ordos Basin, Late Triassic – Early Jurassic, paleogeomorphology, Yanchang formation, Indosinian movement

1 Introduction

The Ordos Basin is the second largest basin in China, fluvial-lacustrine terrigenous clastic rock deposits were developed in the Mesozoic Triassic Yanchang formation and Jurassic Yan'an formation, and it is the main oil-generating layer and reservoir in Ordos Basin [1–5]. In recent years, several 100 million-ton oil reservoirs have been discovered in the lower strata of the Yanchang formation of Triassic in the Jiyuan area of the Ordos Basin, whereas multiple oil-rich areas have been discovered successively in the upper strata of the Yanchang formation. However, there are few studies on the upper strata of the Yanchang formation, and the formation rule of the reservoir is still unclear, which affects the exploration and development process of the reservoir in the Ordos Basin. Therefore, based on the drilling and seismic data in the Jiyuan area of Ordos Basin, the Triassic–Jurassic paleogeomorphologic features were described in detail, and the enrichment rules of the top reservoirs of the Yanchang formation were studied. Chang 1 subsection is located at the top of the Triassic Yanchang formation in the Jiyuan area of Ordos Basin. The sedimentary characteristics and reservoir control factors of Chang 1 reservoir was studied. This study will help to understand the distribution of oil reservoirs, and further evaluate the role of Jurassic palaeogeomorphologic morphology in the reservoir accumulation process at upper strata of the Yanchang

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formation. It can provide scientific basis for reservoir exploration in the Yanchang formation and deepen the understanding of late Triassic lake basin evolution.

2 Geological setting

2.1 Ordos Basin

The Ordos Basin is located in the western part of the north China block, with an area of approximately 320,000 km² (Figure 1). It is a residual inland craton basin that was formed by the superposition of multistage tectonic movement [4,6–8]. The Ordos Basin is a craton basin superimposed by the Paleozoic platform and its margin depressions and the inner depressions of the Mesozoic and Cenozoic platforms. Since the Paleozoic, multiple sets of reservoir and cap assemblages that contain abundant oil and gas resources have been deposited in the Ordos Basin. The Mesozoic petroleum in the Ordos Basin is predominately concentrated in the Yan'an formation of the Jurassic and

the Yanchang formation of the Triassic (Figure 2). The Yanchang formation was further subdivided into ten segments, from the bottom to the top, ranging from the Chang 10 subsection to Chang 1 subsection [9–14]. The Yan'an formation, which overlies the Yanchang formation, was divided into ten stratigraphic units (Yan 10 to Yan 1 vertically from bottom to top), and it primarily developed fluvial swamp and shallow lacustrine sediments [15–18]. The Indosinian movement at the end of the Triassic uplifted the Ordos Basin as a whole, and the sedimentary evolution is obviously controlled by the tectonic movement around the basin. The strata on the top of the Yanchang formation were subjected to different degrees of weathering and river erosion [19,20]. The Triassic–Jurassic paleogeomorphology affects the depositions and oil reservoir distributions of the upper strata of the Yanchang formation [21]. The river erosion by the paleo river in the Triassic–Jurassic period, and various paleogeomorphic patterns was formed, such as high land, valley, brae, mound, and river terrace. The Fuxian formation and Yan 10 period deposits were primarily controlled by the paleogeomorphology of the upper surface of the late Triassic, which developed a set of coarse clastic fluvial deposits [22–24].

Figure 1. Schematic geological map showing the tectonic subdivision of the Ordos Basin (modified after Jiang et al. [8]).

2.2 Jiyuan area

Jiyuan area is in Midwest of Ordos Basin, bordered by the Xiyuan obduction zone to the west, relatively gentle structure spans two tectonic units of Tianhuan depression and Yishan slope (Figure 1). In recent years, significant oil exploration has been made in the middle and lower strata of the Yanchang formation in Jiyuan area, at the same time, several small scale and high output oil reservoirs have been discovered in Chang 1 subsection that of the top strata of the Yanchang formation [21,25–27]. The upper stratigraphic reservoir of the Yanchang formation is mainly concentrated in Chang 1 subsection in Jiyuan area (Figure 2). In Midwest of Ordos Basin where Jurassic paleochannel is not well developed, the lower overlying strata have been cut to a lesser extent, and the Chang 1 subsection still has remnants of different degrees. Due to the denudation of the Triassic–Jurassic paleo river, Chang 1 subsection is incomplete and unequal in thickness. Chang 1 reservoir distribution is mainly controlled by the Triassic–Jurassic paleogeomorphology [28]. Based on the description of paleogeomorphic morphology and the determination of the residual thickness of Chang 1 formation through drilling and seismic data, the study analyzed the sedimentary facies of Chang 1 and the accumulation rule of Chang 1 reservoir.

Figure 2: Interpretation of tectonic events and stratigraphic correlation in Ordos Basin: (a) tectonic movement of the Ordos Basin since the Triassic (modified after Li et al. [17]) and (b) upper Triassic and lower Jurassic stratigraphy in the Ordos Basin, T_{J9}: the Yan 9 subsection coal seam of Yan'an formation corresponds to the formation of reflection layer, T_J: the bottom of Yan'an formation corresponds to the seismic reflection layer, and T_{T7}: the mud shale at the bottom of Chang 7 subsection is the regional marker layer.

3 Methods

The data include approximately 500 well logging data points, seismic reflection data, and approximately 50 wells over 200 m of core data (Figure 3). The Mesozoic marker layer in the study area is clear and can be compared with other layers. The Yan 9 subsection coal seam of the Yan'an formation corresponds to the formation reflection layer T_{J9}, the bottom of the Yan'an formation corresponds to the seismic reflection layer T_J, and the mud shale at the bottom of the Chang 7 subsection is the regional marker layer T_{T7}. According to the seismic record and seismic wave velocity before inversion, the seismic profile is converted from the time to depth domain. A representative seismic exploration line (076351fz2) was selected, and the seismic line layer at

the bottom of the Chang 7 subsection was leveled using the balanced profile method to restore the Jurassic ancient river morphology. The paleogeomorphological map of the study area was drawn using the imprinting method, and the paleogeomorphologic features of the Triassic–Jurassic period in the Jiyuan area were restored and divided into paleogeomorphologic units.

The sedimentary system and sedimentological characteristics of the Chang 1 subsection in the Jiyuan area were studied by selecting typical coring wells. The ranges of the sedimentary system and vertical sedimentary superposition characteristics were determined through a representative well-to-well comparison [29–32]. The reservoir enrichment rule was analyzed by connecting the well profiles of the reservoir in the Chang 1 subsection in the Jiyuan area.

Figure 3: Well location and seismic profile of the Jiyuan area: H08FZ6317, H01FZ6337FZ, and 076351fz2 represent the seismic lines passing through the drilling position, and the pink dots represent the drilling for coring.

4 Results

4.1 Paleogeomorphology of Triassic–Jurassic System

The seismic inversion section from the bottom of the Yan 9 subsection of the Yan'an formation to the bottom of the Fuxian formation in the Jiyuan area clearly depicts the paleogeomorphology of the Triassic–Jurassic system [33–35]. By analyzing the waveforms and morphological features of the section, representative seismic exploration lines were selected, and the bottom of the Chang 7 subsection was leveled using the balanced section method to restore the Jurassic paleogeomorphology according to the geological characteristics of the T_{j9} and T_j marker layers. In the east–west seismic profile perpendicular to the flow of the ancient Ningshan river – a major branch of the Jurassic river, the ancient Ningshan channel is a lenticular reflection. The reflection amplitude in the channel varies from moderate to strong, which may be related to the strong wave impedance interface formed by the vertical superposition of the channel sand body. The seismic reflection of the ancient channel complex is nearly 150 m at its thickest point, and the channel width was approximately 40–50 km (Figure 4). The first-grade ancient Ningshan river can be clearly identified.

During the late Triassic, the Ordos Basin was uplifted by the Indochina movement, and the Triassic–Jurassic paleogeomorphology was formed due to river channel erosion [36,37]. The subsequent deposition of the Fuxian formation and Yan 10 subsection of the Yan'an formation is primarily characterized by channel filling and deposition, whereas the Yan 9 subsection of the Yan'an formation is characterized by compensatory deposition. Only

Figure 4: The seismic line of Jurassic and Triassic reservoirs in the Jiyuan area: (a) H08FZ6317, (b) H01FZ6337FZ, and (c) 076351fz2. Seismic lines were leveled with the bottom of Chang 7 subsection, T_{j9} : seismic reflection Jurassic Yan'an formation of Yan 9 coal seam, T_j : seismic reflection the bottom of the Jurassic, and T_{j7} : seismic reflection the bottom of the Triassic Yanchang formation of Chang 7 subsection, H5, H8, G86, etc., respectively represent the drilling through the seismic line.

the deposition at the top of the Yan 9 subsection filled and leveled the basin strata [21,28]. The stratigraphic thickness of the paleochannel erosion surface of the top of the Mesozoic Triassic Yanchang formation and top of the Yan 10 subsection of the Jurassic in the Ordos Basin can be used as an erosion surface impression to restore the Jurassic paleogeomorphology in the study area [38].

The paleogeomorphology was rebuilt using the impression and comprehensive geological methods. The Triassic–Jurassic paleogeomorphological map was recovered using the sum data of the thicknesses of the Yan 10 subsection and Fuxian formations obtained by drilling. Based on core observation, seismic interpretation data, and impression of stratigraphic thickness, the sedimentary characteristics of pre-Jurassic paleogeomorphology have been studied in Jiyuan area. The research shows that the sedimentary characteristics of the pre-Jurassic ancient river are mainly formed by channel filling deposition, accompanied by erosion, and cutting of the valley. The Ningshan ancient river runs through the study area from northwest to southeast, with a valley spread of 120 km and a main channel about 20–30 km wide. The Mengshan ancient river flows from north to south, the main channel is 10–20 km wide. The average slope of the east slope of Jiyuan Plateau is 9–11 m/km, and there is medium coarse sandstone and fine sandstone strata with a thickness of about 80 m deposited on it. The average slope of the south slope of Jiyuan plateau is 5–7 m/km, and terraces are developed at the front of the slope. It also shows that the paleogeomorphology in Jiyuan area can be divided into five paleogeomorphology units: plateau, slope zone, paleogeomorphology, valley area, and interfluvial mound. The paleogeomorphology in the pre-Jurassic includes Jiyuan plateau, Dingbian plateau, Anbian plateau, Mengshan ancient river, Ningshaan ancient river, and other two ancient rivers. Ancient terraces were developed in the south of Jiyuan plateau, the south of Dingbian plateau, and the west of Anbian plateau. Slope zones were developed on both sides of the valleys of Mengshan ancient river and Ningshaan ancient river, and interrivers mounds were developed in the river channels of Mengshan ancient river. With seismic profile evidence, the paleogeomorphologic features can be clearly identified from the Triassic–Jurassic geomorphology map of the Jiyuan area. The Jiyuan area is located west of the ancient Mengshan river and north of the ancient Ganshan river. The area was eroded and denuded by the ancient Ningshan river, and the Dingbian plateau in the north and Jiyuan plateau in the south are preserved (Figure 5).

Figure 5: The Paleogeomorphology of Triassic–Jurassic in the Jiyuan area: JYP: Jiyuan plateau, DBP: Dingbian plateau, ABP: Anbian plateau, NSAR: Ningshan ancient river, MSAR: Mengshan ancient river, JSAR: Jinshan ancient river; the green line segment in the figure represents the position of the seismic line, the color mark on the right explains the thickness of the ancient river course, the yellow high value area represents the ancient plateau, the study area includes Jiyuan plateau, Dingbian plateau, and Anbian plateau; and the blue area represents the ancient river course, Mengshan ancient river, and Jinshan ancient river.

4.2 Residual thickness of Chang 1 subsection

The Indosinian movement in the late Triassic caused the Ordos Basin to lift and denude. After a complete water receding process, it gradually shifted from a deep-water depositional environment to land depositional environment, and it entered the peneplain stage in the Chang 1 sedimentary period. The upper strata of the Yanchang formation were eroded, and the denudation degree was the most severe in the southeastern study area. The denudation of the Chang 1 formation was exhausted, and later river erosion resulted in the limited distribution range of the Chang 1 subsection (Figure 6a). The large quantity of drilling and logging data and paleogeomorphology features were used to accurately characterize the residual formation thickness map of the Chang 1 subsection in the Jiyuan area. The residual thickness of the Chang 1 subsection of the Yanchang formation is approximately 0–80 m, the thickness is mostly less than 50 m, and the oil-bearing strata are predominately concentrated in the lower part of the Chang 1 subsection (Figure 6b and c).

Figure 6: The distribution characteristics of Chang 1 residual thickness in the Jiyuan area: (a) the contour map of Chang 1 subsection residual thickness, the blue line segment represents the position of the connecting well profile, (b) profile of wells G68-X45 in Chang 1 residual thickness, and (c) profile of wells H57-B286 in Chang 1 residual thickness.

4.3 The Chang 1 Sedimentary Facies in the Jiyuan Area

Due to the influence of strong intracontinental orogenic activities in the southern Qinling orogenic belt [2,37], the basement of the basin rose, resulting in different subsidence rates in different Ordos Basin areas, and several shallow lakes were formed, especially in the eastern basin that formed the Chang 1 new settlement center.

The Jiyuan area is located in the central and western Ordos Basin, where shallow delta deposits developed in the late Triassic Yanchang formation [31,33,38]. Due to the late upliftment and denudation, only a portion of the strata remained. Through core observations, it was found that there were many carbonized plant stems and coal lines in the Chang 1 subsection in the study area, indicating the environmental swamp facies deposition in the delta plain, slump deformation structures generated by the rapid deposition in the subaqueous distributary channel, and vertical wormholes reflecting the weak hydrodynamic environment (Figure 7).

During the Chang 1 depositional period, delta deposition developed in the study area, delta front deposition developed in most areas, and delta plain deposition developed in some areas. According to the drilling coring and logging data, the sedimentary facies of the Chang 1 subsection in the Jiyuan area were divided (Figure 8). The region exhibits an overall monoclinical structure, where the terrain is gentle and there are meandering river deposits. Sedimentary microfacies are mainly subaqueous distributary channels in the delta front. The sedimentary microfacies assemblage is characterized by channel sand dams, shoals, crevasse fans, natural levees, and flood plains (Figure 9).

The Jiyuan area is located in the middle and west of the Triassic lake basin, where the river enters the lake basin from the northwest, and it predominately belongs to the delta deposition. Based on the many vertical wormholes, carbonized plant roots, coal lines, and other aquatic sedimentary markers that developed in the Chang 1 subsection (Figure 7), the logging spontaneous potential curve is characterized by large a box shape (Figure 8), and the lake shoreline of Chang 1 in the Jiyuan area is an arc-shaped line distributed in the Xiaojianzi–Baoziwan–Luopangyuan area, with a northwest–southeast trend. The delta plain facies are primarily distributed in the northern Jiyuan area, Pengtan, and Anbian (Figure 10). The Chang 1 reservoir is primarily composed of water distributary channel in the delta plain and an underwater distributary channel sand body in the delta front. Rivers control the distribution law of the reservoir sand bodies. During the sedimentation process, the distributary channel maintains transversal migration, which allows the distributary channel sand bodies to exhibit a wide distribution range and sufficient connectivity, and the thickness along the extension direction of the channel is stable. From the west to east of the Chang 1 subsection, there are four belts of distributary channel sand bodies. The accumulated longitudinal thickness is 10–30 m, and the transverse extension width is 3–10 km (Figure 10a). The distributary channel sandstones deposited in Chang 1 of the Jiyuan area exhibit a fine grain size and sufficient sorting property.

Figure 7: Photographs of the drilling cores in the Jiyuan area: (a) vertical wormhole in the gray–black mudstone from the drilling cores in Well G159, (b) carbon dust in the medium grained sandstone from the drilling cores in Well G55, (c) carbon dust in the gray–black mudstone from the drilling cores in Well G68, (d) vertical wormhole in fine grained sandstone from the drilling cores in Well A72, (e) collapse structure in fine grained sandstone from the drilling cores in Well A72, and (f) collapse structure in the medium sandstone from the drilling cores in Well A47. The drilling well location is showed in Figure 9(c).

5 Discussion

5.1 Paleogeomorphic characteristics of the pre-Jurassic in Jiyuan area

Based on core observation, seismic interpretation data and impression of stratigraphic thickness, the sedimentary characteristics of pre-Jurassic paleogeomorphology have been studied in Jiyuan area. The paleogeomorphology in the pre-Jurassic includes Jiyuan plateau, Dingbian plateau, Anbian plateau, Mengshan ancient river, Ningshaan ancient river, and other two ancient rivers. Ancient terraces were developed in the south of Jiyuan plateau, the south of Dingbian plateau, and the west of Anbian plateau. Slope zones were developed on both sides of the valleys of Mengshan ancient river and Ningshaan ancient river. Recent studies demonstrate that pre-Jurassic paleogeomorphic characteristics affect the depositions and oil reservoir distributions of the upper strata of the Yanchang formation [28,29]. The deeper the Jurassic ancient river eroded downward, the older the strata exposed. The oldest strata observed in Ningshaan ancient river valley are the Chang 6 Formation. The thickness of Fuxian formation and Yan10 strata decreased, and the young strata appeared on terraces, slopes, and

ancient plateaus on both sides of the ancient valley. The plateau preserved strata in the pre-Jurassic paleogeomorphology of Jiyuan area are part of Chang 1 subsection [28,31–35].

5.2 Reservoir forming conditions of Chang 1 reservoir in Jiyuan area

According to earlier studies, the Chang 1 reservoir in the Jiyuan area exhibits the following favorable conditions for reservoir formation: (1) the Chang 7 high-quality source rocks provide abundant oil sources for reservoir formation [2,39,40], (2) in the lower part of Chang 1 subsection, there is a large area of longitudinally overlapping genetic sand bodies, which is an important channel for oil migration [41–43], (3) the microfracture system formed by the reservoir sandstone of the Yanchang formation after the multistage tectonic movement transformation has become the oil and gas migration system [16,44], and (4) the channel erosion at the top of the Yanchang formation resulted in the formation of another oil migration channel of the Chang 1 reservoir near the plateau in the Jiyuan area.

Figure 8: The sedimentary microfacies well profile of Chang 1 subsection in the Jiyuan area: (a) the sedimentary microfacies profile of the delta front from the drilling cores in Well G68 and (b) the sedimentary microfacies profile of the delta front from the drilling cores in Well Y156. The drilling well location is showed in Figure 9(c).

5.3 The characteristics of Chang 1 reservoir in Jiyuan area

Important hydrocarbon source rocks that formed by the deep lake facies in the Jiyuan plateau of the Chang 1 subsection came from the deep lake facies of the Chang 7 period [45–50]. The longitudinal superimposed sandstone in the upper strata of the Chang 7 subsection is the primary oil

migration transport conductor [51–56]. The Chang 1 reservoir formation model assigns the distributary channel sand body as the reservoir and upper sedimentary mudstone as the shelter. A lithologic-structure reservoir was formed in the Jiyuan plateau (Figure 10a). The Chang 1 reservoir belongs to the northwest provenance supply, and the channel sand body extends in the northwest to southeast direction. Under the control of the nose-shaped structure tilting westward, a

Figure 9: The sedimentary facies distribution of Chang 1 subsection in the Jiyuan area: (a) the sedimentary facies profile of wells G132-G94-G68-G29 shows the characteristics of the sedimentary facies from the delta plain to the delta front, (b) the sedimentary facies profile of wells Y295-Y177-Y233 shows the characteristics of the delta front, and (c) the sedimentary facies distribution of Chang 1 subsection in the Jiyuan area, the red lines represent the profile positions of sedimentary interconnect wells.

Figure 10: The oil target area of Chang 1 subsection in the Jiyuan area: (a) the sand thickness contour of Chang 1 subsection in the Jiyuan area, the pink area represents the target area for oil exploration of Chang 1 subsection, the blue isoline represents the structural data of the top of the connected sand body of Chang 1 subsection, and the red lines represent the positions of oil reservoir profile and (b) the oil reservoir profile of Chang 1 subsection in the Jiyuan area.

reservoir was formed at the height of the structure. The oil–water differentiation is particularly clear in the low exploration site of the west wing of the structure, and the east wing sandstone facies into the mudstone to form optimal shielding conditions, demonstrating clear lithologic–structure reservoir features (Figure 10b).

6 Conclusions

The Ordos Basin was uplifted by the Indosinian movement in the late Triassic, and the strata at the top of the Yanchang formation in the study area experienced different degrees of river erosion, which formed the

paleogeomorphic features of the pre-Jurassic at the top of the Yanchang formation. The Late Triassic–Early Jurassic paleogeomorphology includes the ancient Ningshan river, ancient Mengshan river, ancient Ganshan river, Jiyuan plateau, and Dingbian plateau in the Jiyuan area. Based on the characteristics of Late Triassic–Early Jurassic paleogeomorphic unit and analysis of the exposed strata at the top of the Yanchang formation in the Jiyuan area. Chang 1 subsection was formed in the upper part of the Yanchang Formation. A few parts of Chang 1 subsection were lost due to downward erosion of the strata by the Jurassic ancient river. The paleogeomorphology was formed by the downward erosion of the Yanchang formation by the Jurassic ancient river. Combined with the erosion of Chang 1 subsection by ancient river in pre-Jurassic, the formation regularity of Chang 1 member reservoir is discussed. The Chang 1 residual strata are predominately concentrated in the Jiyuan and Dingbian plateaus. The residual thickness of the Jiyuan area is between 0 and 80 m, most of the area is less than 50 m thick, and the oil-bearing interval is primarily concentrated in the lower part of the Chang 1 subsection. The Chang 1 depositional period in the Jiyuan area was related to the primary delta plain and delta front deposition. The reservoir sandstone is mostly a distributary channel sand body with a wide distribution and sufficient connectivity. The main part of the distributary channel sand body is fine-grain sand with a good sorting characteristic. Under the control of the nose-shaped structure plunging to the west, the reservoir of the Chang 1 subsection in the Jiyuan area is primarily concentrated in the high structure of the sand body. The Chang 1 reservoir in the Jiyuan area is a typical tectonic-lithologic reservoir.

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