The influence of the pre-existing topography on the deposition systems, the development of the Lower Jurassic reservoirs and hydrocarbon accumulation in Central Western Ordos Basin

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ABSTRACT

Pre-existing topography not only influenced the development of the Jurassic depositional systems and the reservoirs, but also controlled the hydrocarbon accumulation in Central Western Ordos Basin. Detailed reconstruction of the paleotopography and mapping of the depositional systems and reservoir fairways reveal that the two are closely related. In order to better understand their relationships, detailed environmental facies, channel fairways, source directions of the sediment supplies, burial depth/history, and paleobathymetries have been rebuilt and mapped out using well, seismic and log data. The mapping results show that the pre-existing topography and paleogeography prior to the deposition of the Jurassic rocks have a clear influence on (1) a monadnock rising from a third-order valley; (2) sediment microfacies that result in primary reservoirs, but also controlled the hydrocarbon accumulation in Central Western Ordos Basin. Detailed reconstruction of the paleotopography and mapping of the depositional systems and reservoir fairways reveal that the two are closely related. In order to better understand their relationships, detailed environmental facies, channel fairways, source directions of the sediment supplies, burial depth/history, and paleobathymetries have been rebuilt and mapped out using well, seismic and log data. The mapping results show that the pre-existing topography and paleogeography prior to the deposition of the Jurassic rocks have a clear influence on (1) a monadnock rising from a third-order valley; (2) sediment microfacies that result in primary reservoirs, but also controlled the hydrocarbon accumulation in Central Western Ordos Basin.

1. Introduction

In the late Triassic, the Ordos Basin was affected by Indosinian movement, with the top part of the YanChang Formation experiencing efflorescence and stream erosion and forming the ancient landform landscape. Over this landscape, a river system is widely distributed both vertically and horizontally, driving the formation of ravines. In this background, the Jurassic strata have been deposited. Therefore, for Jurassic oil and gas exploration in the Ordos Basin, accurate rebuilding of the paleogeography is important, as is an understanding of the paleogeographical influences on and regulation of oil–gas accumulation.

Previous researchers have made great strides in this paleomorphological rebuilding effort (Lv et al., 2000), finding that branch channels are apparently equally spaced, with main channels intersecting at sharp angles, and that the reservoir is primarily under the control of a monadnock uplift in the tertiary river valley. This information has provided a solid basis for directing oil exploration, Zhao Junxing (Zhao et al., 2001) mainly discusses the ways of rebuilding paleogeomorphology and its relationship with the late oil reservoir through rebuilding the paleogeomorphology of the Ordos Basin before Jurassic. Dai Jinyou (Dai and He, 2005) used the methods of residual thickness to recover the paleogeomorphic features of the Ordovician.

The paleokarst landform types are relative to the accumulation of natural gas but much of this work was limited to 2D or quasi-2D plan plotting and could not provide a relatively accurate predictive data for exploration and production. On the basis of previous work and taking the Midwest Ordos Basin as an example, the current paper uses a 3D geological modeling technology to rebuild pre-Jurassic paleogeography to further our understanding of the paleogeographical factors controlling oil–gas accumulation.

2. Research area location

The structural features of the Ordos Basin include an asymmetrical basin with a wide and gently angled east wing and a narrow west wing. Faulted fold systems are developed along all the four margins of the basin, but the internal structure is relatively simple and the terrain stratum is mild, generally with a dip of less than 1°. The basin has no secondary structures, and tertiary structures include only a series of nose-shaped uplifts of small amplitude. Based on its current structural formation, basement properties, and structural features, the Ordos Basin can be divided into six primary structural units: the Yinmeng uplift in the north; a zone of bruchfalten on the west edge; the Tianhuan Depression in the west; the Shanbei slope in the middle; the Weihei uplift in the south; and the Western Shanxi flexural-fold belt in the east (Yang, 2002). In terms of its regional structural position, the area of interest is mainly located in the midwestern portion of the Shanbei slope, a soft slope belt on the north edge of the lake basin.
(Fig. 1). The investigated horizon is mainly the Middle–Lower Jurassic Ordos Basin (Table 1).

Because of extensive stream erosion, the common residual thickness of the Chang 1 stratum on the top of the Yanchang Formation in the area of interest is only several meters to several tens of meters in depth. Some places are so denuded that the Chang 2 stratum is even exposed. Because of erosional cutting and lateral accretion of ancient rivers, several sublevel ancient rivers have developed, as have marginal bank facies sandbodies, forming a unique paleogeographical landscape in the area of interest. The Fuxian and Yanan Formations of the late Lower Jurassic are deposited only on this trachydiscontinuity. The Fuxian Formation was the initial filling, and the Yan 10 period was an overlap valley fill until its last stage; the pre-Jurassic paleotopography has become increasingly level since. There is no evident lamination mark between the Fuxian Formation and Yan 10 in the area of interest. The compact construction, which formed because of the Fuxian + Yan 10 zone thickness and lithologic difference, inherited the structural form of the top surface of the Yanchang Formation, and their structural culmination coincides well. Based on these features, this paper explores Fuxian + Yan 10 as a single unit of investigation.

3. The paleogeography rebuilding method

3.1. Analysis of the sedimentary environment and sedimentary facies

The Fuxian period represents infilling sediment at the initial stage of the Jurassic, mainly restrictive braided stream macrofragment sediment in the ancient valley. On this base, Yan 10 sediment developed as erosion, an accumulative deposit where the stream was dominant.

Because of fan-shaped and zonal conglomerates generated by a contributory water system and master river burst, the Fuxian + Yan 10 period is, on the whole, a river facies sedimentary system. The area of interest has mainly developed into main stem riverbed and marginal bank microfacies, contributory watercourse marginal banks, and floodplain microfacies. Two main stems have large widths and thicknesses, and the remaining watercourses have small widths and thicknesses. Until the late stage of Yan 10, pre-Jurassic paleotopography had become increasingly level, with a reduced landform height and diminished stream sediment in both strength and scale.

3.2. Lithologic analysis and sandbody distribution

Under the influence of torrential river deposits, the lithology of Fuxian + Yan 10 mainly consists of medium-grain feldspar quartz-like sandstone, with a lenticle rock stratum coming next in sequence, and parallel bedding and oblique stratification on the upper part. At the late stage of Yan 10, sandstone in the stratum was mainly packsand, medium sandstone, and mudstone, with an evident increase in the interbed coal seam.

The sandbody distribution of the Fuxian + Yan 10 period demonstrates paleogeographical control (Fig. 2) and is mainly regulated by two ancient river courses, the ancient Ningshan and Mengshan rivers. Watercourse sandstone constitutes the bearer and reservoirs for the secondary migration of oil–gas.

3.3. Paleocurrent direction and provenance analysis

The paleocurrent direction of the river is also an important basis for distinguishing paleotopography. Provenance analysis can indicate directional sign and trends in grain-size change in the sediment. The ancient Mengshan River in the area of interest was distributed approximately from the north–northwest to southeast. The ancient Ningshan River flowed from the northwest to the southeast, joining the Mengshan and then flowing into the Ganshan ancient river zone.

According to data on heavy minerals collected from rock cores in the area of interest, the types of heavy minerals at the bottom of the Fuxian Formation are mainly melilchrysos, kalbaite, garnet, and sphene. They can be divided into two kinds of major heavy mineral combination according to heavy mineral assembly and content plane variety trends: the melilchrysos + garnet combination zone in the Pengtan District and the melilchrysos + kalbaite combination zone in the Wuqi District. These features show that the provenance of the Fuxian Formation bottom is mainly the northwest.

3.4. Paleothickness restoration (decompaction correction)

The key to rebuilding this paleogeography is to determine the ancient elevation depth of the Fuxian + Yan 10 period. Taking into account ancient sea level variation, the ancient elevation depth of this period is equivalent to the sum of the sea level’s water depth (paleodepth) and the thickness of Fuxian + Yan 10. This paper adopts the backstripping method for decompaction restoration of paleothickness (Mao et al., 1998).

Stratum denudation in this area must be considered before restoration. Many methods are possible for restoring denudation

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<td>Upper Triassic/Middle–Lower Jurassic stratigraphic scale of the Ordos Basin.</td>
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thickness, including stratigraphic cross-section pairing, sonic differential time, vitrinite reflectance, fluctuation analysis, and sedimentation rate. This paper uses only the stratigraphic cross-section pairing method to accurately estimate points with evident denudation thickness. Most regions in the area of interest experienced little denudation during this period.

Decompaction correction of a stratum complies with the following assumptions: a solid volume of sedimentary formation does not change during sedimentation; compaction only occurs in depth direction and transversal action is not considered; and the degree of compaction depends on embedded depth and is irreversible. The specific method, in general, to first calculate the formation skeleton thickness, then apply the assumption that formation skeleton thickness is fixed and use the framework thickness-computing formula to deduce the stratum’s ancient embedded depth calculation formula. By plugging in the corresponding parameter values, we can obtain the stratum’s ancient embedded depth data.

The reasoning is that an exponential relationship exists between porosity and embedded depth, as follows:

\[ \phi(z) = \phi_0 \exp(-cz) \]  

where \( \phi(z) \) is the porosity function that takes the embedded depth of the stratum as a parameter; \( \phi_0 \) is the terrene porosity; \( c \) is the compaction factor (1/m); and \( z \) is the embedded depth of the stratum (m).

This formula is suitable for deep decompaction correction. The area involved in this paper is embedded deeply, having no large fault or flexure action, and the lithologic character is mainly sand-mudstone: thus, this formula is used to restore paleothickness, and the evolutionary relationship of formation porosity may be expressed as follows:

\[ \phi(z) = p_s \phi_s(z) + p_m \phi_m(z) \]  

where \( p_s, p_m \) is the content of sandstone/mudstone in the stratum, as decimals, \( p_s + p_m = 1 \); and \( \phi_s(z), \phi_m(z) \) is the function of the porosity of the sandstone/mudstone in the stratum versus depth.

For calculation of formation skeleton thickness, the following applies:

\[ h_t = \int_{h_1}^{h_2} (1 - \phi(z)) \, dz \]  

where \( h_t \) is the framework thickness of the stratum (m); and \( h_1, h_2 \) is the current embedded depth of the stratum from bottom to top (m).

According to burial state and the principle that volume is constant during superficial deposit:

\[ h_t = \int_{h_1}^{h_2} (1 - \phi(z)) \, dz = \int_0^h (1 - \phi(z)) \, dz \]  

where \( h \) is the depth of the bottom interface at the time of deposition, namely the ancient embedded depth (m).

The final iterative formula is as follows:

\[ h_{i+1} = h_i + F \left( h_i \right) - F(0) / (i = 0, 1, 2, \ldots) \]  

where \( F(h) \) is a primitive function of \( \phi(h) \). The initial value is \( h_{(0)} = h_1 + h_2 \) calculated until \( |h_{i+1} - h_i| < 0.01 \) m.

To apply this model, select a typical well for the area of interest in this paper, adopt a sonic differential time method, and use the least square method to work out the compaction curve of two lithologic characters, i.e., sand and mud, respectively: \( \phi_s(z), \phi_m(z) \). The area is

\[ \phi_s(z) = 0.38 \exp \left( -3.64 \times 10^{-4} z \right) \]  

\[ \phi_m(z) = 0.67 \exp \left( -7.55 \times 10^{-4} z \right) \]

Finally, use a completion well logging figure to calculate the percentage content of sandstone and mudstone and thus restore the
The paleodepth of the basin may be determined according to sediment dispersal rules, sedimentary structure, ancient life type, and ecology marks. Any method used can only roughly estimate paleodepth. Generally, the macrofragment content of a lake basin is shallow-water deposit, and grit sediment decreases and mudstone sediment increases from shallow water to deep water. Change in sedimentary structure depends on sediment color, water body depth, and changes in hydrodynamic conditions. In deep water, relatively deep water basins mainly form tenuous horizontal bedding, developed in a continuous rhythm: turbidite in a deep lake has a flysch structure, flute cast, and gutter cast as characteristic depositional marks; the bedding type in shallow-water areas is diversified, developed in an intermittent rhythm, and shows ripple marks and the development of washout erosion; and the bedding-plane structures, such as weather shake, rain print, and rill marks, all reflect the exposure of the sediment above water.

Ancient life is a reliable marker for determining paleodepth. In a lacustrine sediment environment lacking in fossil remains, ichnofossils such as domicinia, repichnia, and other bioturbate structures can be used to determine paleodepth.

3.6. Paleogeography restoration

Combined analysis of data such as precipitation facies, ore mass distribution, provenance of paleocurrent direction, paleothickness reconstruction, and paleobathymetric correction highlights the ancient elevation depth of the Fuxian + Yan 10 stratum. When these data are constrained by the Yanchang Formation's residual thickness method, an accurate restoration of pre-Jurassic paleogeography (Figs. 3 and 4) in the area of interest can be obtained via the stratigraphic correlation profile method and the use of 3D geological modeling technology (McCarthy et al., 1998; Journel et al., 1998; Magdalena and Bayer, 2003; Vargas-Guzmán and Hisham, 2004; McLarena et al., 2004; Subbey et al., 2004; Long et al., 2007).

3.7. Division of paleogeographical units

The paleogeographical pattern in the area of interest consists of three slopes, one highland, one platform, two river valleys, one beam, and one monadnock: namely, the Dingbian, Jingbianxi, and Jiyuandong slopes, the Jiyuan highland, the Wuqi platform, the ancient Ningshan and Mengshan river valleys, the Xinan boundary beam, and the monadnock on either side of the ancient rivers. Each pattern is defined and elaborated later.

Slope is a paleogeographical unit with a relatively high landform and mainly comprises the transitional belt between the valley and highland.

River valley is the morphologic unit with the lowest landform. The area consists of Classes II, III, and IV valleys, i.e., the Ningshan ancient river and the Mengshan ancient river, which belong to the Class II valley. The Class III valley belongs to a tributary watercourse that flows into the Class II valley, and the Class IV valley belongs to a tributary watercourse that flows into the Class III valley. The ancient Ningshan River is located in the west of the area of interest, showing a northwest distribution and flowing into the ancient Ganshan River area from northwest to southeast. The ancient Mengshan River is located in the east of the area of interest, distributed almost in a northwesterly to southeasterly direction. The Class III valley is a branch of the Class II water system and constitutes a branching system together with the Class II water system.
Fig. 3. Jurassic paleogeography in the Jiyuan–Hujianshan area.

Fig. 4. Seismic interpretation of a section of the 00125 measuring line.
most favorable for capturing the oil–gas migrating upward along the fossil erosion surface. The lithologic character of such a sandbody is mainly medium-rough, medium fine-grained sand. Grading is evidently better than the bed phase sandbody: granularity is moderate, heterogeneity is small, the physical property of the reservoir bed is good, and it is the most favorable reservoir bed for petroleum accumulation.

(5) A differential compaction structure under control of paleogeography is the determinant for obtaining high yield. At the end of the Indosinian movement, a local structure plane of erosion surface overlying the formation is completely consistent with the fluctuation state of the erosion surface. This differential compaction structure is based on fluctuation in the paleogeography that is dominated by differential compaction of overlying sediments. Such a structure has the features of early formation and successive development and is an indication area for long-term migration of oil–gas. Because its genesis is related to fluctuation of the erosion surface and sandbody distribution of the river, such a structure is always accompanied by eroded monadnock and river facies sandbodies and distributed in groups and belts. These areas are also located in the most favorable areas for migration of oil–gas, thus forming a compacted structure oil reservoir with a wide range.

5. Conclusions

In cases of inadequate seismic data in the area of interest, a great deal of qualitative analysis comprising paleotectonics, lithofacies paleogeography, and provenance analysis provides the foundation for successful restoration of an area’s paleogeography. Interpretation of data from geological findings, drilling and logging, and fine 3D geological modeling technology, along with quantitative analysis such as paleothickness rebuilding and paleobathymetric correction, are all required for the accurate restoration of paleogeography. A paleogeography model can be modified and completed in a timely and dynamic fashion, based on actual exploration conditions, and it also can provide a reliable basis for exploratory development, informing well-site deployment and reducing exploration risk.

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References