Research Article

Pattern and Geological Meaning of Oblique Progradational Filling Within the Late Triassic Lake in the Ordos Basin

Yanga Hua[1,3], Wang Daxin[2], Pu Renhai[1*], Li Huiqiong[1], Xu Pengye[1]

[1]Department of Geology, Northwest University, Xian, 710069, China

[2]Changqing Oilfield Company, Petro China, Xian, 710018, China

[3]China National Petroleum Corporation, Beijing 100007, China

*Corresponding author: Renhai Pu, State Key Laboratory of Continental Dynamics, Department of Geology, Northwest University, Xian, 710069, China. Tel: +862988302202; Email: 552418459@qq.com

Abstract

With the technical progress of seismic exploration in the Loess Plateau, a number of large-scale oblique Progradational sequence reflections have been seen in the deep-water area of the lacustrine Triassic Yanchang Formation of the Ordos Basin in central to western China. These Progradational sequences come from different margins of the lake: four from the southwest, two from the northeast, and one from the southeast. Each lenticular Progradational sequence can be divided vertically into three parts including topset, foreset and bottom set, consisting of delta, deeper lake and gravity flow depositional complexes, respectively. A Progradational sequence usually penetrates a few lithostratigraphic Mbrs from C7 to C3 of the Yanchang Formation that are divided and correlated using well data. Seismic sections show that well data-defined lithostratigraphic units such as the C6, C4+5 or C3 Mbrs are in fact simultaneous deposits contained in the same Progradational sequence or they correlate to different Progradational sequences over long distances. The clinoform reflections show an ancient lake bed form in the southwest steep slope (3-5°) and the northeast gentle slope (2-2.5°) of the Yanchang Formation.

The slope gradient controls the distribution of tight sandstone reservoirs. Due to the actions of gravity or storms, the sandy sediments were more easily transported to the lower part of the foot of the southwest steep slope, so the sandstones of this slope foot are richer than those on the foot of the northeast gentle slope of the lake. The oblique filling pattern of Progradational sequences might exert an important influence over the effectiveness of water driving during oil pool development.

Introduction

For a long time, research on the stratigraphic division, correlation and sedimentology of the Late Triassic Yanchang lake basin have been based on the lithostratigraphic of drilling data. In recent years, due to progress in seismic exploration technology in the Loess Plateau and improvements in the quality of seismic data [1], oblique Progradational reflection sequences have been identified in the lacustrine Upper Triassic Yanchang Formation in the central and southern portions of the Ordos Basin.

These Progradational reflections not only indicate the diachronism of the lithostratigraphic units divided and correlated using wells but also provide useful information for interpreting the sedimentary facies, predicting tight sandstone distributions, and estimating the paleo-depths of the lake basin [2-4]. Progradational reflection phenomena of lacustrine strata were also observed in the Neogene Lake Pannon in Hungary [5], Lake Van in Turkey [6] and the West Snake Basin in Idaho [7]. A specific relationship exists between Progradational reflections and lithostratigraphy, lithology and sedimentary facies [8-10]. They are significant for our understanding of basin evolution, the filling process and sandstone reservoir distribution of delta and gravity flow deposits. Especially in deep-lake environments, the sandstone reservoirs are often associated with different assemblages of submarine fan systems [11-14]. For Quaternary and Precambrian rocks related to glacial lacustrine deposition and lacking fossils, seismic interpretation plays an important role in the establishment of

the sequence stratigraphy and the identification of depositional systems [15-20]. Seismic onlap and clinoform reflections are sometimes helpful to clarify the relationship between shallow-water and deep-water deposits and influxes of different sediment supplies [21-22]. Integrated research using seismic and well data facilitates the understanding of the control of paleoclimate, paleo structure and sea-level fluctuation on the filling and evolution of lacustrine basins [23-25].

Based on well lithostratigraphy, Yanchang lake was previously considered to have been filled gradually by approximately parallel planar depositions [26], but the existence of seismic clinoform sequences completely changed this interpretation. Furthermore, it intuitively reveals useful information about the lake bedforms, the ancient water depth and the distribution of tight sandstone reservoirs. Within the deep-lake area of the Ordos Basin, oil is produced mostly from tight sandstones that are mainly sandy debris flow and turbidities deposits [27,28] that are thick and widely distributed [29,30]. According to the deep-water turbidities of the C6 Mbr on the southwestern lake margin and the horizon angle (0.47°) between the C6 and C7 Mbrs, Lv et al. (2008) [31] considered the lake should be deeper and steeper on the southwest margin slope, and shallower and gentler on the northeast marine slope. Ma et al. (2009) [32] identified the C6-C7 Mbr clinoform reflections in seismic profiles and inferred the existence of turbidity deposits in front of them. According to the C6-C7 Mbr braided delta and turbidity deposits in the southwestern margin and meandering river and delta deposits in the northeastern margin of the lake, Ding et al. (2011) [33] inferred that the lake bed form should have been gentle in the northeast and steep in the southwest. We see many oblique seismic Progradational reflections in the Yanchang Formation in the lake basin that directly reflect the steepness of the southwest slope and the gentleness of the northeastern slope. Integrated interpretation of well and seismic data shows oblique filling patterns and the history of the lake basin and their impact on the distribution of tight sandstones and the injections of water in oil pool development. The novelty in the present work as compared to cited literature are mainly three aspects as following:

1. The depositional transformation from the delta to coeval gravity flow within a Progradational sequence is first clearly defined through integrated interpretation of well and seismic data.

2. The control effect of lake bed form on the distribution of gravity flow and delta sandstones is proposed for the first time.

3. The cause of the high injection production ratio in water drive development of oil pools might have been caused by diachronous well pick correlations within a Progradational sequence.

Geological Setting

The Ordos Basin is located in central to western China (Figure 1). The basin covers an area of 260,000 km² and is currently the largest petroliferous basin in China. The two major petroleum systems in the basin consist of a gas-producing Upper Paleozoic coal-bearing system and an oil-producing Upper Triassic lacustrine system. The lacustrine oil-bearing area of the Upper Triassic in the central and southern portions of the basin measures approximately 80,000 km², and its annual oil yield is approximately 40,000,000 tons. The study area covers the entire Yanchang Formation lake basin in the southern portion of the Ordos Basin (Figure 1).
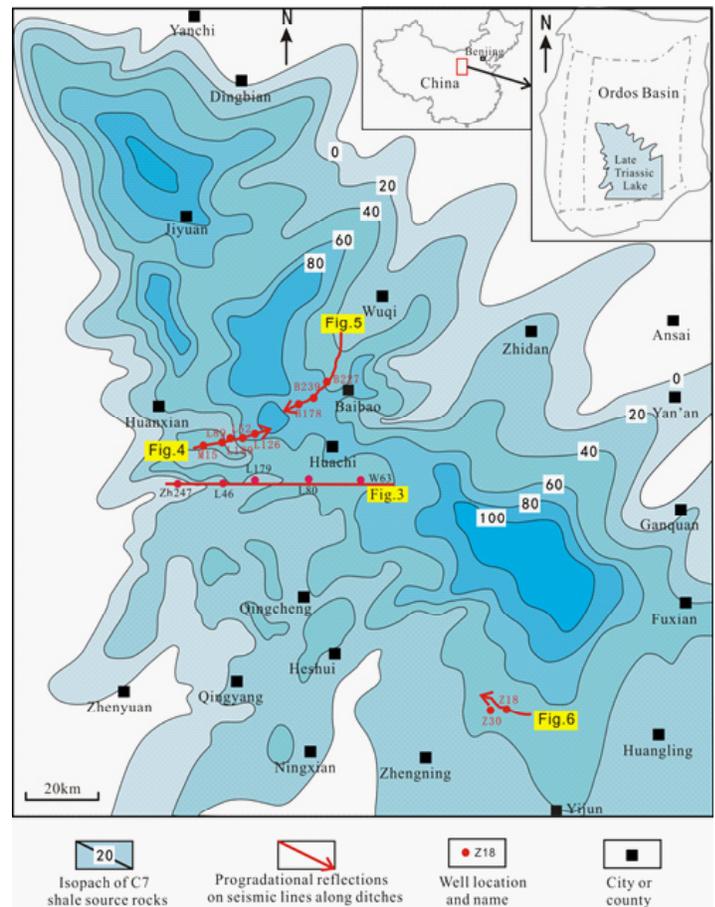

Figure 1: Map of the study area and isopachs of the lacustrine shale source rocks of the C7 Mbr of the Yanchang Formation in the Ordos Basin, China. The shale thickness indicates the approximate extent of the Late Triassic lake.

The Ordos Basin is a composite basin, which overlapped on the early and late Paleozoic craton and formed during the Middle Triassic [34]. Currently, the Ordos Basin is bounded by the Yinshan Mountains to the north, the Qinling Mountains to the south, the Lvliang Mountains to the east, and the Helan-Liupanshan Mountains to the west [35]. Earlier studies indicated that during

the Middle and Late Triassic, the northern, western and eastern borders of the basin were all in relatively stable tectonic settings, but the southwestern Qilian-Qinling Mountains were experiencing collisional orogenesis between the North China Block and the Yangtze Block [36]. During the Middle and Late Triassic, the Huabei Craton gradually shrank and entered the evolution period of the inland Ordos Basin. Due to Late Triassic regional tectonic activity, a set of fluvial, lacustrine and deltaic clastic sediments was deposited, and they are stratigraphically named the Yanchang Formation. In the Ordos Basin, the Yanchang Formation records a complete history of the generation, development and extinction of the Triassic Yanchang lake. In particular, the 20- to 60-m-thick shale of the C7 Mbr in the middle of the Yanchang Formation represents the time when the lake basin was the deepest (Figure 1). Two major deltaic systems entered from the northeast and southwest margins during the filling of the lake basin. Between the two deltaic systems is a northwest-southeast extensional area of deep water where widespread deposition of gravity flows occurred [37]. It is generally believed that the Qilian-Qinling orogenic belt to the southwest and the Yinshan archicontinent to the northeast provided clastic sediment for the filling of the lake basin. Meanwhile, a secondary sediment source was supplied from the west-southwest margin [38-41]. The Yanchang Formation is approximately 900 to 1000 m thick on the southwest side and approximately 600 to 800 m thick on the northeast side. The Zhangjiatan shale isopachs at the base of the C7 Mbr of the basin indicate extension in the northwest direction and opening to the southeast of the lake basin (Figure 1).

The contacts between the Yanchang Formation and the overlying Jurassic Yan'an Formation or Fuxian Formation and the underlying Middle Triassic Zhifang Formation are unconformities. Based on sedimentary cycles and marker beds of Zhangjiatan shale, the Yanchang Formation is divided into 10 lithostratigraphic Mbrs, namely (in downward succession), the C1 Mbr (abbreviation for Chang 1 Member), C2 Mbr, C3 Mbr, etc., through the C10 Mbr (Figure 2) (Yang 2002) [37]. Each Mbr is approximately 80-120 m thick and approximately parallel to the marker Zhangjiatan shale of the C7 Mbr (Figure 2).
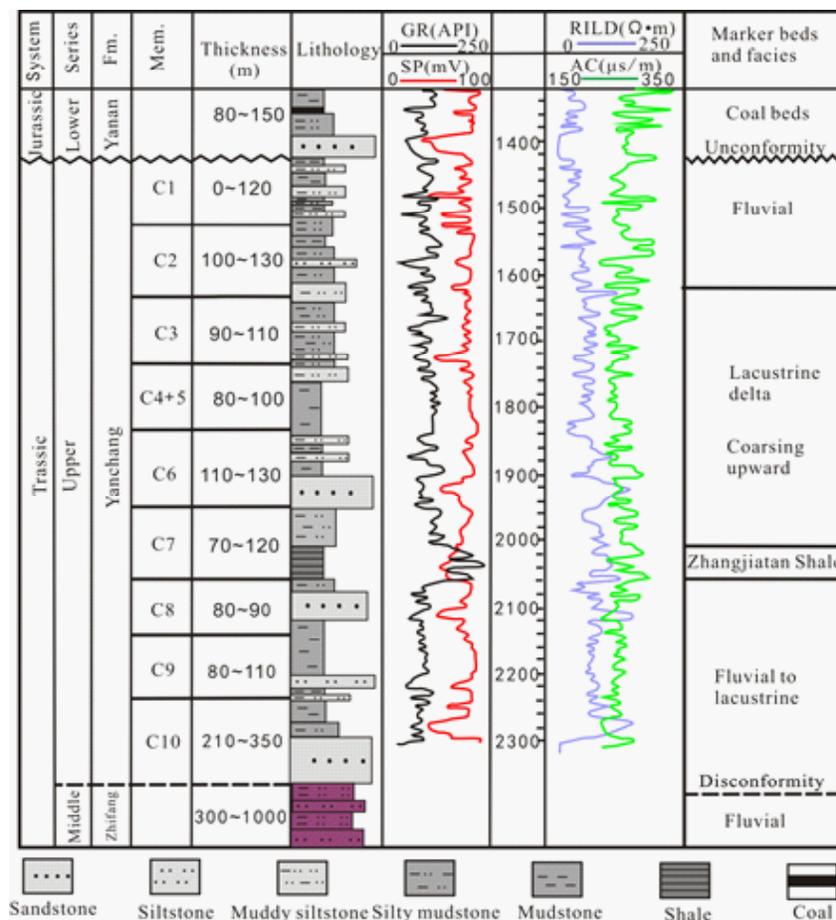

Figure 2: Stratigraphic column of the Triassic Yanchang Formation in the Ordos Basin.

Data and Methods

Although oil pools underlie the Loess Plateau, only two-dimensional (2-D) and two blocks of approximately 100 km^2 of 3-D seismic surveys have been finished [2,42]. The 2-D seismic survey included curved lines along the valleys or ditches and straight lines along east-west and north-south profiles (Figure 1). The density of the 2-D survey grid was relatively sparse, with a spacing of approximately 2 km× 1 km at the densest location. The total number of wells should have been in excess of 10000 within the lacustrine range, and the exploration well spacing was approximately 3-5 km. We selected more than 30 typical 2-D seismic lines with Progradational reflections and 420 wells located at or near the lines that cover the whole lake basin; from these data, we attempt to obtain deep insight into the geologic meaning and reservoir distribution of the Progradational sequences. Based on previous drilling and core research results [3,4,43], combined with the integrated interpretation of seismic Progradational sequences in this paper, an oblique basin filling pattern is proposed. Additionally, based on the seismic Progradational sequences, we discuss the well stratigraphic diachronism, the control of the lake slope gradient over the distribution of the tight sandstone reservoir, and the influence of oblique sandstone over the effectiveness of water injection during the development of water drive.

Division and Distribution of Seismic Progradational Sequences

The main frequency of seismic profiles for the Mesozoic interval is approximately 28 Hz, and the peak event is negative. There are two sets of high-amplitude reflections in the seismic profile that serve as markers for regional seismic stratigraphic correlation. They are caused by the low-velocity coal seam of the Jurassic Yanan Formation and the shale of the Triassic C7 Mbr (Figure 3). According to the toplap, downlap and onlap terminations associated with the clinoform reflections, the part of the Yanchang Formation from the C7 to the C1 Mbr is divided into several Progradational sequences, within which four sequences are distributed along the southwestern margin of the lake (Figures 3 and 4) and two sequences are distributed on the northeast (Figure 5) and southeast margins (Figure 6). Each sequence is actually a lens-shaped oblique Progradational body that is composed of depositional complexes from delta to gravity flows toward a deep lake, with a duration of approximately 3-5 Million years. The lower part of the Progradational sequence usually entered the C7 Mbr, and the upper part consists of C6 and C4+5 or C6, C4+5 and C3. In fact, a seismic Progradational sequence penetrates 2-4 stratigraphic Mbrs in a well. The four foreset sequences from the southwestern lake margin penetrate from the C3 to the C7 Mbr, and the corresponding toplap points gradually move up from the top of C4+5 to the top of C3 (Figure 4a). On the northeastern lake margin, the Progradational sequence I penetrates from the C6 to the C7 Mbr (Figure 5a). On the east-northeastern lake margin, the Progradational sequence II penetrates from the C4+5 to the C6 Mbr, and on the southeastern lake margin, two Progradational sequences penetrate from the C3 and C4+5 Mbrs (Figure 6a). The sandstone velocity of the Yanchang Formation ranges from 4200 to 4500 m/s, mudstone from 4000 to 4300 m/s, and the shale from 3800 to 4100 m/s. Therefore, the wave impedances of sandstone and mudstone have low contrast, but there are high impedance contrasts between shale and the other rocks. An individual 5- to 20-m-thick low-velocity shale typically exists between different Progradational sequences, so it usually forms a high-amplitude event bounding the Progradational sequences. An individual Progradational sequence usually consists of 150-250 m of siltstone and mudstone intercalated with 10-30 m of fine sandstones (Figures 4b, 5b and 6b). Individual fine sandstone often forms a short event with a moderate to weak amplitude, so siltstone and mudstone reflections are difficult to distinguish (Figure 4).
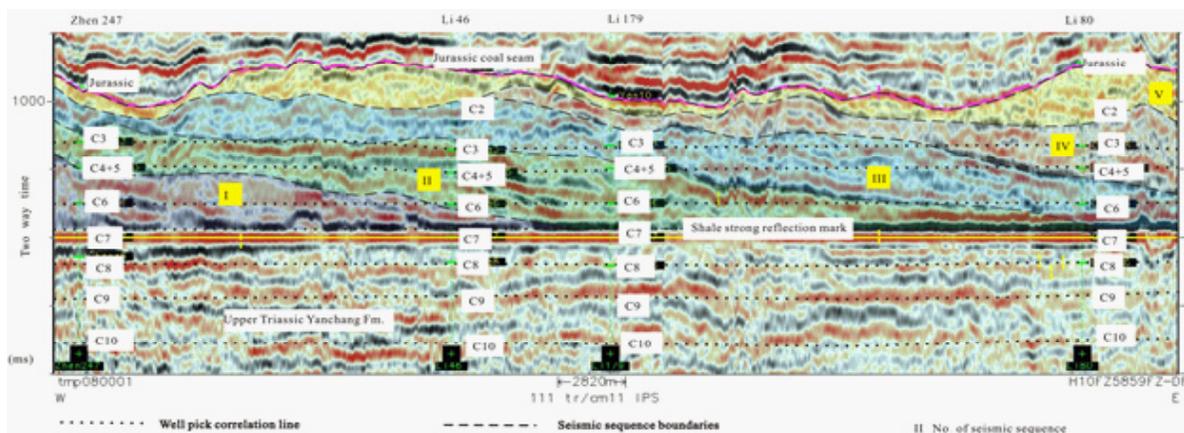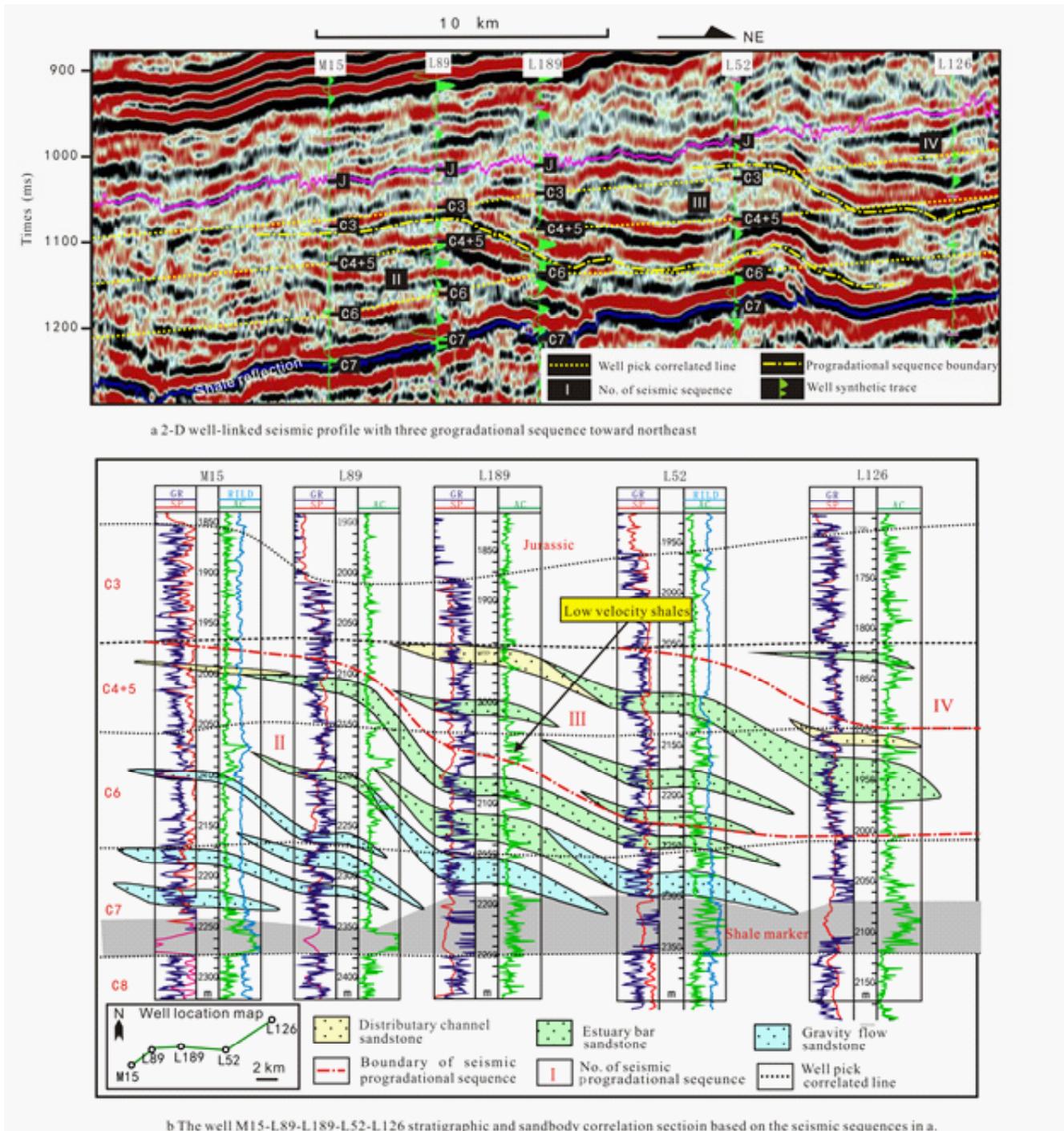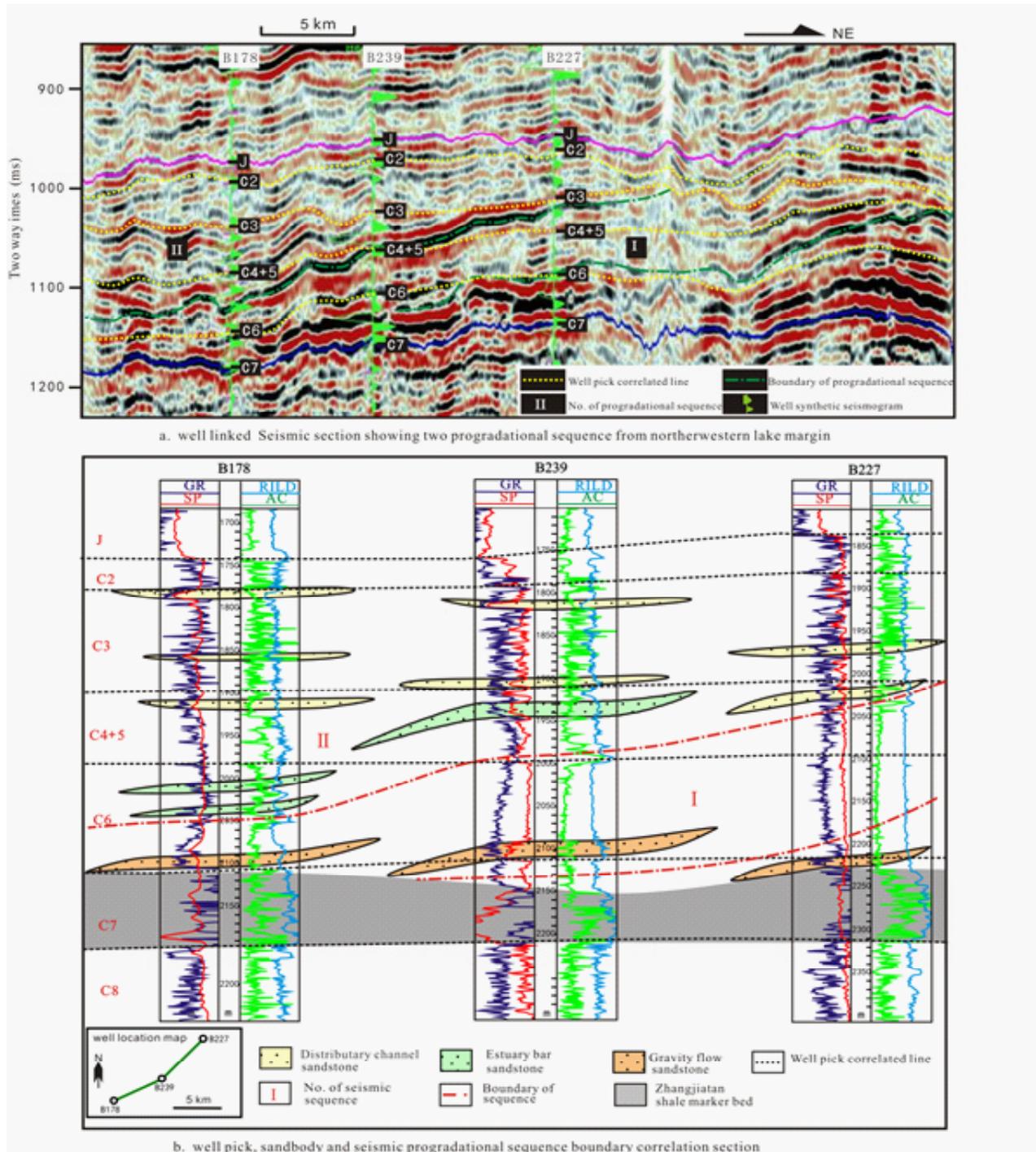

Figure 3: Interpretation of Progradational fill sequence of the Yanchang Formation lacustrine basin along the seismic profile through wells Zhen140-Li46-Li179-Li80. The location of the profile is shown in Figure 1.

a 2-D well-linked seismic profile with three grogradational sequence toward northeast

b The well M15-L89-L189-L52-L126 stratigraphic and sandbody correlation sectioin based on the seismic sequences in a.

Figures 4(a,b): A 2-D well-linked seismic section located on the southwestern steep slope of the lake. (a) shows three clinoform sequences of the Upper Triassic Yanchang Formation and their well lithostratigraphic pick and sand body correlation sections. (b) The upper part of the C4+5 Mbr in wells M15 and L89 likely correlates with the lower part of the C6 Mbr in wells L189 and L52 and extends to the interior of the C7 Mbr in well L126. Within a sequence, sandstone microfacies have transformed from distributary channel and estuary bar deposits in the upper part to gravity flow deposits based on core and log analyses.

a. well linked Seismic section showing two progradational sequence from northerwestern lake margin

b. well pick, sandbody and seismic progradational sequence boundary correlation section

Figures 5(a,b): (a) Upper panel is a well-linked seismic section showing the Progradational reflection located on the NNE margin of the lake. Three well-picked correlation lines intersect clinoform horizons. (b) The lower panel is the well-linked cross section along the 2-D seismic line, which shows massive gravity flow deposits that likely originated from upstream deltaic deposits. See Figure 1 for the section location.
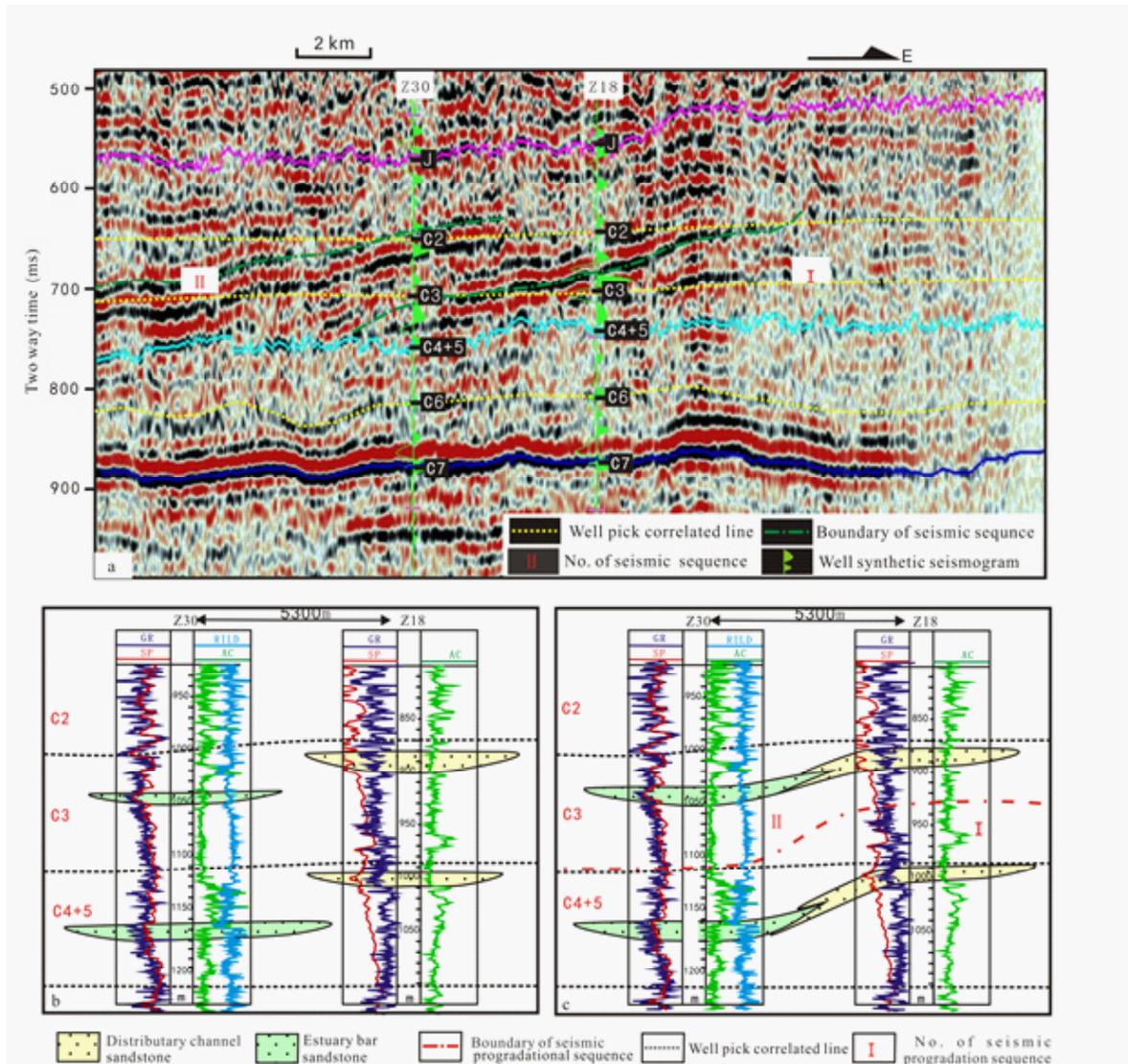
Figures 6(a,b): (a) 2-D well-linked seismic section showing the progradational sequence located on theSEE margin of the lake in Figure 1. The toplap and downlap surfaces correspond to the top of the C3 Mbr and the base of the C4+5 Mbr in the wells, respectively, but intersect the base C3 Mbr. (b) shows the flat diachronous correlation and isolated distribution of the channel sand bodies in well Z18 and the estuary bar sandbodies in well Z30. (c) shows the oblique isochronous sandstone-linked correlations based on the above clinoform sequence.

It was considered based on the well data that the filling of the lake by the delta had occurred simultaneously from various directions, but seismic interpretation shows variations in the time, scale, and order of the delta and gravity flow filling from different directions. The earliest influxes of delta and gravity flows occurred from the southwest and northeast as sequence I that mostly belongs to the C6-C7 Mbrs. Subsequently, as the toplap surface migrated upward gradually, there was an influx of delta from the east-northeast, which was represented by the C4+5 to C7 Mbrs, and then from the southeast, which was represented by the C3 and C4+5 Mbrs. The delta

in the southwest was the most stable where the toplap surfaces of sequences II, III and IV moved gradually from the top of the C6 Mbr to the C3 Mbr. Based on calibration of well seismic horizons, the topset and foreset intervals of the Progradational sequences approximately correlate to the C3 to C6 Mbrs. The bottomset interval of the Progradational sequences approximately correlates to the C7 Mbr.

Lacustrine Oblique Progradational Filling Pattern

The Late Triassic Yanchang Formation in the Ordos Basin is represented by a complete sedimentary cycle consisting of a relative water inflow-withdrawal sequence and is characterized by multiple sediment supplies and filling cycles. From the C10 to the C8 Mbr of the Yanchang Formation, the lacustrine basin began to develop, and the scale of the delta systems was relatively small. The clinoform reflections are not observed in the seismic profiles due to the sub seismic scale of the deltaic deposition during this period [9]. As the basin subsidence intensified, the water body became deeper and larger, and a set of stable main hydrocarbon source rocks was deposited in the lake basin, which is 20 to 60 m thick and called the Zhangjiatan shale as the lower part of the C7 Mbr. After the shale deposition occurred, the rivers and deltas around the lake transported large amounts of clastic material to fill the lake with oblique Progradational deposits, resulting in deep-water gravity flow deposition in the center of the lake. Then, the lake began to shrink, and it was finally filled by fluvial deposition [26]. According to the dozens of long regional 2-D seismic lines covering the whole lake basin, the starting and ending positions of each seismic Progradational sequence can be found on seismic profiles, and their corresponding planar positions are depicted individually in Figure 7. In Figure 7, three filling patterns of lake deposition are shown: an area of deep-lake parallel aggradational filling (blue), an area of lake clinoform filling (green) and an area of shallow lake to delta plain parallel aggradation (yellow). The vertical filling pattern of the lacustrine Yanchang Formation can be simplified as the section model of Figure 8, in which the red part of the lake margin corresponds to the brown part of Figure 7, meaning shallow lacustrine to deltaic plain deposition of the C4+5 and C3 Mbrs. The green and yellow-green colors in Figure 8 represent the lake slope and delta front to prodelta distribution of the C3-C6

Mbrs, corresponding to the green section of Figure 7. The cerulean portion of the lake basin in Figure 8 is a parallel aggradational filling zone, corresponding to the blue scope of Figure 7, approximately as the central lacustrine deposition of the C3 and C4+5 Mbrs. During this period, the lake became small, except locally in the southeast portion [44]; no seismic clinoform reflection is seen in the center of the basin, showing a parallel aggradational filling pattern. Then, the lake area gradually decreased until the fluvial filling by the C2 and C1 Mbrs, which were mostly eroded before the deposition of the overlying Jurassic rocks. Different from the previous understanding of well lithostratigraphy and geology, the basin oblique Progradational sequences indicate that the lake basin of the C7 to C3 Mbrs was not filled vertically and simply by parallel planar strata with nearly equal thickness but experienced many events of oblique Progradational filling and parallel aggradational filling in the center.
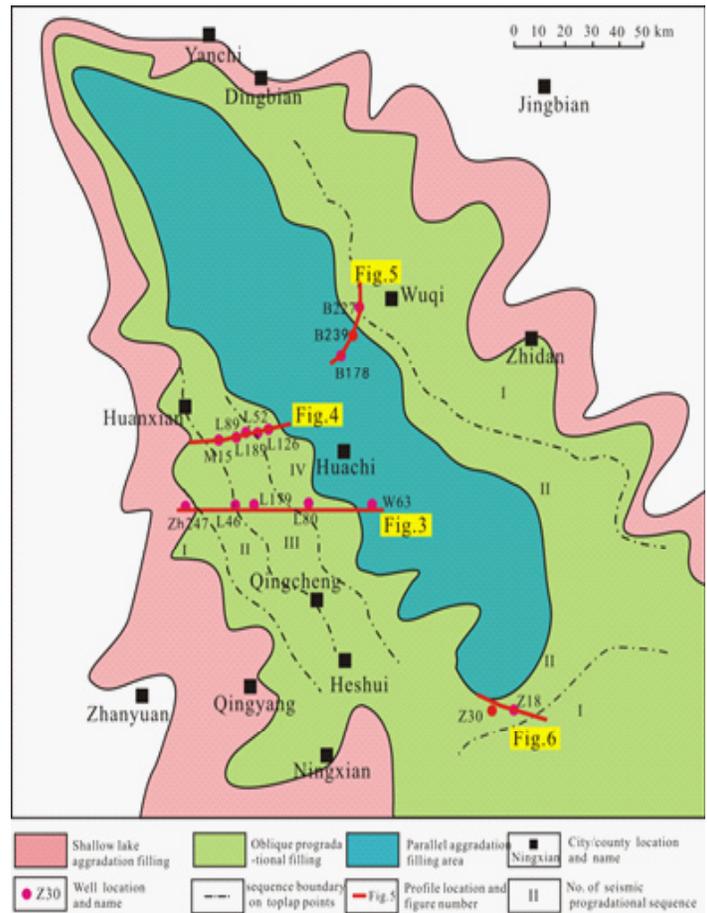
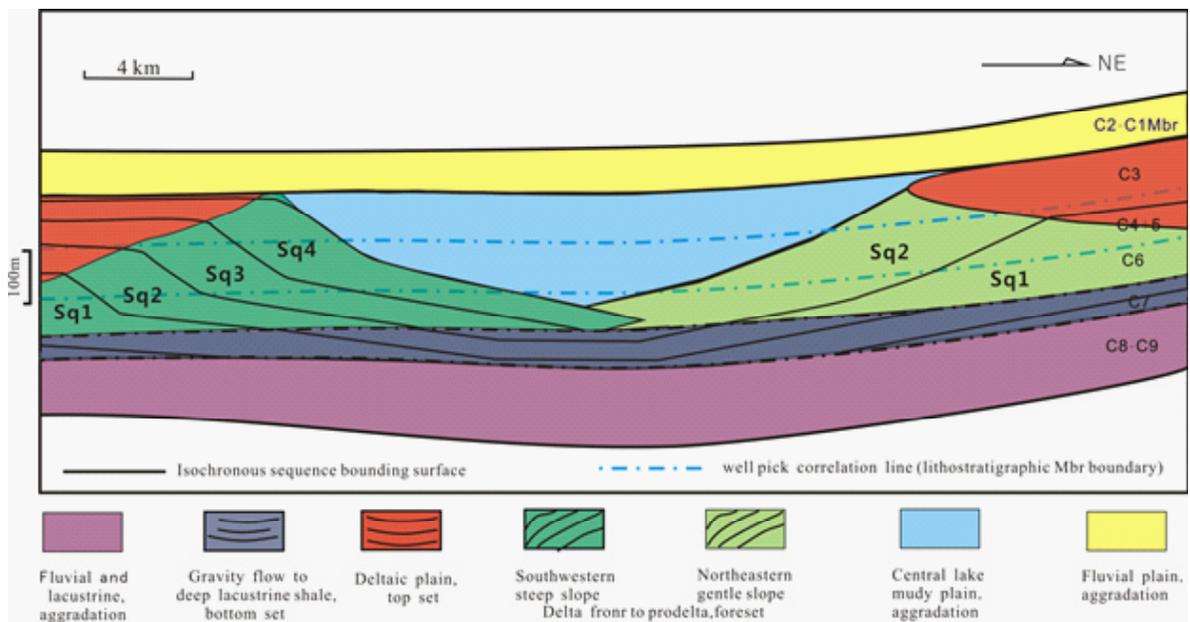**Figure 7:** Sketch map of the lake filling model.

Figure 8: Profile pattern of the lake basin filled by clinoform sequences, which consist of four sequences on the southwestern steep slope and two sequences on the northeastern gentle slope. The corresponding pattern map is shown in Figure 7.

Discussion

Relationships Among Progradational Sequences, Well Lithostratigraphy and Depositional Subfacies

Most of the Progradational sequences seen here are sigmoidal and lens-shaped in configuration and can be divided into three intervals vertically: the upper, middle and lower, also called the topset, foreset and bottomset, respectively [8]. Based on integrated interpretation of well logs, cores and seismic sequences, relationships among the topset, foreset and bottomset, well stratigraphic units and depositional subfacies are identified (Figure 9). The topset and bottomset of a Progradational sequence represent approximately parallel aggradation, and only the Foresets display the feature of clinoforms.
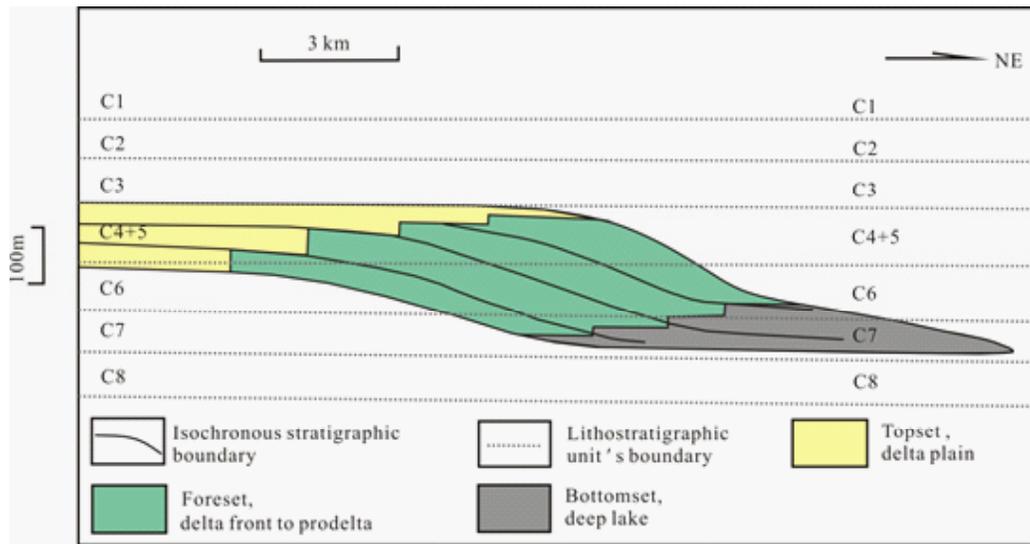

Figure 9: Schematic diagram of the relationships among the sigmoidal-type Progradational sequences, well lithostratigraphic units, and sedimentary subfacies.

Relationship Between Progradational Sequences and Stratigraphic Mbrs in Wells

For a long time, the internal structure of the Ordos Basin displayed features of "overall rising and descending and flat up and down in a parallel fashion" [34,37,45] Therefore, the individual stratigraphic units of the Yanchang Formation were thought to exhibit essentially a layer-cake stratigraphy of approximately equal thickness throughout the basin. The stratigraphic Mbrs shown in Figure 3 were established based on this understanding. In the shallow lake plain and fluvial facies scope, no stratigraphic diachronism was observed on the seismic profiles from the C10 to the C1 Mbr. However, due to the lateral influx of the delta and gravity flows, clinoform reflections are evident in the central lake basin on the seismic profiles. Because every delta and gravity flow depositional complex contains multiple lithostratigraphic Mbrs in the vertical direction, the well pick correlation lines intersect the isochronous seismic horizons (Figures 4-7).

The Foresets of the Progradational sequences are typically present in the C6 Mbr, and only a small portion may be found in the C4+5 and C3 Mbrs. The topset is usually seen in the C4+5 and C3 Mbrs, and the bottomset is typically present in the C7 Mbr, with a small portion present in the lower part of the C6 Mbr (Figure 9). This association means that in the deep-water area of the lake basin, the thickness of lithostratigraphic units is smaller than the Progradational sequence, and a given Progradational sequence can contain multiple diachronous lithostratigraphic units. However, in the region of shallow lake and fluvial facies without clinoform reflections, any given lithostratigraphic unit is still parallel to seismic horizons and should reflect an isochronous sedimentary interface.

Relationship Between a Progradational Sequence and Depositional Subfacies

A Progradational clinoform reflection can develop in different depositional environments [8,46]. The analysis of sedimentary facies based on the large amount of well data along the seismic lines with Progradational sequences indicates that the Progradational reflections of the Yanchang Formation primarily correspond to lacustrine mudstone and siltstone intercalated with deltaic and gravity flow sandstones [47,48]. The deltaic sandstone consists mainly of distributary channel sandstone with bottom scour and estuary sandstone coarsening upward (Figure 10a). The gravity flow deposits consist primarily of fine sandstone deposited by sandy debris flows (Figure 10b), turbidity currents (Figure 10c) and slide-slumps (Figure 10d). Based on the well core observations, the difference between the sandy debris flow sandstone and the turbidities sandstone is that the former is massive and relatively thick; a typical individual bed is approximately 0.5-10 m thick; at the thickest, it may be more than 25 m. Such sandstones display no bedding, and the particle size is uniform and mostly fine grained. The turbidities sandstones are typically thin, less than 0.5 m thick, and display graded bedding, parallel stratification, and ripples associated with a Bouma sequence [6,11, 22,47,49]. The topset of sigmoidal-type Progradational sequences (upper part) is typically composed of delta plain subfacies; the foreset (middle part) is composed of delta front and prodelta subfacies; and the bottomset (lower part) is typically composed of deep-water gravity flow deposits. The foreset concept of the seismic sequence here borrows the concept of the delta foreset, but the two are not the same in scale and meaning. The former usually is larger in scale or thickness and can contain deposits of the delta front, prodelta, gravity flow, deep lake, etc. [7,46].
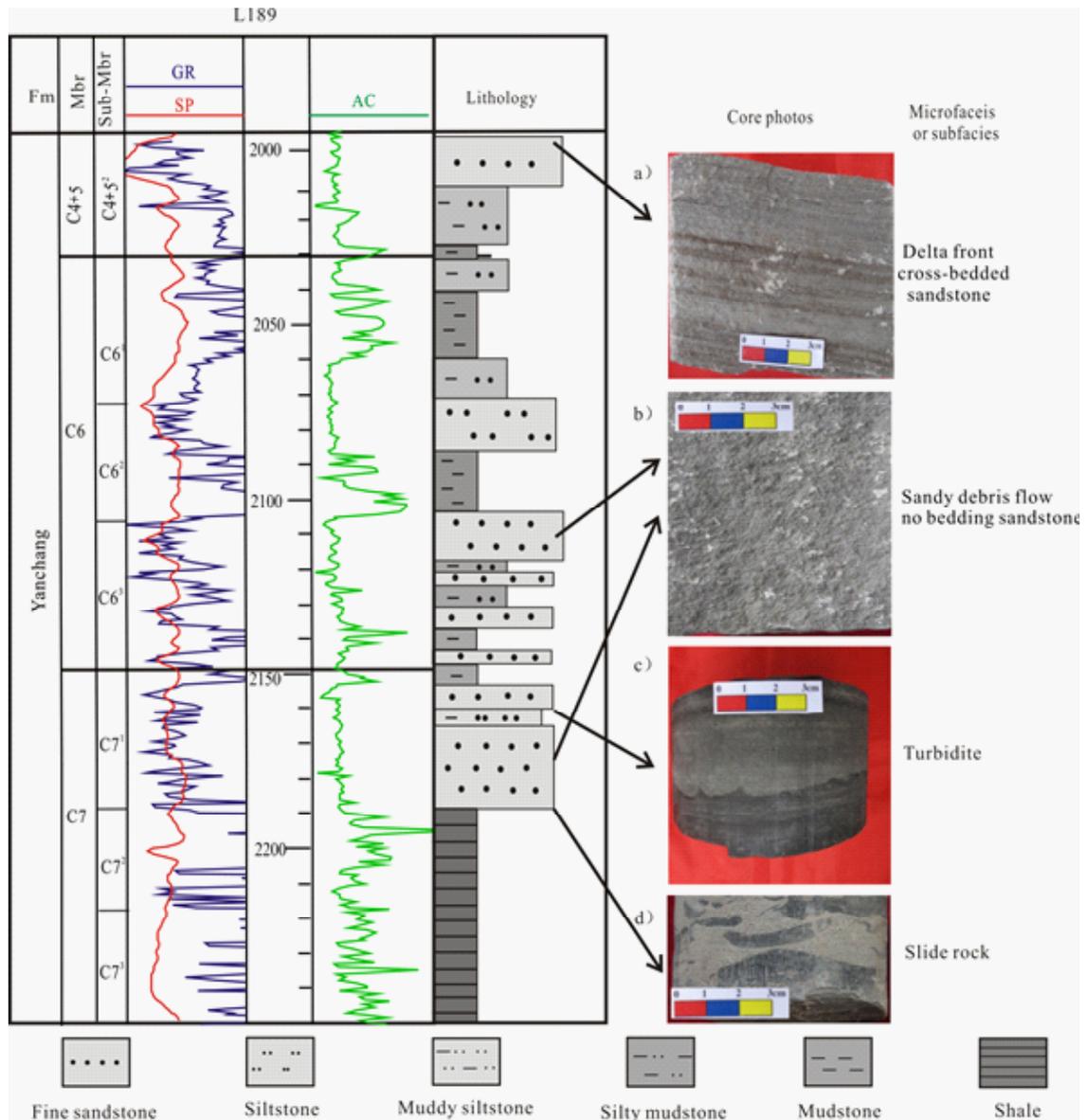
Figure 10: Well log and cores characterizing delta and deep-water gravity flow deposits corresponding to the Progradational sequences of the Yanchang Formation. See Figure 7 for well location.

Relationship Between Lithostratigraphic Units and Depositional Subfacies

The C6 Mbr consists of mostly delta front and prodelta subfacies, and sometime the lower part contains gravity flow sandstones. In the C4+5 and C3 Mbrs, the delta front and prodelta subfacies are developed only in the center of the lake basin, and the lake-margin deposits are characterized by delta plain and fluvial facies. The middle and upper parts of the C7 Mbr are composed primarily of gravity flow and deep-lake subfacies. This consideration was proposed early by geologists and has been accepted whether or not the seismic data interpretation is referenced.

Relationship Between Deltaic and Gravity Flow Deposition

Based on core examinations and an integrated study of a large amount of well data, the middle and upper C7 Mbr corresponding to the bottomset of a Progradational sequence are composed mainly of gravity flow deposits, which consist of slide-slump, sandy debris flow, and turbidity flow clastic rocks and mudstone [28,40,47]. According to the oblique Progradational sequence interpretation, gravity flows in the C7 Mbr should result from the slope of the prodelta and delta front deposits represented by the C6 Mbr and should not form by lateral transport of C7 Mbr sediments themselves. The gravity flow deposits in the bottomsets and the delta deposits in the Foresets of a Progradational sequence should be coeval.

The conclusion in paragraph 6.1.3 noted above matches the traditional understanding held by geologists regarding the sedimentary facies of the Yanchang Formation. However, the other three conclusions differ. Geologists always search for the C7 Mbr deltaic deposits near the lake margins to demonstrate that they represent the upstream portion of deep-water gravity flow material deposited in the lake center, but no delta facies have been found in the C7 Mbr. The oblique Progradational sequences in the seismic profiles clearly indicate the simultaneous heterogeneous relationship between the C7 Mbr gravity flow deposits and the C6 and C4+5 Mbr deltaic deposits.

Ancient Water Depth and Slope Inferred from The Progradational Sequences

Currently, determinations of ancient water depth are based primarily on the sedimentary structures, paleoecology, and authigenic minerals of sediments [50,51]. These data are typically obtained from cores or outcrops. In the absence of paleontological data, it is difficult to restore the ancient water depth [52]. Based on the statistical analysis of numerous sedimentary structures and ostracods, Chen (2004) [53] estimated that the greatest lake paleo-depth represented by the C7 Mbr was 60 m. Zou et al. (2008) [40] concluded that the paleo-depth in the deep-water region represented by the Yanchang Formation was 30-60 m based on studies of sedimentary facies. Zhang et al. (2011) [54] used the cobalt (Co) contents of sedimentary rocks to determine that the greatest paleo-depth recorded by deposition of the C7 Mbr shales ranged from 45.39 m to 128.38 m. Pekar and Kominz (2001) [55] and Plink-Bjorklund, Mellere, and Steel (2001) [56] proposed to estimate water depth using the height of seismic clinoforms and relevant geological information (e.g., paleontological data). For a Progradational sequence consisting of deltaic to gravity flow deposits, the original height of the clinoform can be regarded as the paleo-depth. The principle for such analysis is shown in Figure 11. Wood (1994) applied this method to estimate that the paleo-depth of the Eocene lacustrine basin in the West Snake Basin was approximately 100 m and that the slope of the lake basin indicated by the Progradational sequences was less than 6°. The paleo-depth of the Eocene Pannon lake basin in Hungary estimated using this method by Sztanó et al. (2013) [5] was approximately 400-500 m (without a decompaction correction), and the paleo-slope was 1.5-3°. A key factor in estimating paleo-depths is to determine the values of H0 and K in the formula in (Figure 11), where H0 is the vertical distance between the toplap point and the downlap point for the same horizon in a sequence. H0 can be obtained from two-way time measured from a seismic profile and transformed into depth using a synthetic seismogram and a decompaction correction. From the simulation of rock compaction, we estimate that the final compaction coefficient K of pure sandstone in the continental basin is 0.2, and the final K of pure mudstone is0.6-0.7 [57]. Based on the approximate statistics, the sandstone content is 30-50% and mudstone 50-70% in the Yanchang Formation. Consequently, K is 0.3.
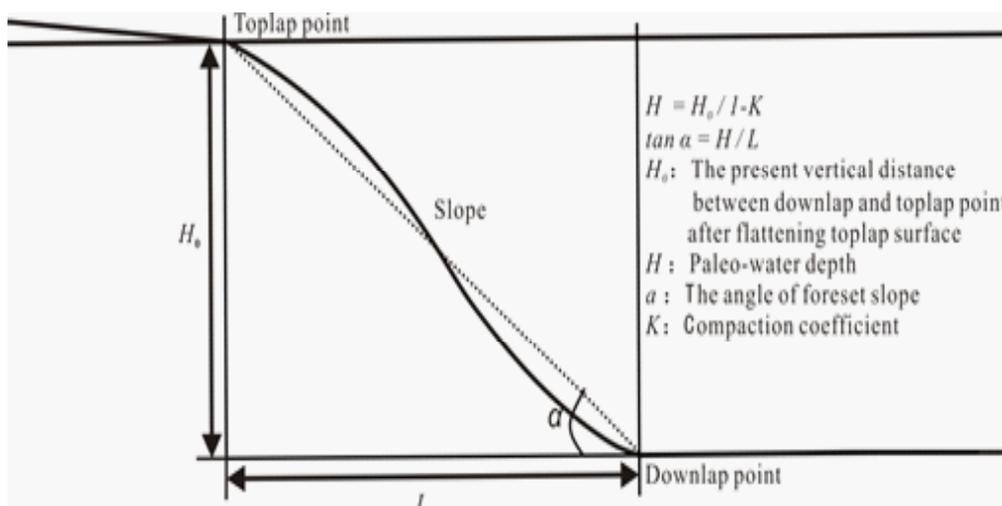

$$H = H_0 / 1 \text{-} K$$
$$\tan \alpha = H / L$$

H_0: The present vertical distance between downlap and toplap point after flattening toplap surface
H: Paleo-water depth
a: The angle of foreset slope
K: Compaction coefficient

Figure 11: Schematic diagram for calculating the paleo-slope angle and paleo-water depth using a clinoform reflection.

Figure 5 shows that the sigmoidal-type Progradational sequence in the west of the lake basin spans from the C4+5 Mbr to the Zhangjiatan shale marker of the C7 Mbr. Based on the aforementioned method, the greatest paleo-depth during this period represented by the C4+5 through C7 Mbrs was 228 m. As the delta advanced toward the center of the lake basin, the paleo-depth gradually decreased to 170 m and 140 m. The paleo-depth should represent the vertical paleo-depth from delta plain and fluvial deposition to gravity flow deposition on the floor of the lake. The paleo-depth suggested by the Progradational sequence consisting of the C3 and C4+5 Mbrs from the east-southeast in the southeastern lake was 157 m (Figure 7). The slope of the oblique foreset can be used to approximate the paleo-slope at the corresponding position of the lake. The method used to calculate the Progradational reflection slope angle α is shown in (Figure 11). The results indicate that the overall slope angle α of the Progradational sequence on the southwest margin of the lake basin is greater than that on the northeastern margin. The maximum slope angle α on the southwest margin of the lake is 5.5°, and it is generally 3.5°-5°; this margin is referred to as the steep slope. The slope angle α on the northeast margin of the lake is generally 2.5°-3.5°; this margin is referred to as the gentle slope. In general, the floor of the lake basin was gently sloping in the northeast and steep in the southwest [58].

Possible Influence of the Progradational Sequence On the Water Flooding Effect

The oblique filling pattern of the Progradational sequences with dips of 2-5° means that water may flow along a path that is different from that imagined within a lithologic unit during water flood development of the delta oil pool in the Yanchang Formation. Consequently, the water drive effect may decrease if a sand body is not correlated obliquely between wells within the same seismic sequence. The injection of water into a sub-Mbr sandstone reservoir in a well may make another sub-Mbr reservoir work in the neighboring wells. As shown in (Figure 12), when the dips of three10-m-thick oil sandstone reservoirs are 3° within a Progradational sequence and the water is injected into the C6^1 and C6^2 sub-Mbr reservoir sandstones in well A, the effect is observed only in the C6^2 reservoir in neighboring well B 500 m away, and no desired result is produced in the C6^1 sub-Mbr reservoir. Figure 12b indicates that the dip is still 3° but the thickness of the sandstone reservoir is 30 m, and only the C6^2 sub-Mbr reservoir is perforated. We can see in such a situation that water injected from well A can only partially arrive at the C6^2 reservoir in adjacent well B and can hardly reach the C6^2 in well C at all. Most of the injected water may have entered the C6^3 reservoir of adjacent wells. During the current oil production for the delta reservoir, a reservoir sand body contained in a sub-Mbr such as C6^1 or C6^2 or C6^3 is regarded as an individual seepage unit to perforate. The injection production ratio is as high as 2:1~5:1, and the water injection effect is certainly not ideal. Such a high injection production ratio has always been attributed to inferred fractures or faults that were likely to be distributed between wells, along which injected water might have flowed into other layers. To date, water flow along inclined sandstone has not been seriously considered, which needs further research in actual pool productions.
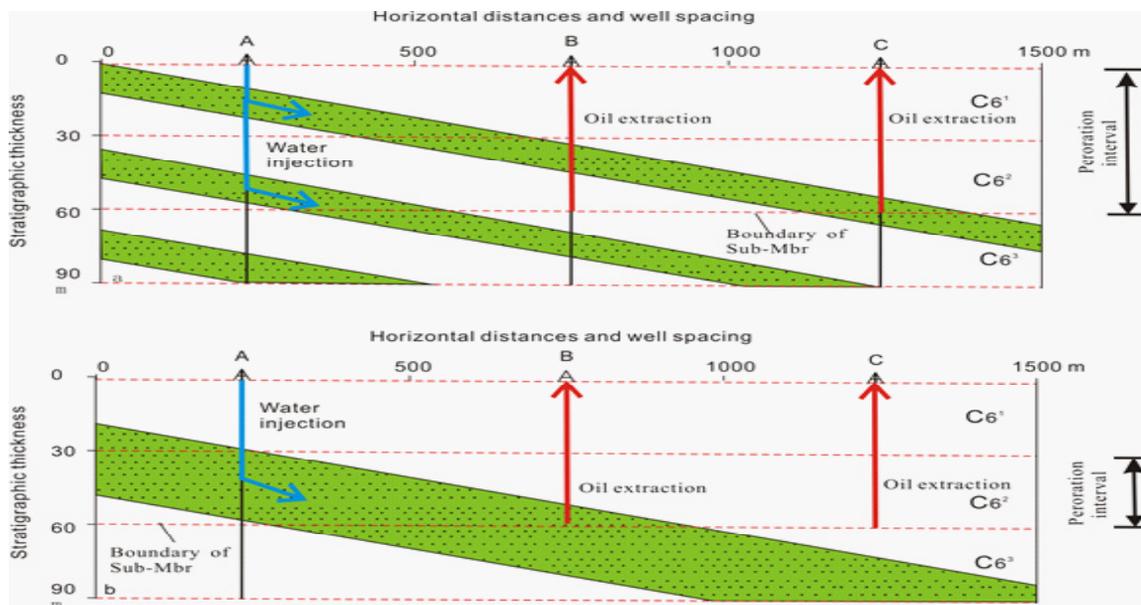

Figure 12: (a) When the clinoform dip of three 10-m oil-bearing sandstones is 3°, well spacing is 500 m and the C6^1 and C6^2 sub-Mbrs are both perforated, water injection in well A can only partially arrive at the C6^2 sub-Mbr in the neighboring well B, and no effect occurs in C6^1. (b)

Distribution of Favorable Sandstone Reservoirs

By the end of 2012, the proven hydrocarbon reserves in the Late Triassic Yanchang Formation reached 30.7510×10^8 t [36], and the annual oil yield exceeded 40,000,000 tons. The oil reservoirs are mainly in the C6 and C8 Mbrs in the lake basin, followed by the C2, C3, C4+5, and C9 Mbrs and Lower Jurassic sandstones [59]. Statistical results indicate that the oil reservoirs with large reserves and high yield capacities are mainly distributed where both high-quality hydrocarbon source rock of the C7 Mbr and a large favorable Progradational delta and gravity flow sandstone exist. Sandstone reservoirs associated with Progradational sequences consist of two types. One type is deltaic distributary channel sandstone and estuary sandstone located at the middle and upper interval of a Progradational sequence, corresponding to the C3 to $C6^2$ sub-Mbrs, with permeability from 0.1-5 md. The other type is sandy debris flow sandstone located at the lower interval of a Progradational sequence, corresponding to the $C6^3$-$C7^2$ sub-Mbrs, with permeability from 0.01-0.5 md and planar distribution as shown in (Figure 13). Although the latter is tight, its oil-bearing properties are good due its proximity to

the hydrocarbon source rock, and it has become the main oil exploitation in tight sandstone in recent years. The pre predicted total tight oil reserve is approximately 30×10^8 Figure 13, the C7 Mbr tight oil sandstone in the deep- actually corresponds to the gravity flow sandstones con the bottomset interval of Progradational sequences. We that at the foot of the southwest steep slope, the sandston is higher with a lobe-shaped distribution, but at the fo northeast slope, deep-lake mud was dominant with les flow sandstone. The sandstones on the northeast slope a distributary channel sandstones, which extend in narro The results show that a trade-off relationship exists bet deltaic sandstone on the ramps and gravity flow sandsto slope foot. The clinoform dip of a Progradational sequen a difference in the distribution of two types of sandstone On the northeast gentle slope, the deltaic distributary and estuary sand bodies are relatively well developed w sandstone content of approximately 20-40%. In the s steep slope zone, however, primarily prodelta mud d occurred with lower sandstone content of approximately A portion of sandstone that might have been deposited in t environment in the southwest steep slope was transporte gravity flow induced by storms and earthquakes to the s and floor of the lake basin. Thus, the tight sandstones a with gravity flows are mainly distributed on the lake basin floor close to the southwest steep slope (Figures 13 and 14).
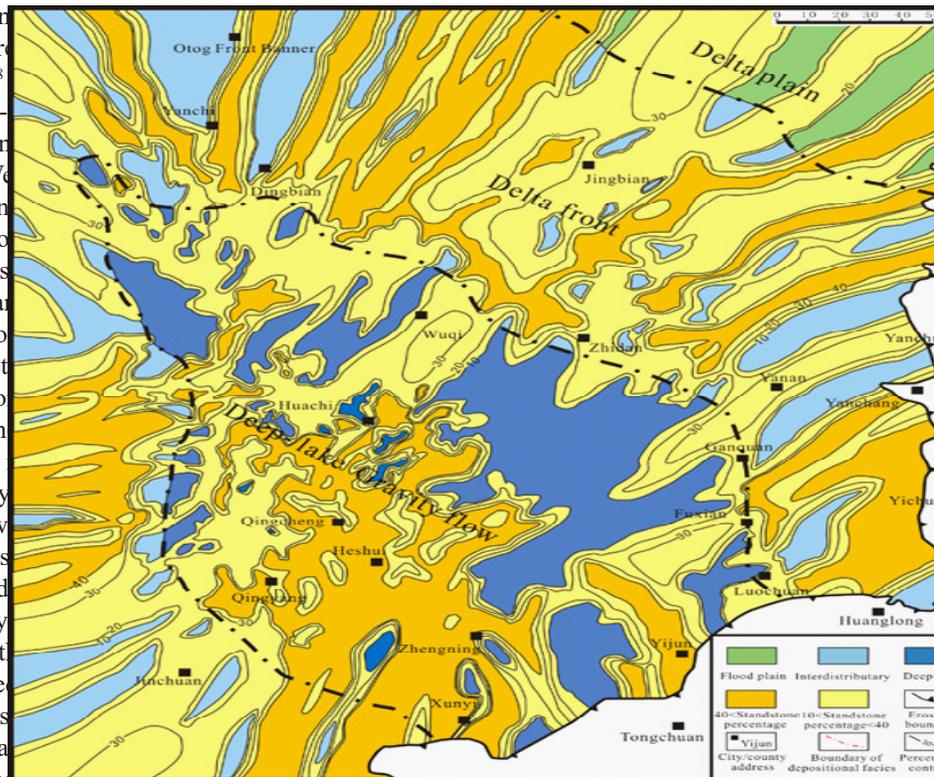

Figure 13: Tight sandstone content and depositional facies map of the C7 Mbr based on data from approximately 2000 wells (modified from Yang et al. 2013). The gravity flow sandstones occur more commonly in the southwestern steep slope foot of the lake.
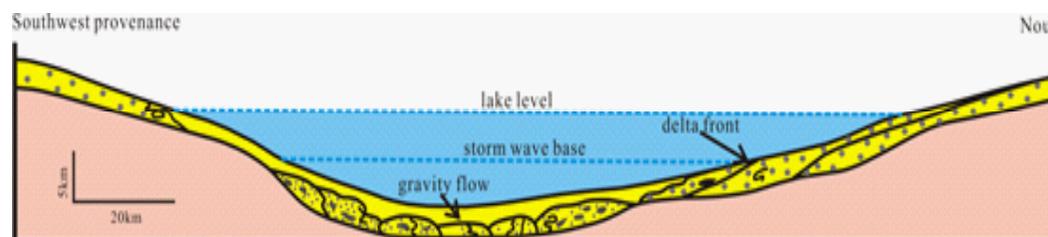

Figure 14: Schematic diagram of the delta and gravity flow sandstone distribution that is dependent on the slope angle of the asymmetric

Yanchang lake basin. The deltaic sandstone is rich in the northeastern gentle slope (<2.5o) of the lake and is relatively rare in the southwestern steep slope (>3.5o) of the lake. The gravity flow sandstones occur more commonly in the steep slope foot and the center of the lake.

Conclusions

(1) The 20- to 60-m-thick black shale source rock in the Late Triassic Yanchang Formation in the central and southern Ordos Basin belongs to the lower part of the C7 Mbr. It is distributed across a northwest-trending area measuring 60,000 km². Extensive delta and gravity inflows came mainly from the NE and SW directions. In the seismic profile, the Progradational sequences of the Triassic Yanchang Formation, bounded by toplap, onlap and downlap surfaces, mainly penetrated the lithostratigraphic C7 and C6 Mbrs, or C6 and C4+5 Mbrs, or C4+5 and C3 Mbrs, or C7 to C3 Mbrs, respectively. There are four Progradational sequences in the southwest steep slope, whereas there are two Progradational sequences in the northeast gentle slope and southeastern margin of the lake. The well lithostratigraphic Mbrs are diachronous from the view of seismic Progradational sequences. The clinoform reflections indicate that the source of the gravity flow sandstone of the C7 Mbr originated from the delta represented by the C6 to C3 Mbr rather than from the C7 Mbr itself.

(2) The clinoform sequences were located in shallow- to deep-lake areas. The middle and upper intervals of a Progradational sequence consist primarily of prodelta mudstone and siltstone interbedded with delta front distributary channel and estuary bar sandstones; the lower interval consists of deep-water gravity flow depositional complexes. Due to the diversion of the delta, 5- to20-m-thick low-velocity shale typically occurs   between the Progradational sequences, representing a local relative lake transgression.

(3) According to the clinoform reflections, the greatest paleo-depth of the Yanchang Formation lake basin was 228 m, and the greatest paleo-slope was 5.5°. The southwest steep slope of the lake basin was generally 3.5-5°, and on the steep slope, the deposits were dominated by prodelta mud with relatively rare sandstones, and parts of them were transported by gravity flows to the slope foot and floor of the lake basin. The northeast gentle slope was generally 2.5°- 3.5°. In addition to the prodelta mud, a large amount of delta front sand was deposited on the gentle slope. The tight sandstone of the C7 Mbr that was deposited as gravity flows on the lake basin plain was derived primarily from the southwest slope. The delta and gravity flow sandstones in the Yanchang Formation lake basin of the Ordos Basin have formed the largest low-permeability and tight sandstone oil reservoir in the basin.

(4) The water drive effect may decrease if a sand body is not connected obliquely between wells within the same seismic Progradational sequence. At present, the injection production ratio is as high as 2:1~5:1 in the delta oil pools of the deep-lake area.

The reason for this might be due not only to the influence of faults or fractures but also mainly to correlation with the wrong sand body inconsistent with the oblique Progradational sequences.

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