Petroleum Science 19 (2022) 58–73

Contents lists available at ScienceDirect

Petroleum Science

journal homepage: www.keaipublishing.com/en/journals/petroleum-science

Original Paper

The influence of water level changes on sand bodies at river-dominated delta fronts : The Gubei Sag, Bohai Bay Basin

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ARTICLE INFO

Article history:
Received 25 August 2020
Accepted 30 April 2021
Available online 21 September 2021

Edited by Jie Hao and Teng Zhu

Keywords:
Water level changes
River-dominated delta
Delta front sandbodies
Paleogene Shahejie Formation
Gubei Sag of Bohai Bay Basin

ABSTRACT

Changes in water level are one of the important factors controlling the constructive characteristics of deltas. The paper studies the influence of water level changes on sand bodies in the third member of the Shahejie Formation (Es3) on the gentle southern slope of the Gubei Sag, Bohai Bay Basin and draw some conclusions that, for complex sand bodies, with the increase in water level the distributary channels bifurcate frequently, from a simple branching shape to a network shape along with the increase in the development of crevasse splays, mouth bars and sheet sands. For single sand bodies, with an increase in water level in the slope zone of the lake basin close to the source area, the superimposition style transitioned from vertical cutting-stacking and lateral isolation to vertical stitching, isolation and lateral stitching. However, in the central zone of the lake basin far from the source area, the superimposition style transitioned from vertical stitching and lateral stitching to vertical isolation and lateral isolation. When water level stays stable, the greater the distance from the source area the greater the disaggregation ratio of a single sand body. At the same distance from the source area, higher water level tends to result in greater disaggregation ratio of a single sand body.

1. Introduction

In China, the lake-land transition zone, where the delta develops well, is the main area for hydrocarbon accumulation, with rich oil and gas resources. During the depositional process of lake deposits of river-dominated deltas, due to the frequent fluctuation of the water level of the lake, favorable source-reservoir-caprock assemblages were well developed, resulting in the formation of rich hydrocarbon accumulation zones. Delta front mouth bars, distributary channels and sheet sand are excellent oil and gas reservoirs (Liu et al., 2017). The study of delta deposition began by Gilbert. For more than a century, many researches have been conducted on delta classification, sedimentary characteristics and sedimentary patterns (Zhu et al., 2017; Lai et al., 2017; Zhang et al. 2017, 2018, Chen, 2019; Chima et al., 2019; Xu et al., 2019; Feng et al., 2019). In fact, the hydrodynamic conditions at the formation time of deltas are the most important factor controlling the difference in characteristics of delta deposits and distribution regularity of sand bodies (He et al., 2017; Paz et al., 2020). Different from the marine deltas, which were mainly controlled by rivers, waves and tides (Bhattacharya and Giosan, 2003; Dunne et al., 1988; Yang et al., 2019), there was no tidal influence in lake deposits, the wave influence was also relatively weak, and the river-dominated deltas were dominated. The type, supply intensity, grain size and cohesion of sediments carried by rivers determined the shape of deltas (Orton et al., 1993; Edmonds and Slingerland, 2007, 2010). In addition, many river-dominated deltas have been reconstructed at different degrees due to water level changes (Zou et al., 2008; Luo, 2015; Zhang et al. 2016, 2018; Zhu et al., 2016). The changes of water level and water area might lead to frequent expansion and contraction of the delta towards the lake center, which significantly affected the depositional area and depositional rate of the delta

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https://doi.org/10.1016/j.petsci.2021.09.028
1995-8226/

towards the center of the lake. Therefore, water level changes, like the influence of river, is an important factor controlling the constructive characteristics of deltas. The water level changes not only controlled the evolution of low-level wedges to high-level deltas in moderate to low frequent sedimentary cycles, but also controlled the transit of superposition relationship between subfacies and microfacies and the prograding regularity in high frequent sedimentary cycles (Tsakalos et al., 2018; Yin et al., 2014; Zhu et al., 2016). In wide shallow expanding lake, the fluctuation of the lake water level might affect the characteristics of the deposits after the water entered from rivers into the lakes (Wu, 1983). Due to the gentle slope of the lake, small changes in the lake water level might cause large-scale progradation and retrogradation of the lake shoreline, which can lead to frequent interbedded deposits of above-water and under-water deposits (Jin et al., 2014). Therefore, in the continental lake environment, the seasonal changes in the water level might cause high frequency pulse of expansion and contraction of the water level, which might change greatly the scope and intensity of river action, and affected significantly the position and scale of the deltas (Jin et al., 2014). The full-of-sand phenomenon in some formations in many hydrocarbon bearing basins (Yang et al., 2011) may be explained by the large-scale progradation and retrogradation of the shoreline and delta depositional areas due to the changes in the water level.

As stated above, the lake water level changes could have an important influence on the development of the types and distribution of the delta sand body. However, most studies in this field have only mentioned this phenomenon and have no quantitative discussion of water level changes. In order to take the water level changes as the main controlling factor and discuss the quantitative influence on each order of the delta sand bodies. The authors' team has carried out a series of research. Based on the investigation results of modern deposits and observation of field outcrops, the influence of water level changes on the types, sedimentary structures, and formation processes of delta sand bodies has been preliminarily discussed (Qiu et al., 2016; Wang et al., 2017; Zhang et al. 2016, 2016, 2019). However, limited by available data, at present, the study is only about single sand body and the internal elements of single sand body which can be directly observed by field outcrops and modern deposits, lacking of the quantitative study on the single sand body and complex sand bodies by taking the subsurface work area as study objects, which can provide guidance for oil and gas exploration in lake deltas. In this paper, with the river-dominated delta in the southern gentle slope belt of the Gubei Sag in the Bohai Bay Basin as an example, on the basis of the previous studies about stratigraphic framework and sedimentary distribution regularity, in combination with observation of field outcrops, a preliminary research has been made to clarify the influence of water level changes on the type and distribution regularity of complex sand bodies, and to reveal he evolution characteristics of superimposition style and development scale of single sand body controlled by water level changes.

2. Geological setting

The Gubei Sag is located in the northeast of the Zhanhua Sag in the Jiyang Depression, the Bohai Bay Basin, surrounded by four uplifts, including Chengdong, Zhuangxi, Gudao, and Changdi. The sags and the uplifts are separated by four faults, including Chengdong, Zhuangnan, Gubei and Changdi, resulting in the faulting in the east, west and north sides, and overlapping in the middle and south side. In the Gubei Sag, the source rock is very thick (more than 380 meters in the third member of the Shahejie Formation), the oil source is sufficient, the faults are well developed, and the sand bodies are distributed widely, easy for oil and gas to migrate and accumulate, providing good geologic conditions for hydrocarbon accumulation. The Wuhaozhuang Sub-sag (the East Sub-sag), which is to the east of Gubei Sag, is rich in oil resource, and oil layers have been penetrated from the Dongying Formation to the fourth member of the Shahejie Formation. The proven geological reserves in the third member of the Shahejie Formation are 66.3 million tons. The study area is located in the southwest of the Gubei Sag, in the gentle slope zone related to the Gudao Buried Hill, which is a north-trending monocline as a whole, and on its north is a deep zone of the East Sub-sag (Fig. 1).

From top to bottom, the Shahejie Formation in Gubei Sag can be classified into the first Member (E*s*1), second member (E*s*2), third member (E*s*3) and fourth member (E*s*4). E*s*3 can be divided into 14 Sand Groups, of which the upper E*s*3 corresponds to Sand Groups 0–1, the middle E*s*3 corresponds to Sand Groups 2–8, and the lower E*s*3 corresponds to Sand Groups 9–13 (Fig. 2). The middle and lower E*s*3 are two dichotomous third-order sequences. Both of them experienced progradation and retrogradation. The upper E*s*3 is relatively thin, and locally eroded by later uplifting. In this study, Sand Groups 2–5 in the upper part of the middle E*s*3, which have the most detailed data collection, have been selected.

Five types of sedimentary facies, including delta, fan delta, near-shore subaquatic fan, slump turbidities fan, and lake facies, are developed in the middle E*s*3 in the Gubei Sag. With Sand Group 5 as an example, the delta is developed in the southern gentle slope zone, and accepted source from the Gudao Buried Hill. Divided by the central nose-like structural belt, 3 to 4 deltas in the west advanced toward north, one delta in the east. Small-scale slump turbidities fans are developed in the deep zone of the East Sub-sag. A fan delta is developed in the southwest of the Gudao Buried Hill, and another in the northern steep slope of the Changdi Buried Hill. On the steep slope of the Chengdong Fault in the west, there are horizontally continuous near-shore subaquatic fans, which extend in short distance (Fig. 3).

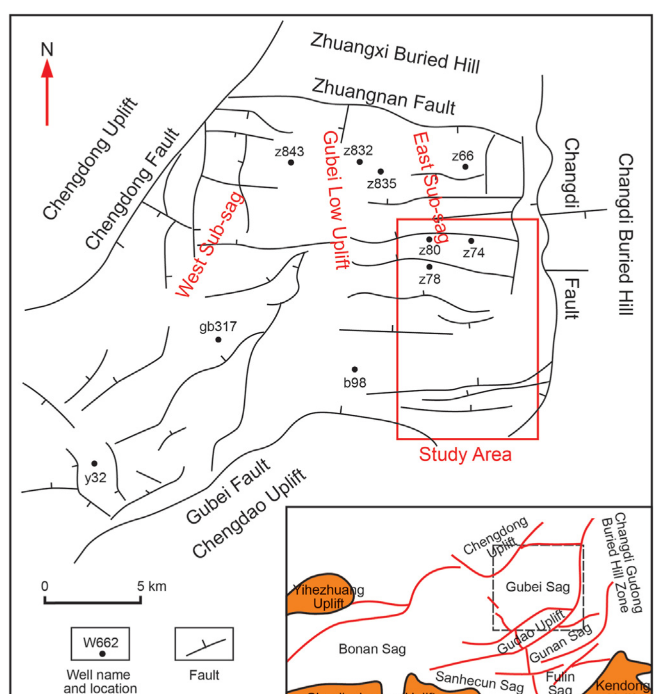

Fig. 1. Structure location of Gubei Sag.

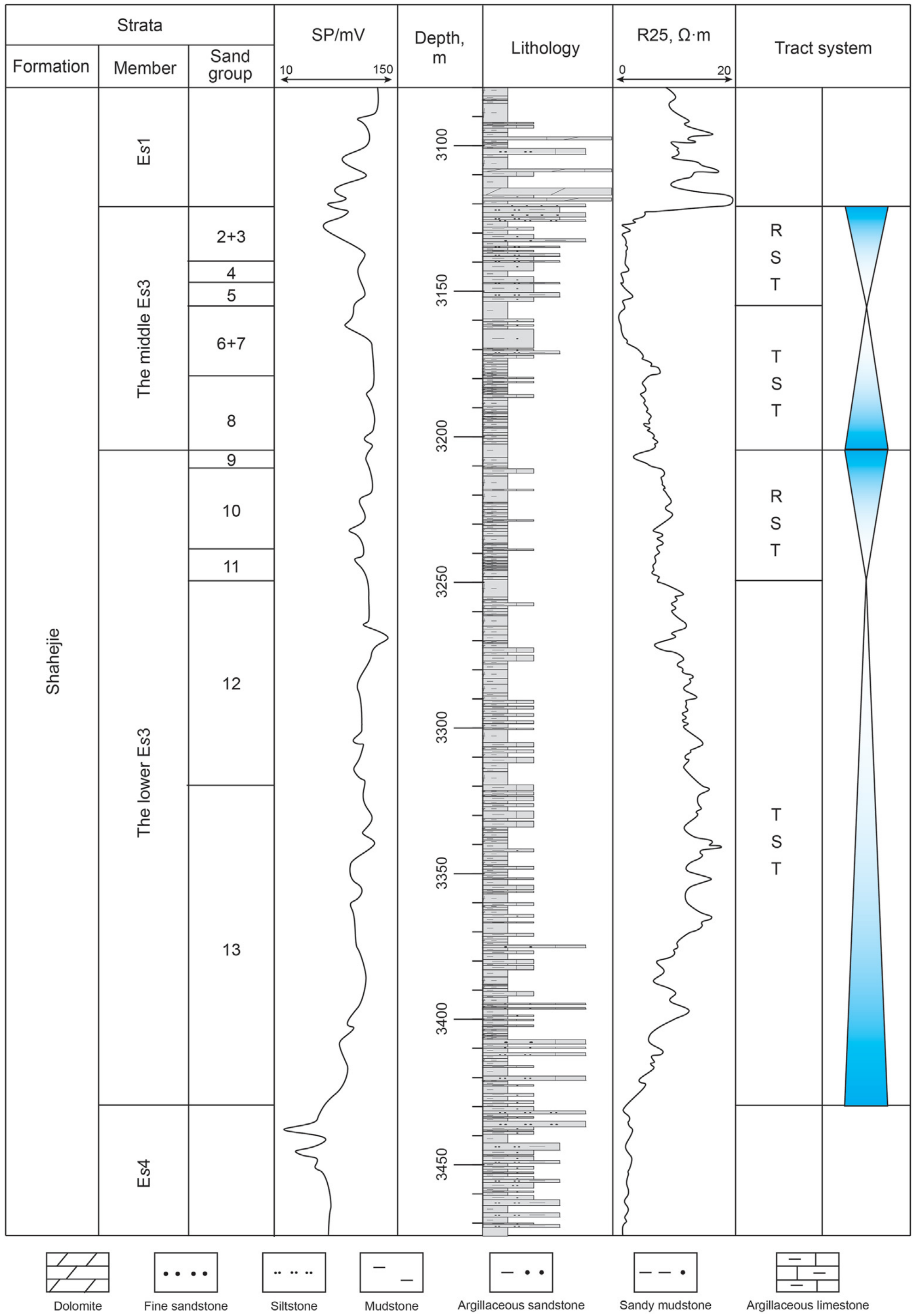

Fig. 2. Stratigraphic framework of the third member of the Shahejie Formation in Gubei Sag.

3. Research data, route and methods

3.1. Research data

In this study, core data, well logging data, seismic data and field outcrops have been used. More than 200 m of cores from 4 typical wells have been observed to make clear about the types and characteristics of the sand bodies in the river-dominated delta front. Logging curves such as Gamma ray (GR), Spontaneous potential (SP), etc. have been used to research on the characteristics of water level changes and to divide the reservoir architecture in the non-cored wells. With 3D seismic data from the study area, the relationship among the sedimentary water depth, the distance of delta distribution and slope angle has been analyzed. Over 100 m of outcrops in the typical river-dominated delta in the Ordos Basin have been observed to make clear about superposition relationship of single-genetic sand bodies.

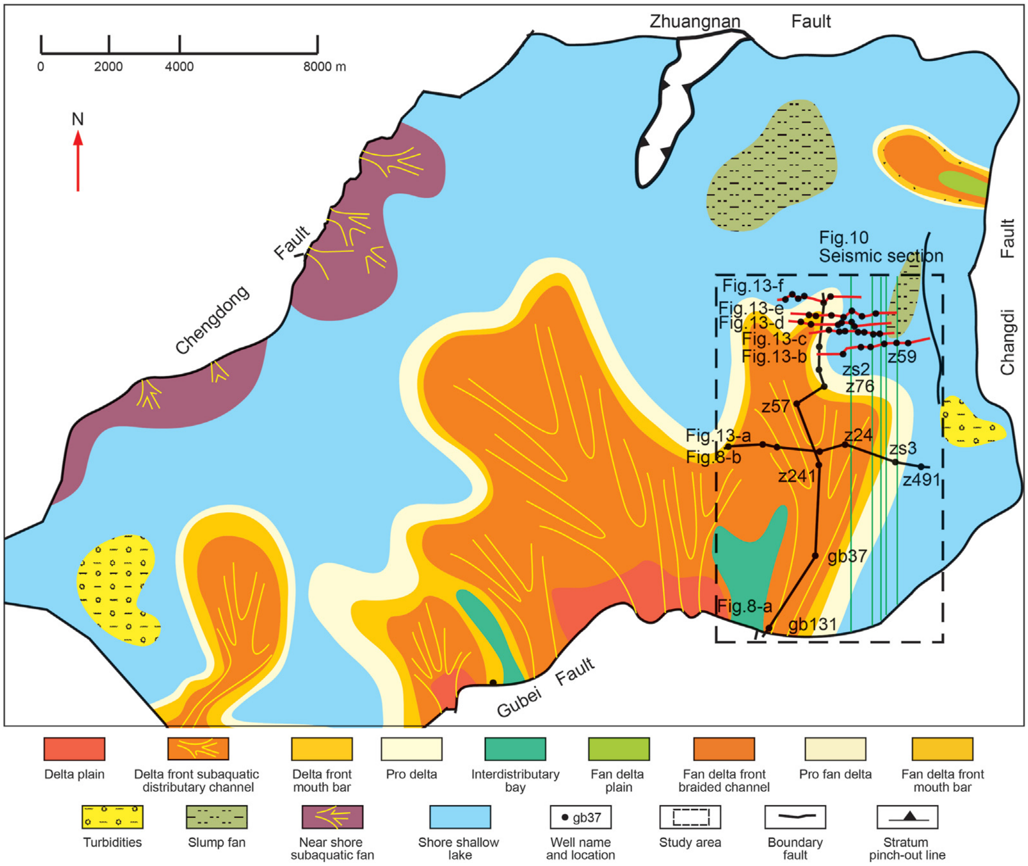

Fig. 3. Planar sedimentary facies diagram of Sand Group 5 of the middle Es3 in Gubei Sag (modified from Zhang et al., 2019).

3.2. Route and methods

3.2.1. Research route

(1) According to the previous research results, we classified the architecture orders of the study area. (2) We clarified the characteristics of water level changes using logging curves. (3) With the results of core observation and rock electricity calibration, we clarified the logging facies characteristics of single-genetic sand bodies from cored wells in combination, and divided the reservoir architecture of non-cored wells. (4) In combination with seismic data, we optimized the well-tie sections perpendicular and parallel to the direction of source, described the distribution of the complex sand bodies. (5) On the basis of the combination patterns of single sand body by observation of field outcrops, we characterized quantitatively the development characteristics of the single sand body on the well-tie sections. (6) In combination with the study results, we discussed further about the influence of water level changes on the sand bodies in the river-dominated delta front.

3.2.2. Research method of water level changes

The wavelet transformation and Fischer plots were chosen to study the water level changes. Logging curves contain rich stratigraphic information which can reflect the cyclicity of measured strata sensitively and continuously. By using continuous wavelet transform to log data, and analyzing the obvious periodic oscillation characteristics of the wavelet coefficient curves at various scales, a certain corresponding relationship can be established with the base level cycles at different orders, which can be used as the division basis of high-resolution sequence stratigraphy (Li et al., 2006). Fischer plots is a method to study the superposition regulation of sedimentary cycles in space and the change trend of sedimentary base level based on the division of high-frequency sedimentary cycles using logging curves (Fan and Li, 1997). The cycle number is generally used as the abscissa, and the accumulative offset of average thickness as the ordinate (Shao et al., 2013). The Fischer plots assumes that all cycles formed in the same period, and the basin subsided linearly. It is more accurate when the number of cycles is more than 50 (Sadler et al., 1993; Su et al., 1995).

In the research process, dbN wavelet basis and Gamma ray (GR) logging curves were optimized. The Gamma ray logging curves were transformed by one-dimensional discrete db10 wavelet to get wavelet coefficient curves of different scales, and the corresponding relationship between the wavelet coefficient curve and the base level cycle was established. According to the number and thickness of base level cycles of different orders, Fischer plots was made to analyze the water level changes.

3.2.3. Research method of sedimentary depth and distribution distance

The height or thickness of the delta foreset beds is generally close to the water depth (Glørstad et al., 2011). Using the thickness or height of the delta foreset beds is a reliable quantitative method to study water depth. The results will be better to calculate the ancient water depth over the seismic section across wells (Zhong et al., 2015). In this study, the sedimentary water depth and distribution distance were calculated by measuring the thickness and length of the foreset beds on the seismic section across wells.

Seismic sections which have complete reflection events of delta topset beds, foreset beds and bottomset beds were selected. After flattening the topset beds, the shape is close to the shape of deltas at deposition. Statistical analysis has been conducted about the depth from the topset beds to the bottomset beds, and this depth is the depth of the delta front. By differentially correcting the mudstone and sandstone in each well, the sedimentary depth in the well can be obtained. The length of the reflection event of each foreset bed was read, and this length is the distribution distance of the delta front. Then the slope angle can be calculated.

4. Result

4.1. Classification of architecture orders

In this paper, the six orders architecture classification method for river facies (Miall, 1985, 2002, 2006) has been used to classify the architectures of underground reservoirs in the study area. As shown in Fig. 4, the 1st-order interface is the bedding system interface, the 2nd-order interface is the bedding system group interface, which can be identified in cores. The 3rd-order interface corresponds to the mud interlayer between the accretions within a single sand body, which is used to identify the sedimentary cycles in a single sand body, and can be identified in cores and on logging curves. The 4th-order interface is interface of single sand body, which can be used to separate sand bodies deposited during the same period, and can be identified in logging curves, but it is not easy to observe in cores. The 5th-order interface is the interface between the complex sand bodies composed of single sand body deposited during the same period, and usually the complex sand bodies are stable in lateral continuity. The 6th-order interface corresponds to the interface of the complex delta composed of multi-stage complex sand bodies. In this study, it corresponds to the layer interface, because in some layers, only one-stage complex sand bodies are developed, that is to say that the layer interface may be 5th-order interface or 6th-order interface. Therefore, in this paper, the interface of the layer is regarded as the interface of the complex sand body.

4.2. Characteristics of water level changes

Well z59 was taken as an example. Under the control of the third order sequence, through the wavelet transform, it was considered that the d10, d7, d5 and d4 wavelet coefficient curves could be correlated with long term, medium term, short term and ultrashort term base level cycles respectively (Fig. 5). The medium-term cycle has a good correspondence to the sand groups. The first four medium cycles correspond to Sand Groups 5, 4, 3 and 2-2, respectively, and the latter two medium cycles correspond to Sand Group 2-1. The changes of the medium cycles corresponded to the changes of the mid-frequent water level changes, which controlled the development characteristics of the complex sand bodies. 54 ultrashort cycles have been quantitatively analyzed by using the Fischer plots. The results show that the cumulative offset of average thickness of each cycle in Sand Groups 2–5 increased first and then decreased. The rise and fall of Fischer plots' curve represent the changes of the accommodation space and also reflect the changes of the lake level. The rise of the curve represents the rise of the lake level and the fall of the curve represents the fall of the lake level (Shao et al., 2013). Therefore, from Sand Group 2-1 to Sand Group 5, the relative water level increased first and then decreased, Sand Group 2-2 was at the highest water level.

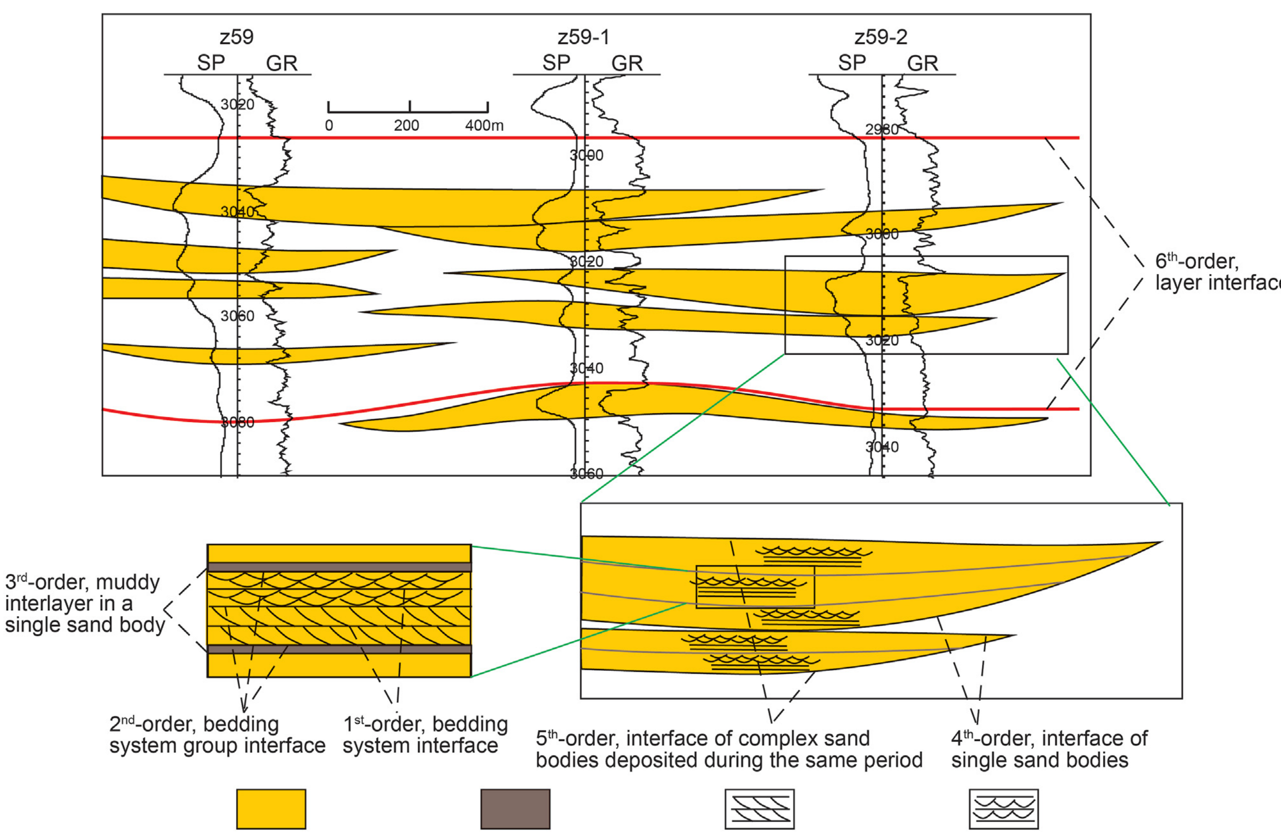

Fig. 4. Schematic diagram of the interface classification in Gubei Sag.

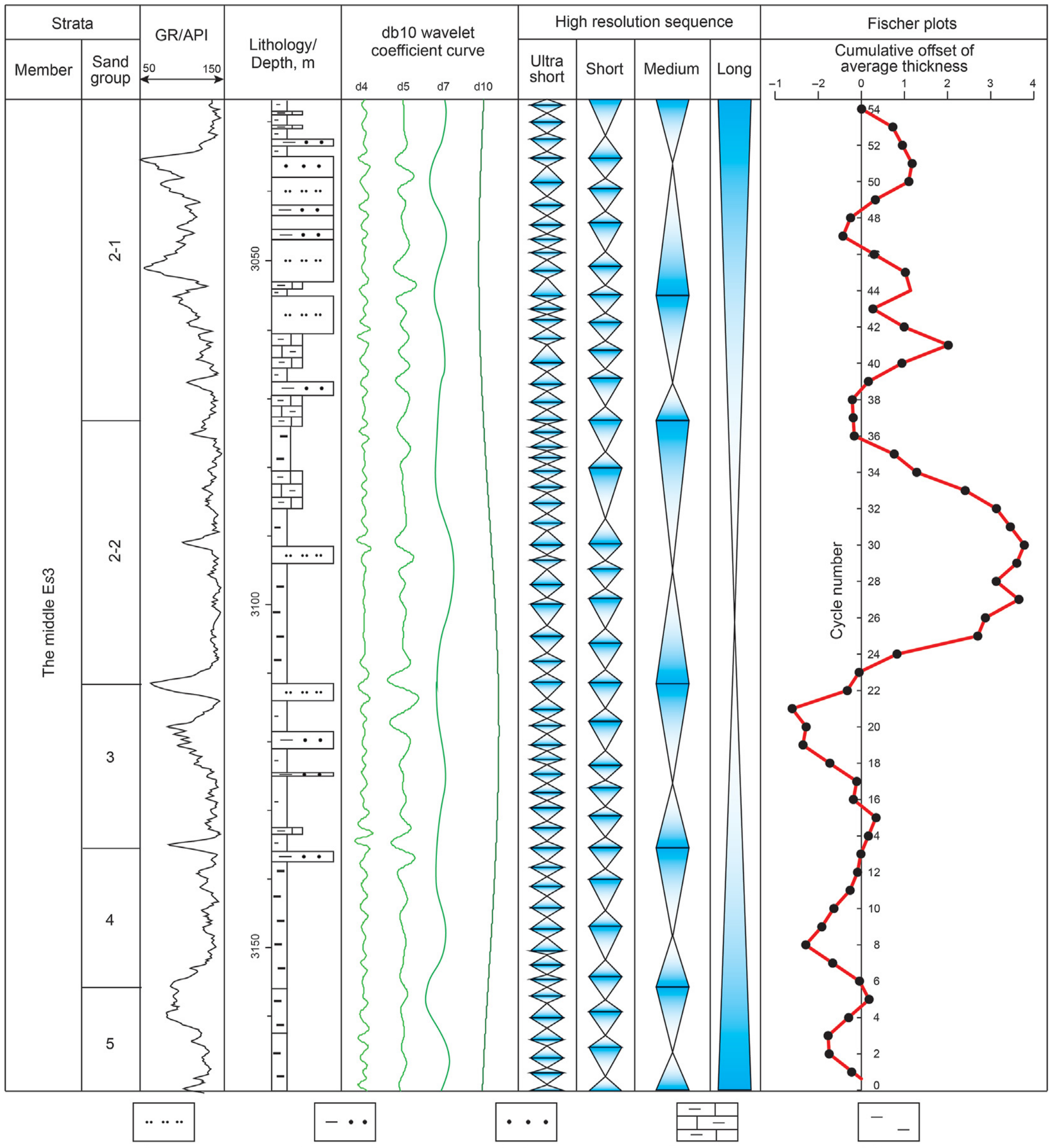

Fig. 5. High resolution sequence stratigraphic framework and water level changes of Sand Groups 2–5 in Well z59.

4.3. Depositional and logging facies characteristics of sand bodies in cored wells

Through core observation, the identified single-genetic sand bodies (4th-order architecture element) include five types, including delta front subaquatic distributary channels, mouth bars, sheet sands, crevasse splays, and shore shallow lake stripped sands.

The extension of a delta plain channel toward subaquatic is called a subaquatic distributary channel, which is the architecture element with the largest development area and the largest amount of sand bodies in the delta front. The subaquatic distributary channel is relatively coarse in lithology, and is mainly composed of thick gravel-bearing sandstones and coarse sandstones, usually in a positive sequence. Due to the combined action of traction currents and waves, the sedimentary structures are very complicated. After each stage of strong water flow, lag gravels and erosion surfaces (Fig. 6a) were developed at the bottom. At the bottom of the distributary channel, massive beddings and granular beddings can be seen, which were caused by quick deposition. Upwards, there are parallel beddings (Fig. 6a), wedge-shaped cross beddings, and tabular cross beddings (Fig. 6b) formed by the traction flow, which are indicative of the strong hydrodynamic conditions. The middle of the GR curve is a box or bell shape with micro teeth. The fine teeth increased at the upper part, converged at the center line of the teeth, and sudden change occurred at the bottom (Fig. 7a).

The sand-bearing water carried by the distributary channel entered the lake at the exit of the mouth in planar jetting way. Affected by the friction of the mouth bank and bottom, the flow rate and sand transport capacity reduced, and the sand was unloaded at the outlet, forming a mouth bar. Compared with the distributary channel, in mouth bar, the lithology is fine, mainly composed of fine sandstones and siltstones, being medium to thick in thickness, intercalated with 3–10 cm thin mudstones, being well sorted, and the whole formation is in a reverse order sequence. Wedge-shaped cross beddings (Fig. 6c), wave-formed cross beddings and wavy beddings are developed. Biological shell (Fig. 6d), iron nodules and carbonaceous lamination (Fig. 6e) can be observed. The GR curve is in a funnel shape, with medium-high amplitude, and the lower part

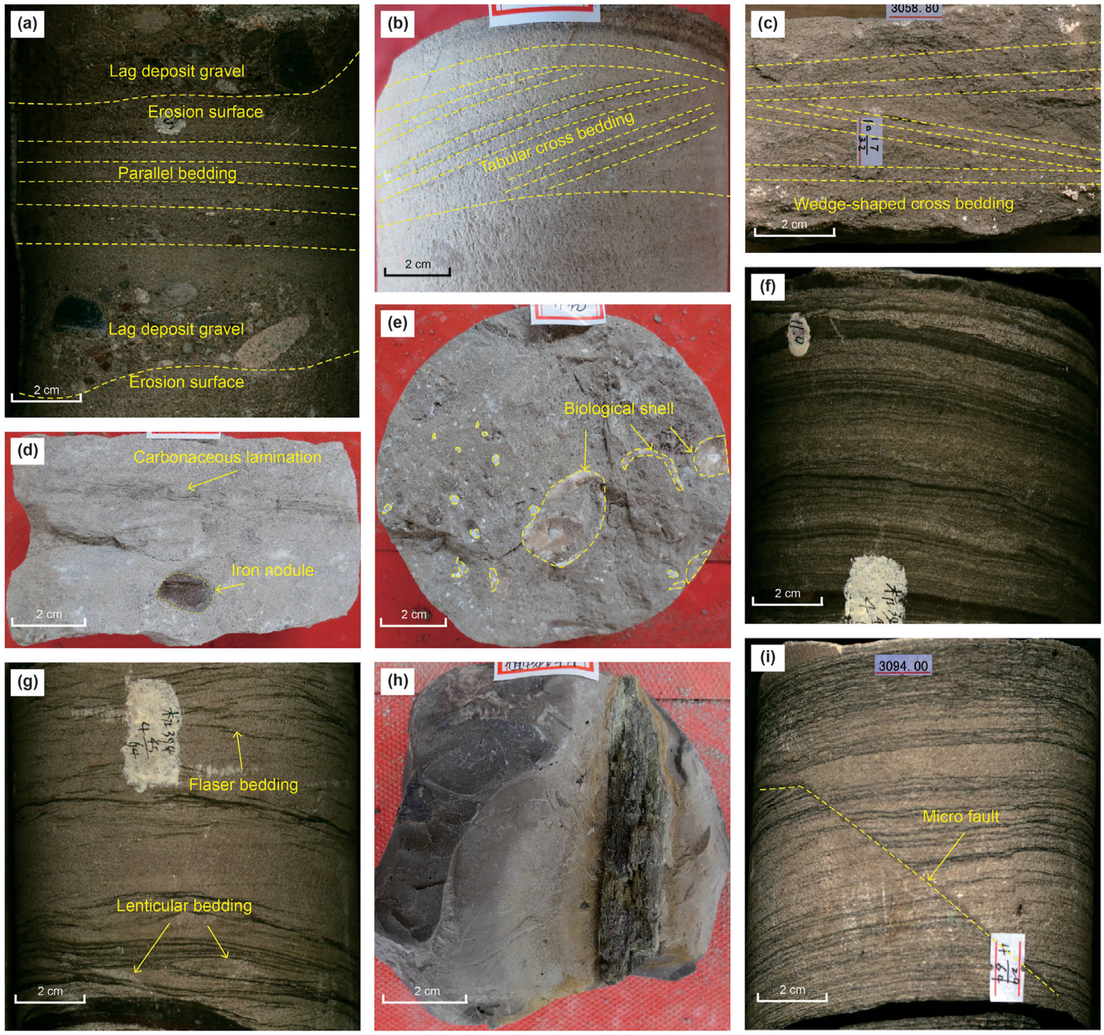

Fig. 6. Core photographs showing typical sedimentary structures in river-dominated delta front of the middle Es3 in Gubei Sag: (a) lag deposit gravel, erosion surface and parallel bedding in subaquatic distributary channel, Well z394, 3262.7 m; (b) tabular cross bedding in subaquatic distributary channel, Well b991, 2872.3 m; (c) wedge-shaped cross bedding in mouth bar, Well z701, 3058.8 m; (d) carbonaceous lamination and iron nodule in mouth bar, Well z241, 3232.5 m; (e) biological shell in mouth bar, Well z241, 3218.8 m; (f) wavy bedding in sheet sand, Well z394, 3098.2 m; (g) flaser bedding and lenticular bedding in sheet sand, Well z394, 3098.1 m; (h) plant stem in crevasse splay, Well z941, 3300.27 m; (i) micro syndepositional faults in crevasse splay, Well z394, 3094.1 m.

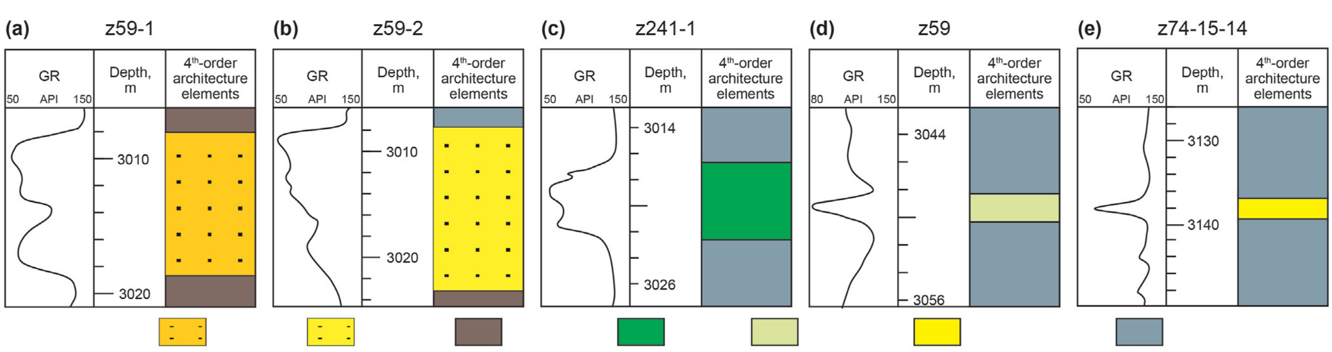

Fig. 7. Logging identification templates of different single-genetic sand bodies in river-dominated delta front of the middle Es3 in Gubei Sag.

has been toothed, and the center line of the teeth changes upward from gentle to steep, with foreset amplitude combination (Fig. 7b).

The sheet sand is a thin sand layer with a large area, and deposited on the wing of a mouth bar after being washed by lake waves, composed of interbedded thin siltstones and mudstone interlayers, and well sorted. Horizontal beddings, wavy beddings (Fig. 6f), flaser beddings and lenticular beddings (Fig. 6g) are the common sedimentary structures. The GR curve is in finger-shaped or funnel-shaped, being toothed, and the curve amplitude is low (Fig. 7c).

Crevasse splays are tongue-shaped deposits left after the sediments carried by flood rushed to subaquatic distributary channels during the flood period. The grain is coarse. The lithology is composed of mudstone intercalated with medium-thick lenticular sandstone. Washed-filled structure, plant stems (Fig. 6h) and intralayer deformation structure, such as micro fault (Fig. 6i), can be observed. The middle of the GR curve is in finger-shaped or box-shaped, being slightly toothed, the upper and lower parts are usually straight mudstone baselines (Fig. 7d).

Shore shallow lake stripped sand (lake sand) refers to the thin and stripped silty sandstones and argillaceous siltstones developed in a shore shallow lake area, usually intercalated in thick mudstone. Massive bedding and wavy bedding can be seen. The GR curve is in finger shape with medium-low amplitude, or in funnel shape with thin layers, being slightly toothed (Fig. 7e).

4.4. Distribution characteristics of complex sand bodies in delta front

4.4.1. Sectional distribution characteristics

In order to make clear about the development characteristics of sedimentary facies and the distribution regularity of sand bodies in the base level cycles, two sections perpendicular and parallel to the source direction have been selected (Fig. 8):

(1) Parallel to source direction (N–S)

As shown in Fig. 8a, from the Sand Group 5 to Sand Group 3, with the rising in lake level, the delta gradually receded to the vicinity of Well z241, the thickness of the complex channel sand body decreased, and the range of deep to semi-deep lake increased gradually. During the depositional period of the Sand Group 2-2, the lake level dropped rapidly, and the delta advanced to the center of the lake basin. The delta plain extended to the area near Well gb37. The front sand body was mainly a subaquatic distributary channel and extended to the area near Well zs2. The thickness of complex channel sand body was large. Sand Group 2-1 progradated further, and the front sand body extended to the vicinity of Well z75. In the sedimentary section as a whole, with the changes of lake level, the delta sand bodies are characterized by retrogradation first and then progradation.

(2) Perpendicular to source direction (E-W)

As shown in Fig. 8b, the section is dominated by delta front sand bodies, and subaquatic distributary channel sand bodies can be found in every sand group. In Sand Group 5, two distributary channel sand bodies from two source directions are developed, with large thickness in vertical. With the rising of the lake level, the thickness of the distributary channel sand bodies in Sand Groups 4 and 3 decreased gradually, and the width decreased gradually. In Sand Group 3, mouth bars were well developed around Wells z241-6 and zs3, and front sheet sands were well developed around Well z241-11. During the depositional period of Sand Group 2-2, the lake level declined rapidly, and the delta from the western source diverged westward to Well z242-10, while the delta from the eastern source diverged into two branches around Wells zs3 and z491. During the depositional period of Sand Group 2-1, the lake level was the lowest, two delta front subaquatic distributary channels were seriously diverged, resulting in thickest single sand body. Crevasse splays were developed around Well z24. In terms of the number of sand bodies, the number of single sand body in Sand Group 3 is the least, with relatively higher water level. The number of single sand body in Sand Group 2-1 and Sand Group 5 is relatively large, with relatively low water level.

4.4.2. Planar distribution characteristics

During the depositional period of the Sand Group 5, the lake level was relatively low, and the source from the Gubei Uplift injected the area near Well gb131, and moved northward and bifurcated into two branches. Overall, the subaquatic distributary channels were less bifurcated, appeared as narrow single-channel sand bodies on the plane. The mouth bar sand bodies were developed at the forefront of the subaquatic distributary channels, with a small area. Crevasse splays were developed around Well z43, with a small scale. Flaky sheet sands were developed around wells z242-10, z75 and z59-23 at the forefront of the delta front. A small area of deep lake, semi-deep lake deposits were deposited in the northernmost East Sub-sag. During the depositional period of the Sand Group 4 and the Sand Group 3, the distribution pattern of the delta was basically similar to that of the Sand Group 5. With the rising in lake level, the distribution area of the delta plain decreased, and the subaquatic distributary channels at the delta front widened gradually, and moved toward the center of the East Sub-sag by a short distance, while the bifurcation was more frequent, and the forefront of the distributary channel sand body was in a network shape. The development area of mouth bars and sheet sand bodies increased, and the area of deep lakes and semi-deep lakes was larger in the East Sub-sag. During the depositional period of Sand Group 2-2, the lake level dropped rapidly, and the delta moved northward to the East Sub-sag. A new delta sourced from the southeast of the study area was developed. The sand bodies of the two divergent delta channels was not wide, and the bifurcation ability towards the east and west sides was weak, with obvious channelization characteristics. The distribution area of the delta plain was relatively large, and the development area of the mouth bar and sheet sand bodies was relatively small. The depositional period of Sand Group 2-1 was similar to that of Sand Group 2-2, but the distribution area of the sand bodies of front channel and mouth bar increased slightly.

In general, during the depositional period of Sand Groups 5, 4, and 3, the lake level was relatively high, the delta plains were small, and the lateral spreading capacity of delta front was relatively strong, so mouth bar sand bodies were well developed. In the foremost, due to the superposition of multiple channels and late wave transformation, the sand bodies were connected on a large area, in a net shape. During the depositional period of Sand Groups 2-2 and 2-1, the lake level was lower, the area of the delta plain was larger, and the advancing capacity in the direction along the provenance was relatively strong. Therefore, the mouth bar and sheet sand bodies were less developed, and the channelization characteristics of the entire delta were obvious, in branches shape (Fig. 9). From Sand Group 5 to Sand Group 2-1, the lake level rose first and then fell, the lake shore line moved first towards the shore, and then towards the lake basin.

4.4.3. Sedimentary depth, foreset beds length and slope angle

Five seismic sections have been selected within the development range of a river-dominated delta in the middle Es_3 on the east side of the gentle slope belt in the southern part in the Gubei Sag (The location of the survey lines is shown in Fig. 3). Reflection events of 20 complete delta topset beds, foreset beds and bottomset beds have been identified in the 5 seismic sections (Fig. 10). According to the research method in 3.2.3, statistics and calculation have been conducted about the depth, length and slope angel of each foreset bed (Table 1). According to Table 1, the length of the foreset beds and sedimentary depth is a linear relationship, while the slope angle and sedimentary depth is logarithmic. The greater

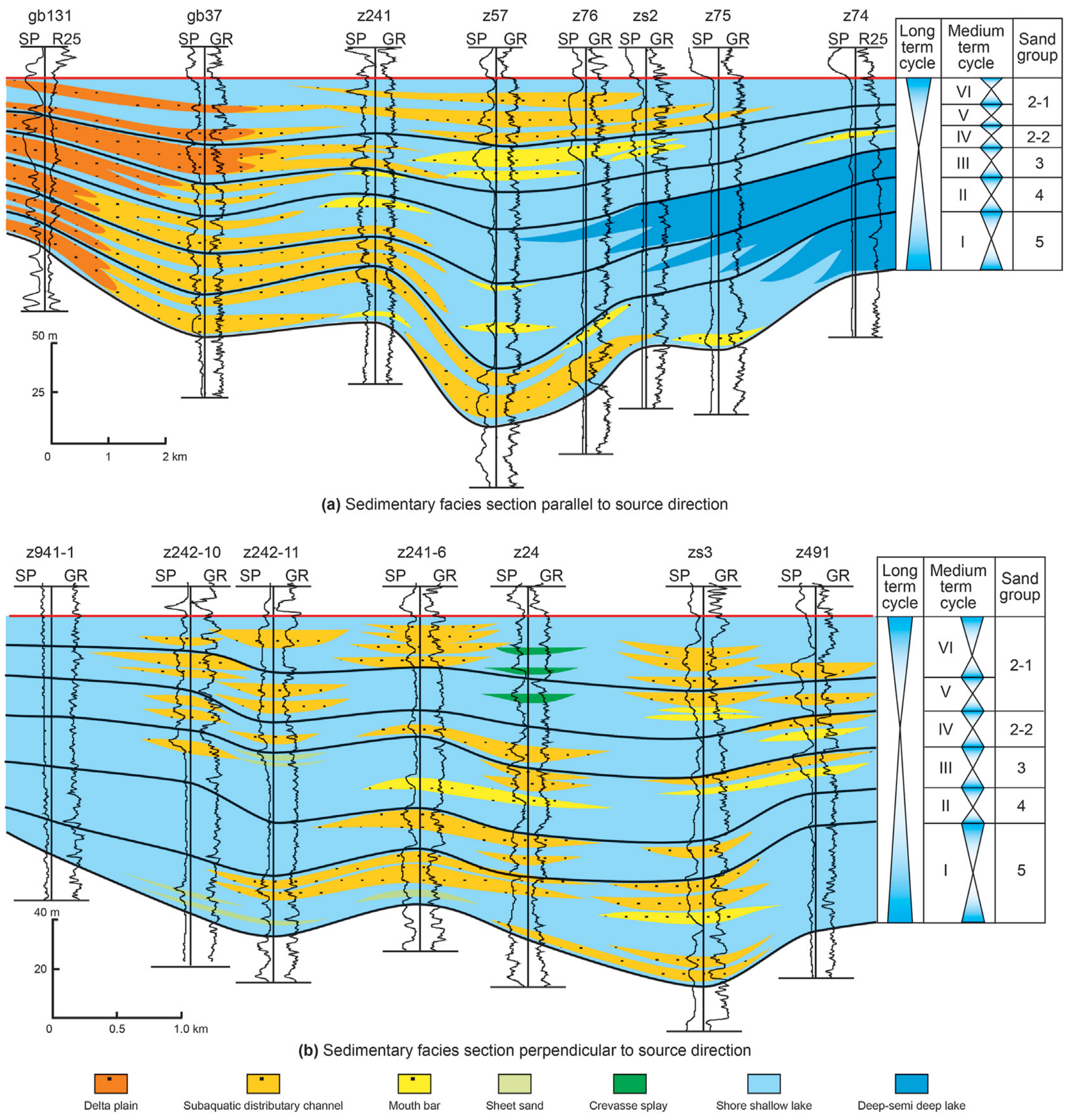

Fig. 8. Well-tie sedimentary facies sections of the middle Es3.

the sedimentary depth, the longer the horizontal length of the foreset beds, and the larger of the slope angle. The slope angle eventually approached a maximum value, which is the end angle (Fig. 11).

4.5. Influence of water level changes on single sand body of river-dominated delta

4.5.1. Superimposition of single sand body

The superimposition style of sand bodies has an important influence on the hydrocarbon accumulation. Because there is no outcrop in the middle Es3 in the study area, the typical river-dominated delta outcrops of the Jurassic Yan'an Formation in Shenmu area of Ordos Basin were selected by the research group to conduct field investigation (Qiu et al., 2016). Based on this, referring to the previous study on identification marks of single sand body (Feng et al., 2014), The superimposition style and distribution characteristics of sand bodies were further summarized. The previous study shows that the third sedimentary episode of Yan'an formation in Shenmu area was the period of accelerated subsidence due to the strong activity of boundary faults and developed river-dominated lake delta. There were mainly multi-stage superimposition of subaquatic distributary channels and crevasse splays in vertical. Other sedimentary microfacies included sheet bars and interdistributary bays. Because of the frequent subsidence of the lake basement and the rise of the lake level, all kinds of sand bodies had small thickness and good lateral stability (Xia et al., 1991; Qiu et al., 2016). Similar to the Shenmu delta, during the sedimentary period of Es3 in the research area, the Gubei fault in the southern boundary of Gubei sag started the activity and gradually entered the peak period. The research area developed typical river-dominated delta (Luo, 2019). It was mainly composed of Subaquatic distributary channel, mouth Bar, interdistributary bay and distal bar (Qiu et al., 2019). The characteristics of fault activity and the main types of sedimentary microfacies in the two area were similar during the sedimentary period of the lake deltas, and the lake level changes both had obvious control on the vertical facies sequence and the plane combination of the delta. Therefore, the outcrops study in Shenmu area can provide guidance for the research on the superimposition style of single sand bodies controlled by the lake level changes in the Gubei sag.

The three outcrops in Fig. 11 are located in Kaokaowusu gully,

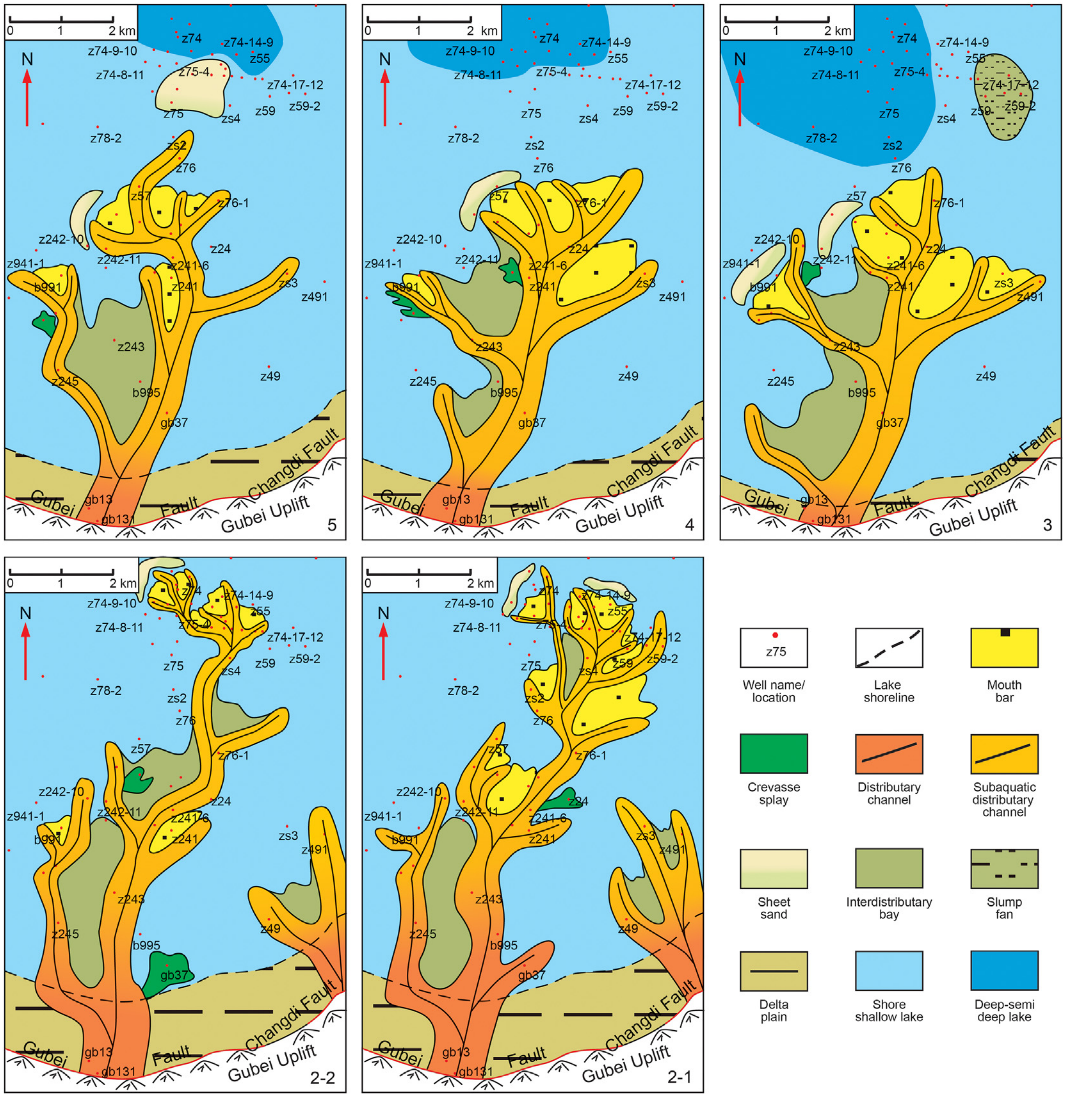

Fig. 9. Planar distribution of sedimentary facies from Sand Group 2 to Sand Group 5 in the middle Es3.

and their coordinates are 39°02′38″N, 110°18′02″E; 39°03′16″N, 110°21′29″E; 39°02′35″N, 110°17′50″E. Three superimposition styles among single sand body have been identified on the outcrops, including cutting-stacking, stitching and isolated (Fig. 12). Then following the principles of visualization and practicability, combined with the development characteristics of the sand bodies in the study area, we divided vertically the single sand body in the study area into three superimposition styles, including cutting-stacking, stitching and isolated, and horizontally into stitching and isolated styles.

The cutting-stacking style refers to that under strong hydrodynamic conditions, the previous developed sand bodies were cut and washed by the later developed sand body, and then they were contacted closely (Fig. 12a). The cutting-stacking style usually appeared only in the vertical superimposition relationship. There were obvious eroded surfaces or lithological abrupt changes at the interface of different single sand body. There was no muddy barrier between two single sand bodies. This style mainly occurred between two channel sand bodies, or between that of a single channel and a mouth bar, or occasionally between two mouth bar sand bodies.

The stitching style refers to that when two sand bodies were contacted with each other horizontally or vertically, the previous developed sand body was not cut by the latter sand body (Fig. 12b). The stitching type might appear in vertical and horizontal superposition, and there probably exists a thin muddy barrier or a sudden change in lithology between the interfaces. Vertical stitching was mostly the contact between two distributary channel sand bodies, two mouth bar sand bodies or a channel and a mouth bar sand body, while the horizontal stitching mostly appeared in two sand bodies of the same type.

The isolated style appeared when the space between two sand bodies was larger than the volume of accommodation space due to rising of water level, only fine muddy or sandy mudstone deposits were accepted (Fig. 12c). As a result, the sand bodies were surrounded by muddy sediments. The isolated style might appear both in horizontal and vertical, and can be seen in various single sand body of subaquatic distributary channels, mouth bars, crevasse splays, or front sheet sand.

In the northern part with dense well spacing, six sections perpendicular to the source direction have been selected for characterizing the single sand body. The location of the survey lines is shown in Fig. 3.

As shown in Fig. 13a, the amount of single sand body in the

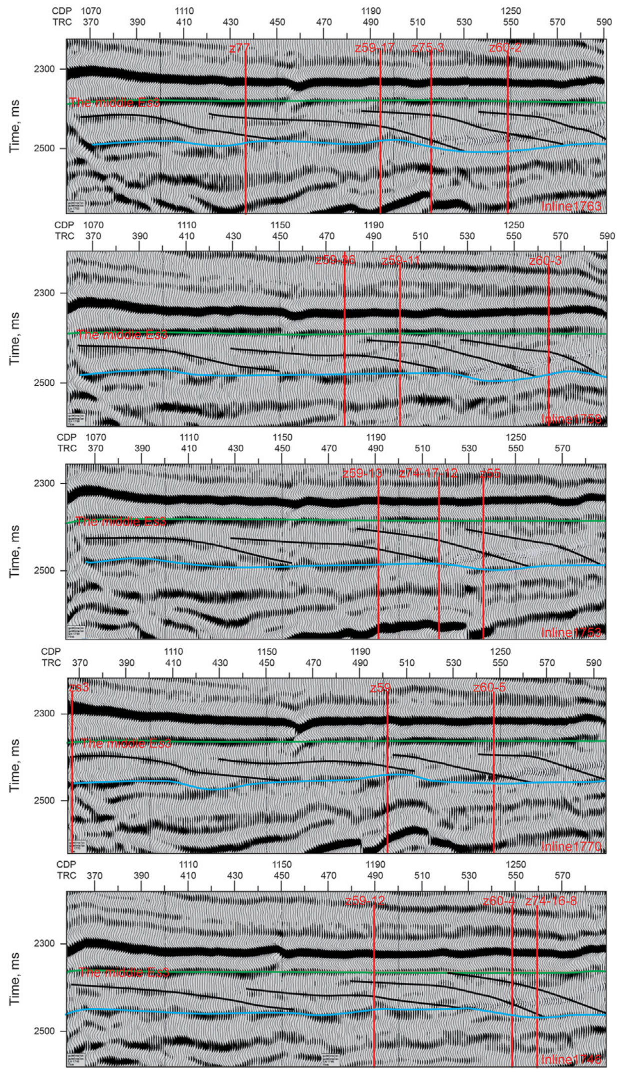

Fig. 10. Seismic profiles for progradational reflection in the middle Es3, Gubei Depression (modified from Zhang et al., 2019).

subaquatic distributary channels is the largest on this section, mostly concentrated in Sand Groups 2-1, 2-2 and 5, with relatively low lake levels, while the amount of single sand body was less in Sand Group 3, with a higher lake level. The single sand body was mainly in stitching and cutting-stacking styles, mostly appeared in the distributary channel and mouth bar sand bodies in Sand Groups 2-1, 5 and 3. There are less isolated sand bodies, which appear mainly in the crevasse splays and front sheet sands. The well spacing on this section is relatively large, and the statistical analysis has not been done on the width of the sand bodies.

On Fig. 13b, the section 1 is farther away from the source, and near the East Sub-sag. The amount of single sand body is relatively large in Sand Groups 2-1 and 2-2, with lower lake levels, most of which are in subaquatic distributary channels. In the Sand Groups 3, 4, and 5 with higher lake levels, the source supply was very weak, and the amount of single sand body was relatively small, mainly thin lake belt and frontal sheet sand. The superposition on section of Fig. 8b is quite different from that on the section of Fig. 8a. The cutting-stacking style only appears in Sand Group 2-1 at the lower lake level, the stitching style appears in Sand Groups 2-1 and 2-2. There are only isolated single sand body in Sand Group 3 to Sand Group 5, with high lake levels.

On Fig. 13c, the section 2 is farther away from the source area, the amount of single sand body in the subaquatic distributary channels decreased, while the amount of single sand body in the mouth bars increased, most of which appeared in Sand Group 2-1 and 2-2, with lower lake levels. From Sand Group 3 to Sand Group 5, there are only a few shore-shallow lake sand strips, sheet sand, and slump turbidity fan. In Sand Groups 2-1 and 2-2, the sand bodies are mostly cutting-stacking and stitching styles; in the subaquatic distributary channels, the sand bodies are cutting-stacking styles, and in the mouth bars, the sand bodies are isolated. Most sand bodies in Sand Groups 3–5 are isolated, with less lateral stitching.

On Fig. 13d, the section 3 is farther away from the source area, the sediments became less, and the number of single sand body in the distributary channels was less than that in the mouth bars. Cutting-stacking sand bodies appeared in the mouth bars, the isolated and spliced sand bodies appeared in the subaquatic distributary channels, and a small amount of stitching thin lake sand bodies appeared in Sand Group 3, with a higher lake level.

Table 1
Sedimentary depth, foreset beds length and slope angle of river-dominated delta estimated by seismic data.

Line No.	Foreset beds No.	Sedimentary depth, m	Foreset beds length, m	Slope angle, °
inline1770	1	74	716	5.86
	2	103	1,192	4.94
	3	78	724	6.13
	4	174	1,523	6.53
inline1753	1	101	918	6.27
	2	153	1,339	6.53
	3	143	1,116	7.29
	4	179	1,375	7.4
inline1758	1	82	929	5.04
	2	103	983	5.98
	3	153	1,199	7.29
	4	193	1541	7.15
inline1763	1	59	929	3.62
	2	162	1,436	6.42
	3	141	1,177	6.82
	4	206	1,537	7.63
inline1746	1	42	914	2.63
	2	113	1,202	5.39
	3	139	1,235	6.4
	4	162	1,404	6.57

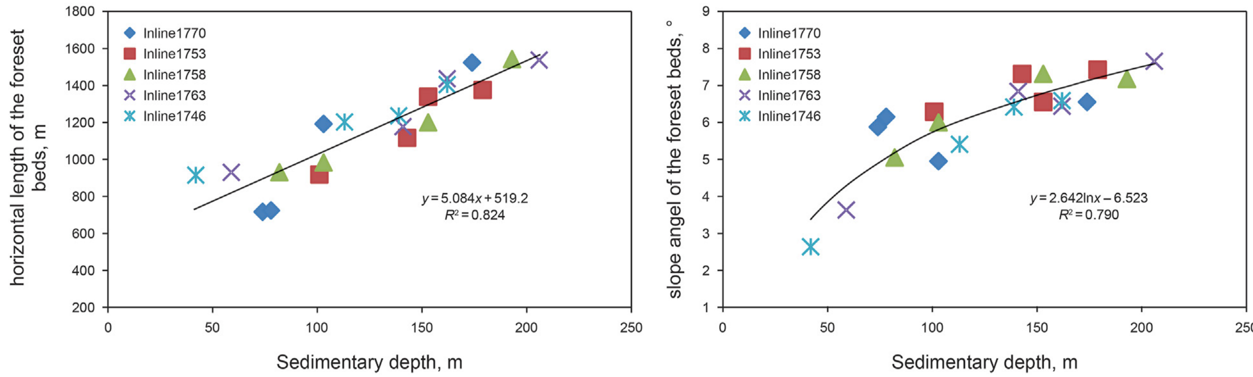

Fig. 11. Horizontal length and slope angle of the foreset beds vs. sedimentary depth.

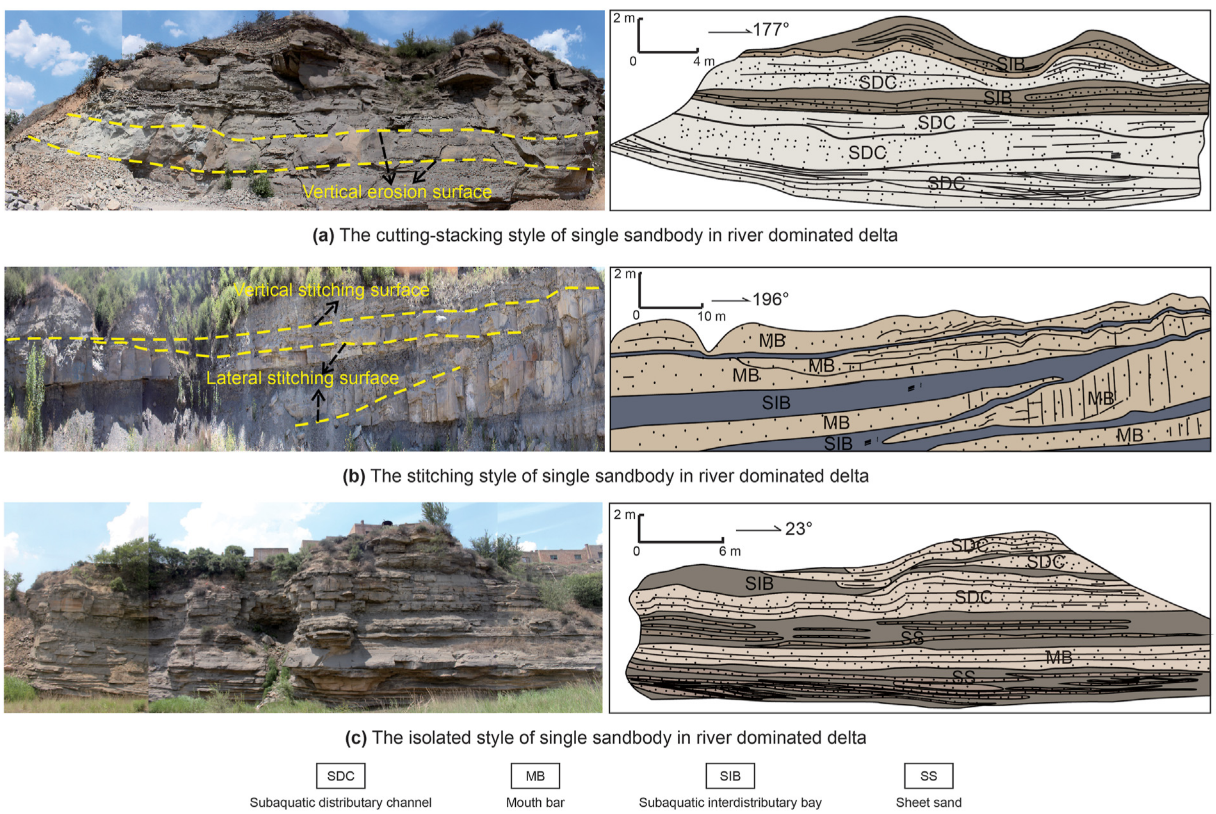

Fig. 12. The superimposition styles of single sand body in river-dominated delta on Kaokaowusu section (modified from Qiu et al., 2016).

On Fig. 13e, on the section 4, only cutting-stacking sand bodies appeared in the subaquatic distributary channels in Sand Group 2-1 and Sand Group 3, and the others were mostly isolated. The number of single sand body reduced further, and most single sand body were developed in the subaquatic distributary channels.

On Fig. 13f, the section 5 is located in the northernmost part of the study area, with the least source supply. The single-sand bodies are dominated by thin lake sand belts, with few single-sand bodies in the subaquatic distributary channels and the mouth bars. Stitching sand bodies only appear in the distributary channels in Sand Group 2-1 and Sand Group 2-2, and the others are isolated.

4.5.2. Scale of single sand body

Fig. 14a shows the statistical analysis of the single sand body on the five sections (Fig. 13b to f) in the north area with a small well spacing. For the single sand body in the subaquatic distributary channels, the mouth bars, and the shore shallow lake, which are relatively large in quantity, we estimated the disaggregation ratio of the single sand body with the half-float method by logging curves. For the width of a single sand body, if it is fully developed between two wells, the width is the interval between the two wells, and if it pinches out between two wells, the width is three-fifths of the distance between the wells.

In terms of the disaggregation ratio, the largest is the sand bodies in shallow lakes, followed by those in mouth bars, and the smallest is in channel sands (Fig. 14b). From section 1 to section 5, which are gradually away from the source, the terrain decreased gradually, and the sedimentary depth gradually increased. Except for the deviation caused by the small number of single sand body on section 5 and fewer statistical samples, the average

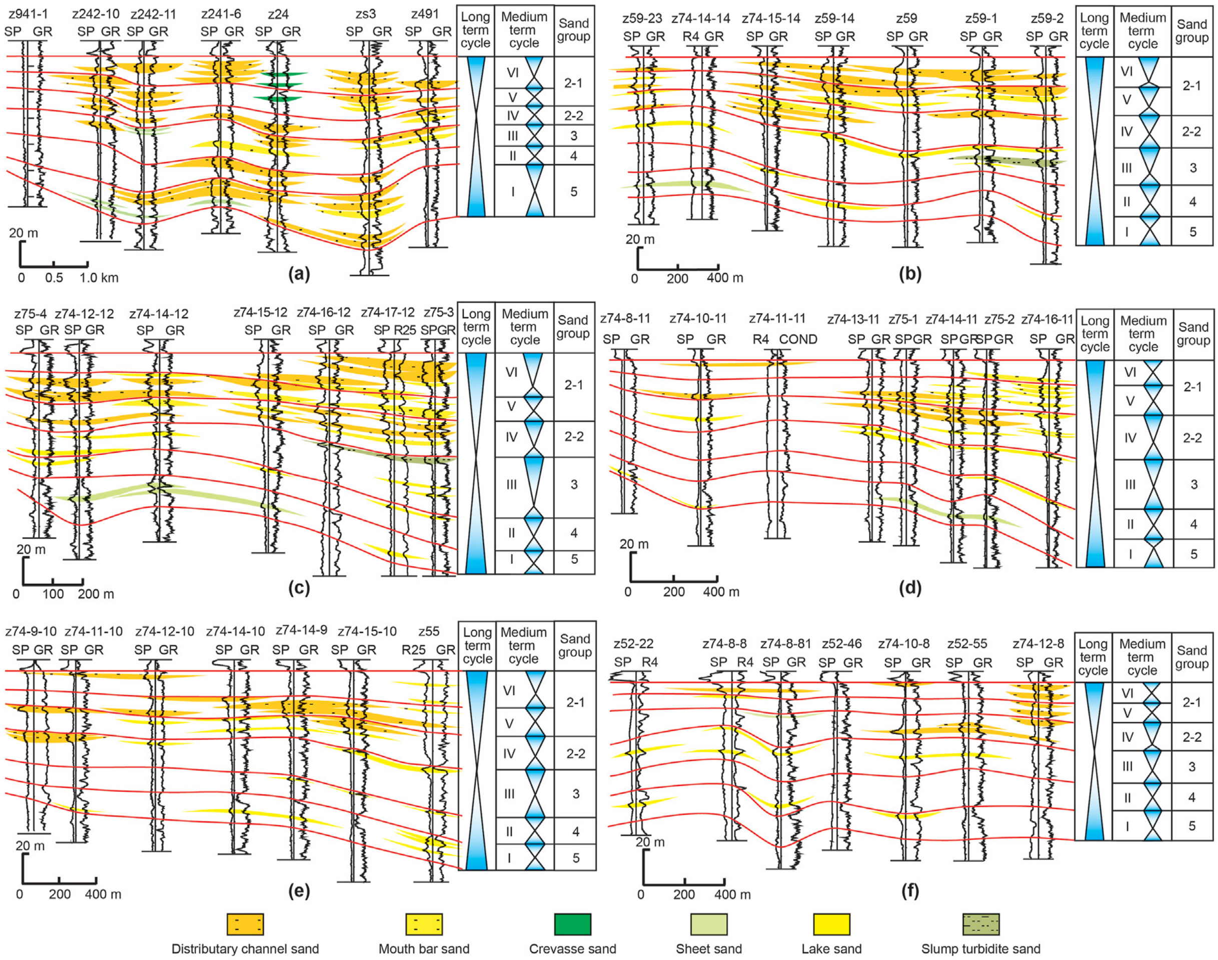

Fig. 13. The textures of the delta front sand bodies in Sand Group 1 to Sand Group 5 of the middle Es3.

disaggregation ratio of the single sand body on other sections are gradually increasing (Fig. 14c). Compared with the average disaggregation ratio in different sand groups, it can be seen that disaggregation ratio is larger in Sand Group 5 and Sand Group 3, with relatively high water level, and disaggregation ratio is smaller in Sand Group 2-2 and Sand Group 2-1, with relatively low water level (Fig. 14d).

According to the data above, if the source distance is the same, the higher the water level, the weaker the down-cutting capability of the distributary channel, the stronger the wave influence, and the greater the disaggregation ratio of the sand body. In the same sand group, increasing the distance away from the source area, the sedimentary depth became larger due to the lowering of the terrain. However, on the other hand, due to the attenuation of the water energy of the distributary channel, the down-cutting capability became weak gradually, and the disaggregation ratio increased gradually.

5. Discussion

Based on the study results above, the influence of water level changes on complex and single sand body in river-dominated delta fronts has been summarized, and the delta depositional model which can reflect the influence of water level changes has been established (Fig. 15).

5.1. *Influence of water level changes on complex sand bodies*

Firstly, the changes in water level might affect the lateral distribution of complex sand bodies. During the process of water level rising to high position, the delta has a stronger tendency to distribute perpendicular to the source direction, and the distributary channel bifurcates, in a network shape. With more and more crevasses and mouth bars forming, a large amount of sheet sand appeared after being reconstructed by waves, and the delta gradually takes on a fan-shaped shape with mostly reverse in vertical sequence. When the water level decreases to a low position, the delta tends to distribute along the source direction in shape of dentrites, the bifurcation ability of the channels becomes weak. The amounts of crevasses and mouth bars reduces, resulting in less frontal sheet sand. The sand bodies are mostly isolated, to form bird-foot shape, and mostly positive vertical sequence. At a medium water level, the delta also tends to medium in distribution shape and distribution distance of complex sand bodies.

Secondly, the changes in water level may affect the distribution distance of the delta front. When the water level decreased, the distribution distance of the delta front decreased, while the distribution distance of the delta plain increased. Because the slope angle of the delta plain is usually smaller than that of the front, the enlargement of delta plain is greater than the decreasing of the delta front. Therefore, the lake shoreline moves toward the lake basin, and the delta develops forward. When the water level becomes low, usually large plains with small fronts got appeared.

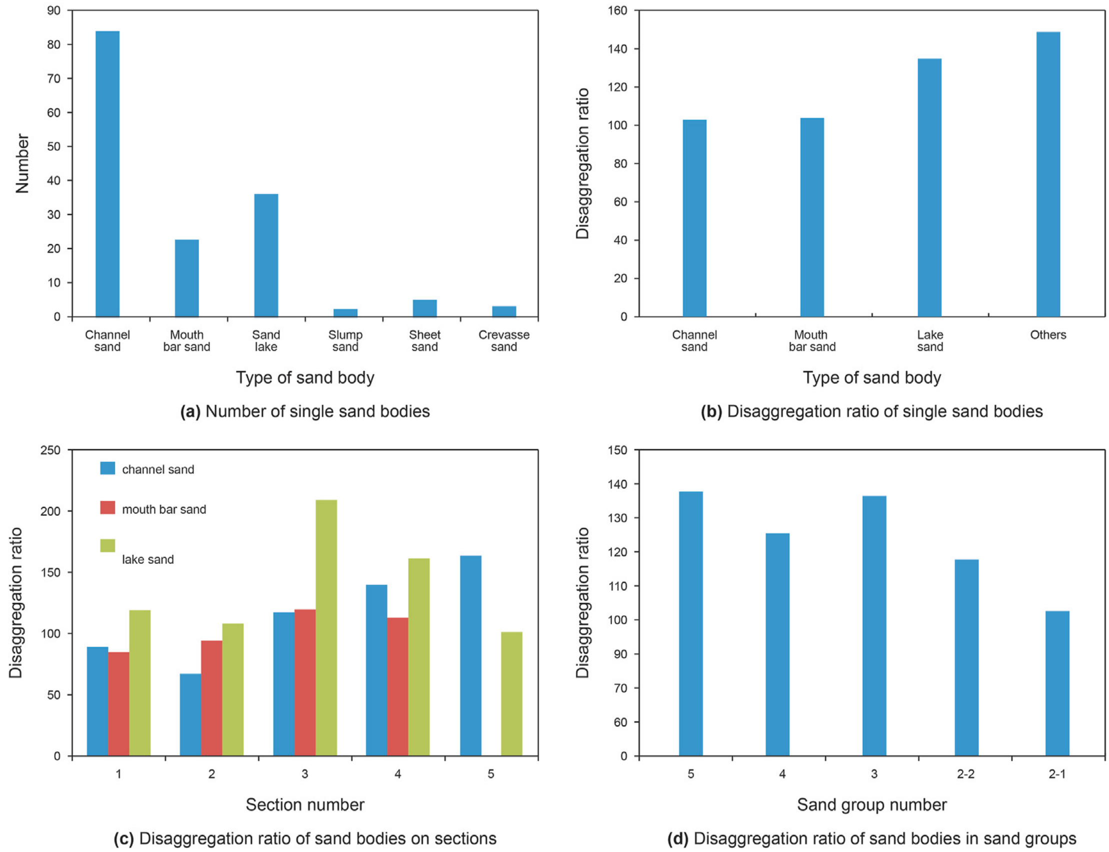

Fig. 14. Statistics of single sand body on 5 sections in the north of Gubei Sag.

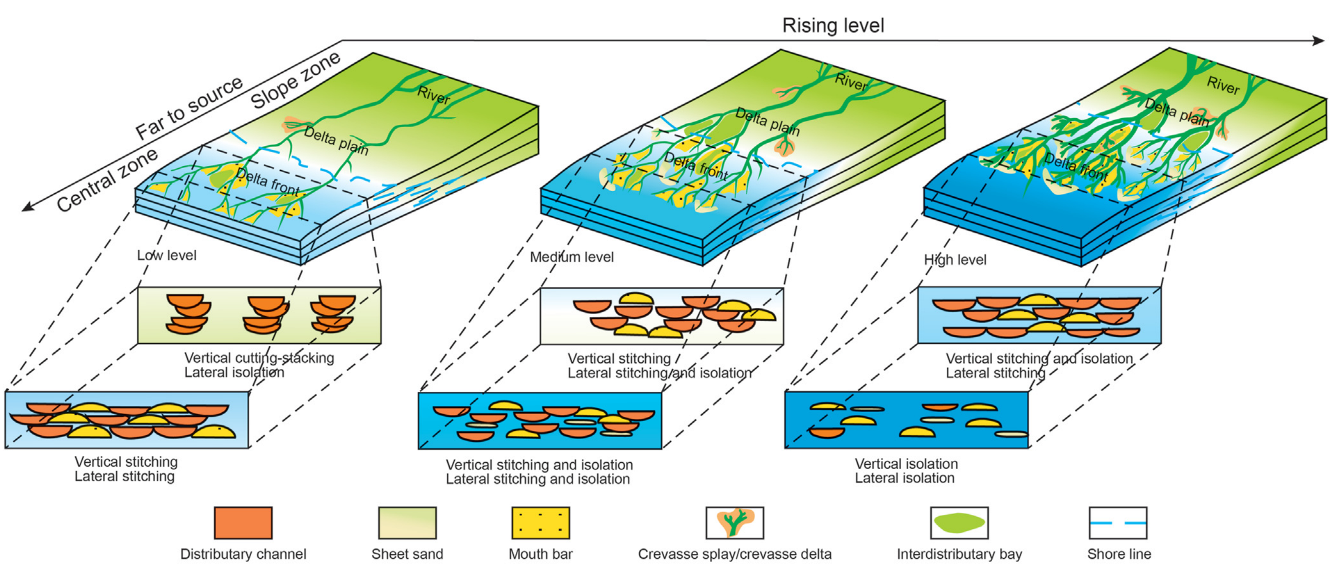

Fig. 15. Sedimentary models of river-dominated delta affected by water level changes (modified from Zhang et al. 2016).

When the water level rise, it can also increase the distribution distance of the delta front, decrease the distribution distance of the delta plain, and the decrease of the plain is mostly more than the increase of the front. With the contraction of the shoreline, the delta also has a corresponding regressive deposition.

5.2. Influence of water level changes on single sand body of river-dominated delta

Firstly, the changes in water level affected the superimposition style of single sand body. Without considering the influence of tectonic movements and changes in the amount of erosion on the A/S value, it is believed that with the rising of water level, the accommodation space increased. The farther away from the source, the smaller the amount of sediment supply. In the slope zone with more sediment supply, with the rising of water level, the A/S value gradually increased, and the superimposition style of single sand body changed gradually from vertical tangential stacking and lateral isolation to vertical stitching and isolation as well as lateral stitching. In the central zone where the supply of sediment is insufficient under the rising of water level, the A/S value gradually increased. However, at the same water level, the A/S value in the central zone is usually greater than that in the slope zone, and the superimpose style of single sand body may change from vertical stitching and lateral stitching to vertical isolation and lateral isolation.

Secondly, the change of water level can also affect the development scale of single sand body. With the same distance to source, the higher the water level, the weaker the down-cutting capability of distributary channels, the stronger the wave influences, and the greater may be the disaggregation ratio of the sand body. In the same sand group, with the decrease in terrain, the depositional distance and depositional depth of the delta also increase, the down-cutting capability of distributary channels gradually became weak, and the disaggregation ratio increases gradually.

6. Conclusion

Based on the previous investigation results of the authors' team, the river-dominated delta in the subsurface work area was selected for quantitative analysis. The influence of water level changes on sand bodies at river-dominated delta fronts was discussed.

(1) Water level changes greatly influence the develop of complex sand bodies in delta in the planar distribution pattern and distribution distance. For the single sand body at the delta front, the influence is mainly on the superimposition style and development scale.
(2) During the process of the water level rising from low level to high level, the complex sand bodies in distributary channels diverged frequently, changing from branch shape to reticulated shape, and the amount of crevasse splays, mouth bars, and sheet sand increased, thus increase the distribution distance of the delta front decrease the distribution distance of the plain. The deltaic degradation occurs and tends to transform from the small front-great plain to the large front-small plain.
(3) During the process of the water level rising from low to high, the superimposition style of single sand body in the slope zone transits from vertical cutting-stacking and lateral isolation to vertical stitching and isolation as well as lateral stitching. In the center of the lake basin, the superimposition style of single sand body transits from vertical stitching and lateral stitching to vertical isolation and lateral isolation. Facies such as distributary channels, mouth bars, and shore-shallow lake in which there contains more sand bodies, the disaggregation ratio of the single sand body increased correspondingly. With the same distance to the source, the higher the water level, the weaker the down-cutting capability of the distributary channels, and the stronger the influence of the wave, the greater the disaggregation ratio. In the same sand group, with the decrease in terrain, the depositional distance and depositional depth of the delta also increase, the down-cutting capability of the distributary channels gradually became weak, and the disaggregation ratio increased gradually.

Acknowledgements

The authors are grateful to Shengli Oil Company of Sinopec Group for their support in completing the research. This work was supported by Research Foundation of China University of Petroleum-Beijing at Karamay (No. XQZX20210004).

References

Bhattacharya, J.P., Giosan, L., 2003. Wave-influenced deltas: geomorphological implications for facies reconstruction. Sedimentology 50 (1), 187–210. https://doi.org/10.1046/j.1365-3091.2003.00545.x.
Chen, H.Q., 2019. Flow unit characteristics of fan delta front deposits and its influence on reservoir development - taking yulou oil bearing sets in some experimental area in west depression in Liaohe Basin in China as an example. J. Petrol. Sci. Eng. 179, 44–55. https://doi.org/10.1016/j.petrol.2019.03.043.
Chima, K.I., Couto, D.D., Leroux, E., et al., 2019. Seismic stratigraphy and depositional architecture of Neogene intraslope basins, offshore western Niger Delta. Mar. Petrol. Geol. 109, 449–468. https://doi.org/10.1016/j.marpetgeo.2019.06.030.
Dunne, L.A., Mcpherson, J.G., Shanmugam, G., et al., 1988. Fan-deltas and braid deltas: varieties of coarse-grained deltas: discussion and reply. Geol. Soc. Am. Bull. 100 (8), 1308–1310. https://doi.org/10.1130/0016-7606(1988)100<1308:FDABDV>2.3.CO;2.
Edmonds, D.A., Slingerland, R.L., 2010. Significant effect of sediment cohesion on delta morphology. Nat. Geosci. 3 (2), 105–109. https://doi.org/10.1038/ngeo730.
Edmonds, D.A., Slingerland, R.L., 2007. Mechanics of river mouth bar formation: implications for the morphodynamics of delta distributary networks. J. Geophys. Res. 112 (F3), 237–254. https://doi.org/10.1029/2007JF000874.
Fan, T.L., Li, Q.M., 1997. Analysis techniques of sedimentary base-level and their application. Oil Gas Geol. 18 (2), 108–114. https://doi.org/10.11743/ogg19970205 (in Chinese).
Feng, C.J., Bao, Z.D., Yang, L., et al., 2014. Reservoir architecture and remaining oil distribution of deltaic front underwater distributary channel. Petrol. Explor. Dev. 41 (3), 358–364. https://doi.org/10.1016/S1876-3804(14)60040-9.
Feng, W.J., Zhang, C.M., Yin, T.J., et al., 2019. Sedimentary characteristics and internal architecture of a river-dominated delta controlled by autogenic process: implications from a flume tank experiment. Petrol. Sci. 16 (2), 1237–1254. https://doi.org/10.1007/s12182-019-00389-x.
Glørstad-Clark, E., Birkeland, E.P., Nystuen, J.P., Faleide, J.I., et al., 2011. Triassic platform-margin deltas in the western Barents Sea. Mar. Petrol. Geol. 28 (7), 1294–1314. https://doi.org/10.1016/j.marpetgeo.2011.03.006.
He, M., Zhuo, H., Chen, W., et al., 2017. Sequence stratigraphy and depositional architecture of the Pearl River Delta system, northern South China Sea: an interactive response to sea level, tectonics and paleoceanography. Mar. Petrol. Geol. 84, 76–101. https://doi.org/10.1016/j.marpetgeo.2017.03.022.
Jin, Z.Q., Li, Y., Gao, B.S., et al., 2014. Depositional model of modern gentle-slope delta: a case study from Ganjiang delta in Poyang Lake. Acta Sedimentol. Sin. 32 (4), 710–723. https://doi.org/10.14027/j.cnki.cjxb.2014.04.011.
Lai, J., Wang, G.W., Fan, Z.Y., 2017. Sedimentary characterization of a braided delta using well logs: the upper Triassic Xujiahe formation in central Sichuan Basin, China. J. Petrol. Sci. Eng. 154, 172–193. https://doi.org/10.1016/j.petrol.2017.04.028 (in Chinese).
Liu, H., Xia, Q.L., Zhou, X.H., 2017. Geologic-seismic models, prediction of shallow-water lacustrine delta sandbody and hydrocarbon potential in the Late Miocene, Huanghekou Sag, Bohai Bay Basin, northern China. J. Palaeogeogr. 7 (1), 66–87. https://doi.org/10.1016/j.jop.2017.11.001.
Li, X., Fan, Y.R., Deng, S.G., et al., 2006. Review on methods for studying strata sequence with log data. Well Logging Technol. 30, 411–416. https://doi.org/10.16489/j.issn.1004-1338.2006.05.009 (in Chinese).
Luo, Q.H., 2015. Further discussion on water-transgression delta: genesis of great thickness large distributed sandstone of Xujiahe formation in Sichuan Basin, 33, 845–854. https://doi.org/10.14027/j.cnki.cjxb.2015.05.00 (in Chinese).
Luo, X., 2019. Structural evolution and 'golden zones' of hydrocarbon exploration distribution in Gubei sub-sag. CNKI:SUN:SYHN.0.2019-02-002 Petrol. Geol. Eng. 33, 1–5 (in Chinese).
Miall, A.D., 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. Earth Sci. Rev. 22 (4), 261–308. https://doi.org/10.1016/0012-8252(85)90001-7.
Miall, A.D., 2002. Architecture and sequence stratigraphy of pleistocene fluvial systems in the Malay Basin, based on seismic time-slice analysis. AAPG Bull. 86 (7), 1201–1216. https://doi.org/10.1306/61EEDC56-173E-11D7-8645000102C1865D.
Miall, A.D., 2006. Reconstructing the architecture and sequence stratigraphy of the preserved fluvial record as a tool for reservoir development: a reality check. AAPG Bull. 90 (7), 989–1002. https://doi.org/10.1306/02220605065.
Orton, G.J., Reading, H.G., 1993. Variability of deltaic processes in terms of sediment supply, with particular emphasis on grain size. Sedimentology 40 (3), 475–512. https://doi.org/10.1111/j.1365-3091.1993.tb01347.x.
Qiu, L.W., Yang, B.L., Zhang, Y., 2016. Lake level effect on main sandbodies of delta front: a case study from outcrops of the Jurassic Yan'an Formation in Shenmu area, Ordos Basin. J. Palaeogeogr. 18 (6), 939–950. https://doi.org/10.7605/gdlxb.2016.06.071 (in Chinese).

Qiu, L.W., Du, S.H., Dai, L., et al., 2019. Sedimentary characteristics and their controlling factors of the third member of Shahejie Formation in Gubei sag. Xinjing Pet. Geol. 40 (2), 161–167. https://doi.org/10.7657/XJPG20190206 (in Chinese).
Sadler, P.M., Osleger, D.A., Montanez, I.P., 1993. On the labeling, length, and objective basis of Fischer plots. J. Sediment. Petrol. 63 (3), 360–368. https://doi.org/10.1306/D4267AFF-2B26-11D7-8648000102C1865D.
Shao, C., Fan, T.L., Sun, Y., 2013. A case study on Yaojia Formation of Changyuan District: Fischer plot analysis based on natural gamma data. Resour. Ind. 15 (1), 64–70. https://doi.org/10.13776/j.cnki.resourcesindustries.2013.01.005 (in Chinese).
Su, D.C., Li, Q.M., Luo, G.W., et al., 1995. Method for drawing fischer plots and its applications on studying cyclic sequences—example from middle Cambrian Zhangxia formation, Western Hills of Beijing. CNKI:SUN:XDDZ.0.1995-03-001 Geoscience 9 (3), 279–283 (in Chinese).
Tsakalos, E., Dimitriou, E., Kazantzaki, M., et al., 2018. Testing optically stimulated luminescence dating on sand-sized quartz of deltaic deposits from the Sperchios delta plain, central Greece. J. Palaeogeogr. 7 (2), 130–145. https://doi.org/10.1016/j.jop.2018.01.001.
Wang, J., Yang, Y., Zhang, Y., et al., 2017. Impact of water level change on sedimentary characteristics of distributary channel in Poyang Lake delta. J. China Univ. Pet. 41 (1), 1–10. https://doi.org/10.3969/j.issn.1673-5005.2017.01.001 (in Chinese).
Wu, C.Y., 1983. Structural lake deltas and oil-gas distribution. Acta Sedimentol. Sin. 1, 5–26. CNKI:SUN:CJXB.0.1983-01-002.
Xia, W.C., Lei, J.X., Wang, C.Y., 1991. The depositional architecture of the lacustrine deltaic system with subaqueous distributary channel of Yan'an formation in southern Ordos Basin. CNKI:SUN:DQKX.0.1991-02-013 Earth Sci. J. China Univ. Geosci. 16, 219–228 (in Chinese).
Xu, Z.H., Wu, S.H., Liu, Z., et al., 2019. Sandbody architecture of the bar finger within shoal water delta front: insights from the lower member of Minghuazhen formation, Neogene, Bohai BZ25 Oilfield, Bohai Bay Basin, east China. Petrol. Explor. Dev. 46, 335–346. https://doi.org/10.1016/S1876-3804(19)60013-3.
Yang, B., Paik, S., Choi, Y., et al., 2019. Sedimentology of a wave-dominated and tide-influenced deltaic system, upper Middle Miocene, southwestern Ulleung Basin, Korea. Mar. Petrol. Geol. 101, 78–89. https://doi.org/10.1016/j.marpetgeo.2018.11.045.
Yang, Y.Q., Qiu, L.W., Jiang, Z.X., et al., 2011. A depositional pattern of beach bar in continental rift lake basins: a case study on the upper part of the Sha-4 Member of the Shahejie Formation in the Dongying Sag. CNKI:SUN:SYXB.0.2011-03-006 Acta Pet. Sin. 32, 417–423 (in Chinese).
Yin, T.J., Zhang, C.M., Zhu, Y.J., et al., 2014. Overlapping delta: a new special type of delta formed by overlapped lobes. CNKI:SUN:DZXE.0.2014-02-009 Acta Geol. Sin. 88 (2), 263–272.
Zhu, X.M., Zeng, H.L., Li, S.L., et al., 2016. Sedimentary characteristics and seismic geomorphologic responses of a shallow-water delta in the Qingshankou Formation from the Songliao Basin, China. Mar. Petrol. Geol. 71, 131–148. https://doi.org/10.1016/j.marpetgeo.2016.09.018.
Zhu, X.M., Li, S.L., Wu, D., et al., 2017. Sedimentary characteristics of shallow-water braided delta of the Jurassic, Junggar basin, Western China. J. Petrol. Sci. Eng. 149, 591–602. https://doi.org/10.1016/j.petrol.2016.10.054.
Zhang, L., Bao, Z.D., Dou, L.X., et al., 2018. Sedimentary characteristics and pattern of distributary channels in shallow water deltaic red bed succession: a case from the Late Cretaceous Yaojia formation, southern Songliao Basin, NE China. J. Petrol. Sci. Eng. 171, 1171–1190. https://doi.org/10.1016/j.petrol.2018.08.006.
Zhang, L., Bao, Z.D., Lin, Y.B., et al., 2017. Genetic types and sedimentary model of sandbodies in a shallow-water delta: a case study of the first Member of Cretaceous Yaojia Formation in Qian'an area, south of Songliao Basin, NE China. Petrol. Explor. Dev. 44 (5), 770–779. https://doi.org/10.1016/s1876-3804(17)30087-3.
Zhang, Y., Qiu, L.W., Yang, B.L., et al., 2016a. Effects of water level fluctuation on sedimentary characteristics and reservoir architecture of a lake, river dominated delta. J. Cent. S. Univ. 23 (11), 2958–2971. https://doi.org/10.1007/s11771-016-3360-1.
Zhang, Y., Lu, F.M., Qiu, L.W., et al., 2019. Effects of river dominated level and water level fluctuations on distribution distance of a lake, river dominated delta. CNKI:SUN:SYDX.0.2019-04-002 J. China Univ. Pet. 43 (4), 11–20 (in Chinese).
Zhang, Y., Qiu, L.W., Yang, B.L., et al., 2016b. Research on sedimentary characteristics of river dominated delta mouth bar and influences affected by water level fluctuations during the formation. CNKI:SUN:TDKX.0.2016-05-007 Nat. Gas Geosci. 27 (5), 765–775 (in Chinese).
Zhong, J., Li, Y., Shao, Z., et al., 2015. The ultr-water lake of middle Sha-3 formation during Paleogene in Dongying sag, NE China. Geol. J. China Univ. 21 (2), 320–327. https://doi.org/10.16108/j.issn1006-7493.2013160.
Zou, C.N., Zhao, W.Z., Zhang, X.Y., et al., 2008. Formation and distribution of shallow-water deltas and central-basin sandbodies in large open depression lake basins. CNKI:SUN:DZXE.0.2008-06-012 Acta Geol. Sin. 82, 813–825 (in Chinese).