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ORIGINAL PAPER - PRODUCTION GEOLOGY

# Origin and classification of the composite sand bodies of the delta front in $K_1q^4$ of the Quantou Formation in the central region of the Fuyu oil field

**Mengsi Sun[1] · Chiyang Liu[1] · Yang Yang[2] · Congjun Feng[1]**

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**Abstract** This study discusses the formation mechanisms of the delta front reservoir of $K_1q^4$ of the Quantou Formation in the central region of the Fuyu oil field and summarizes the types of deposition based on an analysis of facies markers and a comprehensive study of the sedimentary microfacies using well cores, logs, and geologic data. The results show that $K_1q^4$ of the Quantou Formation mainly formed through shallow-water sedimentation on a delta front and includes five sedimentary microfacies: underwater distributary channels, underwater natural levees, underwater diversion bays, river mouth bars, and distal bars. Due to the effects of allocyclicity, the composite sand body evolved by vertical overlaying, whereas because of the effects of autocyclicity, the composite sand body evolved by horizontal transport. Three main types of composite sand bodies are located in the study area, including composite underwater distributary channels without levees, composite underwater distributary channels with natural levees, and composites of underwater river mouth bars with distributary channels.

**Keywords** Delta front · Underwater distributary channel · Composite sand body · Overlaying type

✉ Mengsi Sun
784335021@qq.com

[1] Department of Geology, State Key Laboratory of Continental Dynamics, Northwest University, Xi'an 710069, China

[2] Bureau of Geophysical Prospecting, CNPC, Zhuozhou 072751, Hebei, China

## Introduction

Studies of composite sand bodies are the core and basis of reservoir sedimentology. Composite sand bodies can macroscopically control the geometry and distribution of the sand bodies in a reservoir (Zhang et al. 2009, 2010; Er et al. 2013; Li et al. 2013) and microscopically control the internal variations of the physical properties in the reservoir (Zeng et al. 2013; Cao et al. 2010; Zhu et al. 2012; Ji et al. 2013). The overlaying properties of a composite sand body can significantly affect seismic waveforms; therefore, the distribution of a sand body can be predicted using waveform classification techniques (Jing et al. 2014). The overlaying relationship of a composite sand body reflects the vertical evolution of the hydrodynamic properties, the provenance, and the sedimentary facies during its formation (Tian et al. 2013). The scale of the composite sand body can control the physical properties of the reservoir; the thicker the composite sand body is, the stronger its compressional resistance is to preserve the original intergranular pores and provide channels for the transport of late stage acidic fluids to form a reservoir with good physical properties (Fu et al. 2013). The type of composite sand body can directly affect the results of water injection during the exploitation of an oil reservoir. The best water drive effect is obtained from braided river sands, followed by meandering river sands, while delta sands have the poorest performance and result in the most oil remaining in the reservoir (Zhao et al. 2014). Therefore, studies of composite sand bodies are useful for determining the mechanism and distribution of sand bodies with different origins, the reservoir heterogeneity, and the potential remaining oil, to predict reservoir performance and to increase the ultimate recovery factor.

Using an analysis of facies characteristics, such as the grain size characteristics, sedimentary bedding, and structure, we use the reservoir of the delta front in $K_1q^4$ of the Quantou Formation in the central region of the Fuyu oil field as an example to summarize and classify the sedimentary microfacies and to analyze the sedimentary evolution. The results are used to analyze the origin of the composite sand body and summarize the overlaying type of the composite sand body to establish a basis for a fine-scale characterization of the individual sand bodies in this area and to potentially extract the remaining oil.

## Geological background of the study area

The Fuyu oil field is located on the eastern edge of the central part of the southern Songliao Basin on the Fuyu no. 3 structure of the Fuxin uplift belt, as shown in Fig. 1. It is an anticlinal uplift with multiple high points that are caused by fault complexity. The oil field is mainly controlled by the structure and is classified as a mesoporous, mid-permeability sandstone structural oil reservoir. The target stratum for oil exploitation is $K_1q^4$ of the Quantou Formation, which is composed of typical lake-basin shallow-water delta sediments that mainly include siltstone and fine-grained sandstone with a constant reservoir distribution.

The Songliao Basin is a Mesozoic-Cenozoic continental petroliferous basin. From bottom to top, the strata of the Songliao Basin are composed of two suites of Mesozoic and Cenozoic rift and basin sediments. The rift strata are middle and upper Jurassic in age, and the basin strata include Cretaceous, Neogene, and Quaternary systems. The Cretaceous system is the main sequence of the Songliao Basin and is divided into upper and lower systems. The lower Cretaceous system, from bottom to top, is composed of the Denglouku Formation ($K_1d$), the Quantou Formation ($K_1q$), the Qingshankou Formation ($K_1q^n$), the Yaojia Formation ($K_1y$), and the Nenjiang Formation ($K_1n$). The

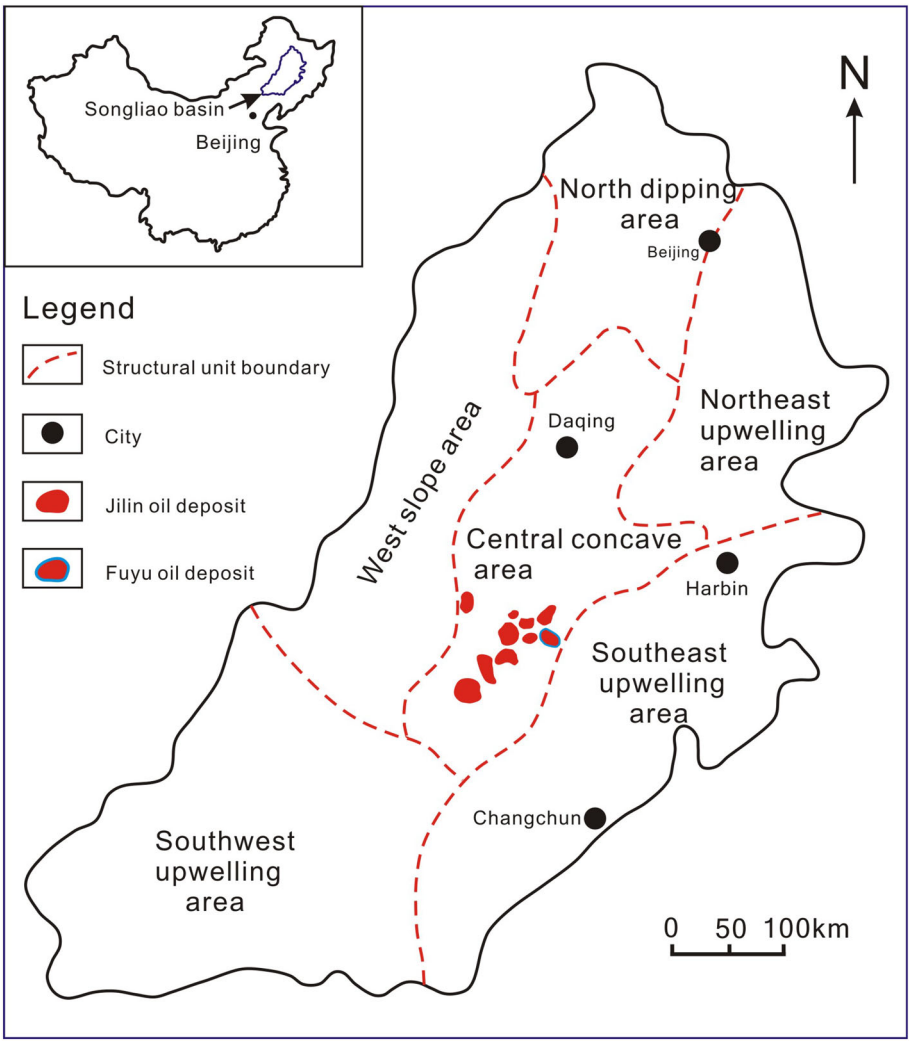



**Fig. 1** Location map of the Fuyu structural oil field (see Ref. Shu et al. 2003 with minor revisions)

main oil-bearing intervals are the Quantou, Qingshankou-Yaojia, and Nenjiang-Mingshui Formations (Fig. 2).

$K_1q^4$ of Quantou Formation is mainly composed of fine-grained sandstone, siltstone, and mudstone. The sediments consist of quartz, feldspar, and detritus. The average quartz content is 34.5 % with a range from 21.3 to 47.4 %. The feldspar content is relatively high with an average of 48.6 % and a range from 15 to 60 %, most of which is orthoclase. A large amount of the feldspar has been weathered to kaolinite. The average detritus content is 16.9 % with a range from 7.8 to 50 %, and it is mainly composed of igneous rock. The heavy mineral assemblage is zircon-granite-tourmaline-apatite, which indicates that the parent rock is acidic magmatic rock. The major cement is mud with a small amount of calcite. The average muddy cement content is 17.3 % with a range of 6–24.7 %. The medium maturity of the mineralogy indicates a nearby provenance, which suggests that the formation is a continental lake-basin deposit (Hu et al. 2008).

## Analysis of sedimentary microfacies

### Grain size analysis

The cumulative probability curve of $K_1q^4$ of the Quantou Formation is a typical two-stage curve that is mainly

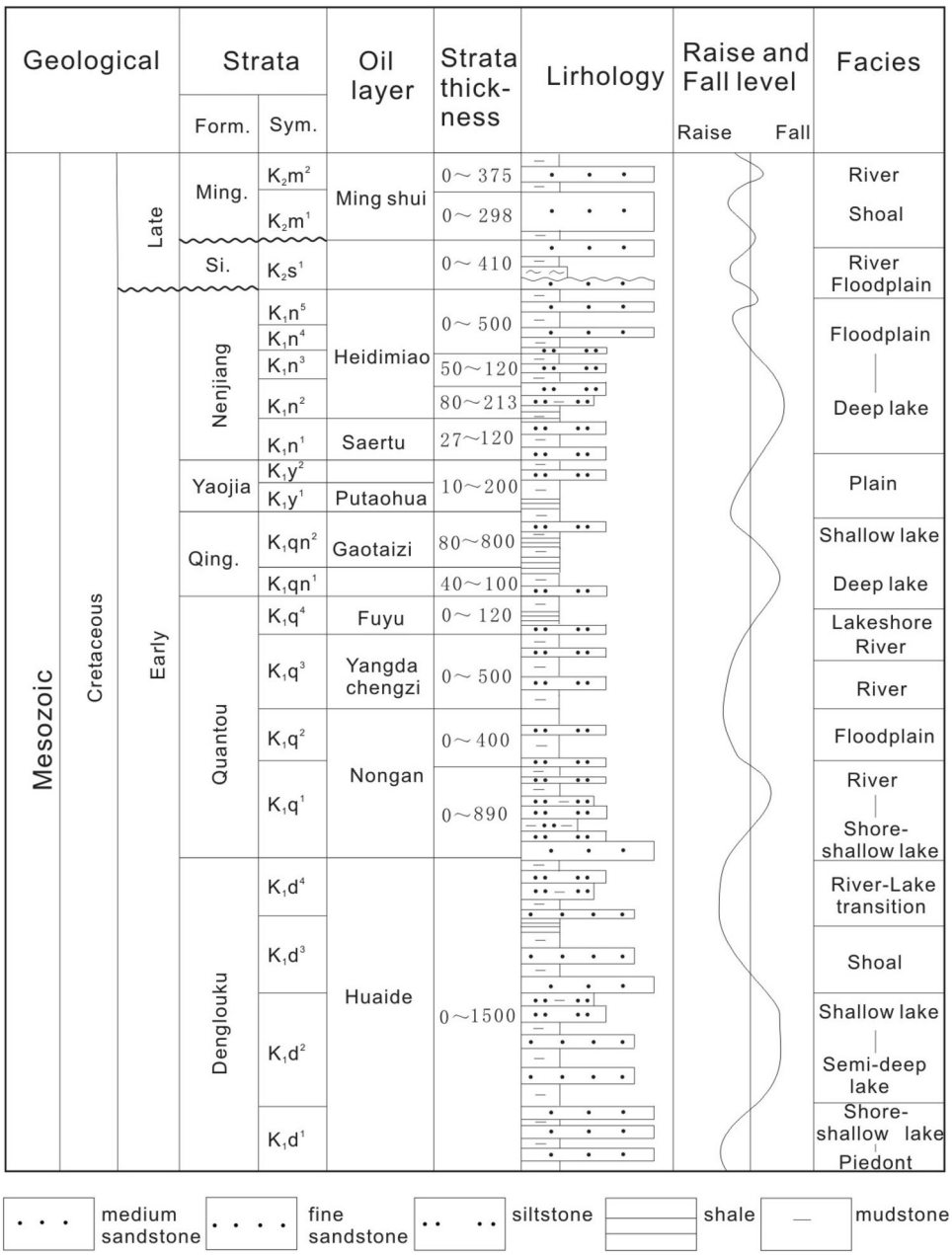



**Fig. 2** General stratigraphy of Fuju structural oil field showing lirhology and depositional events. *Form* formation, *Sym* symbol, *Ming* Mingshui, *Si* Sifangtai, *Qing* Qingshankou

composed of bouncing and suspended sediment. The total jumping sediment content is 75 % with $\varphi$ values of 1–3, and it mainly consists of fine-grained sand and medium sand. Suspended sediment makes up 20–25 % of the sediment and can be divided into two subcategories. The suspension subcategory has $\varphi$ values of 3–7.5 and is composed of well-separated silt, whereas the subcategory with $\varphi$ values over 7.5 is composed of muddy or silty mudstone. The jumping and suspended sediments are finer grained than the river sediment sand body; they consist of fine-grained sand and silt and thus belonged to a sand body that formed in a waterway, as shown in Fig. 3.

## Bedding and structure

The sedimentary bedding and structure of the clastic rock are directly associated with the hydrodynamic conditions, such as strength, sedimentation rate, and the effects of water flow. These three properties are different in different mediums, which result in different types of sedimentary bedding and structures. $K_1q^4$ of the Quantou Formation contains diverse types of bedding and structures. The marine distributary channels include cross bedding as shown in Fig. 4a, lenticular bedding, parallel bedding as shown in Fig. 4b, blocky bedding, and slump structures. Erosion surfaces as shown in Fig. 4c and discontinuity surfaces as shown in Fig. 4d are well developed. The underwater natural levees contain parallel bedding and lenticular bedding, and the underwater diversion bays include crumpled structures and parallel bedding. All of these bedding types form at smaller scales with weak hydrodynamics, and most occur in the delta front sediments.

The facies characteristic, such as the color, grain size, bedding structure, and fossil features of the mudstone, and the regional background material demonstrate that $K_1q^4$ of the Quantou Formation is composed of interbedded sandstone-mudstone sediment. In general, the sand content is higher than the mud content. The two clearly non-fluvial end-member sediment types and the local development of reversed graded sediment at the river mouth bar imply that this area is a delta front. From bottom to top, all of $K_1q^4$ is composed of water-intrusion sediment of a shallow delta front.

## Microfacies types

$K_1q^4$ of the Quantou Formation is composed of shallow-water sediments that were deposited at a delta front. Five sedimentary facies can be identified from observations of rock cores: underwater distributary channel, underwater natural levee, underwater diversion bay, river mouth bar, and distal bar.

1. Underwater distributary channel: this microfacies is mainly composed of thick to moderately thick layered sandstone and siltstone that is interbedded with thin layered mudstone or calcic siltstone. It contains cross bedding, parallel bedding, and blocky bedding. The erosion surface is at the bottom and occasionally contains remnant sediment. The main vertical sequence is composed of positive cycles with a small number of inverted layers and some composite cycles. In profile, the sand body has a flat top and a convex bottom with a two-stage grain size curve. The main log curves are box- and bell-shaped as shown in Fig. 5a.

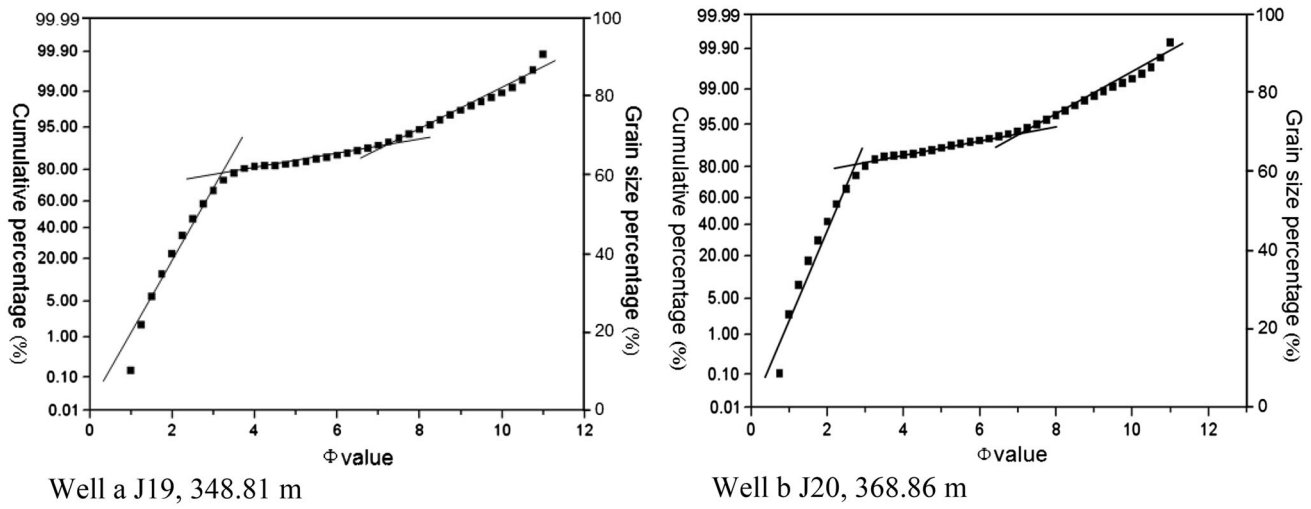
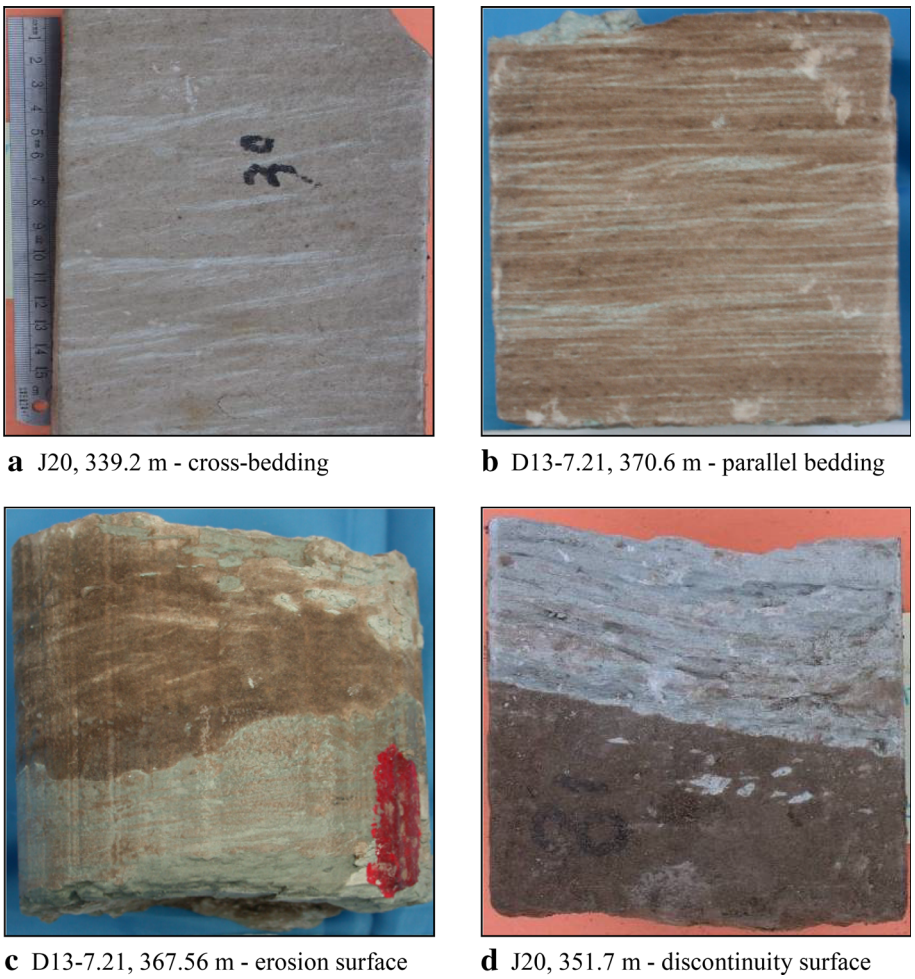



**Fig. 3** Cumulative probability curves of $K1q^4$ of the Quantou Formation in Well J19 from the Fuyu oil field



**a** J20, 339.2 m - cross-bedding

**b** D13-7.21, 370.6 m - parallel bedding

**c** D13-7.21, 367.56 m - erosion surface

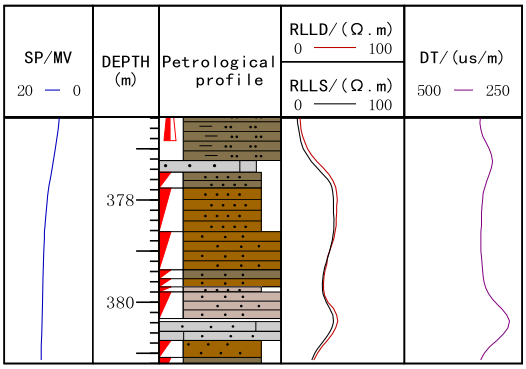
**d** J20, 351.7 m - discontinuity surface

**Fig. 4** Sedimentary structures of $K1q^4$ of the Quantou Formation in Well J19 of the Fuyu oil field

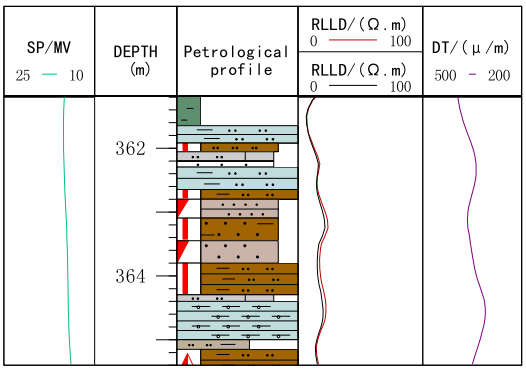
2. Underwater natural levee: this microfacies is mainly composed of interbedded siltstone, muddy siltstone, and silty mudstone with small-scale cross bedding and parallel bedding. The cumulative probability grain size curve includes one or two stages. The curves in the wells have serrated shapes as shown in Fig. 5b.
3. Underwater diversion bay: this microfacies is mainly composed of gray, gray-green, and gray-black mudstone and silty mudstone with wavy bedding, parallel bedding, and fossil structures. The curves in the wells are low and flat as shown in Fig. 5c.
4. River mouth bar: this microfacies is mainly composed of medium and thick layered sandstone and siltstone. Flat climbing ripple bedding, small-scale cross bedding, and lenticular bedding are present with rare erosion surfaces. The vertical sequence contains coarsening-upward inverted layered cycles with rare positive cycles. In profile, the shape of the sand body has a convex top and a flat bottom. The curves in the wells are funnel shaped as shown in Fig. 5d. There are only a few river mouth bars in this area.
5. Distal bar: this microfacies is mainly composed of muddy siltstone and silty mudstone. Parallel bedding, wavy bedding, and lenticular bedding are present with inverted layered cycles that gradually coarsen from the bottom to the top. The curve in the well has small-scale funnel shapes as shown in Fig. 5e.

## In-plane phase analysis

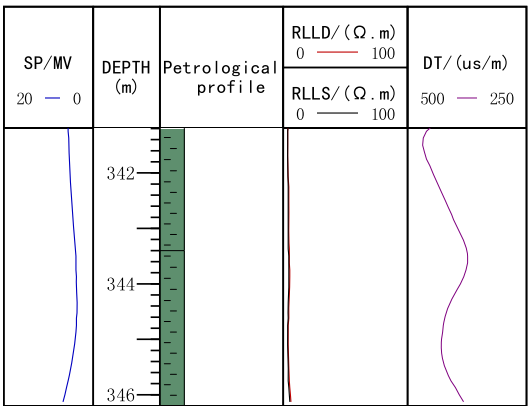
We use the sixth sub-layer as an example of the sedimentary characteristics of the delta front subfacies in the study area. The provenance is from the southwest (Liang et al. 2008). The underwater distributary channel sand body is mainly located in the southwestern part of the study area and decreases in width and thickness to the northeast,



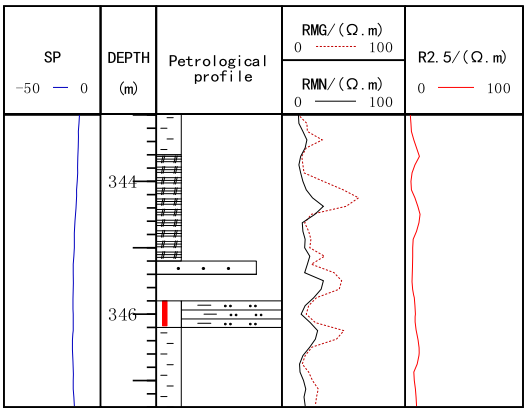

**a** Well J19 - underwater distributary channel



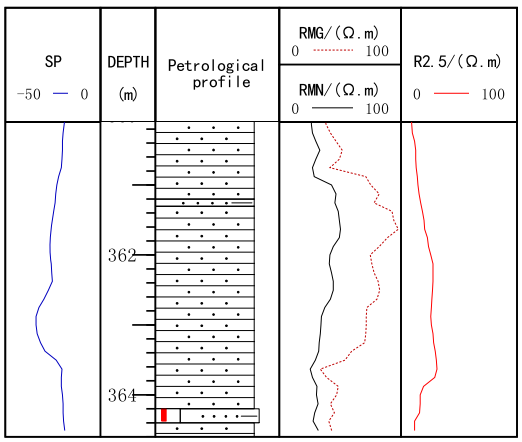

**b** Well J20 - underwater natural levee




**c** Well J19 - Underwater diversion bay




**d** Well T36 - distal bar




**e** Well T36 - river mouth bar.

**Fig. 5** Facies of $K_1q^4$ of the Quantou Formation in Well J19 of the Fuyu oil field

whereas the northeastern region contains underwater diversion bay sediments as shown in Fig. 6.

## Sedimentary evolution

During the different stages of lake filling, the type of sand body structure, the mode of overlaying, and the relative preservation of the underwater distributary channel on the delta front can be affected by the variation of the ratio between the accommodation space and the sedimentary supply (*A*/*S* ratio). To study the variations in the distribution and depositional characteristics of the sand body in the underwater distributary channel with different *A*/*S* ratios, the in-plane distribution of the sedimentary microfacies

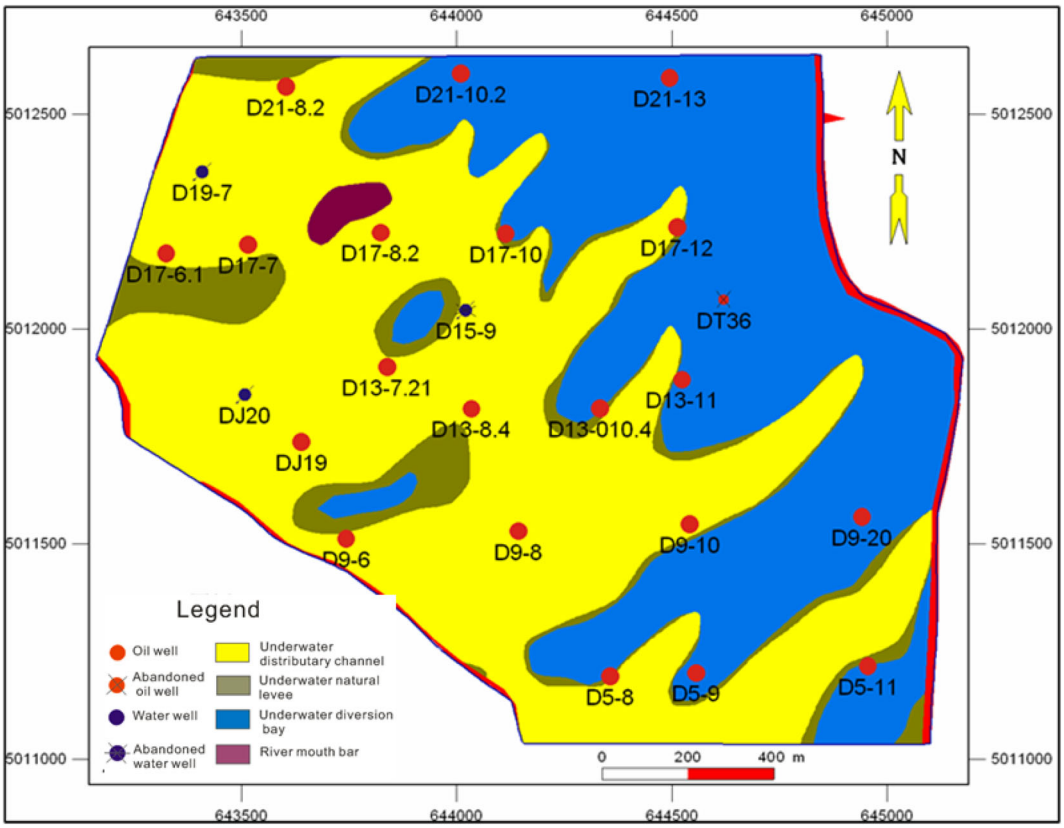



**Fig. 6** In-plane facies of the sixth sub-layer of $K_1q^4$ of the Quantou Formation in Well J19 of the Fuyu oil field

that are controlled by lake filling can be identified in 13 sub-layers at the scale of the short-term cycle (referred to as the sub-layer in oil production) using information from the densely spaced wells as shown in Fig. 7.

Under the large-scale background of lake filling, $K_1q^4$ of the Quantou Formation includes three lake drainage sub-cycles and three lake filling sub-cycles. During the process of lake drainage, because of the increasing sediment supply, the accommodation space is reduced, and the in-plane shapes of the sand bodies transition from streaks to single or multiple blocks with increasing width and thickness of the sand body. In contrast, during lake filling, the accommodation space increases due to the decreasing of sedimentary supply, and the shapes of the sand bodies transition from single and multiple blocks to streaks and dendrites with decreasing width and thickness.

## Origin and classification of the composite sand body

The composite sand body represents the framework of the delta front reservoir in the study area and has a complicated spatial structure. Over a large area, thick oil-bearing layers are usually composed of multiple individual sand bodies, and the complexity of the connections and the differences in the characteristics can result in complicated reservoir heterogeneity. Therefore, an understanding of the composite sand body is based on detailed characterizations of the individual sand bodies (Liu 2009; Hu et al. 2014).

### Origin of the composite sand body

Most of the study area is composed of the delta front subfacies sediments. Based on the study of the sedimentary subfacies, four subenvironments for the sand body can be identified, including underwater distributary channels, underwater natural levees, river mouth bars, and distal bars. Two types of composite sand bodies can be identified based on the origins of the sediments:

1. Composite sand bodies with different origins:
   In-plane composite sand bodies with different origins are large-scale composite sand bodies that are composed of multiple blocks with linear and irregular shapes as shown in Fig. 8a, whereas vertical composite sand bodies with different origins form a thick sand layer or oil layer as shown in Fig. 8b.
2. Composite sand bodies with similar origins:
   The analysis of the composite sand bodies with similar

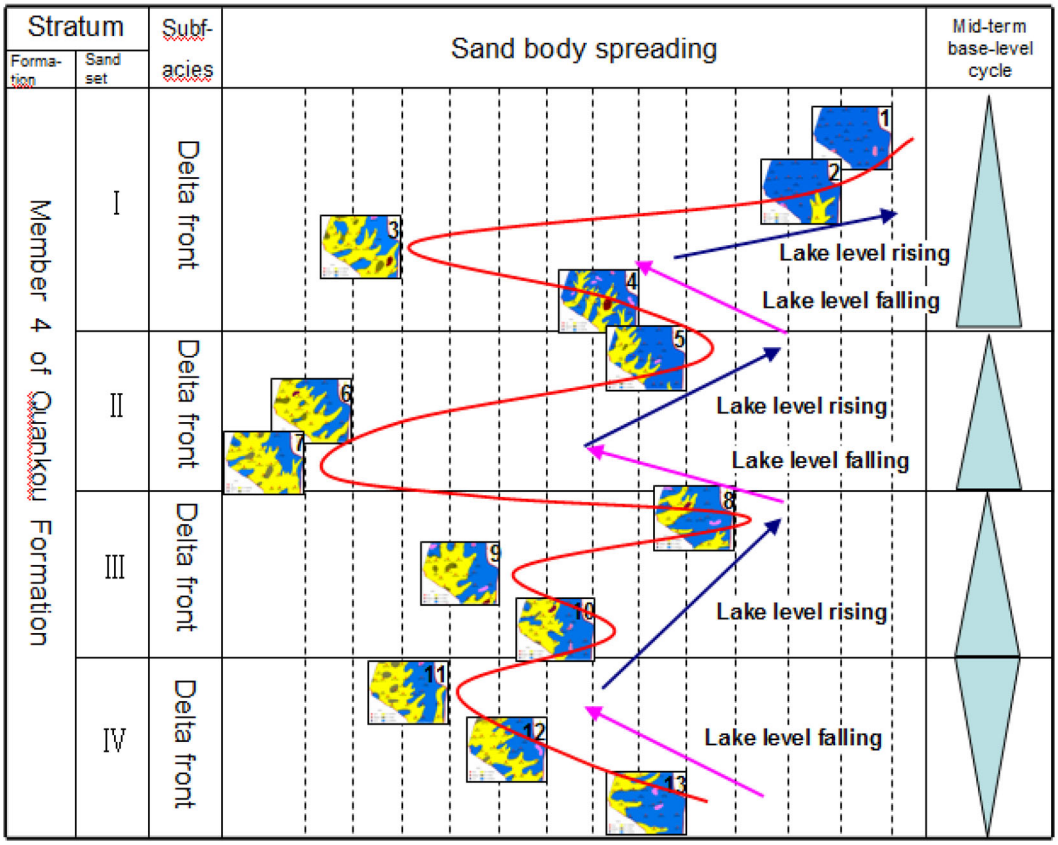
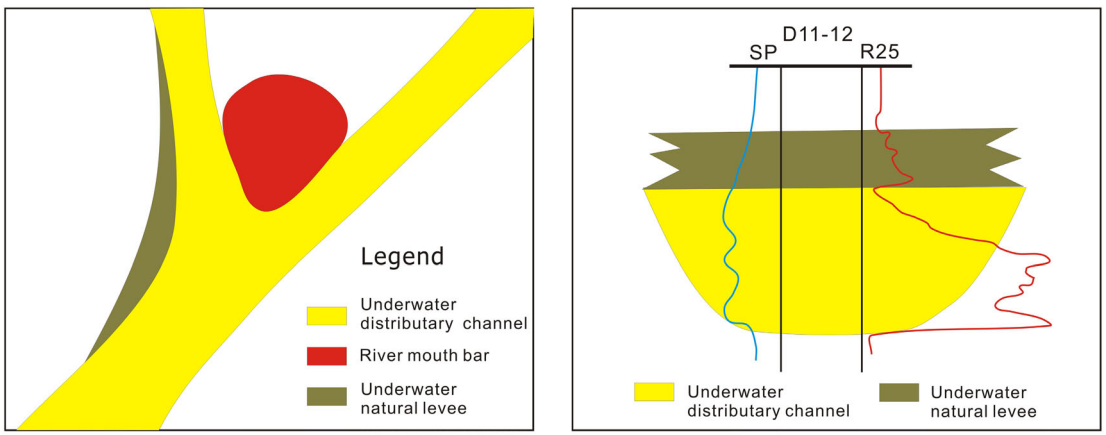



**Fig. 7** Sedimentary evolution of $K_1q^4$ of the Quantou Formation in Well J19 of the Fuyu oil field




**a** In-plane composite sand bodies with different origins

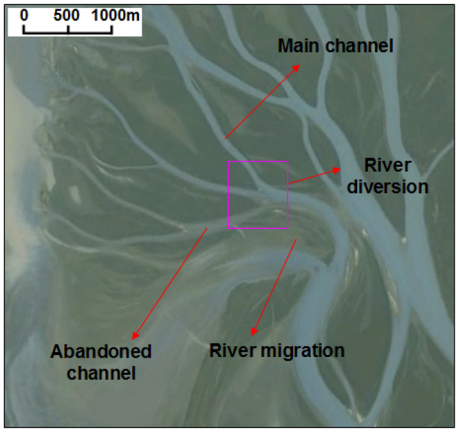
**b** Vertical composite sand bodies with different origins

**Fig. 8** Composite sand bodies with different origins

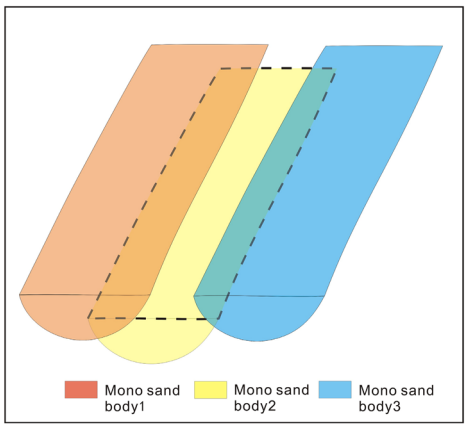
origins focuses on the sand bodies of underwater distributary channels, which form due to the frequent migration and bifurcation of underwater distributary channels as shown in Fig. 9a or the vertical overlaying of multiple underwater distributary channels as shown in Fig. 9b.

Due to the effects of allocyclic factors, such as lake level rising, accommodation space, and sedimentary supply

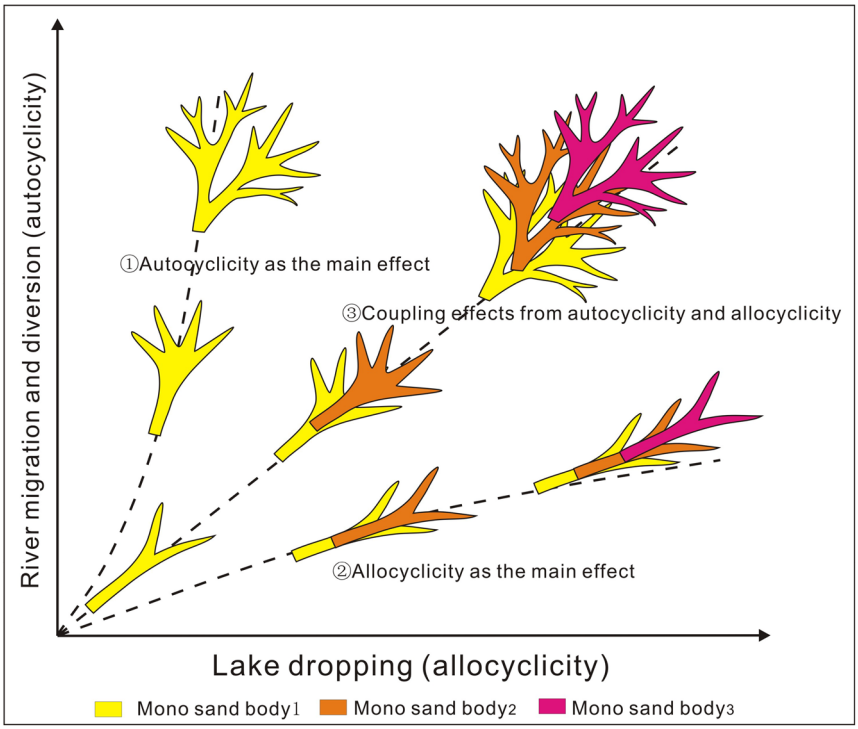
**Fig. 9** Composite sand bodies with similar origin




**a** Migration and diversion of underwater distributary channels (Poyang Lake 2012)




**b** Vertical overlaying of multiple underwater distributary channels



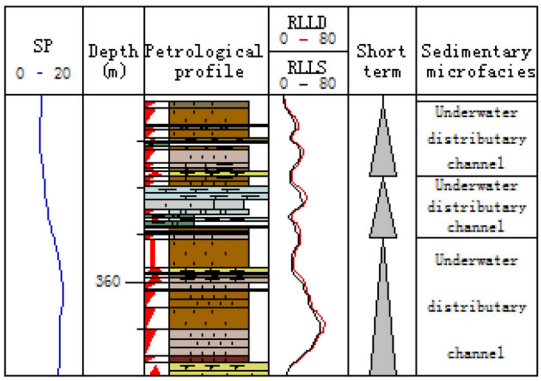

**c** Effects of allocyclicity and autocyclicity on the evolution of an underwater distributary channel

rate, the main evolutionary mode of the composite sand body is vertical overlaying, which includes diverse modes such as progradation, retrogradation, and aggradation. Because of the effects of autocyclic factors, such as river migration and diversion, the composite sand body evolves by horizontal transport. Because of the coupled effects of allocyclicity and autocyclicity, the composite sand body experiences both vertical overlaying and horizontal transport, which complicates its evolution as shown in Fig. 9c.

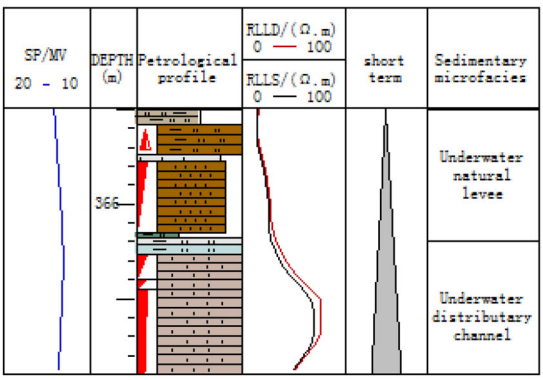
## Overlaying mode of the composite sand body

The delta front in the study area contains three types of sand bodies. Because of the effects of lake filling, accommodation space, and the sediment supply in the different stages of lake filling, the degree and position of the development of the sand bodies are different, which results in different connections between different genetic sand bodies and composite modes.

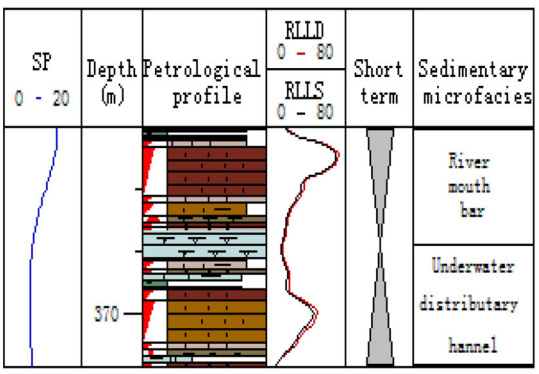
1. Composite underwater distributary channel—underwater distributary channel:
   This block-shaped sand body forms through the vertical stacking of sand bodies in a multi-stage underwater distributary channel that forms an erosion surface or remnant sediment at the bottom. It represents a composite cycle that is composed of multiple positive vertical cycles, which can be observed in sub-layers 3, 6, 7, 9, 10, and 11 in the study area. This type of composite sand body develops during the late stage of lake draining and the early stage of lake filling. During times of low accommodation space, many asymmetric short-term deepening upwards base-level cycles can form. The curve in the well has a box shape of overall fining-upward sequences as shown in Fig. 10a.
2. Composite underwater distributary channel—underwater natural levee:
   This type of composite sand body forms near the well developed underwater natural levee. An erosional surface can be observed at the bottom of the sand body in the underwater distributary channel; the grain size decreases from the bottom to the top, which implies typical positive cyclic sedimentation that can be observed in sub-layers 4, 5, 8, 12, and 13. It can form during processes of both lake filling and draining. During times of high accommodation space, numerous asymmetric short-term deepening upwards base-level cycles can form. The curve in the well is bell-shaped of fining-upward sequences as shown in Fig. 10b.
3. Composite underwater distributary channel—river mouth bar:
   Because river mouth bar sand bodies are relatively rare in the study area, this type of composite sand body is also rare. The grain size becomes finer and then coarser from the bottom to the top, which implies a typical positive and inverted layered cycle. When the lake level first rises and then drops, this type of composite sand body can form as a symmetric short-term base-level cycle that becomes deeper and then shallows upwards. The curve in the well has a composite bell-shape (fining-upward) and funnel-shape (coarsening-upward) sequences as shown in Fig. 10c.




**a** Multiple composite underwater distributary channels




**b** Composite underwater distributary channel - underwater natural levee




**c** Composite underwater distributary channel-river mouth bar

**Fig. 10** Overlaying types of composite sand bodies in $K_1q^4$ of the Quantou Formation in Well J19 of the Fuyu oil field

## Conclusion

1. Based on information from rock cores, measurements from wells, and geologic data of facies markers, such as grain size and bedding structure, $K_1q^4$ of the Quantou Formation in the study area is interpreted as shallow-water delta front sediments that include five sedimentary microfacies: underwater distributary channel, underwater natural levee, underwater diversion bay, river mouth bar, and distal bar.
2. Due to the effects of allocyclicity, such as lake rising, accommodation space, and sediment supply rate, the composite sand body mainly evolves by vertical overlaying. Meanwhile, because of the effects of autocyclicity, such as river migration and diversion, the composite sand body mainly evolves by horizontal transport. In addition, because of the coupled effects of allocyclicity and autocyclicity, the composite sand body experiences both vertical overlaying and horizontal transport, which complicates its evolution.
3. Three main types of composite sand bodies are located in the study area, including composite underwater distributary channels without levees, composite underwater distributary channels with natural levees, and composites of underwater river mouth bars with distributary channels.

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