DOI 10.1007/s12182-008-0016-2

Sedimentary facies of the Silurian tide-dominated paleo-estuary of the Tazhong area in the Tarim Basin

Zhang Jinliang[1,2] * and Zhang Zhongjie[2]

[1] College of Resource Science and Technology, Beijing Normal University, Beijing 100875, China
[2] School of Marine Geo-Science, Ocean University of China, Qingdao, Shandong 266100, China

Abstract: As the relative sea-level rose, a paleo-estuary was formed by the marine inundation of the braided river incised valley during the period of the lower sub-member of the upper member of the Kalpingtage. formation of the Silurian in the Tarim Basin, west China. Sandstone-mudstone rhythmite, tidal structures and bimodal cross-bedding are common in these deposits, indicating that tides played a significant role in generating the sedimentary structures and the estuary type was tide-dominated. Five depositional facies were grouped: tidal river, sandy and muddy subtidal flat, tidal flat, tidal bar, tidal channel on the basis of lithology, electric properties, rhythmicity, sedimentary structure, fossil and the contact relationship. The sediment distribution showing first fining seaward and subsequent coarsening seaward from head to mouth, implies the two sediment sources in the paleo-estuary. The paleo-estuary of the Tarim Basin is very different from other representative estuaries. The most important distinction is that there are two adjacent estuaries joined by tidal flat onshore and by sandy and muddy subtidal flat in the sea at the same time, while the others only have one. So the Tazhong paleo-estuary shows a good architecture model for the tide-dominated estuary.

Key words: Tarim basin, Silurian, tide-dominated estuary, tidal river, tidal bar

1 Introduction

The Kalpingtage sandstones of the Silurian are one of the important sets of oil and gas reservoir bed intervals in the Tazhong (central Tarim) area, Tarim Basin on which many studies have been done. Some researchers thought that the deposit of the Kalpingtage sandstones was a perezone-shelf sediment in the middle member and a tidal flat sediment in the upper member (Gu, 1996; Hou et al, 1997; Qi and Su, 1999; Cheng and Wang, 1999; Zhu et al, 2001), while others believed that the whole Kalpingtage Formation was deposited in a tidal flat environment (Zhu et al, 2005). However, according to abundant core observations and descriptions combined with electrical properties and regional sedimentary background, we concluded that the deposit of the lower sub-member of the upper member of the Kalpingtage formation is mainly an estuary system.

The physical conditions of an estuary are complicated. The sediments are influenced by a complex combination of tides and tidal currents, oceanic waves, locally generated waves, river discharge, precipitation temperature, and local flora and fauna. In recent years, many studies have been carried out on the incised-valley fill deposit that accumulated from the last glacial sea-level lowstand to the present (Dalrymple et al, 1994). Pritchard (1967) defined the estuary as a semi-enclosed marginal-marine body of water in which the salinity is measurably diluted by the fluvial discharge. Fairbridge (1980) defined the estuary as an inlet reaching a river valley as far as the upper limit of tidal rise. While Dalrymple et al. (1992) argued that it was the seaward portion of a drowned valley system which was considered to extend from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth. Though the estuaries have been defined somewhat differently by the geologists, geographers and chemists, they are considered in a general sense to be the lower courses of rivers open to the sea. Estuaries can be classified into three types (tide-dominated, wave-dominated, mixed wave- and tide-dominated), based on the dominating hydrodynamic characteristics and the kinds of sediment and sediment bodies formed in the estuary (Dalrymple et al, 1992). Some well known tide-dominated estuaries include the South Alligator in northern Australia (Woodroffe et al, 1989), the Gironde estuary, France (Allen, 1991) and the Bay of Fundy, Canada (Dalrymple et al, 1990; Dalrymple and Zaitlin, 1994). The storage potential of the estuarine sediments is generally high. Nevertheless, few estuarine deposits have been reported in the geologic record, because they are not easy to be identified from the related fluvial, deltaic, lagoonal, or shallow-marine deposits. It is of great academic value to study the sedimentary characteristics of the paleo-estuary in the Tarim Basin, which was formed during the period of

*Corresponding author. email: jinliang@ires.cn
Received November 14, 2006

the lower sub-member of the Kalpingtage Formation of the Silurian. Furthermore, the study could guide the oil and gas exploration in this area.

2 Geological background

The Tarim Basin in west China is a complex superimposed craton basin with a set of strata from Cambrian to Quaternary overlying the Archaean and the Proterozoic crystalline basement. The studied Tazhong (central Tarim) area about 9 $\times 10^3$ km^2 in size, locating in the desert of the Tarim Basin, belongs to the Tazhong low-bulge of the Central Uplift, bounded in the north by the Manjiaer Sag, in the south by the Tangguzibasi Sag, in the east by the Tadong Sag, and to the west by the Bachu Arch (Hou et al, 1997) (Fig.1). Two big faults are developed in this area. One is a NW trending reverse fault (No.1 fault) with a throw of 2200 m, which cuts both the Ordovician and the Silurian strata (Jia, 1997; Wu et al, 2005). The other is a nearly east–west fault horst belt (Central Fault Horst Belt) dividing the Tazhong Uplift into the North Slope and the South Slope.

During the Silurian, the Tarim Basin was a stable craton depression where terrigenous clastic offshore depositional systems were developed, turning thicker from the west and south to the east and north respectively. Based on high resolution sequence stratigraphy, the Silurian was divided into the Yimugantaw Formation, the Tataaiertage Formation and the Kepingtage Formation from top to bottom, and the Kepingtage Formation could be further subdivided into the upper member and the middle member with the lower member absent (Zhang et al, 2005) (Fig.2). In the lower sub-member of upper member of the Kalpingtage Formation, a tide-dominated paleo-estuary sedimentary system was developed, composing of gravels, sandstone, siltstone and mudstone.

3 Study methods

Since the Silurian sandstones were the target of exploration and development, fifty-eight wells have been drilled in the lower sub-member of Kalpingtage Formation of which 12 wells were cored, and all of them were logged. We described and photographed all the cores, analyzed the electrical properties of all the wells. At the same time, the grain size was measured every 50 cm. Then, we analyzed and studied the sedimentary facies and their characteristics on the basis of the core description results combined with well log interpretation and regional geologic setting.

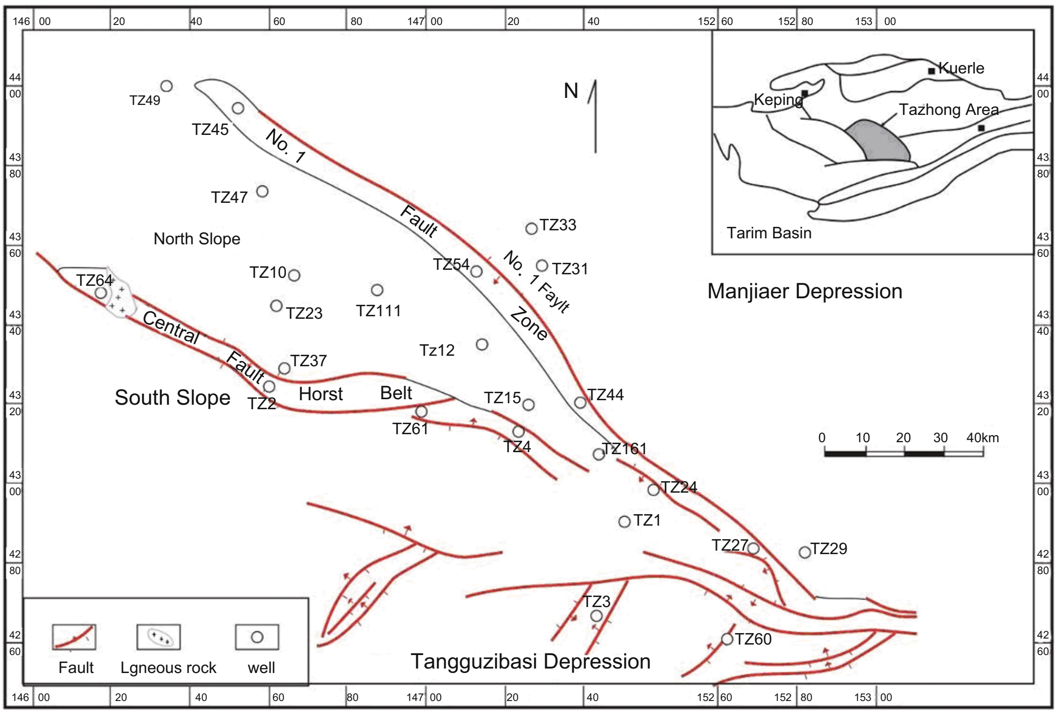

Fig. 1 Structure and well locations of the studied area

4 Sedimentary facies

Facies analysis was carried out on the cores of the lower sub-member. Finally, five sedimentary facies, labeled A-E, were characterized on the basis of lithology, rhythmicity, electrical properties, sedimentary structures, grain size, fossils and contact relationship. Each was interpreted in terms of its depositional environment.

4.1 Facies A (tidal river)

This facies, which mainly occurs in the middle part of the cores obtained from the well TZ161, consists of superimposed fining-upward and thinning- upward units, of which each was preserved differently. The top of the succession was not

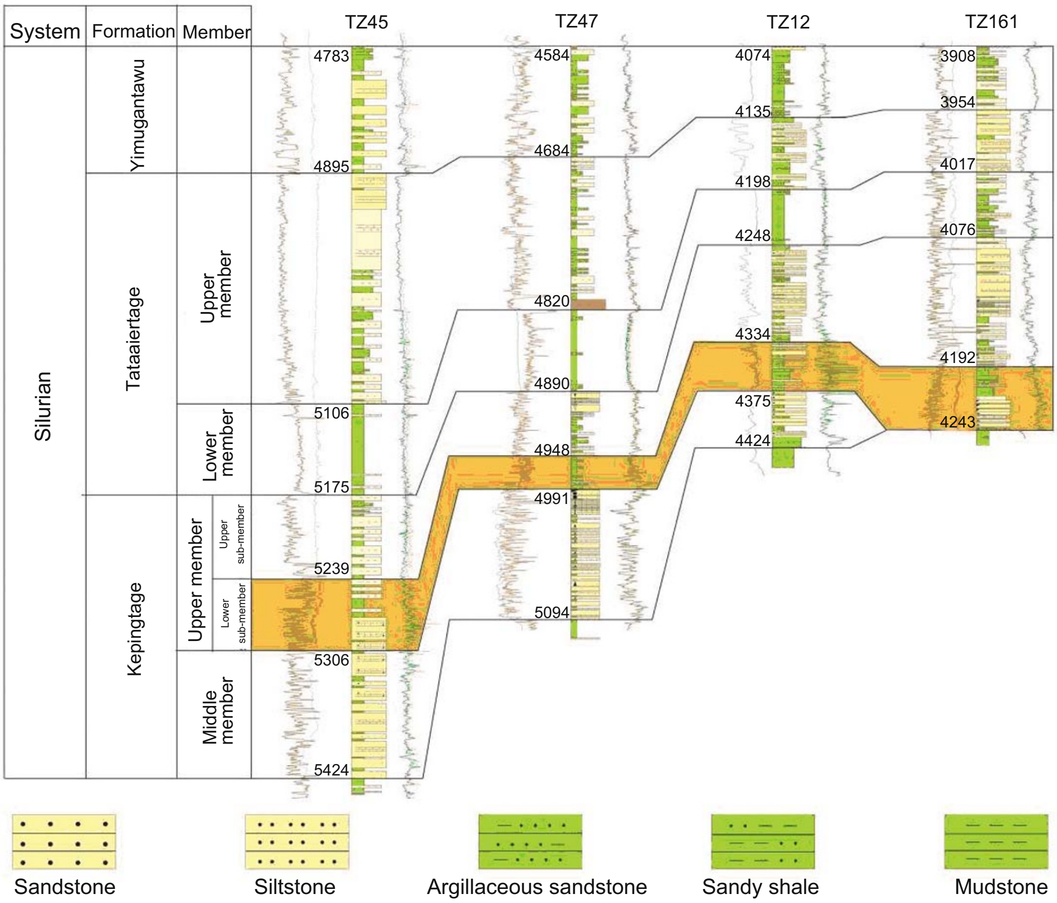

Fig. 2 Silurian strata summary of the Tazhong area

recovered but was more than 5m thick (Fig.3). Each unit has an erosional surface that is overlain by a lag deposit composed of gravels, mud pellets, rip-up clasts and wood fragments, about several to dozens of centimeters in thickness. Gravels are well rounded, and some of the mud pellets are bidirectionally arranged. Upward, the lag deposits change gradually into poorly sorted medium-to-coarse sand with trough and tabular cross-bedding (Fig. 4 A, B). Commonly, medium-to-coarse sand is overlain by well-sorted silty-to-fine sand showing cross or parallel bedding, and is sometimes intercalated with thin mud layers (Fig. 4 C). The top of the succession is the muddy sediment with ripple, wavy, lenticular bedded, very fine to fine sand. Sandy sediment is absent in some of the units and the lag sediment is covered directly by the muddy sediment. The shale content is usually less than 15%, lower than in any other facies.

Facies A is located at the head of the paleo-estuary. The lateral association with the marine sediment and the poorly sorted medium-to-coarse sand in the lower part of the succession indicate that the sediment was from supplied by the braided river (Hori et al, 2001; Lin et al, 2005). The well-rounded gravels in the lag deposits may reflect that they had been reformed by the tide. And the bimodal cross-bedded fine sandstone may show the characteristics of the bimodal currents. Moreover, wavy, lenticular bedded very fine to fine sand imply that the tides played a significant role in the formation of the facies. Fining-upward and thinning-upward unit is similar to various tide-influenced distributary rivers described by Allen (1991), and Galloway and Hobday (1983). So this facies is interpreted as tidal river deposits. Absence of muddy sediment in some units may be caused by the succession not being completely preserved, or from alluvial channels in the low-water season, when sand was not sufficient (Wang and Zhu, 1989).

4.2 Facies B (tidal bar)

Facies B was mainly observed in the well field where tidal energy was high, such as the well field of TZ44, TZ31 and TZ45, developing parallel to the length of the paleo-estuary, ranging in length from hundreds of meters to dozens of kilometers, in width about hundreds of meters, in height about dozens of meters. Facies B is made up of cross-bedded sandstone with some minor siltstone and mudstone showing an coarsening-upward and thickening-upward facies succession (Fig. 5). The lower part of the coarsening-upward unit consists of mudstone and siltstone with wavy and lenticular bedding. Indeterminate bioturbation and burrows are common. As the thickness and proportion of the sandstone increase upward, wavy and flaser bedding dominate. In the middle part of the unit, medium-to-coarse sandstone showing parallel and cross lamination occurs, and sometimes mudstone is abundant. The upper part of the

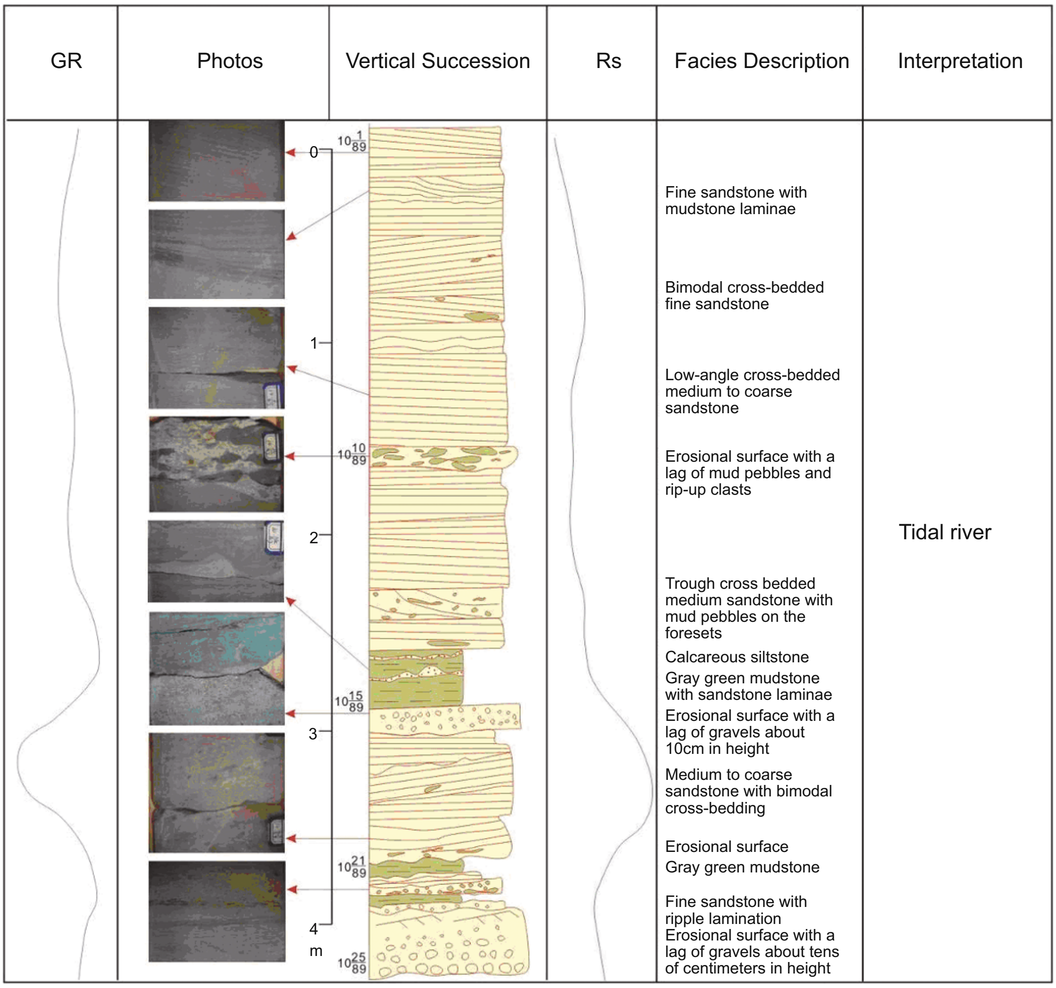

Fig. 3 Sedimentary succession of the overlapping upward-fining units of facies A of the well TZ161

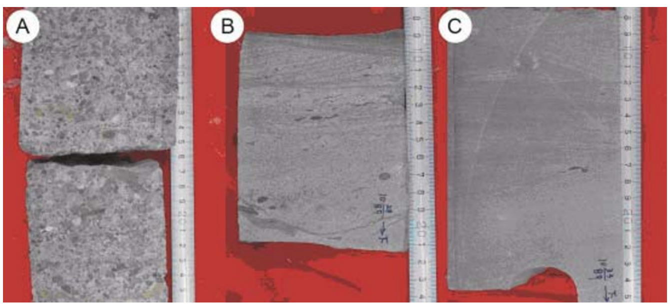

Fig. 4 Characteristics of facies A of the well TZ161: (A) Lag deposit composed mostly of well-rounded gravels and mud pellets; (B) Poorly sorted trough cross-bedded coarse sandstone; (C) Bimodal cross bedding fine sandstone

coarsening-upward sandstone contains cross-bedding with well-developed drapes on the foresets, mudstone laminae and intraclasts (Fig.6 A, B and C).

Usually, there are two kinds of contact relationship between the coarsening-upward unit and the overlying sediment. In most cases, the coarsening-upward unit is overlain by muddy tidal rhythmite, which is similar to the tidal bar in the Gironde estuary (Fenies and Tastet, 1998). Less commonly, it has a sharp erosional surface with the overlying facies and is overlain by channelized cross-bedded sandstone.

The abundance of lenticular, wavy, and flaser bedding in Facies B indicates a strong tidal influence on the deposition procedure. Bimodal cross-bedding shows the bimodal tidal currents: both flood current and ebb current, but more commonly, cross-bedding in one specific part is unidirectional, representing the main tidal flow (Scholle and Spearing, 1982). The well-developed drapes on the foresets of the cross-bedding indicate the alternating periods of low and high energy of the tidal cycles (Visser, 1980; Holz, 2003). The proximity to the sea and coarsening-upward succession which is analogous to the tidal bars generated in interpreted ancient estuarine valley-fill and tide-dominated deltaic deposits (Allen, 1991; Galloway and Hobday, 1983; Willis, 2000) suggests that Facies B is a subtidal migrating tidal bar. The presence of these bars tended to dissipate the tidal energy, on the other hand, they could constrict the incoming tidal currents between the tidal bars to increase their velocity for more distance up the estuary (Boggs, 1995).

4.3 Facies C (sandy and muddy subtidal flat)

This facies, which was observed in all the cores, comprises siltstone, mudstone, and muddy-sandy tidal

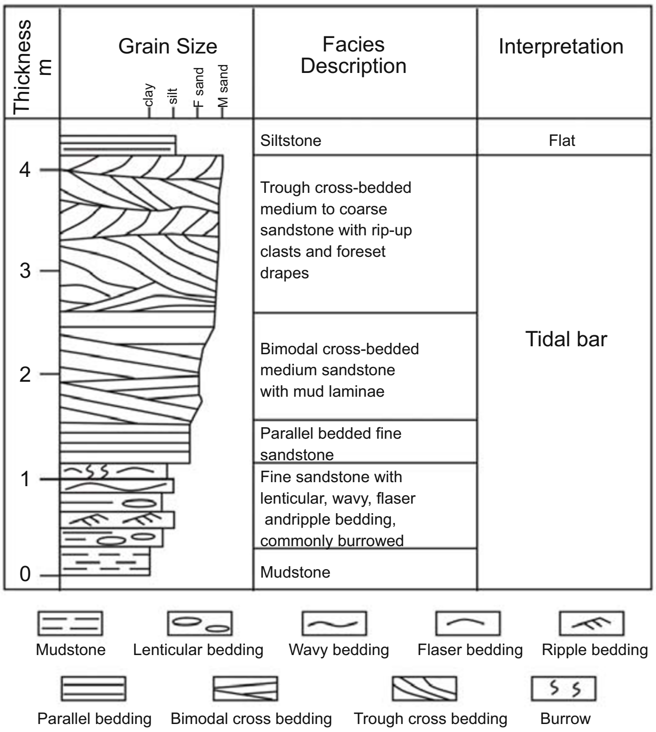

Fig. 5 Sedimentary succession of an upward-coarsening facies B of the Well TZ44

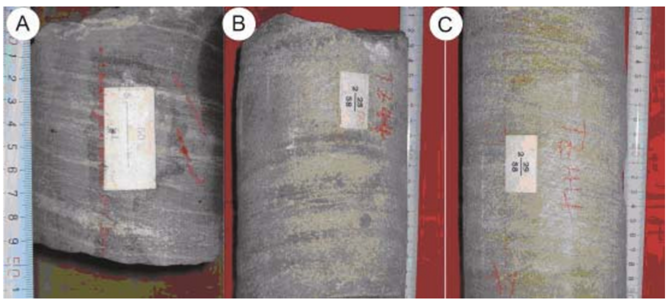

Fig. 6 Cross-bedded coarse sandstone of tidal bar: (A) Cross-bedded coarse sandstone with rip-up clasts of the Well TZ45; (B) Cross-bedded coarse sandstone of the Well TZ44; (C)Cross-bedded coarse sandstone with well-developed drapes on the foresets of the Well TZ45

rhythmite developing wave ripple, lenticular, wavy, and cross lamination (Fig.7 A and B). The facies ranges from 1.6 to 6 m in thickness and has transitional contacts with the overlying and underlying facies. The shale content is approximately 50%. Bioturbation and burrows are so strong that many primary sedimentary structures were destroyed (Fig. 7 C and D). Deformational structures, whose scales range from small slumps several centimeters thick to large structures tens of centimeters or more thick, are fairly common in deposits, particular in the muddy sediment (Fig. 7 A).

Facies C is adjacent to the tidal bar and tidal channel, and it is interpreted to be sandy and muddy subtidal flat. Sand and silt layers reflect the clastic sedimentation generated during the tractional period of the tidal cycles (Dalrymple et al, 1992; Holz, 2003; Morales et al, 2006), while the muddy part reflects the slack water period because the presence of

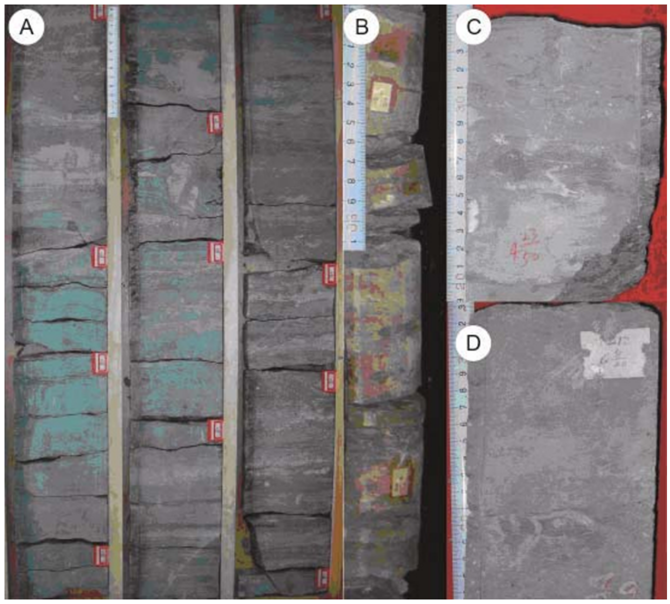

Fig. 7 Characteristics of Facies C: (A) sandstone-mudstone rhythmite of the Well TZ11; (B) sandstone-mudstone rhythmite of the Well TZ201; (C) bioturbation of the Well TZ11; (D) bioturbation of the Well TZ12

the positive charged ions in seawater neutralized the negative charges on clay particles which caused the flocculation of clay particles (Wang and Zhu, 1989; Boggs, 1995; Holz, 2003). The rhythmite in the flat is also very common in other estuaries. The thickness variation of the sandstone and mudstone layers in the rhythmite is interpreted to be generated by the tidal fluctuation reflecting alternating neap and spring tides (Tessier and Gigot, 1989; Hori et al, 2001; Choi and Dalrymple, 2004). Lenticular and wavy bedding are typical structures generated by the tide. The asymmetrical wavy ripple that is similar to the type d couplets of the paleo-Yangtze River estuary implies that waves also affected the formation of the facies (Hori et al, 2001; Wang and Zhang, 1996). Deformational structures are fairly common in deposits, particular in the muddy sediment (Scholle and Spearing, 1982).

4.4 Facies D (tidal flat)

This facies, which occurs in the wells TZ20, TZ201 and TZ4, consists of dark brownish-red to grayish-green mudstone containing very fine to fine sand laminae (Fig.8 A). Usually the facies which has a transitional contact with the underlying sediment, ranges from 1 to 5 m in thickness. The shale content is generally more than 55%. Burrows, bioturbation and deformational structures are common, but lenticular, wavy and flaser bedding is typical where the primary sedimentary structures are preserved well. Current ripple showing trough and tabular cross bedding is also observed (Fig. 8 B, C and D). As the supply of mud became higher and higher, the proportion and thickness of muddy laminae increased, while sandstone laminae were more and more discontinuous. At the same time, wavy and lenticular bedding became dominant. As a result, the sandstone was replaced by the brownish-red to grayish-green mudstone with the thickness of tens of centimeters.

Facies D also contains lots of thin (<1m) channel-form sandstones whose distribution is irregular, and sometimes they superimpose upon each other. The sandstone, which has an erosional base with a lag deposit, is composed of fining-upward succession of fine sand with cross bedding (Fig.8 E and F). Abundant evidence of tidal activity is contained in the form of wavy and lenticular bedding. The bioturbation is also common (Fig.8 C and D).

Facies D is mainly at the edge of the paleo-estuary. The color of mudstone is dark brownish-red to grayish-green, indicating that the mudstone was oxidized when it was formed (Fenies and Tastet, 1998). Lenticular, wavy and flaser bedding are typical tidal structure. The cyclic internal packaging of sand-rich laminae and mud-rich laminae reflect the cyclic variation in tidal current speed during the neap-spring cycles. It is analogous to cyclic tidalite packages described by Dalrymple et al (1990) in the Salmon River Estuary and by Fenies and Tastet (1998) in the Gironde estuary. What is more, the sediment features of this facies are similar to the tidal flat at the boundary of modern tide-dominated estuary and delta (Beets et al, 2003). So Facies D is interpreted as tidal flat and the channel-formed sandstone is interpreted to be tidal creeks draining the tidal flat. Since each succession of the tidal flat is sometimes more than 4 m in thickness, the paleo-estuary is a meso-tidal to macro-tidal estuary.

4.5 Facies E (tidal channel)

Facies E interbedded with tidal bars and sandy and muddy sub-tidal flat, mainly occurs in the cores of the wells TZ44, TZ45 and TZ31, but the characteristics of the well TZ45 is

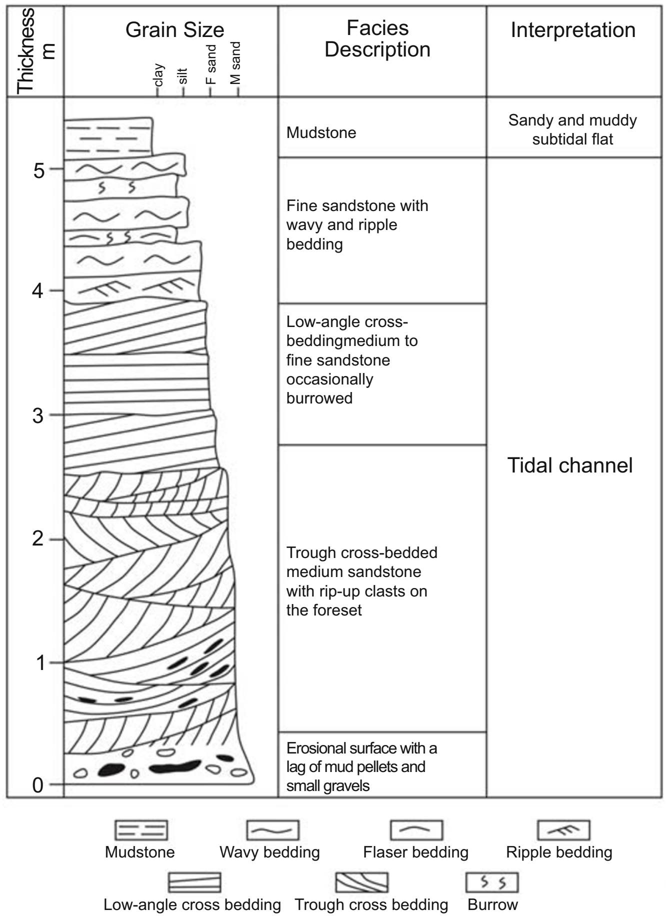

Fig. 9 Sedimentary succession of an upward-fining facies E of the Well TZ45

Fig. 8 Sedimentary characteristics of Facies D: (A) Brownish-red mudstone with lenticular siltstone of the Well TZ201; (B) Deformational structure of the Well TZ20; (C) Brownish-red and grayish-green mudstone with wavy bedded sandstone of the Well TZ20; (D) Grayish-green mudstone with lenticular and wavy bedded sandstone of the Well TZ20; (E) The lag deposit of a channel bottom of the Well TZ20; (F) Cross-bedded channel-formed sandstone of the Well TZ201

the most noticeable. This facies is made up of channelized sandstone ranging from 1 to several meters in thickness, which depends on the speed of the tidal current (Fig.9). The channelized sandstone which has a sharp erosional surface with a lag of mud pellets and small gravels about 10 cm in thickness, contains trough cross-bedding, low-angle cross-bedding, ripple lamination, and wavy bedding. In most cases, the cross-bedding indicates a dominating unimodal paleocurrent. However, if we observe carefully, we can find a subordinate inverse paleocurrent (Fig.10 A, B and C). Rip-up clasts usually underlie the foresets, while mud laminae occur in the upper part of the succession. Now and then burrows are observed. There is an upward-fining grain size trend from medium- and fine-grained sandstone at the bottom to fine and very fine-grained sandstone at the top boundary. And the scale of the sedimentary structure also has an upward-decreasing trend from bottom to top.

Facies E is located in the mouth of the paleo-estuary. It is interbedded with tidal bars and sub-tidal flat and the well sorted medium- and fine-grained sandstone at the bottom to fine and very fine-grained sandstone at the top boundary, which indicates that the sediment was from the marine sources supplied by the sea (Boggs, 1995; Weber et al, 2004). The erosional surface at the bottom of the succession may probably result from the scouring of the underlying facies in

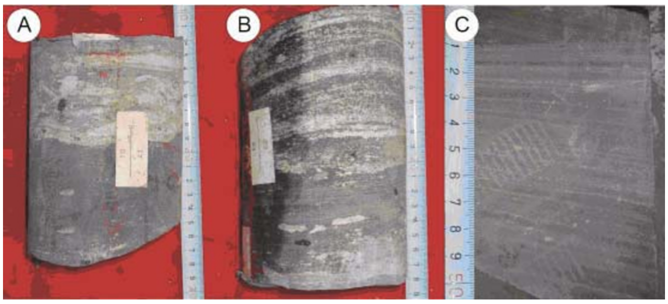

Fig. 10 Characteristics of facies E: (A) Lag deposit composed mostly of gravel and clasts of the Well TZ45; (B) Trough cross-bedded medium sandstone of the Well TZ45; (C) Bimodal cross- bedded fine sandstone with of the Well TZ31

relation to marine transgression (Cattaneo and Stee, 2003; Capo et al, 2006). The mud pebbles and rip-up clasts observed in the lag and foresets may have been eroded and transported from the muddy subtidal flats (Hori et al, 2001). The two reverse paleocurrent directions, in which one is dominating, reflect the characteristics of the tidal current. What is more, the fining-upward channelized sandstone is similar to the sandy tidal channel deposit described by Scholle (1982). So Facies E is interpreted as tidal channel.

5 Facies distribution

In the middle member of the Kalpingtage Formation, the Tazhong area was dominated by coarse braided delta deposition which received sediment from the developed braided channels. But at the stage of the lower sub-member of the upper member of the Kalpingtage Formation, a large scale ingression took place, when the relative sea-level rose continually to the highest point at the last stage and the coast line advanced from north to south. As a result, most braid channels were submerged. At the same time the fluviatile action weakened also. Correspondingly, the supply of sediment from the southern uplift decreased and the tidal action as well as the wave action, especially the tidal action became prominent. Eventually, a tide-dominated estuary sedimentary system was deposited. Progradation filled and destroyed the estuary continually, causing a deltaic sedimentary system to form during the period of the upper sub-member.

The sand body thickness map (Fig. 11) shows that, the sand body of the lower sub-member is thin and most of them are less than 20 m in thickness. However, the sand body in the well field of TZ45 is deeper, with a thickness from 20m to 35 m. And there is a downward trend of the sand body thickness from center to circumambience. The ratio of sand body thickness/bed thickness is corresponding to sand body thickness, that is, the area with a thicker sand body has a higher ratio relatively (Fig.12). We can conclude that the sediment of the Tarim paleo-estuary is high in shale content, and the sand body is generally perpendicular to the coastline, which can show the characteristics of tidal action. On the other hand, it is indicated that there are two conjoint estuaries developed in the upper second member. The well developed sand body and the high ratio in the two ends of the estuaries also showed that the estuaries received sediment from both fluvial and marine sources.

Two conjoint estuaries, joined by tidal flat onshore and by sandy and muddy subtidal flats in the sea, were developed during the period of the lower sub-member of the upper member of the Kalpingtage formation. Fig.12 shows the facies distribution sequence of the paleo-estuary system from continent to sea as follows: tidal river, tidal flat, sandy and muddy subtidal flat, tidal bar and tidal channel. The fluvial environment which occurred upstream of the tidal current limit does not belong to the estuary environment, so fluvial sediment is absent in the cores. The abundance of tidal rhythmite and bimodal cross-bedding of the estuary sedimentary structures show clearly that the paleo-estuary is a tide-dominated type (Dalrymple et al, 1992). Tidal river facies consists of superimposed fining-upward and thinning- upward successions with a lag deposit of mud pebbles, gravels and wood fragments. The sandy and muddy

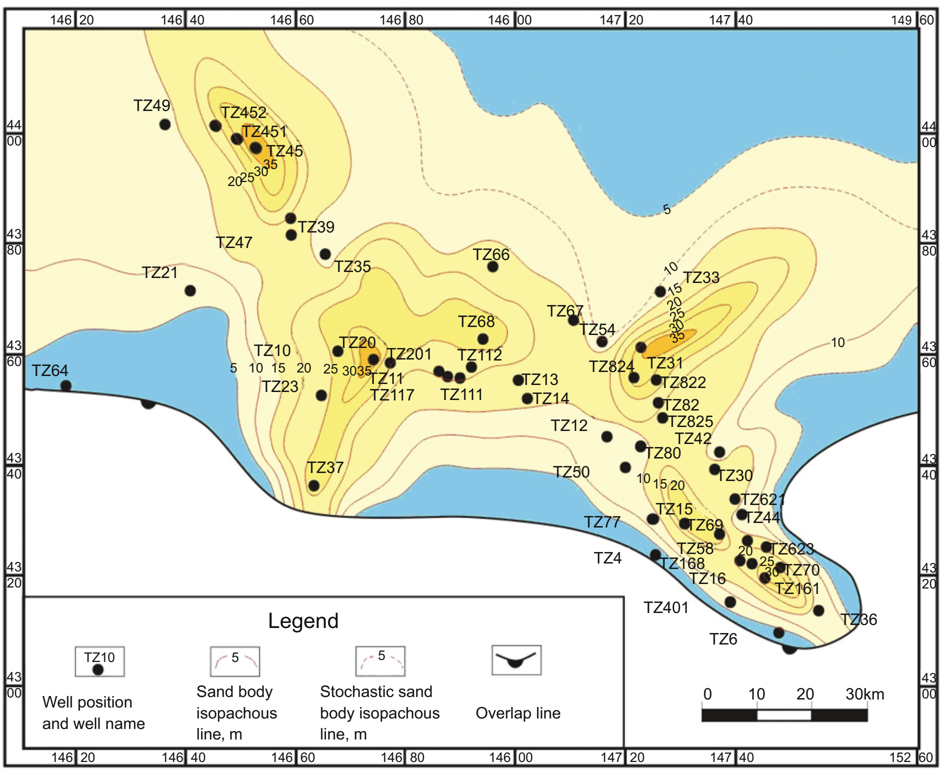

Fig. 11 Thickness map of sand body of the paleo-estuary of the Tazhong area

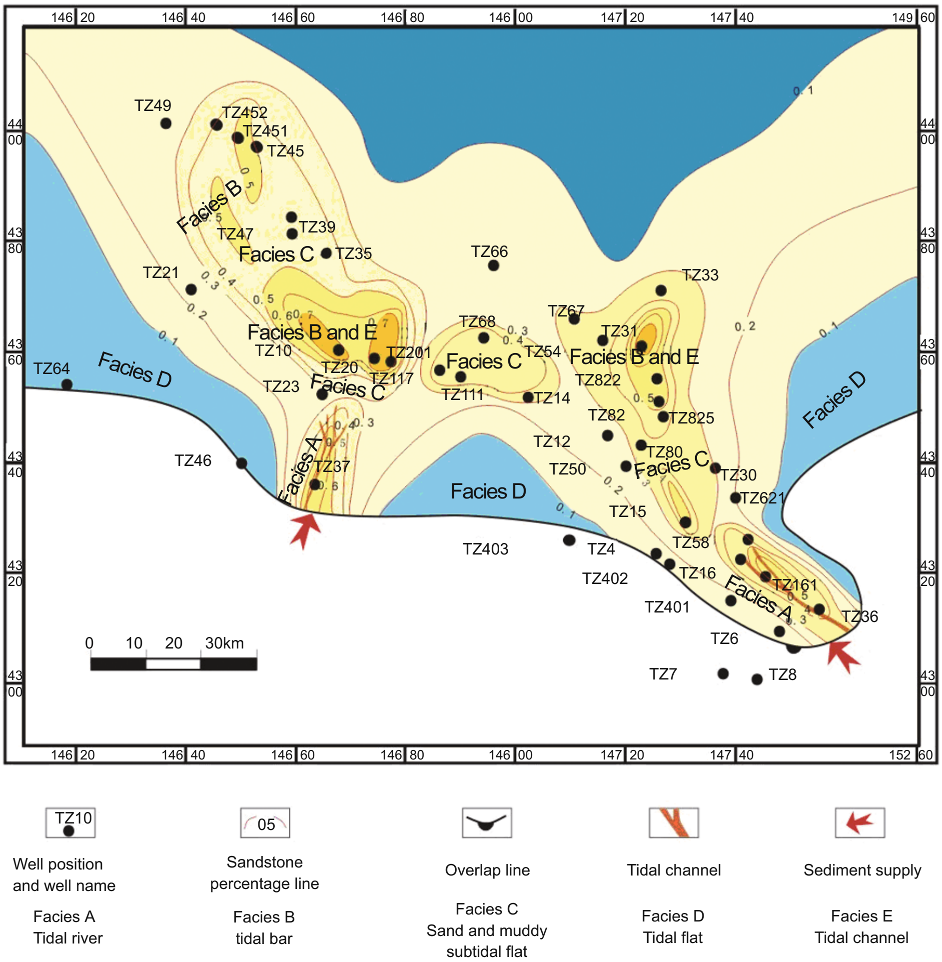

Fig. 12 Facies distribution of the paleo-estuary of the Tazhong area

sub-tidal flats prevailing in the area where the mixing-energy was low was characterized by sand-mud rhythmite. Grain size decreases dramatically from tidal river to sandy and muddy subtidal flat, suggesting that most fluvial deposits supplied by bedload were accumulated at the tidal river area, while suspended sediments were transported to the middle of the estuary, even further seaward (Wang and zhu, 1989). The tidal flat with tidal structure mainly occurred around the sides of the estuary. However, it is observed both at the seaward edge of the estuary mouth and within the estuary from time to time. Since the tidal flat successions were great in thickness, sometimes more than 4 m, the tide action was strong and the paleo-estuary was a meso-tidal to macro-tidal estuary. Tidal bar and tidal channel superimposed with each other usually occurred at the mouth of the estuary, such as the well field of TZ31 and TZ45. Grain size increased from sandy and muddy subtidal flat to tidal bar and tidal channel, suggesting that coarse sediment from the marine source was mainly deposited in the area where the deposition was influenced by the tide process. Fig.13 shows the schematic facies model of a composite transgressive vertical sequence of the paleo-estuary system.

Table 1 Comparison of the characteristics of the tide-dominated estuaries

	Tazhong	Yangtze River	Gironde	South Alligator	Bay of Fundy
Numbers of estuaries	two	one	one	one	one
Estuary area, km^2	9×10^3	2.7×10^4	1.6×10^3	1.4×10^3	2.5×10^2
Maximum tidal range, m	4 – 6	4.6	6	5 – 6	16.3
Main sediment source	Fluvial and marine	Fluvial	Fluvial and marine	Fluvial and marine	Marine

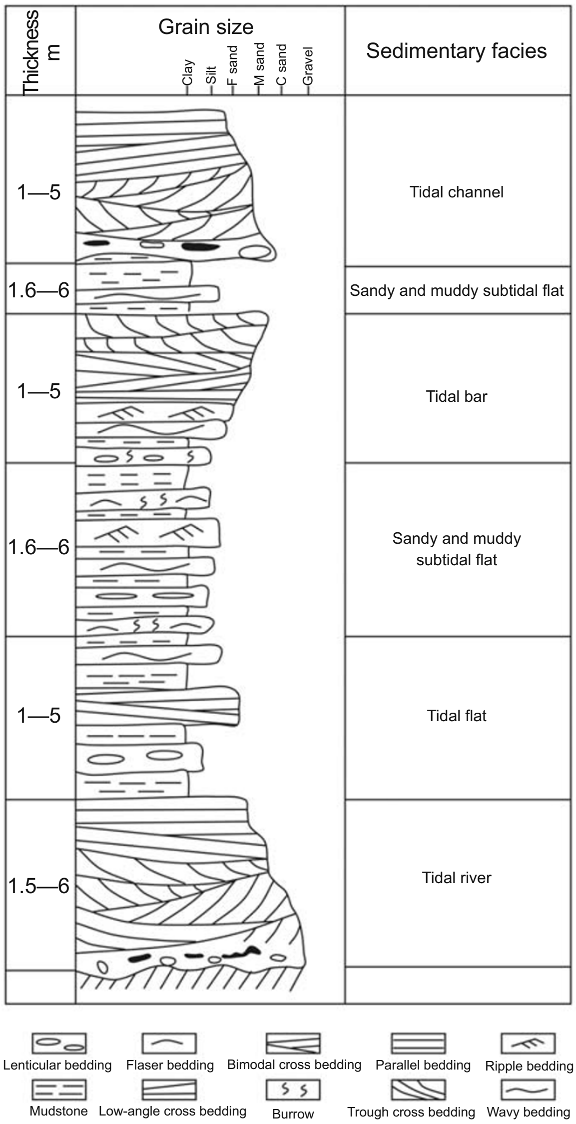

Fig. 13 Schematic facies model of a composite transgressive vertical sequence of the Tazhong paleo-estuary

6 Comparison with other tide-dominated estuaries and discussion

Dalrymple et al (1992) classified the estuaries into tide-dominated, wave-dominated, mixed wave- and tide-dominated types based on their dominating hydrologic characteristics and the kinds of sediment and sediment bodies formed in the estuary. This classification is in widespread use among geologists especially sedimentologists in recent years. The paleo-estuary of the Tazhong area should also be included into the tide-dominated type according to its sedimentary characteristics. However, the paleo-estuary of the Tazhong area has its own features (Table 1), which is different from the other well-known tide-dominated estuaries, for example, the paleo-Yangtze River estuary (Hori et al, 2001; Wu et al, 2006), the South Alligator (Woodroffe et al, 1989), the Gironde estuary (Allen, 1991) and the Bay of Fundy (Dalrymple et al, 1990; 1994).

The most important difference between Tazhong paleo-estuary and others is that there are two conjoint estuaries joined by tidal flat onshore and by sandy and muddy subtidal flat in the sea. Both the Tazhong paleo-estuary and the paleo-Yangtze River estuary belong to the large scale estuary category. However, they have different sediment sources. The Tazhong paleo-estuary received sediment from both fluvial and marine sources. Different sources led to different characteristics of the sediment distributions. The sediment distribution of the Tazhong paleo-estuary shows fining seaward from head to central part and fining landward from mouth to central part, which is similar to the smaller estuaries as the South Alligator and the Gironde estuary. However, there is only one fining seaward trend from head to mouth in the paleo- Yangtze River estuary.

Dalrymple et al (1992) presented a model of a tide-dominated estuary on the basis of the small estuaries with marine-source sediment. Thus, elongated tidal sand bars were developed in an idealized tide-dominated estuary. The model of Hori et al (2001) was based on the facies distribution of paleo-Yangtze River estuary, which is a large river estuary influenced strongly by a large amount of fluvial sediment discharge as well as tides. Neither of the two models can be applied to the Tazhong paleo-estuary, because there are two conjoint estuaries receiving sediment from both fluvial and marine sources at the same time, and the tidal rivers, tidal bars and tidal channels are all developed well. Therefore, we should take all kinds of the tide-dominated estuaries into account, including the Tarim paleo-estuary, when renewing the models of the tide-dominated estuaries.

Acknowledgements

This research is financially supported by the China National Key Research Program (No. 2004B616A02). We are also appreciated Drs Xie Jun, Zhang Xin, Liu Xiaolin, Qin Lijuan, Jiang Yiming and Zhang Xiaohua for their supports and contributions during this study.

References

Allen G P. Sedimentary processes and facies in the Gironde estuary: a recent model for macrotidal estuary systems. Clastic Tidal Sedimentology. Can. Sco. Petrol. Geol. Men. 1991. 16: 29-40

Beets D J, Groot T D and Davies H A. Holocene tidal back-barrier development at decelerating sea-level rise: a 5 millennia record, exposed in the western Netherlands. Sedimentary Geology. 2003.158: 117-144

Boggs S Jr. Principles of sedimentology and stratigraphy. USA: Prentice Hall. 1995. 395-406

Cattaneo A and Stee R J. Transgressive deposits: a review of their variability. Earth-Science Reviews. 2003.62 : 187-228

Capo S, Sottolichio A, Brenon I, et al. Morphology, hydrography and sediment dynamics in a mangrove estuary: The Konkoure Estuary, Guinea. Marine Geology. 2006. 230: 199-215

Cheng F H and Wang G W. On logging-sequence stratigraphy of the Silurian in Tazhong Area. Acta Sedimentologica Sinica. 1999. 17(1): 58-62 (in Chinese)

Choi K S and Dalrymple R W. Recurring tide-dominated sedimentation in Kyonggi Bay (west coast of Korea): similarity of tidal deposits in late Pleistocene and Holocene sequences. Marine Geology. 2004. 212: 81-96

Dalrymple R W and Zaitlin B A. High-resolution sequence stratigraphy of a complex, incised valley succession, Cobequid Bay-Salmon River estuary, Bay of Fundy. Canada. Sedimentology. 1994. 41: 1069-1091

Dalrymple R W, Zaitlin B A and Boyd R Estuary facies model: Conceptual basin and stratigraphic implications. Jour. Sed. Petrology. 1992. 32: 1130-1146

Dalrymple R W, Zaitlin B A and Middleton G V. Dynamics and facies model of a macrotidal sand-bar complex, Cobequid Bay-Salmon River estuary (Bay of Fundy). Sedimentology. 1990. 37: 577-612

Dalrymple R W, Boyd R and Zaitlin B A. History of research, types and internal organisation of incised-valley system: introduction to the volume. Incised-Valley System: Origin and Sedimentary Sequences, Dalrymple R. W., Boyd R. and Zaitlin B. A. (Eds.), Incised-Valley System: Origin and Sedimentary Sequences. SEPM Spec, Publ, 1994. 51: 3-10

Fairbridge R W. (1980) The estuary: Its definition and geodynamic cycle in E. Olausson and I. Cato (eds.), Chemistry and biochemistry of estuaries. New York: John Wiley & Sons. 1-35

Fenies H and Tastet J. Facies and architecture of an estuarine tidal bar (the Trompeloup bar, Gironde Estuary, SW France). Marine Geology. 1998. 150: 149-169

Galloway W E and Hobday D K. (eds.), Gu X Z, Gu J Y, Gao Y X, (trans). Terrigenous clastic depositional systems-Applications to petroleum, coal, and uranium exploration. Beijing: Petroleum Industry Press. 1983. 35-40 (in Chinese)

Gu J Y. The sedimental sequence and evolution. Beijing: Petroleum Industry Press. 1996. 1-361 (in Chinese)

Holz M. Sequence stratigraphy of a lagoonal estuarine system—an example from the lower Permian Rio Bonito Formation, Paraná Basin, Brazil. Sedimentary Geology. 2003. 162: 305-331

Hori K, Saito Y, Zhao Q H, et al. Sedimentary facies of the tide-dominated paleo-Changjiang (Yangtze) estuary during the last transgression. Marine Geology. 2001. 177: 331-351

Hou H J, Wang W H and Zhu X M. Study of depositional model of the Silurian system in Tazhong area, Tarim basin. Journal of Sedimentology. 1997. 15(3): 41-46(in Chinese)

Jia C Z. Tectonic characteristics and Petroleum, Tarim Basin, China. Beijing: Petroleum Industry Press. 1997. 295 (in Chinese)

Lin M C, Zhuo C H and Gao S. Sedimentary facies and evolution in the Qiantang River incised valley, eastern China. Marine Geology . 2005. 219: 235-259

Morales J A, Delgado I and Gutierrez-Mas J M. Sedimentary characterization of bed types along the Guadiana estuary (SW Europe) before the construction of the Alqueva dam. Estuarine, Coastal and Shelf Science, 2006. 70: 117-131

Pritchard D W. What is an estuary: physical viewpoint. Washington D.C: Am. Assoc Adv 1967. 3-5

Qi Y A and Su X B. The Early Silurian trace fossils of Tarim basin and parasequence facies associations. Journal of Stratigraphy. 1999. 23 (1): 42-46 (in Chinese)

Scholle P A and Spearing D. Sandstone depositional environments. U.S.A: the American Association of Petroleum Geologists Tulsa Oklahoma.1982. 179-190

Tessier B and Gigot P. A vertical record of different tidal cyclicities: an example from the Miocene Marine Molasse of Digne (Haute Provence, France). Sedimentology. 36: 767-776

Visser M J. (1980) Neap-spring cycles reflected in Holocene subtidal large-scale bedform deposits: a preliminary note. Geology. 1989. 8: 543-546

Wang L C and Zhang J L. Sedimentary environment and facies. Beijing: Petroleum Industry Press. 1996. 84-91 (in Chinese)

Wang Q and Zhu E Q. Marine sedimentology. Shanghai: Tongji University Press. 1989. 5-17 (in Chinese)

Weber N, Chaumillon E, Tesson M, et al. Architecture and morphology of the outer segment of a mixed tide and wave-dominated-incised valley, revealed by HR seismic reflection profiling: the paleo-Charente River, France. Marine Geology. 2004. 207: 3- 17

Willis A. Tectonic control of nested sequence architecture in the Sego Sandstone, Neslen Formation and Upper Castlegate Sandstone (Upper Cretaceous), Sevier Foreland Basin, Utah, USA. Sedimentary Geology. 2000. 136: 277-317

Woodroffe C D, Chappell J, Thom B G, et al. Depositional model of a macrotidal estuary and floodplain, South Alligator, northern Australia. Sedimentology. 1989. 36: 737-756

WuG H, Li Q M, Zhang B S, et al. Structural characteristics and exploration fields of No.1 Faulted Slope Break in TZ area. Acta Petrolei Sinica. 2005. 26(1): 27-30 (in Chinese)

Wu J X, Liu J T, Shen H T, et al. Dispersion of disposed dredged slurry in the meso-tidal Changjiang (Yangtze River) Estuary. Estuarine, Coastal and Shelf Science. 2006. 1-10

Zhang J L, Xie J and Liu X L. Depositional facies and modle of the Silurian strata in Tarim Basin. China's National Key Research Program Report (grant No. 2004BA616A02). Tarim Oil Field of PetroChina Company Limited. 2005. 10-42 (in Chinese)

Zhu R K, Luo P, He D B, et al. Sedimentary facies and models of the Kepingtage Formation of the Silurian in Tazhong Area, Tarim Basin. Journal of Palaeogeography. 2005. 7(2): 198-205 (in Chinese)

Zhu X M, Wang G W and Xie Q B. Characteristics and distribution of depositional systems of the Silurian in Tarim Basin. Journal of t he University of Petroleum (Edition of Natural Science). 2001. 26 (3): 5-12 (in Chinese)

(Edited by Yang Lei)