Pet.Sci.(2008)5:110-118
DOI 10.1007/s12182-008-0018-0

Sequence stratigraphy and depositional systems in the Paleogene, Liaodong Bay

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Abstract: Based on drilling and seismic data, the Paleogene developed in Liaodong Bay can be divided into five third-order sequences bounded by six sequence boundaries. Through analyzing depositional systems in each sequence in detail, the Es-3 time was defined as fast rifting. During the deposition of the Es-3 member, the lake basin was continuous along the N-S direction but compartmentalized along the E-W direction by several N-S trending faults. Deposition was dominated by steep slope fans and fan deltas. The time of Es-2 and Es-1 was stable settling. The lake basin expanded substantially. The fan delta system and braided fluvial system were developed. Carbonate and clastic deposits were formed on the Liaoxi (west Liaohe) Rise. The time of Ed-3 time was again fast rifting. During this time, shale was deposited. In the time of Es-2 , tectonic movement weakened. The basin was higher in the west and north, and lower in the east and south. A series of delta depositional systems were developed and small-scale slumping turbidite fans were present in semi-deep lake to deep lake. In the time of Ed-1, tectonic movement stopped. Flood plain deposition occurred. Finally the paper presents the characteristics of evolution and distribution of depositional systems both vertically and horizontally.

Key words: Liaodong Bay, Paleogene, sequence, depositional system

1 Introduction

The Liaodong Bay lies in the northern part of the Bohai Bay Basin. It is located within the same tectonic unit as the Liaohe sub-basin (Fig.1). From west to east, there exist the Liaoxi Depression, Liaoxi Low Rise, Liaozhong Depression, Liaodong Rise, Liaodong Depression. The tectonic framework is characterized by three depressions and two rises. These tectonic units are parallel with one another, trending in the NE-SW direction (Fig.2). Liaodong Bay is bounded by the Liaodong Uplift in the east. Most of the structural lows are half-grabens. The rises are divided into high and low ones. Oil and gas fields discovered are mainly distributed on the low rises, especially on the middle and northern segments of the Liaoxi Low Rise.

Hydrocarbon exploration indicates that oil/gas generation and distribution are controlled not only by structures but also by the distribution of depositional systems. With regard to the Paleogene in the Bohai Bay Basin and Liaodong Bay, some studies about sequence and deposition have been made (Liu and Zhao, 1994; Qi et al, 1994; Zhao et al, 1996; Jiang et al, 2001; Xu et al, 2005; Fan et al, 2006; Li et al, 2006), but most of those studies were confined to a particular part of the Liaodong Bay. Some studies covering the whole Liaodong Bay have been published (Dong et al, 2007; Jia et al, 2007;

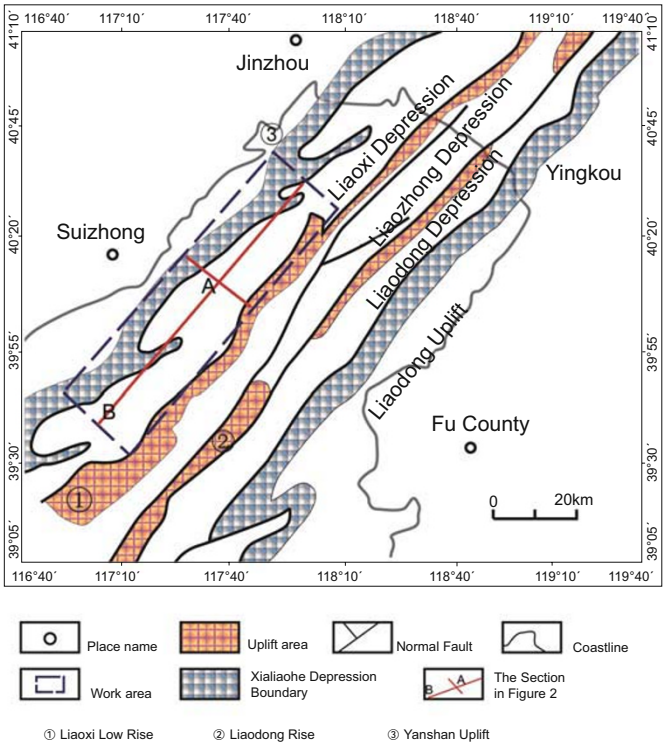

Fig. 1 Map showing location of the Liaodong Bay (After Xu et al, 2005)

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Received July 27, 2007

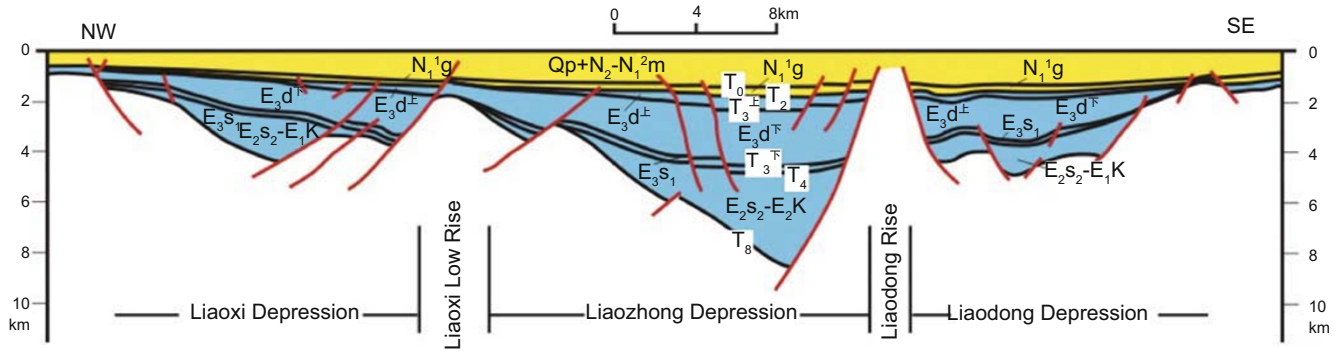

Fig. 2 Geologic cross section of the Liaodong Bay Basin (After Bohai Research Institute of CNOOC, 2005)

Jiang et al, 2007; Jiang et al, 2007; Li et al, 2007; Liu et al, 2007). Based on the previous studies and our up to date data base, we made an integrated study of the stratigraphic sequence and depositional systems in the Paleogene in detail and give a more thorough picture of sedimentary facies maps according to the analyses of drilling data, well logging data, and seismic data. In addition, our study has clarified the relationship between reservoir distribution and depositional systems, and has provided scientific evidence for studying the hydrocarbon accumulation patterns and hydrocarbon exploration in the future.

2 Classification of the Paleogene in Liaodong Bay

Liaodong Bay is a typical non-marine rifting lake basin. There are many elements controlling sequence developments in non-marine environments. Sequences were deposited in a short period of time (Wang et al, 1997), and research methods of marine facies sequence cannot be applied (Deng, 1995). The evolution from fluvial to lacustrine environment occurred in the Liaoxi Depression in the Paleogene time, sequences were classified depending on tectonic mechanism, lake level fluctuation and deposition evolution influenced by these two elements (Xu, 1996).

Identifying the sequence boundary is the key element of sequence classification. By analyzing drilling data, well logging data and the evolution from fluvial to lake environment and based on the relationship between lake level fluctuation and deposition evolution, six third-order sequence boundaries (SB1~6) were identified and five third-order sequences (SQ1~5) were classified for the Paleogene in the

Table 1 Tectonic movements and sequence stratigraphy from the Paleogene to the Neogene

Geological time	Orogeic structure episodes	Chronostratigraphy	Lithostratigraphy		Sequence boundary/ seismic interface	Third-order sequence	Forth-order sequence	Sequence boundary stage	Bohai schedule
Quaternary	Late Himalayan Period	Holocene						SB7 19.3Ma	2.6Ma
		Pleistocene							
Neogene		Pliocene	Minghuazhen formation		SB7/T_0	SQ7			5.3Ma
		Miocene	Guantao formation			SQ6			24.6Ma
Paleogene		Oligocene	Dongying formation	Member1	SB6/T_2	SQ5	HST	SB6 2.0Ma	
							TST		
							LST		
				Member2	SB5/T_3^1	SQ4	HST	SB5 3.7Ma	30.3Ma
							TST		
							LST		
				Member3	SB4/T_3^2	SQ3	HST	SB4 2.5Ma	32.8Ma
							TST		
							LST		36.0Ma
	Early Himalayan Period		Shahejie formation	Member1	SB3/T_3 T_4	SQ2	TST	SB3 5.2Ma	
				Member2	SB2/T_5		LST		38.0Ma
		Eocene	Shahejie formation	Member3	SB1/T_6	SQ1	HST	SB2 4.0Ma	
							TST		42.0Ma
							LST		
				Member4				SB1 23.0Ma	50.5Ma
		Paleocene			SB-UP/T_8				
	Yanshan Movement	Prepaleozoic-Archaean						SB-UP	65.0Ma

central and southern parts of the Liaoxi Depression (Table 1).

2.1 SQ1 (Es-3 time)

T6 is the corresponding seismic reflector of SB1. Because of ambiguous geologic age, T6 probably contains merged T6, T7 and T8, so it is equivalent to a second-order sequence boundary that lasted 27 Ma.

SQ1 consists of low stand systems tract (LST), transgressive systems tract (TST) and high stand systems tract (HST). The depositional system of LST in the Lower Es-3 member includes alluvial fan, braided fluvial delta, fan delta and steep slope fan deposits. On seismic sections, wedged reflections can be found, which means a course of filling and leveling up in rifting depression. TST is the deposition formed by shallow lake, semi-deep lake and deep lake conditions in the middle Es-3 member. Many onlaps during the lacustrine expending phase indicate the development of a shallow lake. The upper Es-3 member is characterized by the condensed section (CS) during the maximum flooding surfaces (MFS). Continuous strong reflectors can be found on seismic sections. This indicates the maximum flooding surfaces (MFS) and follow-up semi-deep lacustrine environment. HST is the deposition formed after MFS. At the same time, the basin was characterized mainly by lacustrine facies with subordinate delta facies and sub-lacustrine fans. The uppermost part of HST suffered erosion and truncation.

2.2 SQ2 (Es-2 and Es-1 times)

SQ2 consists of the first and second members of the Shahejie Formation and is bounded by SB2 and SB3. Its deposition lasted 5.2 Ma. It is about 100-400 m thick and characterized by parallel or sub-parallel sheet seismic facies. The sedimentary environment was a stable lacustrine environment with a low-energy water body and a relatively low depositional rate. Because of small thickness and short time interval on seismic reflections, internal structures of seismic facies and system tracts can not be identified easily. On the margin of basin, however, LST and TST (lake expanding systems tract) are still identified. LST is the deposition formed mainly by braided fluvial deltas and channels with locally developed alluvial fans. The others are steep slope fans lying in the footwalls of two faults. TST is the deposition formed in delta and shallow lake conditions.

2.3 SQ3 (Ed-3 time)

SQ3 comprises the third member of the Dongying Formation. The bottom boundary SB3 is T3 seismic reflector and the top boundary SB4 is T32 seismic reflector. The sequence that lasted 2.5Ma was characterized by rapid deposition in a short period of time. SQ3 consists of LST, TST and HST. LST was the deposition formed by braided river delta, lake-floor fan and steep slope fan. They are distributed on the margin of the basin and the footwall of bounding faults of the Liaoxi Low Rise, Liaodong Rise. TST was formed by lacustrine facies deposition and HST was formed by meandering fluvial, braid fluvial delta, delta and shallow lake depositions.

2.4 SQ4 (Ed-2 time)

SQ4 consists of the second member of the Dongying Formation and is bounded by SB4 and SB5. It lasted 3.7 Ma and is 400-1000 m thick. It is distributed in the central and southern parts of the Liaoxi Depression and beyond the Liaoxi Low Rise to the east. SQ4 can be divided into LST, TST and HST. As the basin area expanded, assemblage of seismic facies and sedimentary facies of system tracts did not coincide with LST, TST and HST. Sedimentary features of fluvial dominated deltas are obvious, with broad distribution and a complete sedimentary sequence. LST was formed by braided fluvial delta, sub-lacustrine channel and turbidite fan deposits. No fans occurred on the steep slope. TST was formed by braided fluvial delta, delta and semi-deep lake depositions. HST was formed by braided fluvial and braided fluvial delta depositions.

2.5 SQ5 (Ed-1 time)

SQ5 is composed of the first member of the Dongying Formation and bounded between SB5 and SB6. It is divided into LST, TST and HST. Based on the combination of seismic facies and sedimentary facies of system tracts, we can conclude that the feature of sedimentary facies was that flood plains were developed. The sequence was denuded regionally.

3 Distribution of depositional systems

A depositional system means a group of sedimentary facies with a genetic relationship. On the basis of seismic sequence analysis and seismic interpretation, sedimentary facies maps of sequences were made for the Paleogene.

3.1 Depositional system of SQ1 (Es-3 time)

During the deposition of the Sha-3 member, the Liaoxi Low Rise divided the Liaodong Bay Basin into Liaoxi Depression and Liaozhong Depression. Deposition occurred only in local regions and the basin tectonic framework consisted of one rise and two depressions (Fig. 3). The features of palaeo-geomorphology were that elongated half-grabens alternated with elongated highs faulted on one side, lying between the Liaodong ancient land and the Yanshan fold belt. The island chain in the Liaoxi Depression formed from secondary horsts or rises consisting of old basement rock. It supplied clastic fragments to the basin and compartmentalized the basin in the E-W direction. The island chain trended NNE-SSW, was 1-4 km wide and divided Liaoxi Depression into two secondary tectonic units: the western offshore zone and eastern lake basin zone. Generally, it was higher in the south than in the north.

Meanwhile, the sedimentary environment was shallow lake - semi-deep lake - deep lake from west to east in the Liaoxi Depression and Liaozhong Depression. A major fault separated the depressions from the Liaoxi Low Rise to the east. Thus, each depression was a typical half graben. The sedimentary environment was deep lake in the thrown side of the major fault. As many short rivers of the drainage system in the Yanshan Uplift and Liaodong ancient land flowed into the depression along the valleys, fan delta-sublacustrine fan

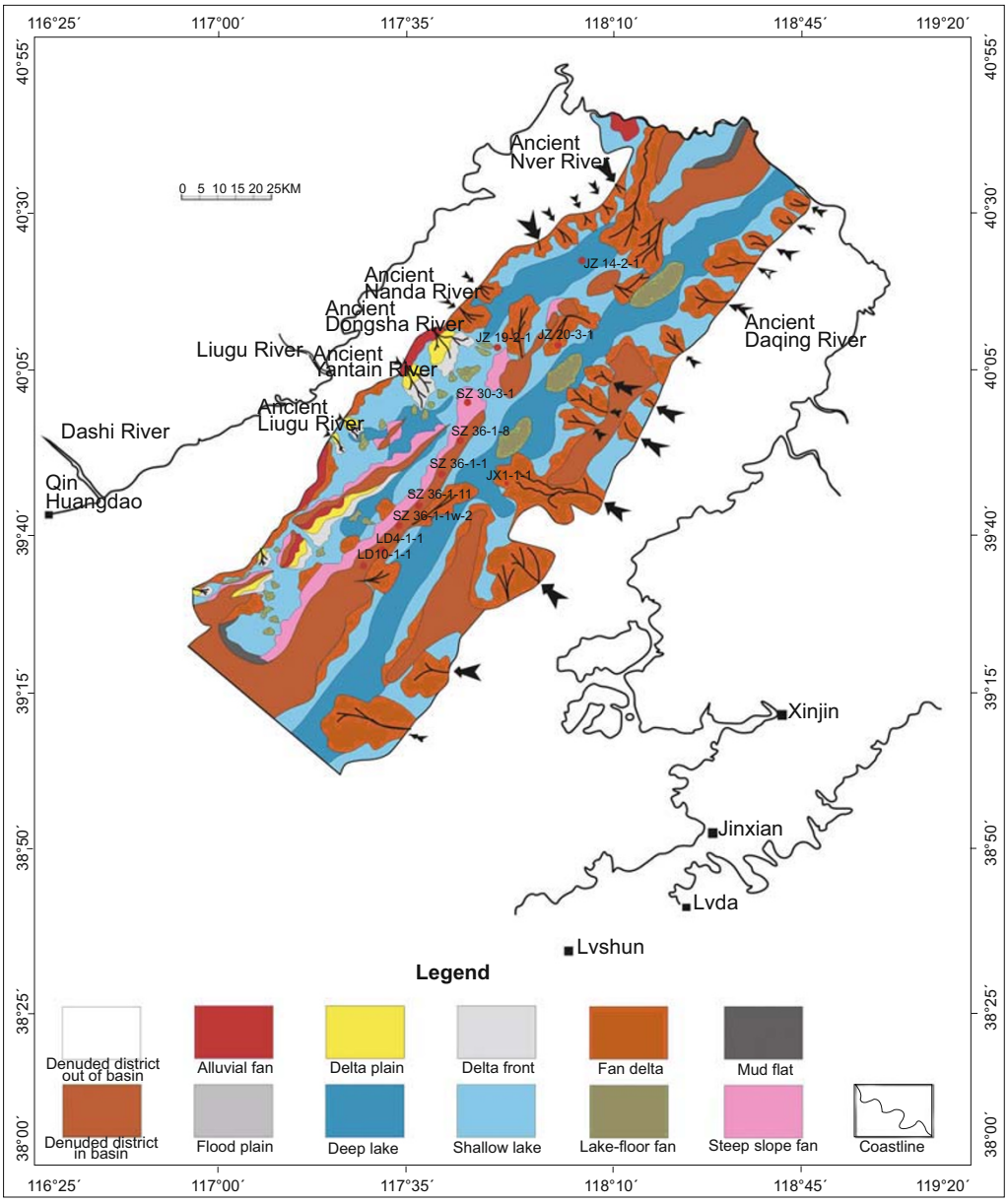

Fig. 3 Distribution map of sedimentary facies in SQ1(Es-3 member) in the Paleogene in the Liaodong Bay

depositional systems were formed. Fans on the steep slope were controlled by the faults.

On the Liaoxi Low Rise, deposition was limited to local parts. The deposits include lake shore facies found in the well JZ20-2-4 and semi-deep lake to deep lake facies influenced by gravity flow in the well JZ20-2-13 and its surrounding areas.

The Liaoxi Depression was separated from the Yanshan Uplift to the west by a transitional gentle slope. On its western part, a braided river-fan delta depositional system was developed. On its eastern part, a semi-deep lake to deep lake depositional system was developed. In addition, lake-floor fans as island chains in the depression provided detrital clasts. As a result, a fan delta-sublacustrine a fan depositional system was developed.

3.2 Depositional system of SQ2 (Es-1 time, Es-2 time)

In the Es-2 time, the lake was shallow. Red beds were encountered on the margin of the southern depression of the Liaoxi Depression. But deposition occurred in parts of the submerged Liaoxi Low Rise. The sedimentary environment was shorezone-shallow lake in the Liaodong Depression-Liaodong Rise, where clastic fragments from the Jiaoliao Uplift were deposited. Thus, an alluvial fan-braided river-fan delta depositional system was formed. The major fault between the Liaodong Uplift and the Liaoxi Depression succeeded the division features in the Es-3 time. Lake-floor fans were formed in the deep lake on the thrown side of the major fault. But these were different from the lake-floor fans formed in the Es-3 time. The sediment source was

from the fan delta depositional system in the Liaodong area. An alluvial fan-(braided river)-fan delta-sublacustrine fan depositional system was formed from the Jiaoliao Uplift to the Liaozhong Depression. The Liaoxi Low Rise was still not inundated and became a local sediment source. Most of the central and northern parts of the Liaoxi Low Rise was inundated and became a carbonate platform. The deposition was characterized by the front slope deposits, shallow bank deposits on the top of platform, restricted platform deposits and biolithite that were present in the northern JZ20-2-JZ9-3 region (Fig. 4). In such a platform sedimentary environment, carbonate deposits were influenced by intermittent gravity-flow channel deposits. The lake shrank in the Liaoxi Depression, but the deposits were similar to those in the Es-3 time,and a fan delta-sublacustrine fan depositional system was developed. In comparison with that at the Es-3 time and a, the deposits and beach shifted toward the east (Fig. 4).

In the Es-1 time, the dividing feature of the basin weakened. Lake levels were rising and the lake was dominated by shallow-semi deep lake deposits. Surrounding palaeodrainages, such as the ancient Fuzhou drainage, ancient Liuguhe drainage and ancient Liaohe drainage flowed into the lake basin from the east, west and north respectively. Various kinds of small scale depositional systems were formed. In the western Liaodong Depression, the major fault was the boundary between the Liaodong Depression and the Liaodong Rise. In the southwest, the Liaodong Depression conjoined with the Liaozhong Depression. In the southeast, there was a slope between Liaodong Depression and Jiaoliao Uplift. The depression formed by the slope was a typical one characterized by uplifting in the east and subsiding in the west.

In the eastern shorezone-shallow lake, deltas were formed as the ancient Liaohe drainage flowed into the lake. In the western shallow-semi deep lake, sublacustrine fans were formed. Meanwhile, the Liaodong Rise was a sublacustrine highland, characterized by shallow bank deposits and

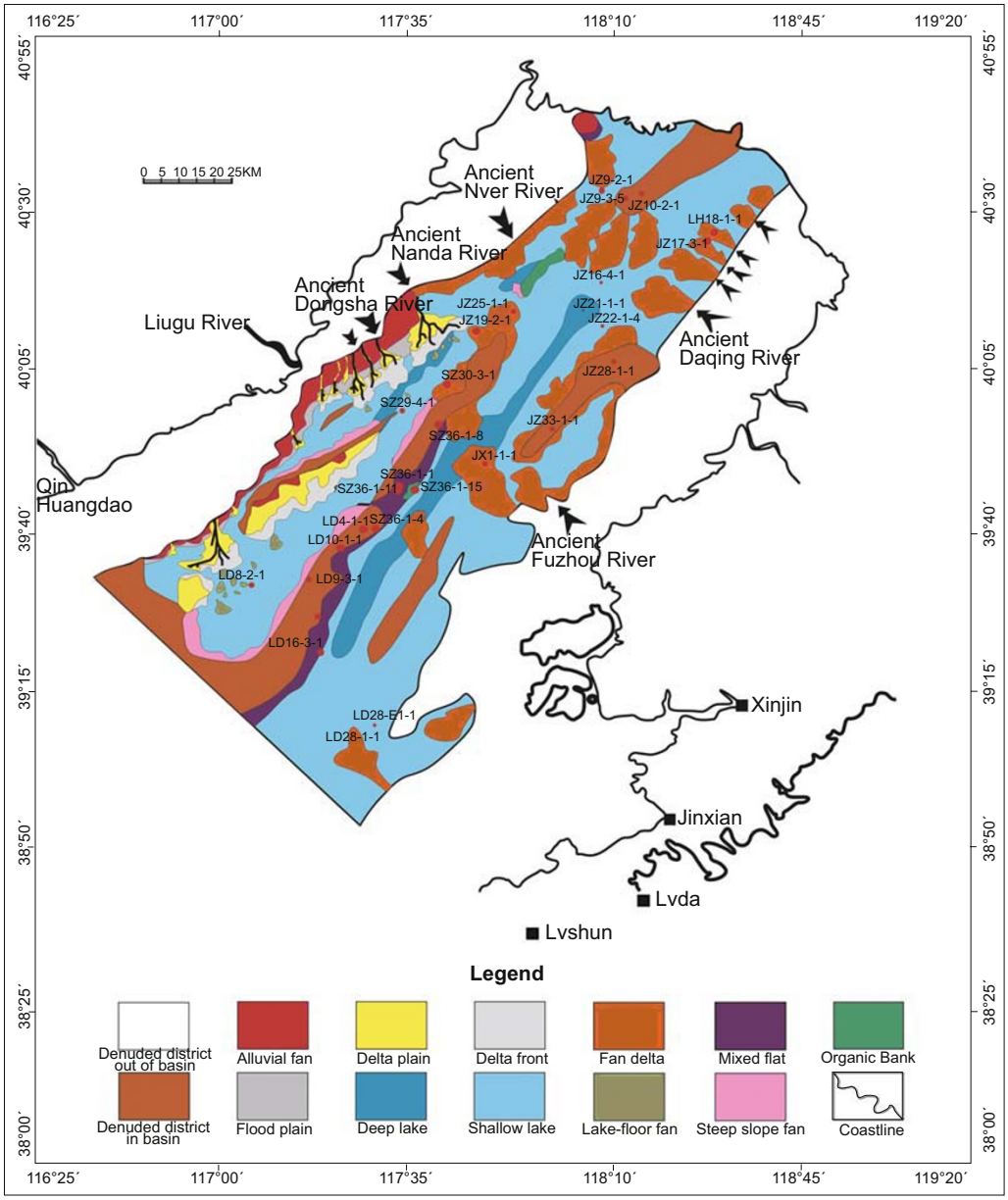

Fig. 4 Distribution map of sedimentary facies in SQ2 (Es-1-2 member) in the Paleogene in the Liaodong Bay

limited thickness, such as in the JZ27-6—JX1-1—LD28-1 region. In the Liaozhong Depression, the lake was deeper, dark shale, oil shale, and dolomitic shale of semi deep—deep lake facies were deposited. Most of the Liaoxi Low Rise was inundated and carbonate platform was formed. The characteristics in the central part are different from those in the northern part. In the northern part, the lake was an open water environment, characterized by lake basin deposits. In the central part, the platform environment was characterized by the JZ20-2 structure. Front slope, shallow platform bank facies and restricted platform facies were laid down. The main provenance was the Yanshan fold belt. Deltas were formed in the gentle slope of the depression. In the semi-deep to deep lake, sublacustrine fan was formed. Thus, a delta-sublacustrine fan depositional system was developed. Well JZ19-2-1 was located in the deep lake environment where shale and oil shale were deposited. Well JZ14-2-1 was located in the open lake environment and shale and microcrystalline dolomite were deposited.

3.3 Depositional system of SQ3 (Ed-3 time)

In the early time of Ed-3, the sedimentary characteristics succeeded those of the Es-1 member. The lake was deeper and open, and turbidite was deposited (Fig. 5). In the late time of Ed-3, the whole Liaodong Bay area was uplifud. The lake shrank and became shallow. With the exception of the Liaozhong Depression, there was no obvious topographic relief within the Liaodong Depression and Liaoxi Depression.

The T3 boundary indicates an important tectonic transition in the Liaoxi Depression with an intensive rifting movement in the basin. Two depositional systems were formed above and beneath T3. The system overlying T3 was characterized by gravity-flow deposits and the one underlying T3 was characterized by drag flow deposits.

Meanwhile, the division weakened gradually in the basin, which was composed of several separated rifts. Lateral

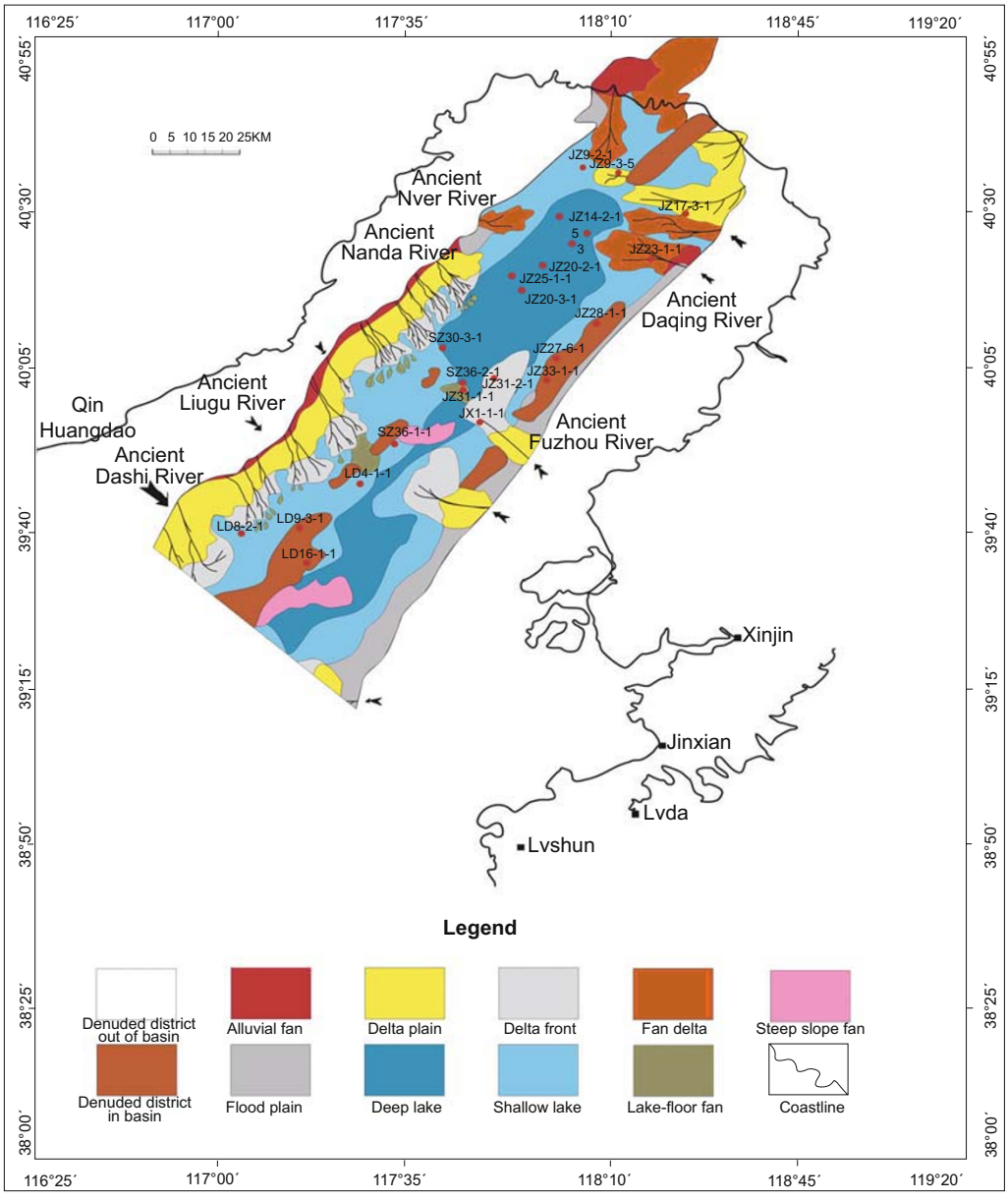

Fig. 5 Distribution map of sedimentary facies in SQ3 (Ed-3 member) in the Paleogene in the Liaodong Bay

connection was improved. Gradually the initially separated depocenters and subsidence centers evolved into a uniform depreesion.

3.4 Depositional system of SQ4 (Ed-2 time)

Lake shorezone, shallow lake and semi-deep lake environments were distributed in turn from west to east. Deltas were formed where the rivers flowed into the lake. In the late time of Ed-3, the Liaodong Bay Basin was uplifted in the north and subsided in the south. Surrounding drainages flowed into the lake, then merged and flowed to the Bozhong Depression. Thus, delta deposits were formed in the upper Ed-2. A meandering fluvial-delta depositional system was developed.

There was some early altitude difference between Liaodong Depression and Liaodong Rise and the difference decreased later. Deltas were formed in shore-shallow lake environments, and extended into the Liaodong Depression. It can be presumed that the meandering fluvial-delta-sublacustrine fan depositional system was developed first, and the meandering fluvial-delta depositional system was developed later.

The Liaozhong Depression was initially located in a moderate to deep lake environment. In the east, there was further movement on the boundary fault which caused significant gravity slumping. Thus, sublacustrine fans were formed in the deep lake. The sediment provenance was the Jiaoliao Uplift.

As the Liaodong Bay basin was uplifted in the north and subsided in the south, the lake became shallower. The Liaohe drainage shifted forward along the long axis of the Liaoxi Depression and delta deposits were formed (Fig 6).

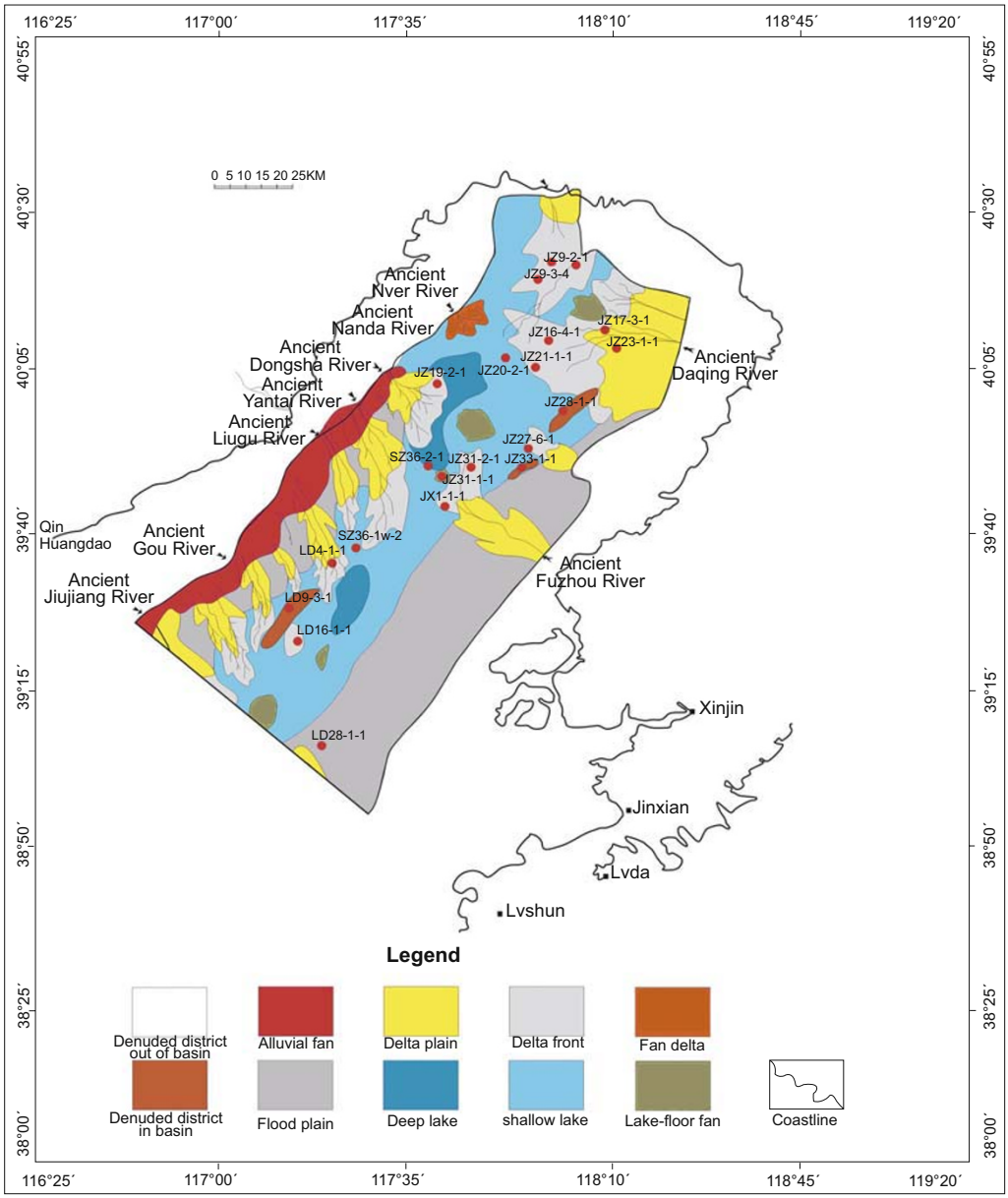

Fig. 6 Distribution map of sedimentary facies in SQ4 (Ed-2 member) in the Paleogene in the Liaodong Bay

3.5 Depositional system of SQ5 (Ed-1 time)

As the Xialiaohe—Liaodong Bay basin rose stably and continuously, the basin shrank and the lake became shallower. As a result, sandstones and conglomerates of fluvial-plain facies were more prominent. At this time, most parts of the Liaozhong Depression, Liaoxi Low Rise and Liaoxi Depression were located in shore, shallow, and semi-deep lake environments. Deltas were formed as rivers flowed into the depression and a the meandering fluvial-delta depositional system was developed. During the later Ed-1 time, the entire basin was uplifted and peneplanation took place (Fig. 7).

In a plan view, fan delta, steep slope fan, and sublacustrine fan deposits were distributed from basin margin to basin center during the deposition of the Es-3 member (SQ1). Fan delta-beach bar-carbonate platform biogenic limestone-turbidite deposits were in turn distributed from basin margin to central uplift and basin center during the deposition of the Es-1 and Es-2 members (SQ2). Braided fluvial delta-sublacustrine fan or turbidite deposits were distributed from basin margin to basin center during the deposition of the Ed-3 member (SQ3). Delta sublacustrine fan deposits were distributed from basin margin to basin center during the deposition of the Ed-2 member (SQ4). A delta depositional system was dominant from basin margin to basin center during the deposition of the Ed-1 member (SQ5). Vertically, semi deep-deep sublacustrine fans were formed in the Es-3 time when rifting took place. Beach bar and carbonate platform deposits were formed in the Es-1 and Es-2 times when uplifting occurred. Semi-deep to deep lake deposition occurred in the Ed-3 time when faulting and sagging happened. Shallow-semi deep-sublacustrine fan or turbidite deposits were formed during the deposition of the lower Ed-2 member and delta fronts were formed in the deposition of the

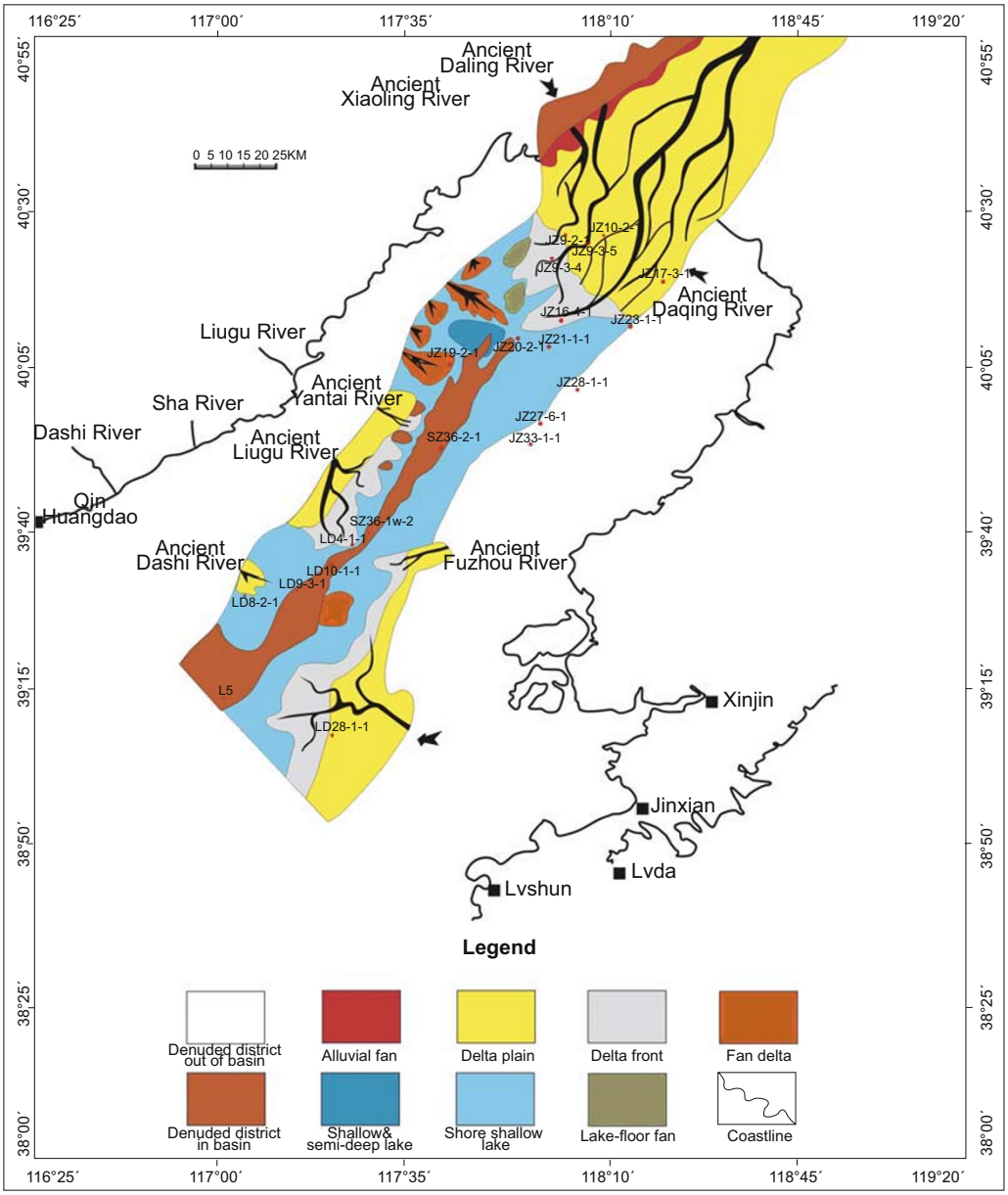

Fig. 7 Distribution map of sedimentary facies in SQ5 (Ed-1 member) in the Paleogene in the Liaodong Bay

upper Ed-2 member. A delta plain system was formed in the deposition of the Ed-1 member.

4 Conclusions

Due to intensive faulting in the Es-3 time, a set of sandstones of steep slope fans and fan delta were developed as reservoir beds. In the Es-2 time the lake became shallow, the climate was dry and fan delta deposits dominated. Due to weak faulting in the Es-1 time, the basin was stable, the sediment supply decreased rapidly, and water salinity increased. The sediments were dominated by carbonate, source rock and dark shale. During the deposition of the Ed formation, rifting occurred again. Intensive faulting deepened the lake rapidly and the basin became starved of sediment. The main deposits were shale in the Ed-3. In the Ed-2 time, the lake reached its maximum extent. After MFS happened, the entire lake basin subsided due to faulting and sagging. Sediments derived from the sources outside the lake basin were transported into the basin. The rivers (ancient Liaohe drainage) were developed along the long axis of the basin and delta deposition occurred. The reservoir-cap assemblages were the best in the Liaodong Bay or even for the entire Bohai Bay area. At the Ed-1 time, fault movement weakened rapidly. Flood plain deposits appeared, but the overlying formation deposited in the Ng time lacked cap rocks. The delta depositional systems were favorable sedimentary facies for petroleum in the Ed-2 member or SQ4 in the Liaoxi Depression and Liaoxi Low Rise. In particular, delta fronts were the most favorable systems. In the eastern Liaodong Depression, beach bar facies in SQ2 and middle fan in SQ1 was the favorable sedimentary facies.

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