The models of sequence stratigraphy and depositional architecture of the rift lacustrine basin in response to the background of extension and strike-slip tectonic mechanisms

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Abstract

Huanghekou depression of Bohai Bay basin is in a special tectonic environment. Due to the existing of the Tan-Lu fault zone the tectonic mechanism of extension and strike slip affected the whole strata profoundly, especially the sequence and depositional models of Palaeogene. This phenomenon led to huge differences of the sequence stratigraphy and depositional architecture. Thus this study aims in using seismic data, complemented by well logs and cores to analyze thoroughly the sequence stratigraphy and depositional architecture of the Huanghekou depression and their models in response to the background of extension and strike-slip tectonic mechanisms in this rift lacustrine basin.

Palaeogene is divided into 9 composite sequences on the basis of unconformities on depression margins and correlative conformities in the depression center. Every sequence is composed of a regional depositional cycle from transgression with an onlapping lacustrine expanding systems tract (EST) to regression with a prograding highstand systems tract (HST). There are five depositional systems in the Huanghekou depression including fan delta, braid river delta, meandering river delta, the lacustrine depositional system and sublacustrine fan.

One of two depositional models is that fan delta and sublacustrine fan were developed in north steep slope. The middle was similar with the north. In south gentle slope depositional systems were braided river deltas. The other is that the depositional system was mainly developed by meandering river delta in the north. In the middle the large-area beach bar can be found and the large scales of braided river deltas were developed continuously in south gentle slope. Finally through the analysis of the physical characters and the sandstone reservoir of the different micro-facies, we know that under the extensional model the best sandstone reservoir distributed in mouth bar and far bar of braided river delta in south gentle slope belt. Under the duplex tectonic mechanisms, the best sandstone reservoir can be seen in beach bar of shore and shallow lacustrine depositional system.

Keywords: Sequence stratigraphy, depositional architecture, tectonic mechanisms, Palaeogene, Depression.

Introduction

The geological researches on lacustrine basins have been developed rapidly for the past few years. Rift lacustrine basins, noticeably, have extremely special but various sequence-depositional architecture patterns which resulted from the comprehensive function of tectonic activities, climate variation and sediments supply. Tectonic activities play a very important role during the formation of rift lacustrine basins by controlling the sequence- depositional architecture patterns of the basins. The basins are under control of extensional stress during the rifting period and therefore the strata sequence and depositional system are obviously controlled by the large-scale syndepositional faults on the basin boundaries or in the basins. Rift lacustrine basins have become a research hotspot. A large amount of researches relating to tectonics and sequence stratigraphy, sedimentology and potential sandstone reservoir have been intensively conducted.

Most of the studies mentioned above are based on the pure extensional background. However, the formation and the evolution of lacustrine basins are not simply controlled by a single tectonic stress mechanism. Take the Paleogene Bohai Bay basin, which evolved on the Mesozoic tectonic background, as an example. During the basin formation, the Pacific plate was subducting under North China plate, causing asthenosphere upwelling and lithosphere thinning. Large-scale fault depression and Tan-Lu fault zone extension occurred. After that, the collision between Indian plate and Eurasian plate continued which led to the large-scale back arc extension of Pacific plate and the dextral strike slip of Tan-Lu fault zone. Although Paleogene Bohai Bay basin was formed on the extensional background, it was also strongly affected by the strike-slip tectonic stress. Because of its special tectonic background, the sequence stratigraphy and depositional system of Bohai Bay basin are more worth to pay attention as compared to other pure fault-depression basins.

Tan-Lu fault zone runs through the Huanghekou depression so that it controlled the formation of the depression. This typical geographical environment and abundant basic data

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provide us favorable opportunity to study this area. In this paper, we took Huanghekou depression, southeast Bohai Bay as an example and discussed the following aspects of Paleogene fault-depression basin under the dual tectonic background of extension and strike-slip: (1) the characteristics of sequence stratigraphy and depositional system, (2) properties of tectonics, especially the tectonics of Tan-Lu fault zone, (3) structural patterns of sequence stratigraphy and depositional system and (4) the distribution of potential sandstone reservoir.

**Database and Methods**

The available fundamental data related to Huanghekou depression is abundant including 1000 km 2D seismic lines (1×1km or 1×2km), 1470 km² 3-D seismic data, 47 exploration wells drilling to Paleogene strata (11 of them are coring wells), cores, well logging data and paleontological records. Our study is based on the combination of all kinds of data. All the data mentioned here are provided by Tianjin branch, CNOOC.

In this study, we focused on traditional sequence frame as well as separate disciplines, such as tectonics, sequence stratigraphy and biostratigraphy. We divided sequence by analyzing the logging information and palaeontological records comprehensively, in the meanwhile, we identified structural surfaces, sequence boundaries and maximum flooding surface by marking seismic unconformities, such as truncation, onlap, toplap and downlap flooding surface by marking seismic unconformities, such as structural surfaces, sequence boundaries and maximum flooding surface by marking seismic unconformities, such as truncation, onlap, toplap and downlap. Geological information and seismologic information are unified in this study. By mutual identifying and calibrating well-logging and seismic data, we have laid a foundation for building a reasonable and accurate sequence frame in the studying area. The terminology used in this paper is from Vail et al.

**Geology setting**

Evolving on the old China-Korea platform, Huanghekou depression covers the area of 2370 km². The depression is located in the Southeast Bohai Bay basin. The north boundary of the depression is Bonan low uplift while the Laibei low uplift is in the south of the depression. The whole depression can be divided into three uplifts and two sags. The largest burial depth is 7000m. The tectonic trend of the depression is nearly W-E. From north to south evolved two half-grabens (Fig.1). Two groups of NNE trending faults in east Huanghekou depression are considered as the west branch of Tan-Lu fault zone. The trend of the faults is oblique to the trend of the depression. On the south gentle slope belt, the faults even vertically intersect the depression (Fig. 1, Fig. 2).

Paleogene Huanghekou depression has experienced 4 complex tectonic activity stages and multi-stage transformation of the lacustrine transgression-regression. The main development period of rifting was from Eocene to Oligocene. The characteristics of tectonic evolution in the depression can be summarized as multistage rifting, multiple cycles’ superposition and multiple genetic mechanisms (Fig. 2). After each rifting period, the fast change of lake level and regional uplifting usually occurred. Because the strata deposited in early stages was eroded, the unconformity type between late-stage strata and former-stage strata is angular unconformity or disconformity (Fig. 3).

The Paleogene Huanghekou depression includes, from old to young, Kongdian, Shahejie and Dongying formation. The Shahejie and Dongying formation can be further divided into the Shahejie 2nd, Shahejie 3rd, Shahejie 4th, Shahejie 5th, Dongying 2nd, Dongying 3rd and Dongying 4th member. Furthermore, Shahejie 3rd member can be divided into lower Shahejie 3rd member and the middle Shahejie 3rd member. One thing should be pointed out here that upper Shahejie 3rd member does not exist due to strong weathering.

Paleogene Huanghekou depression is a potential oil-gas reservoir in Bohai Bay basin (Fig.1). Multi-stage tectonic activities and various sediments supplying systems are advantages in the formation of high-quality reservoir-seal assemblage. Because of its enormous oil-gas exploration potential, Huanghekou depression plays a great role in oil-gas reserving in the area of Bohai Bay basin.

**Sequence stratigraphy and depositional system in rift lacustrine basin**

**Characteristic of sequence stratigraphy:** The sequence boundary of Paleogene Huanghekou depression can be
divided into the 2nd order and the 3rd order sequence boundaries. The 2nd order sequence boundary is defined as regional tectonic unconformities. On seismic images, the 2nd order sequence boundaries can be recognized by tracing the interfaces of toplap and truncation or the surfaces at which seismic wave properties change (Fig.4). According to well-logging data, the 2nd order sequence boundaries can also be identified as surfaces of discontinuity of lithologies, depositional facies and paleontological categories and population (Fig.3).

Compared to the 2nd order sequence boundary, the scales of unconformities or depositional discontinuities are smaller in the 3rd order sequence. The seismic reflection properties of the 3rd order sequence boundaries include onlap, toplap and regional truncation (Fig.4). In terms of well coring and logging, the 3rd order sequence boundaries are also identified as surfaces at which lithology contact relation changes. In the meanwhile, we further divided the 3rd order sequence into system tract, the boundary of which is mfs. The system tract includes EST and HST. Because the slope break belt in this area is missing, LST is not included\textsuperscript{10}. On seismic profiles the maximum flooding surfaces can be easily identified and traced\textsuperscript{10} as reflection surfaces with high continuity and amplitude or the surfaces to which downlap points gradually converge (Fig.4). The maximum flooding surfaces are usually characterized by thick mudstone section in terms of well-logging (Fig. 3).

The Paleogene sequence of Huanghekou depression can be divided into three 2nd order sequences, which are, from old to young, Paleocene-Eocene Kongdian-Shahejie\textsuperscript{4th} member SQ9-8 2nd order sequence, Shahejie\textsuperscript{3rd} member SQ7-6 2nd order sequence and Eocene-Oligocene Shahejie\textsuperscript{2nd} member Dongying SQ5-1 2nd order sequence. We put Kongdian formation and Shahejie\textsuperscript{4th} member in one 2nd order sequence because there is no clear boundary between them. From bottom up the boundaries between each 2nd order sequence are SB9, SB7, SB6 and SB0. SQ7-6 2nd order sequence can be further divided into two 3rd order sequences which are lower Shahejie\textsuperscript{3rd} member SQ7 and middle Shahejie\textsuperscript{3rd} member SQ6. The bottom surfaces of SQ7 and SQ6 are SB7 and SB6. Shahejie\textsuperscript{2nd} -Dongying SQ5-1 2nd order sequence is further divided into five 3rd order sequences: Shahejie\textsuperscript{2nd} member SQ5, Shahejie\textsuperscript{3rd} member SQ4, Dongying\textsuperscript{3rd} member SQ3, Dongying\textsuperscript{2nd} member SQ2 and Dongying\textsuperscript{1st} member SQ1. Corresponding bottom surfaces are SB5, SB4, SB3, SB2 and SB1. We then divided lower Shahejie\textsuperscript{3rd} member SQ7, middle Shahejie\textsuperscript{3rd} member SQ6, Dongying\textsuperscript{3rd} member SQ3 and Dongying\textsuperscript{2nd} member SQ2 into system tracts based on regional geological data. From bottom up, system tracts are ESTSQ7, HSTSQ7, ESTSQ6, HSTSQ6, ESTSQ3, HSTSQ3, ESTSQ2 and HSTSQ2 (Fig. 3).

**Characteristic of depositional systems**

Based on the analysis of seismic and depositional facies, we have identified that the typical depositional systems evolved in Paleogene Huanghekou depression are fan delta, braided river delta, meandering river delta, lacustrine depositional system and sublacustrine fan (Fig.5 and Fig.6).

**Fan Delta Depositional System**

Fan delta is a deltaic deposit formed by progradation of alluvial fan into water-filled basin. The fan delta in this study is close to northern faulted zone and provenance. We divided it into three depositional sub-facies: plain, front and fore-fan delta. The major components of this fan delta are the proximal bar and the distal bar on the advancing edge of the delta. On seismic profiles, the typical characteristics of the fan delta are the wedge-shaped progradation reflection configuration with medium-low frequency, amplitude and continuity (Fig.4a). Well-logging curves are characterized by low gamma, high spontaneous potential of the seawater slurry, obviously toothed and finger-shaped or funnel-shaped pattern (Fig.5).

The dominant lithological association in proximal bar depositional micro-facies is conglomerate, glutentite,
conglomeratic coarse sandstone and coarse sandstone, intercalated with thin-beded dark siltstone and mudstone. The large-scale inclined bedding of mudstone deposits, large-scale cross-bedding and the imbricate or orientated arrangement of gravel can be found in sampled cores. The gravel is dominant by fine gravel (≤7 cm) with shapes of subangular or subrounded (Fig.6). The underwater debris flow deposits accumulated by a small amount of gravel, sand and mud can also be found in this depositional micro-facies. The distal bar depositional micro-facies are unequal interbedded medium sandstone, fine sandstone and dark mudstone (Fig.5). Assorted depositional types have been found in samples cores, including the large-scale inclined bedding of mudstone deposits, large-scale cross-bedding, corrugated and corrugated cross-bedding, the orientated arrangement of gravel and intercalated slump deposits (Fig.6).

**Braided River Delta Depositional System**

Mcpherson et al.\(^5\) defined braided river delta as the coarse debris delta complex formed by progradation of braided river way into water bodies. Braided river delta evolved on both gentle and steep slopes in the depression. Compared to other depositional systems, on seismic profiles, braided river delta is characterized by progradation reflection configuration with medium-low frequency, amplitude and the continuity (Fig.4a,b).

Similar to the fan delta mentioned above, the braided river delta in this study can also be divided into three sub-facies. The major components of the delta are the mouth bar and the far bar on the advancing edge of the delta. For the mouth bar, the dominant rock types are conglomerate, glutenite, conglomeratic coarse sandstone, coarse sandstone, medium sandstone and fine sandstone. And the dominant depositional structures are blocky bedding, the oriented arrangement of gravel in conglomeratic coarse sandstone and the convolute lamination in fine sandstone (Fig.6).

The main patterns of SP well-logging curves are in the shapes of funnel or box and the gamma value is low (Fig.5). Far from the provenance, the far bar is mainly composed of interbedded fine sandstone, dark siltstone and argillaceous siltstone. Apparently, the rock grain size decreased due to the long distance between the far bar and provenance. The dominant depositional structures are wedge-shaped cross bedding, load structure and gentle corrugated bedding (Fig.6). The logging curves of far bar are characterized by low-medium gamma value, medium-high spontaneous potential of the saltwater slurry, obvious toothed and finger-shaped or funnel-shaped pattern (Fig.5).

During the period of lacustrine expanding system tract, the water body in the Paleogene sequence of the braided river delta deepened upward. At that time, the far bar overlapped on the mouth bar forming the depositional cycle with grain size decreasing upward. During the period of high system tract, the water body became shallower upward and the braided river delta gradually moved toward basin. The mouth bar was overlapped on the far bar, forming the depositional cycle with grain size increasing upward.

**Meandering River Delta Depositional System**

Meandering river delta is formed by the deposition of the large amount of the terrestrial debris carried by rivers along the long axis direction into the lake (sea) basins. The meandering river delta normally deposited in the mouth region and it is a depositional body with the top tip towards the land. On seismic profiles, the delta is characterized by the progradational reflection with medium-high amplitude and medium continuity.

There are two depositional sub-facies in the meandering river delta in this study region, which are delta front and pro-delta. Mouth bar and far bar on the delta front are two dominant depositional micro-facies in this area. Compared to braided river delta, the sediments grain size in meandering river delta is even smaller. In mouth bar, the dominant rock types are conglomeratic sandstone, medium sandstone, medium-fine sandstone, fine sandstone and intercalated thin-beded mudstone (Fig.5). Large scale oblique bedding can be spotted in the mouth bar sequence (Fig.6). The far bar is made from interbedded sandstone, siltstone, muddy siltstone and mudstone (Fig.5). Gently corrugated bedding and large scale oblique bedding can be found in the far bar sequence (Fig.6).

The meandering river delta in this study area regionally evolved in the middle and late period of Dongying formation, for example, in the sequences of HSTSQ2 and SQ1. The depositional cycle formed in SQ2 has the typical characteristics which include the grain size increasing upward, the reverse cycle with funnel shaped well-logging curve. The complete positive cycle and reverse cycle can be both identified in the depositional cycle evolved in SQ1 sequence (Fig.6).

**Lacustrine Depositional System**

We divided lacustrine depositional system into 3 depositional sub-facies which are shore lacustrine depositional system, shallow lacustrine depositional system and semi deep-deep lacustrine depositional system. In this paper we discussed the shore lacustrine and the shallow lacustrine depositional systems together because the boundary between them is obscure.

**Shore and Shallow Lacustrine Depositional System:** According to the environment of shore and shallow lacustrine and its sediments’ properties, the shore and shallow lacustrine depositional system contained muddy beach, mixed beach and sandy beach bar. And we considered the sandy beach bar deposits as the dominant depositional micro-facies in the study area during the period of Dongying formation. The prosperous period for development of the sandy beach bar deposits was between
HSTSQ3 to ESTSQ2.

Sandy beach bar was often formed in a shore and shallow lacustrine region where the supply of large-sized terrestrial debris is abundant and lake scouring effect is strong. The depositional sequence of the sandy beach bar is composed of fine sandstone and siltstone. The grain size of sediments increased from bottom up (Fig.5). Low angular cross bedding and blocky bedding are dominant depositional structures (Fig.6). The patterns of well-logging curve are characterized by low gamma value, medium-high spontaneous potential of saltwater slurry and toothed bell, finger and funnel shape (Fig.5). The seismic reflection wave is characterized by medium-low amplitude but the seismic wave on the background of medium-low continuous sub-parallel reflection or wedge-shaped spread reflection has high amplitude. Mounded bidirectional downlap structure is spotted on the seismic profile (Fig.4a).

Semi Deep-Deep Lacustrine Depositional System

The sediments in semi deep-deep lacustrine depositional system are dark mudstone with the depth of tens or hundreds of meters, accompanying with turbidity current deposits, parallel bedding and blocky bedding (Fig.6). The well-logging curve has high gamma value, high spontaneous potential of the seawater slurry and toothed pattern (Fig.5). Seismic reflection wave shows high amplitude and high continuous parallel structure (Fig.4a, b).

Sublacustrine Fan Depositional System

Sublacustrine fan was formed by the deposition of debris carried by gravity current. The sediments travelled down the steep slope and deposited on the lake floor. The dominant depositional types in the sublacustrine fan in this study are collapse deposits, debris flow deposits and turbidity current deposits.8,38 There are various sediments in the collapse deposits. The sediments formed the individual depositional blocks of sand and mud with sliding deformation structure showing sliding leap, collapse blend and convolute bedding (Fig.6). Debris flow deposit is a complex of gravel, sand, mud and water.

It is common to see the random arrangement of the long axis of gravel or boulder clay in debris flow deposits. The turbidity current deposits usually appear as B section horizontal bedding and deformed corrugated bedding in Bouma sequence. It is rare to see the upward-fining cycle in the turbidity current deposits. Erosion surface is at the bottom of the deposits (Fig.6). On seismic profile, sublacustrine fan shows as bidirectional downlap reflection wave with mound shape. The well-logging curve shows low-medium gamma value, medium-high spontaneous potential of the seawater slurry and toothed curves with bell and box shape (Fig.5).

Structural characteristic of the rift lacustrine basin

Analysis on the structural characteristic of the Huanghekou depression: The south Huanghekou depression is higher and more flat than the north. From south to north, the depression can be divided into south gentle slope belt, south sag, BZ33 tectonic belt, north sag and north steep slope belt (Fig.1). Multiple tectonic belts are evolved in the south and north while under water upheaval evolved in the middle of the depression.

The tectonic evolution of Huanghekou depression is similar to that of Bohai Bay basin. Based on tectonic profile analysis we believe that Paleogene Huanghekou depression has experienced two tectonic periods. The one is rifting period and another is strike-slip rifting period. The rifting period can further be divided into initial rifting period and active rifting period. Huanghekou depression is under control of strike-slip duplex tectonic mechanisms and therefore evolved three kinds of fault systems in the depression which are (1) the fault system controlling the depression, (2) the west branch strike-slip fault system of Tan-Lu fault zone, (3) the secondary fault system controlled by (1) and (2) (Fig.8).

The “half-graben” fault system controlling the depression is WE. Syndeposition distributed on both north steep slope and south gentle slope in the depression. Two or three groups of syndepositional faults evolved in the depression from Bonan low uplift to north sag and during the period of SQ9-8 depositional sequence the number of syndepositional faults is even bigger (Fig. 9b, Fig. 10). These basin-edge faults evolved in the major fracture of depression-controlling boundary. The boundary subsided continuously because of the huge height difference between upper wall and foot wall caused by long-term activity of the fracture. The depression-controlling fault system, including the 1st order depression-controlling fault system (Fig.9a, Fig.10) that belongs to the single syndepositional faults type, also exists on the south gentle slope due to the tension forced by an oblique basement block (Fig.9c). However, unlike the fault systems on the north slope, those on the south slope are smaller and the number of syndepositional faults in the south is much less than that in the north.

The west branch strike-slip fault system of Tan-Lu fault zone is composed of NNE strike-slip faults and surrounding tectonic units (e.g. strike-slip transform belt). The strike-slip faults show NNE plan distribution and obvious dextral properties. The strike-slip transform belt, consisting of a series of en echelon anticlines, locates in the eastern uplift in Huanghekou depression. Overlaid faults tilt in one direction at the intersection on the west branch of Tan-Lu fault zone, showing negative flower structure on the seismic profile (Fig.7i, Fig.9d).

WE secondary fault systems in the basin are controlled by tensional stress and strike-slip tensional stress. During the rifting period, Tan-Lu fault zone was controlled by extensional stress which is similar to the depression-controlling faults. Depression-controlling growth-faults controlled the evolution of secondary faults in the basin in
initial rifting period. The scale and population of the secondary faults are small and the faults combination shows fault-step pattern. The depression-controlling faults became more active during SQ6-SQ5 depositional period (Table 1) when the population of the en echelon secondary faults became growing and the trend of the secondary faults is the same as that of the depression-controlling faults (Fig.8). During the strike-slip rifting period, Tan-Lu fault zone became to show dextral strike-slip properties and intersected vertically or obliquely with the normal fault in the depression. At this time, the secondary fault system was under control of extension and strike slip, showing WE en echelon arrangement. Fault activity was frequent in this period, especially normal faults, such as the secondary fault system to the south of the north steep slope and the secondary fault system on BZ33 tectonic belt which is more typical (Fig.8).

Analysis on the evolution and effect of the Tan-Lu fault zone

Although the deformation of lithosphere or crust was affected by the extensional stress during the tectonic process of Paleogene Huanghekou depression, for Tan-Lu fault zone, the strike-slip effect was actually more important. Because of the effect of the strike-slip, the differences between Bohai Bay basin and other fault basins are enormous. Therefore, to analyze the development characteristics and evolution history of Paleogene Tan-Lu fault zone is critical in understanding the macro-characteristics of Bohai Bay basin and building the development model of sequence stratigraphy and depositional structure.

It is well-known that Tan-Lu fault zone has experienced multi-stage and multi-property tectonic activities. Different people have different view on Cenozoic kinematics characteristics of Tan-Lu fault zone in Bohai Bay basin. Most people believe that Tan-Lu fault zone was dextral strike slip on the background of Cenozoic Bohai Bay tectonics. But there is still an argument on when the dextral strike-slip occurred.\(^{3,11,13,16,35,49}\)

Here we argue that the Tan-Lu fault zone strike-slip period was between late Eocene to late Oligocene based on the analysis of Paleogene tectonic and topography in the study area. At the beginning of Paleocene, Pacific plate was moving toward East China continental margin, changing from Cretaceous oblique subduction to middle velocity direct subduction\(^{36,47}\). This huge change resulted in the asthenosphere upwelling and lithosphere thinning in eastern China\(^{15,40}\). At that time, Bohai Bay basin was experiencing the large-scale extensional depression and Tan-Lu fault zone extension. Lithosphere thermal effect forced extension which also explains why extension can be passed through discontinuous continental blocks.

The stress field in eastern china changed significantly in late Eocene because of surrounding plate activities. The stress field varied from extension to NE-NEE side extrusion. Tan-Lu fault zone shows obvious dextral strike-slip properties in Oligocene due to the long-distance effect of the collision between Indian plate and Eurasian plate and the large-scale back arc expansion of western Pacific plate\(^{14,17,30,43}\). In terms of Huanghekou depression, this change led to the decreasing activity of depression-controlling growth faults (Table 1). In this study, we named syndepositional faults and calculated eight fault growth indexes in each sequence by counting stratum thickness of different sequences on upper wall and foot wall (Table 1). Between Paleocene and early Eocene, the basin was in the early period of extensional depression and some faults activity were reactivation or inheritance from the old ones, while others are new faults caused by extension.

Middle Eocene is the peak period of fault activity because extensional depression became intense and extensional stress was strong. The scale and population of depression-controlling growth fault became smaller in Late Eocene (Fig.10). The growth index of depression-controlling fault decreased dramatically after SQ5 and syndepositional characteristics even disappeared in some faults (Table 1). This process can also be observed in the changes of the topographic features in each sequence. In south basin edge, the strata on the east and west of the strike-slip fault dislocated obviously due to the dextral strike-slip. The dislocation stopped in Late Oligocene which indicates that the dextral strike-slip ended in Late Oligocene (Fig.11, Fig.12).

However, in the most area of the depression, the boundary faults controlling steep slope are still in extensional stress field without showing any tectonic inversion. This may be because the lateral extrusion has been counteracted by the strike-slip adjusting effect of Tan-Lu fault zone. Another possible explanation is the extensional stress that is vertical to mantle uplift axis has counteracted the lateral extrusion. And this extensional stress was probably caused by thermal expansion and thermal diapir at the bottom of lithosphere.

Tan-Lu fault zone western branch are not only important to tectonic transportation and regulation in Huanghekou depression but also regulating the secondary fault activities. Another regulating factor is the depression-controlling growth fault. The relative strength of these two tectonic mechanisms caused the different features in secondary fault systems.

The active period of the secondary faults determined in this study is in agreement with other studies\(^{3,16}\). The interaction between extensional fault and strike-slip fault not only led to obvious geomorphic units of faulted troughs and valleys (e.g. Bonan low uplift in the north of the depression and Laibei low uplift along the strike-slip fault) (Fig.11, Fig.12b) but also caused the special patterns of sequences and depositional systems since the interaction areas are regions where rivers flew into lakes and debris deposited on lake floor.
Discussion
Models of the sequence stratigraphy and depositional architecture: In terms of dynamics, sedimentation volume distribution reflects ancient tectonics and landform. Different basin types have different dynamic mechanisms. The model and velocity of sediments supply are under control of tectonic process in different degrees and different forms which resulted in different orders in depositional cycles and sequences and different patterns in depositional systems.

The leading depositional principles we used in this study are tectonic controls facies, deep valley controls delta and underwater uplift controls beach bar. We analyzed the sequence, depositional systems, tectonics and topography of Paleogene Huanghekou depression comprehensively. We prefer to discuss the sequence stratigraphy and depositional patterns of Huanghekou depression in two separate periods. One is Paleocene-Middle Eocene on the background of the extension and the other is Late Eocene-Oligocene on the background of the duplex tectonic mechanism of strike slip and extension. In addition, we describe the features of temporal and spatial distribution of the sequence stratigraphy and depositional systems in the depression.

Under the background of the extension tectonic mechanism: From Early Paleocene to Middle Eocene, Huanghekou depression was controlled by extensional stress. The long-term fault activity in north steep slope belt led to the height difference between upper wall and foot wall became larger. Continuous subsiding boundary was formed and sequence stratigraphy was dominant by structural deficiency caused by fault. The features of the middle depression were similar to that of the north depression. However, the south gentle slope belt was quite different from northern depression. Stratigraphic overlap was the dominant type of stratigraphic unconformity.

The extensional stress in south was less strong than north because the slope was gentler and the distance between fault zones was relatively larger. In south gentle slope belt, divergent stress built several sediments output channels on regional highlands which mainly controlled the braided river delta. There were two intervals between north and middle, middle and south tectonic belts. Controlled by fault zones, the accommodation space of these intervals became larger since the lake became deeper. The sediments supply also became more abundant. As the result, the sequence of the depression showed the variation as “thin-thick-thin” (Fig.12a).

At the beginning of the riftting period, several fan deltas and sublacustrine fan depositional systems evolved in the north and middle depression. At that time, the faults were steep. During the progradation, the fan delta gradually evolved into braided river delta because it was controlled by secondary faults. Small scale braided river deltas also evolved in valleys in south gentle slope belt. After that, as the fault activity on basin edge became stronger, the south depression was more and more affected by depression controlling growth faults. While in the middle and south tectonic belts, the scale of fan delta became larger. In the meanwhile, the braided river delta continued evolving in the south tectonic belt valleys.

The scale of the braided river delta also became larger due to the abundant sediments supply in the south. The south belt braided river delta achieved the largest scale in the late pure extensional period when sediments supply was still abundant and the faults on the basin edge were less active (Fig.12a).

Under the background of the extension and the strike-slip tectonic mechanism: Between Late Eocene and Late Oligocene, extensional stress continued affecting on Huanghekou depression. The dextral strike slip of Tan-Lu fault zone was caused by the change of stress fields in Bohai Bay basin in the same time. Valley topography can be found in the depression, especially on the uplifting edge of the depression. Both the population and contribution of sediments supply channels were essentially different from the former ones, which were much more favorable for the formation of depositional bodies (Fig.12b).

Regarding to the strata in this period, strike-slip movement horizontally changed the location where debris was transported into the depression. Consequently, the depositional system migrated horizontally along the strike-slip fault. The depositional system therefore became newer and newer. For example, in Early Oligocene, the west and east provenances in Bonan low uplift were affected by strike-slip deformation in the western branch of Tan-Lu fault zone. As the result, the deltas migrated from south to north and overlapped with each other and the depositional systems formed in valleys during this period also overlapped with each other (Fig.13).

Between Late Eocene to Late Oligocene, structural deficiency which was caused by faults still existed in the north steep slope belt. Due to the inheritance of former faults, the thickness of the stratum in descending fault area increased abruptly and therefore the accommodating space enlarged. The dominant depositional system at the bottom of the north belt was the braided river delta. As soon as lake area extended, the braided river delta would change into meandering river delta due to the top-lifted effect of water body on rivers. From the beginning of Eocene, large-area sandy beach bar has evolved in the middle tectonic belt BZ33.

Under water uplifting, submerged by water, shoal forming and tectonic highlands building by strike-slip faults in this area were all advantages during sandy beach bar formation. In the meanwhile, the basin edge faults almost disappeared in south belt. Some of the faults have transformed into slopes. The dominant unconformity type was stratigraphic
overlap. Affected by Tan-Lu fault zone, several stress fields intersected in the south belt to form several valley channels. Because the braided river delta was highly controlled by these channels, it continuously evolved and finally became a large-scale delta (Fig.12b).

Fig. 3: Frameworks of the Paleogene stratigraphic record of Huanghekou depression in Bohai Bay Basin consists of the Kongdian, Shahejie and Dongying formations in ascending order.

Table 1
The characteristic analysis of key syndepositional faults

<table>
<thead>
<tr>
<th>Fault</th>
<th>Location</th>
<th>Strike Direction</th>
<th>Dip Direction</th>
<th>Paleocene</th>
<th>Eocene</th>
<th>Oligocene</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SQ9-8</td>
<td>SQ7</td>
<td>SQ6</td>
</tr>
<tr>
<td>F1</td>
<td>Besides W4</td>
<td>NNE</td>
<td>NWW</td>
<td>1.20</td>
<td>1.30</td>
<td>1.02</td>
</tr>
<tr>
<td>F2</td>
<td>East to W1</td>
<td>WE</td>
<td>N</td>
<td>1.81</td>
<td>3.65</td>
<td>3.29</td>
</tr>
<tr>
<td>F3</td>
<td>North to W7</td>
<td>NNE</td>
<td>NWW</td>
<td>1.82</td>
<td>1.65</td>
<td>1.94</td>
</tr>
<tr>
<td>F4</td>
<td>Southeast to W5</td>
<td>NEE</td>
<td>SSE</td>
<td>1.21</td>
<td>1.20</td>
<td>2.10</td>
</tr>
<tr>
<td>F5</td>
<td>West of the sag</td>
<td>NS</td>
<td>E</td>
<td>1.23</td>
<td>1.61</td>
<td>2.47</td>
</tr>
<tr>
<td>F6</td>
<td>South to W6</td>
<td>WE</td>
<td>S</td>
<td>1.51</td>
<td>2.68</td>
<td>1.77</td>
</tr>
<tr>
<td>F7</td>
<td>South of the sag</td>
<td>NE</td>
<td>NW</td>
<td>1.61</td>
<td>2.68</td>
<td>3.63</td>
</tr>
<tr>
<td>F8</td>
<td>South to W8</td>
<td>NNE</td>
<td>NW</td>
<td>1.62</td>
<td>1.57</td>
<td>2.21</td>
</tr>
</tbody>
</table>
Fig. 4: 3-D seismic profiles in Huanghekou depression showing the sequence boundaries (SB), the maximum flooding surface (mfs) and the seismic response to the depositional systems in Dongying Formation: (a) Seismic profile through W1 and (b) Seismic profile through W2 and W3.
Fig. 5: Vertical successions of (a) Fan delta depositional system (b) Braided river delta depositional system (c) Meandering river delta depositional system (d) Shore and Shallow lacustrine depositional system (e) Semi Deep-Deep lacustrine depositional system and (f) Sublacustrine fan depositional system in the Huanghekou depression. Wireline logs are gamma ray (GR) and self-potential curve (SP).

Fig. 6: Core photos of representative depositional systems (a) Long-axis oriented gravel of proximal bar and gently corrugated bedding of far bar in fan delta depositional system (b) Convolute bedding and blocky bedding and oriented boulder clay of mouth bar and gently corrugated cross bedding and wedge-shaped cross bedding and load structure of far bar in braided river delta depositional system (c) Gently corrugated bedding and large oblique bedding of in meandering river delta depositional system (d) Blocky bedding and low angular cross bedding in shore and shallow lacustrine depositional system (e) Dark gray mudstone in semi deep-deep lacustrine depositional system (f) Fine sandstone with the convolute bedding and reverse graded conglomeratic coarse sandstones and glutenite with boulder clay in the sublacustrine fan depositional system.
Fig. 7: The history of the tectonic evolution from SQ9 to SQ1 in Huanghekou depression: (1) The initial rifting period (a-b) (2) The active rifting period (c-d) (3) The strike-slip rifting period (e-h) and (4) The present tectonic structure (i).
Fig. 8: The plane distribution of the faults in each sequence of Huanghekou depression.

Fig. 9: The seismic reflection characteristics of various fault systems in Huanghekou depression: (a) The single syndepositional fault in the south gentle slope (b) Multiple syndepositional faults in the south gentle slope (c) Multiple syndepositional faults in the north steep slope (d) The negative flower structure of the west branch of Tan-Lu fault zone.
Fig. 10: The plane distribution of the syndepositional faults in the main sequences of Huanghekou depression.

Fig. 11: The plane distribution of the palaeogeomorphology in each sequence of Huanghekou depression.

Fig. 12: The models of the sequence stratigraphy and depositional architecture of rift lacustrine basin under different structural mechanism background: (a) under the background of the extension tectonic mechanism (b) under the background of the extension and the strike-slip tectonic mechanisms.
Fig. 13: The model of Dongying Formation deposits influenced by strike-slip fault system.

Fig. 14: Sandstone reservoir classification of the different depositional microfacies in Huanghekou depression: (a) Low porosity and permeability reservoir mainly in proximal bar of fan delta (b) Low porosity and permeability reservoir mainly in far bar of fan delta (c) Medium porosity & low permeability and low porosity and permeability reservoir mainly in mouth bar of braided or meandering river delta (d) Medium porosity and low permeability and low porosity and permeability reservoir mainly in far bar of braided or meandering river delta and (e) Medium porosity and medium-high permeability and medium porosity and low permeability reservoir mainly in sandy beach bar of the shore and shallow lacustrine depositional system.
Characteristic of different reservoirs in different models:
Tectonic activity is the most important factor during the formation of rift lacustrine basins. Because the tectonic activity changes topography and therefore changes the erosion rate, sediments supply rate and sediments type. Different depositional systems will form which bring us different types of sandstone reservoirs. The statistical unit used in this paper is depositional micro-facies. We compared physical properties (e.g. porosity and permeability) in different types of sandstone reservoirs (Fig.14). Sublacustrine fan is not available due to data scarce. According to fig.12 and fig.14, under the background of extension, the most favorable sandstone reservoirs distributed in the mouth bar and the far bar in the braid river delta in the south gentle slope belt. In the late stage of extension, favorable shore and shallow lake sandstone reservoirs appeared in the middle tectonic belt but the distribution was limited. Under the background of strike-slip extension, large-area sandy beach bar evolved in the middle tectonic belt because of the continuous underwater uplifting and strike-slip effect. In conclusion, the most favorable sandstone reservoirs are shore and shallow lake sandstone reservoirs.

Conclusion
By combining seismic profiles, well-logging data, core and paleobiological records, we identified 13 sequence boundaries in Paleogene Huanghekou depression. The boundary between Mesozoic and Paleocene is SB1, SB3 is the boundary between Eocene and Oligocene and SB0 is the one between Oligocene and Miocene. Others are boundaries among 3rd order sequences. In addition, we identified three 2nd order sequences and nine 3rd order sequences. 3rd order sequence SQ7, SQ6, SQ3 and SQ2 are further divided into extension tract and high tract. There are various depositional systems evolved in Paleogene Huanghekou depression including fan delta, braid river delta, meandering river delta, lacustrine and sublacustrinefan depositional system.

Based on analysis of tectons and topography, we concluded that the tectonic evolution in Paleogene Huanghekou depression can be divided into two periods which are rifiting period and strike-slip rifiting period. Three fault systems evolved in this area, which are (1) depression-controlling growth fault system. (2) west branch strike-slip fault system of Tan-Lu fault zone and (3) the secondary fault system affected by (1) and (2). The strike-slip period of Tan-Lu fault started in Late Eocene before which was the pure extension period and after which was the period of the duplex mechanisms of extension and strike-slip.

Under the extensional background in Paleogene and Middle Eocene, the north belt sequence in Huanghekou depression was characterized by stratigraphic deficiency caused by faults. The fan delta and sublacustrine fan evolved in this period. The middle tectonic belt was similar to the north belt. The dominant unconformity in south tectonic belt was stratigraphic overlap. The braid river delta was the dominant depositional system in the south.

Between Late Eocene and Late Oligocene, the north belt was controlled by depression-controlling fault system and strike-slip Tan-Lu fault west branch. The stratigraphic deficiency still existed and the dominant depositional system was meandering river delta. The large-scale sandy beach bar evolved in the middle tectonic belt. The large braid river delta was continuously developing in the south belt. The most favorable sandstone reservoirs distributed in the mouth bar and the far bar in south belt braid river delta during the extensional period, while in the strike-slip extensional period, they distributed in sandy bar on shore-shallow lake sandy beach.

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