The Analysis of Tectonic Controls on the Shale Distribution and Its Resource Potential in Lacustrine Basins in East China*

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Abstract

The shale gas and shale oil potentials in the Meso-Cenozoic lacustrine basins are worth investigating since China produces most of its oil from lacustrine basins. The organic-rich semi-deep to deep lacustrine shales are widely distributed in East China, North China, Northwest China, and Southwest China with an area of nearly (23-33) $\times 10^4$ km^2 (Zhang et al., 2009 and Zou et al., 2010). The shale gas and shale oil potentials in these lacustrine basins could be significant since almost more than 50% generated hydrocarbons are still trapped in the source shales. This study mainly focuses on the most important lacustrine shales from rifted basins in East China, e.g., Paleogene Bohai Bay Basin, Cretaceous Songliao Basin, etc. Compared with marine shale, the lacustrine shale has some similarities regarding the extensive distribution within the basin and some similar geochemical parameters. However, for lacustrine basins in East China, there are many unique features in the aspects of tectonic activities, depositional environment, thermal evolution, etc. Generally, the lacustrine shale in East China is characterized by high content of organic matter (up to 30%), lower maturity (usually less than1.5%), high clay mineral content, complex tectonic setting, rapid lateral shale facies changes, and interbedded sandstones or carbonates within the shale. The shale gas potential is mainly distributed in the areas of high maturity shales and shale oil potential is mainly located in areas with low maturity shales for lacustrine basins in East China.

Tectonic activity controls the deposition in lacustrine basins in eastern China. For the Mesozoic-Cenozoic lacustrine basins in East China, the sequence stratigraphic architecture, sedimentary environment, space-time distribution of shales, and the fracture orientation of shales were strictly controlled by episodic tectonic activities. The geochemical properties of shales deposited in different stages also vary. The hydrocarbon generation potentials and shale distribution extent are the largest during the stable subsidence or high lake level

periods. Hydrocarbon source rocks are the shales of the Qingshankou Formation and the first member of the Nenjiang Formation of Cretaceous age in Songliao Basin. In the different stages of evolution and the different depression in the Bohai Bay there have been four sections of hydrocarbon source rocks of Paleogene age: the Kongdian Formation, the fourth member (Es4), the third member (Es3), and the first member of the Shahejie Formation (Es1), the lower part of the Dongying Formation.

Songliao Basin

Songliao Basin in northeastern China is the Mesozoic death continental rift basin and is a part of the eastern China rift system. There are three major faults: North-North East or North East, North West, and East-West of the basin. The NNE and NE trending faults controlled the eastern and the western boundary of the basin. Then the basin was north-northeast trending (Figure 1). The evolution of Songliao Basin is divided into three stages of the early rift, thermal subsidence stage, and the shrinking of the late. The strata of the basin is divided into bottom-up: the upper Jurassic Huoshiling Formation (J3h), the Lower Cretaceous Shahezi Formation (K1sh), the Yingcheng Formation (K1y), the Denglouku Formation (K1d), the Quantou Formation (K1q), the Qingshankou group (K1qn), the Upper Cretaceous Yaojia Formation (K2y), the Nenjiang Formation (K2n), the Sifangtai Formation (K2s), and Ming-water group (K2m) (Figure 2) (Liu et al., 1992).

In different evolutionary stages of the Songliao Basin, there has formed different tectonic palaeogeomorphology controlled by tectonic activity and developed the special types of depositional system of each period. In particular, during the basin thermal subsidence stage, the whole basin has stably subsided. The scope of the basin was expanding and the central uplift belt all sank underwater and gradually disappeared. The basin formed a unified center of the catchment. The subsidence center of the basin coincided with the depocenter. The deposition rate was small. In particular, during the early Qingshankou Formation and the early Nenjiang Formation, they were the two main subsiding stages of the basin. There also developed two major transgressive events. The external environment was conducive to the development of two sets of hydrocarbon source rocks.

During the early Qingshankou Formation (the first member), there occurred the first transgressive event, the entire Qingshankou Formation lithology is black mudstone and bottom-up coarsening; the stratigraphic thickness is about 200-300 m. During the early Nenjiang Formation (the first and the second member), there occurred the second transgressive event, the lithology is black mudstone and oil shale and is widely distributed (Hu et al., 2005). According to the analysis of hydrocarbon source rocks of the Qijia-Gulong Sag in the Songliao Basin, the organic matter of K_1qn is type II, type I and type III. The organic matter of K_2n^1 is type I. The organic carbon content of K_1qn and K_2n^1 are over 2.0%. The source rocks have entered the oil generation threshold (Wang et al., 2005).

In addition, there are many facts to show that two major transgressive events occurred in the depression stage of the basin development and synchronized with the global sea level rise leading to the lake and sea communication. Because of the massive global sea level rise, it caused sea and lake to communicate. The lake surface expanded, the water deepened, the wave base rose, photosynthesis interface shift, and lead to the lake underlying hypoxia tension. So the lacustrine mudstone was rich in organic matter in the formation of K_1qn^1, K_2n^1, and K_2n^2 were preserved to become the main source rocks of Songliao Basin (Figure 2) (Liu et al., 1992 and Wang et al., 2000).

According to the above analysis, during the stage of the early rift, the tectonic activity is strong and the basin is divided into several small rift depocenters. Small range of the lake basin, coupled with near provenance, high potential energy, shallow-water, and rapid accumulation characteristics, as well as frequent volcanic activity, resulting in this stage is not conducive to the development of black shales. In particular, during the basin thermal subsidence stage, the whole basin has stably faster subsided. The early segmentation of isolated small lake basin formed a unified catchment center. The scope of the basin was expanding and the central uplift belt all sank underwater and gradually disappeared. The basin formed a unified center of catchment. The subsidence center of the basin coincided with the depocenter. The deposition rate of the basin is small and the deposition thickness is approximately 3500 m. Wide basin, the slow deposition rate, coupled with the larger paleobathymetry, all of which provides favorable conditions for the development of the deep lake environment and black shale deposition.

In particular, during the early Qingshankou Formation and the early Nenjiang Formation, they were the two main subsiding stages of the basin. There also developed two major transgressive events. The external environment was conducive to the development of two sets of hydrocarbon source rocks. In addition, there are many facts to show that two major transgressive events occurred in the depression stage of basin development, and synchronized with the global sea level rise, leading to the lake and sea communication. The two main subsiding stages of the basin and the two major transgressive events which synchronized with the global sea level rise provided favorable conditions for the formation and preservation of black shales during the early Qingshankou Formation and the early Nenjiang Formation.

Therefore, the basin thermal subsidence, slow accumulation rate, large transgressive event, were the main controlling factors for the formation and preservation of the two sets of black shales of the K_1qn and the K_2n^1 in the Songliao Basin.

Bohai Bay Basin

Bohai Bay Basin was a Mesozoic and Cenozoic rift basin in and while it transformed into a depression basin in the Late Tertiary. From the northwest to the southeast, Bohai Bay Basin is divided into: Jizhong Depression, Cangxian uplift, Neihuang uplift, Huanghua Depression, Linqing Depression, Dongpu Depression, ChengNing uplift, Xialiaohe Depression, Liaodong Bay Depression, Bozhong Depression, and Jiyang Depression. All of the depressions and uplifts composed of the basic structural frame of the basin. The basin is controlled by deep faults between these tectonic units (Figure 3).

The Tertiary sedimentary systems were controlled by the paleo-tectonic, paleogeographic, and paleoclimatic in most areas of Bohai Bay Basin. Episodic tectonic movement and cyclical climate changes controlled the stratigraphic sequence and the development of the sediment in Bohai Bay Basin. Paleogene from bottom-up is divided into the Kongdian Formation (Ek), the Shahejie Formation (Es), the Dongying Formation (Ed) and the Neogene strata are divided into the Guantao Formation (Ng) and the Minghuazhen Formation (Nm) (Cai and Li, 2003). The fault strike directions are NNE-NE and NEE-EW in Bohai Bay Basin. The multi-episodic tectonic evolution of the basin can be divided into the rifting period (65.0-24.6 Ma) and the depression period (since 24.6 Ma). While the rifting period can be further subdivided into three screens: early rifting period (65.0-4 3.7 Ma), a stable rifting period (43.7-36.7 Ma), and a fault-depressed diversionary period (36.7-24.6 Ma). During the basin evolution, the climate has also experienced many cycles of drought-wet-drought, with a corresponding depositional system of the various stages in Bohai Bay Basin region (Figure 4).

According to the analysis of the extension amount of each depression of Bohai Bay Basin (Figure 5), it found that: (1) The extension of the rift stage is the biggest and almost zero in the depression stage; the tectonic activity was mainly tensile in the rift stage, while during the depression stage the tectonic activity was mainly thermal subsidence, and the fracture was very little development. (2) During the rift stage, the slope of the Es3 and Es2 (especially Es3) elongation curve surpasses the other two stretch stages; indicating that the tensile strength of the stretch II screen is greater than the I and III screen. (3) In the Xialiaohe Depression, the Liaodong Bay Depression, and the Bozhong Depression; the slope of the elongation curve is significantly smaller than other depressions during the stage of the stretch I screen, indicating that the Cenozoic tension may start from the western part of the basin and gradually crept to the eastern part of the basin. (4) In the Bozhong Depression, the Jiyang Depression, and the Huanghua Depression; the slope of the elongation curve is slightly larger than other depressions during the stage of the stretch III screen, indicating the fracture development center has been moved in the eastern part of the basin.

Therefore, during the process of Cenozoic evolution of the Bohai Bay, the subsidence center, and the depocenter migrated with the tectonic evolution of the space. The basin depocenter migrated from west to east.

According to the analysis of the basin basement subsidence rate, it found that there formed a series of small rift lacustrine basins in the early stages of rifting. It resulted with multi-deposition centers and the sedimentation rate showing no regularity in the Ek and the Es4. The sediment rate of the western part of the basin is slightly different from the eastern part. In the early stages of the Es3, the main faults of the boundary were intensely active and the basement subsidence is-maximum, resulting in deep lake development. Deposition centers of this period were relatively stable, and the sediments were interbedded mudstone and turbidite sandstones. The basin was gradually shallow in the early stages of the Es2 and the Jiyang movement happened until the late Neogene.

Since the Oligocene, the lake has obviously shrank. In the Es1 and the Ed, the sedimentation rate of the Bozhong Depression was maximum, followed by the Liaodong Bay Depression and the Jiyang Depression. Indicating the subsidence center of this period has migrated to the eastern part of the basin. During the thermal subsidence stage, the accelerate sedimentation were obvious in late Neogene around the Bozhong Depression and has spread to the Liaodong Bay Depression, the Jiyang Depression, and the Huanghua Depression. This phenomenon was not obvious in the Xialiaohe Depression and did not happened in the Jizhong Depression.

During the evolution of basin development, there developed four sections of hydrocarbon source rocks of Paleogene age: the Kongdian Formation, the fourth member (Es4), the third member (Es3), and the first member of Shahejie Formation (Es1), the lower part of the Dongying Formation. The hydrocarbon source rock is the Es4 in the Jizhong Depression. The hydrocarbon source rocks are the Ek and the Es4 in the Huanghua Depression and the southern part of the Jiyang Depression, while the Es3 and the Es1 were in the central and northern parts of the Jiyang Depression. The hydrocarbon source rocks are the Es4, the Es3, and the Es1 in the Liaohe Depression. While the hydrocarbon source rocks are the Es3, the Es1, and the lower part of the Dongying Formation in the Bozhong Depression. The distribution regularity of the hydrocarbon source rocks in space and time is in line with subsidence center migration regularity in Bohai Bay Basin (Guo et al., 2007 and Ren et al., 2008).

The several sets of Paleogene hydrocarbon source rocks are characterized by a large thickness in Bohai Bay Basin of each depression with 500-3000 m, the thickest is 2000-3000 m (the Jiyang Depression, Liaohe Depression and Huanghua Depression). It provides a huge resource potential of shale gas exploration in Bohai Bay Basin (Zhang et al., 2009; Zhang et al., 2008; and Zou et al., 2010). According to the analysis of the shale samples geochemical data (Es4, Es3, and Es1) in Jiyang Depression (Zhang et al., 2008), the results show that the shales have high abundance of organic matter. The organic carbon content is about 1.5% to 10%, up to 18.6% in Es4. The content is about 1.0% to 9%, up to 10.5% in Es3. The content is about 2.0% to 5%, up to 11.6% in Es1. The shale organic matter types of the three sets are better, mainly sapropel type-Partial sapropel hybrid type. The vitrinite reflectance (Ro) of the Es4 and the Es3 shale is about 0.5% to 1.9%, the principal part is at the maturity stage and part is into the high-maturity stage. The vitrinite reflectance (Ro) of the Es1 shale is about 0.3% to 0.7%, the principal part is at the maturity stage and part is into the high-maturity stage. The Ro of the Es1 shale is about 0.3% to 0.7%, mainly in the immature - mature stage.

The tectonic activity is the main factors of the shale, which not only controls the time of the shale development (during the maximum sedimentation period of each rifting period), but also controls the space distribution of shale (The distribution regularity of the hydrocarbon source rocks in space and time is in line with subsidence center migration regularity in Bohai Bay Basin).

Conclusion

Contrast to the conditions of the shale in the two eastern China rift lake basins, it can be easily found that:

1. The time and spatial distribution of the shale is strictly controlled by the basin tectonic evolution (The distribution regularity of the hydrocarbon source rocks in space and time is in line with subsidence center migration regularity in Bohai Bay Basin).
2. The accommodation space controlled by the basin tectonic activity is another condition of shale. Shale developed in the basin's strongly sedimentation stage, regardless of the rift or depression. It requires sufficient accommodation space for shale development.
3. Transgressive is another condition of the shale. While transgressive is related with the tectonic subsidence.
4. The humid climate is a very important auxiliary condition for the shale.

In fact, the development of shale is not only controlled by the structure and climate, in some basins, other factors may take the leading role, such as thriving micro-organisms. The article is no longer for further discussion.

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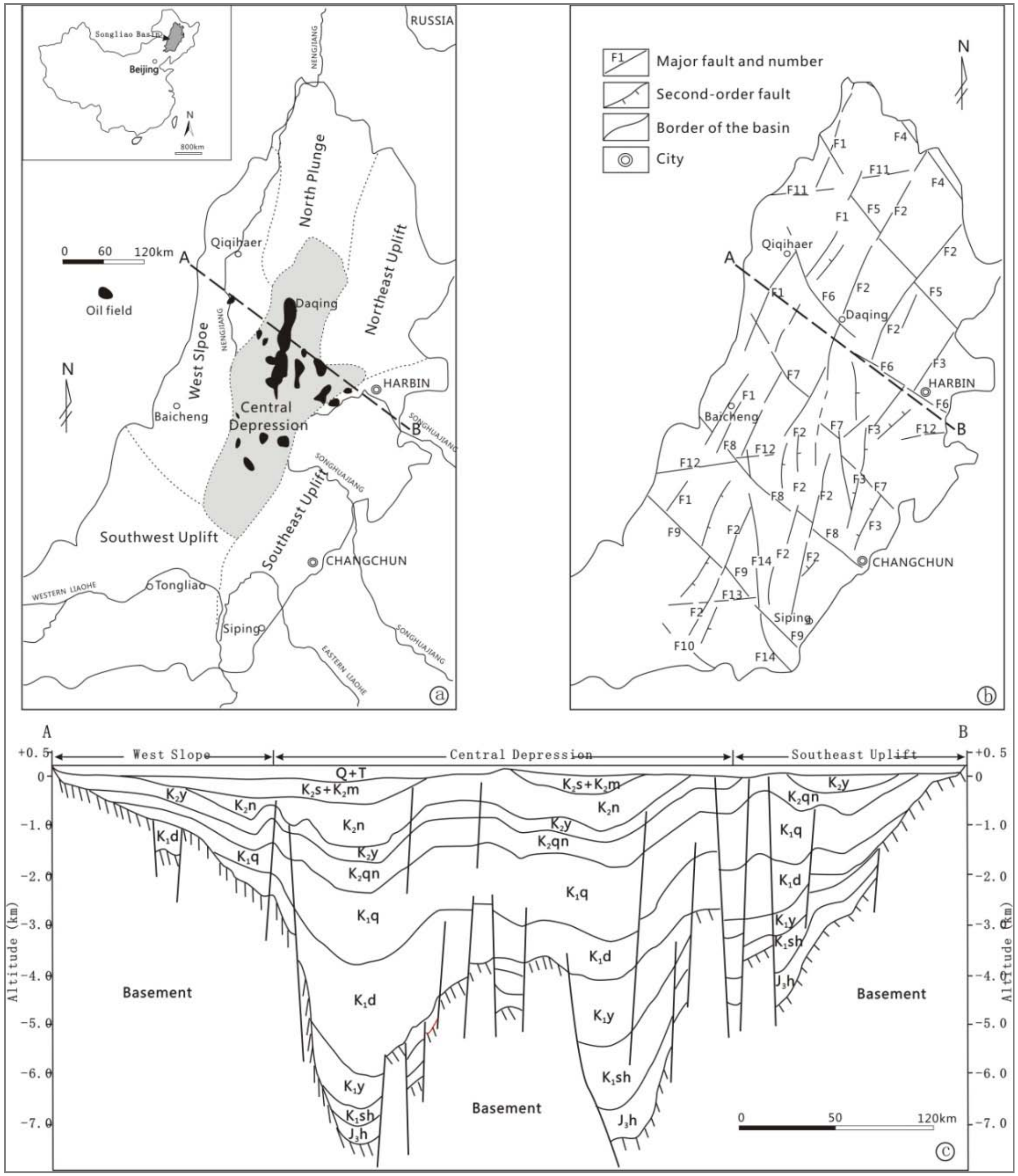

Figure 1. Tectonic framework and distribution of Songliao Basin in J_3h-K_2m.

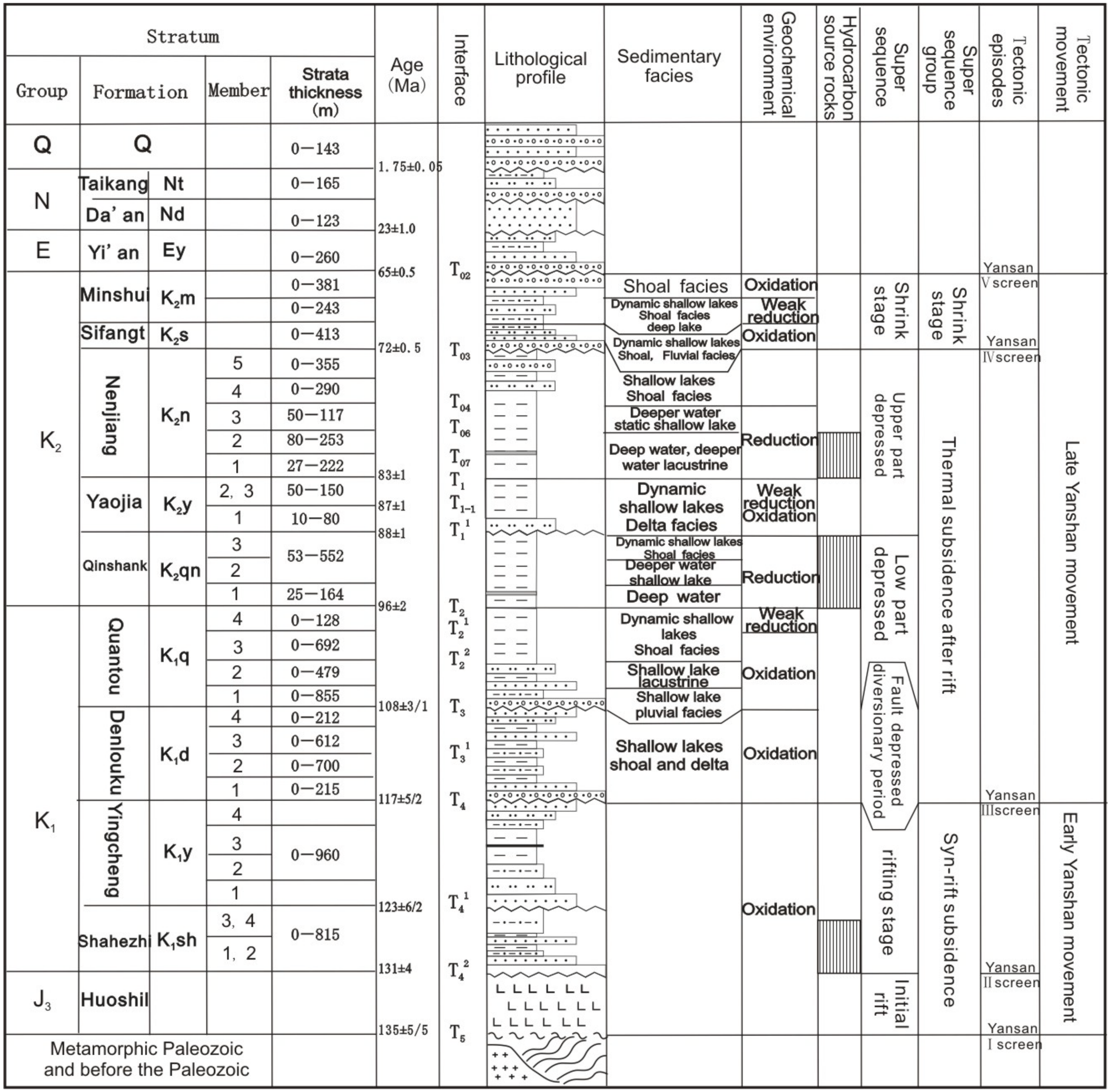

Figure 2. Basin filling evolution and sequence stratigraphic division in Songliao Basin.

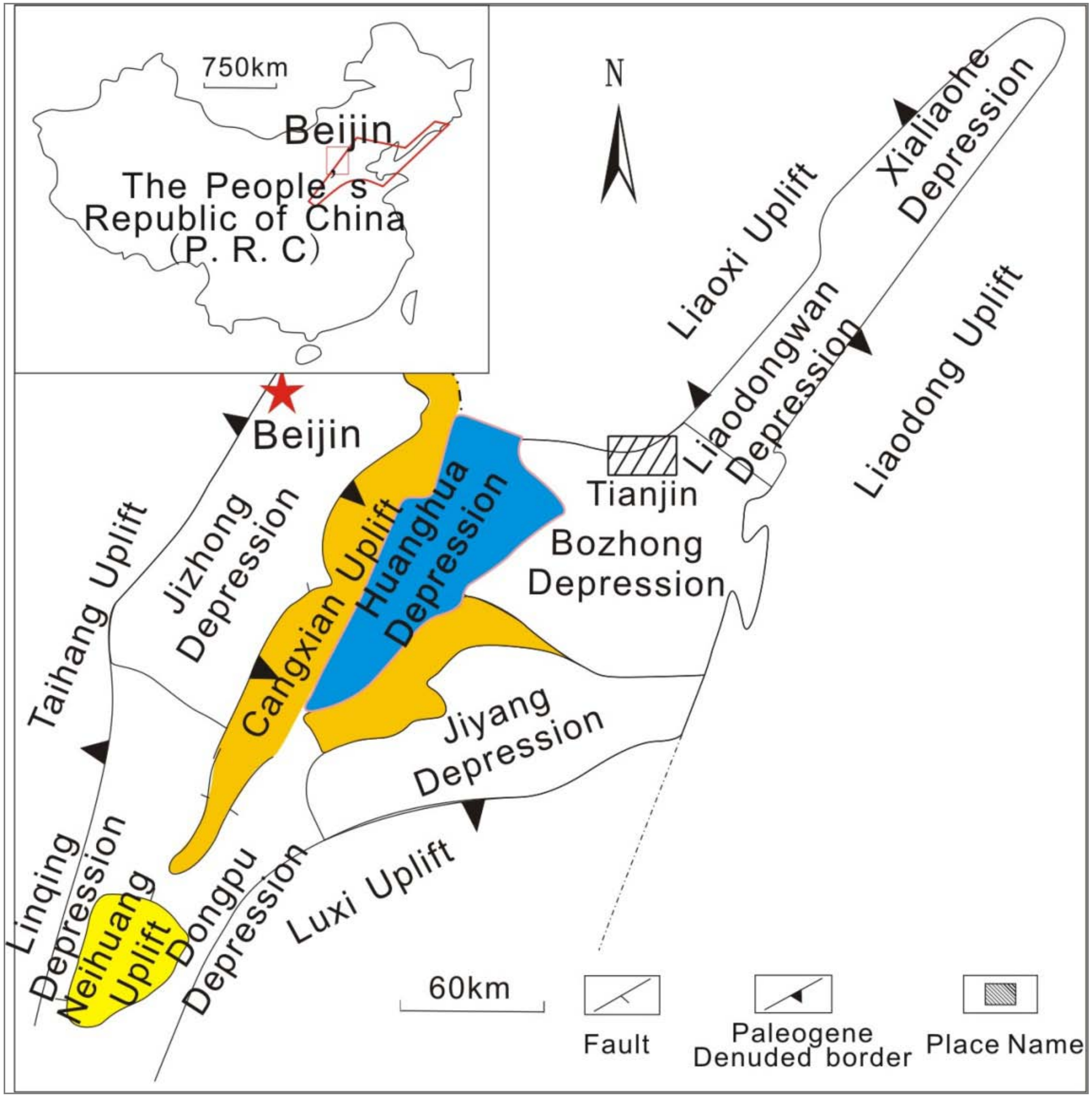

Figure 3. Cenozoic regional tectonic sketch map in Bohai Bay Basin.

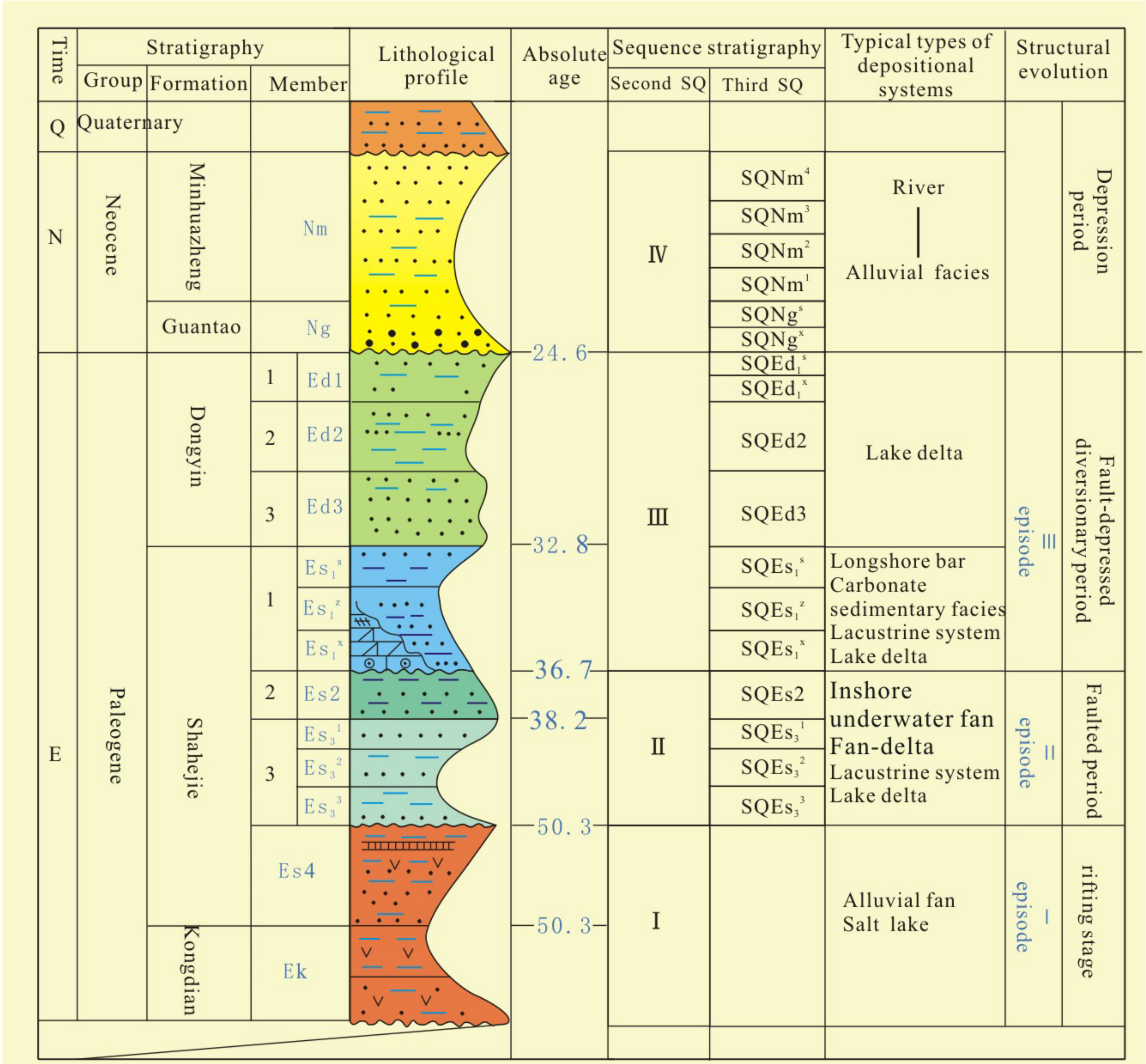

Figure 4. Basin filling evolution and sequence stratigraphic division of Bohai Bay Basin.

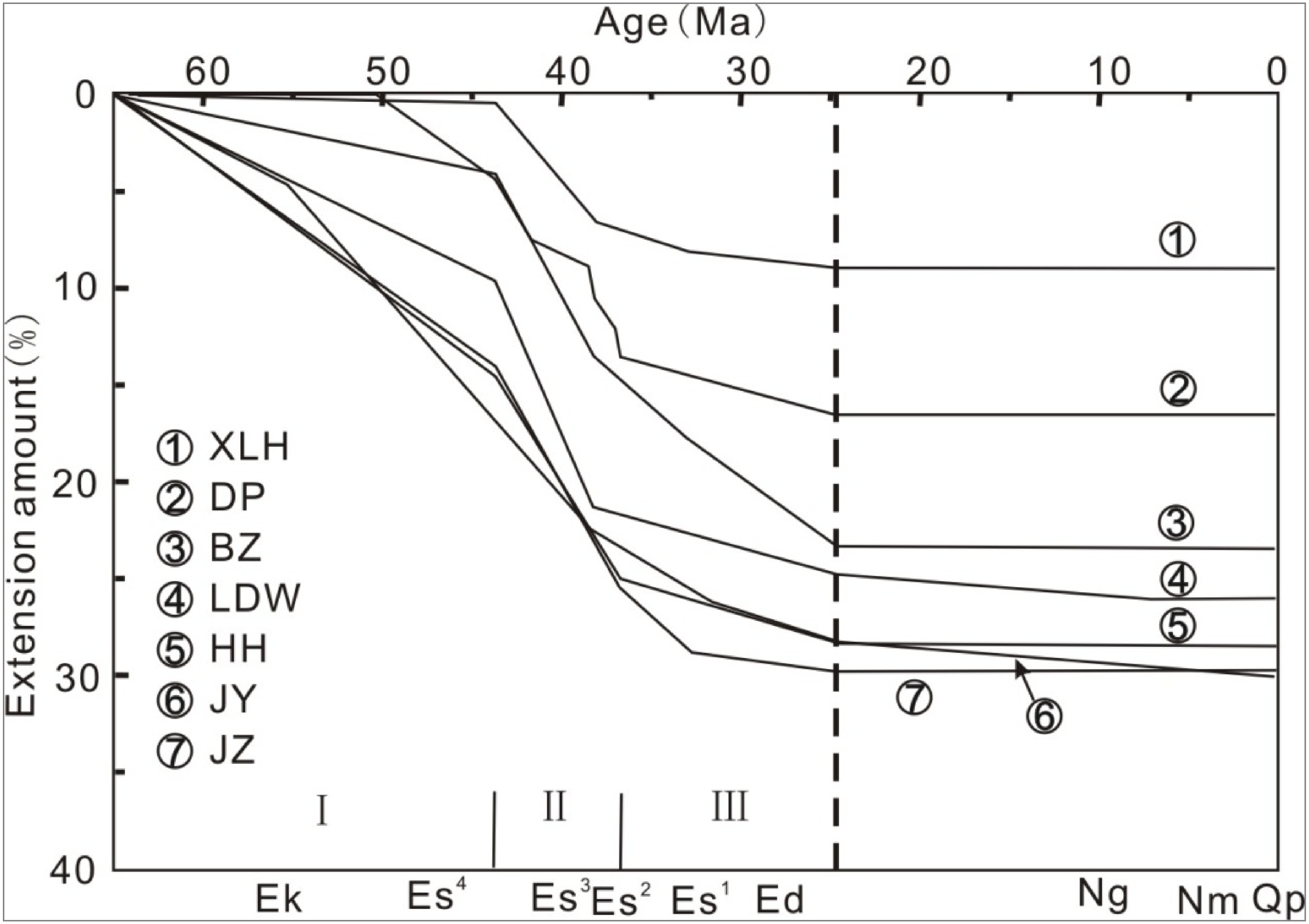

Figure 5. Curves showing the accumulated extension proportions for Bohai Bay Basin in the Cenozoic.