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Sedimentation in a Continental High-Frequency Oscillatory Lake in an Arid Climatic Background: A Case Study of the Lower Eocene in the Dongying Depression, China

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ABSTRACT: The sedimentary environment, formation conditions, sedimentary characteristics and the basin evolution model of high-frequency oscillatory lake in arid climatic background of the Lower Eocene in the Dongying depression were studied through the analysis of drilling cores, sporepollen, geochemistry and geophysics data. During the sedimentary period of the Eocene Ek^1–Es^{4x} formations, because of the frequent alternation between dry and wet climates in the arid climatic background and the gentle paleo-geomorphology, the lake level and salinity of the Early Eocene Dongying depression frequently and rapidly increased and decreased, which is referred to as a high-frequency oscillatory lake. The sedimentation and distribution of sediments in this high-frequency oscillatory lake basin were controlled by the frequently alternating dry-wet climates. During periods with relatively wet climate, the seasonal floods and unstable rivers led to the formation of over-flooding lake deltas in the gentle slope belt, and fine-grained clastic sediments, with minor thin layers of gypsum-salt rocks in the sag belt. During the relatively arid climatic periods, sedimentation occurred mainly in the limited area of the sag belt with thick gypsum-salt rocks. Because of the impact of the salinity stratification of the lake water, these gypsum-salt rocks exhibit annular structural features. A sedimentary cycle of the oscillatory lake began with isochronous flood channels and ended with relatively thick gypsum rocks and salt rocks. The thickness of one oscillatory cycle is generally 4–20 m. The superposition of multiple sedimentary cycles of the oscillatory lake constitutes the overall vertical filling sequence of the high-frequency oscillatory lake basin.

KEY WORDS: oscillatory lake, clastic sedimentation, chemical sedimentation, paleoclimate, Dongying depression, Lower Eocene.

0 INTRODUCTION

Continental lake deposition is the primary source of petroleum resources in China (Zhu et al., 2013) and plays an important role in petroleum exploration and development (Zou et al., 2013). Geoscientists have performed detailed classifications of lake types and have investigated the features of deposition that correspond to the various types (Currie, 1997; Shanley and McCabe, 1994). Paleoclimate is an important factor in determining the environmental features of a lake (Zambito IV and Benison, 2013; Cecil, 1990). The paleoclimate typically affected the type of lake and the features of the sedimentary environment in the lake by affecting the amount of rainfall and evaporation in the region of the lake and thus controls the characteristics of sedimentation in the lake under the relatively stable tectonic conditions (Carroll and Bohacs, 2001; Pederson, 2000; Cecil, 1990). For a lake in a warm and wet climate, the rainfall is abundant, and stable water systems often develop around the lake (Reheis et al., 2005). The amount of water that is introduced into the lake is greater than the total amount of water lost to evaporation and underground seepage, and the lake level remains at the elevation of the lowest outlet. The excess water flows out of the lake basin through a discharge channel. Most lakes formed in such a climatic background are open lake basins (Bracht-Flyr et al., 2013; Rippey et al., 2001; Lewis, 1983). Because of the influence of the wet climate, large and stable rivers often develop on the periphery of the lake. Given the characteristics of an open lake basin, although the lake level remains at the elevation of the lowest outlet, the relative lake level declines continuously over time because the large amount of detritus carried by the peripheral stable water system is constantly being deposited in the lake, and the depth of the lake water continuously shrinks. Relatively large delta sedimentary systems often develop in such lakes (Zhu et al.,

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2012; Zou et al., 2008). By contrast, for a lake in hot and arid climatic conditions, the rainfall is generally low, and the evaporation is relatively strong. The water flow into the lake often exhibits seasonal variations, and stable perennial water-flow systems feeding into the lake are very rare (Reheis et al., 2005). The amount of water that flows into the lake is generally smaller than the total amount of water lost to evaporation and underground seepage, and the lakes formed in this type of climatic background are typically closed lake basins (Bracht-Flyr et al., 2013; Lewis, 1983). The seasonally unstable water flow into the lake causes periodic expansion and shrinkage in the water depth of a closed lake basin, but the water is generally shallow (Mathewes and King, 1989). There is a lack of water exchange between a closed lake basin and its environment, the lake water is prone to evaporate and concentrate, and the lake typically has the features of a brackish lake or salt lake (Webster et al., 2004). The seasonal variations in the lake water cause corresponding changes in the sedimentary environment of the lake, giving rise to unique features in the sedimentation in the lake. Studies indicate that many continental lake basins have experienced hot and arid climates during certain periods and that the sedimentation of such lakes is significantly affected by seasonal variations in the water flow. Lake Eyre in Australia is a seasonal salt lake with salty water that is affected by its arid climatic conditions. Because of the impact of alternating dry and wet climates, the depth of the lake exhibits seasonal expansion and shrinkage, and the lake level exhibits a seasonal rise and fall. The lake has the features of an over-flooding lake, and a certain amount of evaporite has developed within the lake (Fisher et al., 2007; North and Warwick, 2007). The Huiming sag in the Bohai Bay Basin was subject to arid paleoclimatic conditions during the sedimentary period of the Es^{4x}, and the lake level is strongly affected by seasonal floods. The high water level of the flood season and the low water level of the dry season differ considerably, and this difference has led to the formation of the sedimentary environment of an over-flooding lake (Yuan, 2005). The Cretaceous Yuyang Formation on the southwestern margin of the Jianghan Basin is an over-flooding lake sedimentary system that was deposited under arid paleoclimatic conditions (Chen et al., 2007).

The Dongying depression of the Bohai Bay Basin exhibits an interbedded deposition pattern of red and purple mudstones and red and gray sandstones that formed in the gentle slope belt under arid climatic conditions during the deposition of the Ek^1–Es^{4x}, which are referred to as “red beds” in exploration. In the sag belt, there are symbiotic thick deposits of gypsum-salt rocks (Xu et al., 2008). Considerable drilling data, cores and 3D seismic data of the Ek^1–Es^{4x} formations in the Dongying depression provide the abundant basic data for the study of sedimentation. We investigated more than 1 000 m of drilling cores of 32 wells of the Ek^1–Es^{4x} formations. According to the locations of wells and the sedimentary characteristics, we selected 39 samples of mudstones of Well Fsh2, 63 samples of mudstones of Well Guan112 and 40 samples of mudstones of Well L120 to obtain the major elements and trace elements data and the whole-rock X-ray diffraction data. We also collected the sporepollen data of the well L120 from the in-house data base of the Shengli Oilfiled. In this paper, based on an analysis of the paleoclimate and paleotopography, we determine the characteristics of the sedimentary environment in the Dongying depression during the sedimentary period of the Ek^1–Es^{4x} and study in detail the type and characteristics of the sedimentation. We establish the sedimentary filling model and offer some thoughts regarding the study of the sedimentary environments and sedimentation of lakes in arid climatic backgrounds.

1 GEOLOGICAL BACKGROUND

The Bohai Bay Basin is an important hydrocarbon-bearing basin in the eastern part of China. It is a complex rift basin that developed in the North China Platform from the Late Jurassic to the Paleogene. The tectonic evolution of the Bohai Bay Basin includes two major stages, i.e., the rift period (65.0–24.6 Ma) and the depression period (24.6 Ma to the present). Because of influence from episodic events of the Himalayan movement, the evolution of the Bohai Bay Basin during the rift period passed through many stages and can be divided into the initial rift period, the strong rift period, and the faulted atrophy stage (Lampe et al., 2012). The Paleogene formation that developed during the rift stage is primarily composed of clastic rocks and a regional distribution of chemical rocks. From bottom to top, it primarily consists of the Kongdian Formation (from bottom to top, the second and first members (Ek^2, and Ek^1)), the Shahejie Formation (from bottom to top, the fourth, third, second, and first members (Es^4, Es^3, Es^2, and Es^1)), and the Dongying Formation (Ed). The Dongying depression is a secondary tectonic unit of the Jiyang subbasin in the Bohai Bay Basin (Fig. 1a). The Dongying depression is adjacent to the Qingtuozi bulge to the east, the Guangrao bulge to the southeast, the Luxi uplift to the south, the Qingcheng bulge to the west, and the Chenguanzhuang bulge to the north (Fig. 1b). Based on an analysis of its structural features, from north to south, the Dongying depression can be divided into five tectonic belts: the northern steep slope belt, the northern sag belt, the central fault-anticline belt, the southern sag belt, and the southern gentle slope belt (Figs. 1b, 1c). The Eocene sedimentary period of the Ek^1–Es^{4x} was the initial rift period of the Dongying depression. During this period, the tectonic activity was relatively weak, and the terrain was relatively flat (Fig. 1c). Under the influence of an arid climate, a large-scale detrital “red beds” and gypsum-salt deposits developed.

2 THE DEPOSITIONAL ENVIRONMENT OF THE Ek^1–Es^{4x} MEMBERS

2.1 Paleoclimate

A fairly extensive collection of sporopollen fossils have been found in the Lower Eocene Ek^1–Es^{4x} formation of the Dongying depression. Based on the adaptability to humidity of the parent plants, the sporopollen in the study area can be divided into the xerophilous group, the medium group, and the marsh group of the humid group (Liu et al., 2013; Zhang et al., 2013; Wu et al., 2010; Xiao et al., 2007; Guo et al., 2006; Xu and Sun, 1999). The xerophilous group primarily includes *Ephedriptes*, *Retitricolpites*, and *Inaperturopollenites*; the medium group primarily includes *Abietineaepollenites*, *Pinuspollenites*, *Quercoidites minor*, and *Ulmipollenites*; and the marsh group primarily includes *Taxodiaceaepollenites elongation* and *Taxodiaceaepollenites hiatus* (Fig. 2). The humidity sensitivity

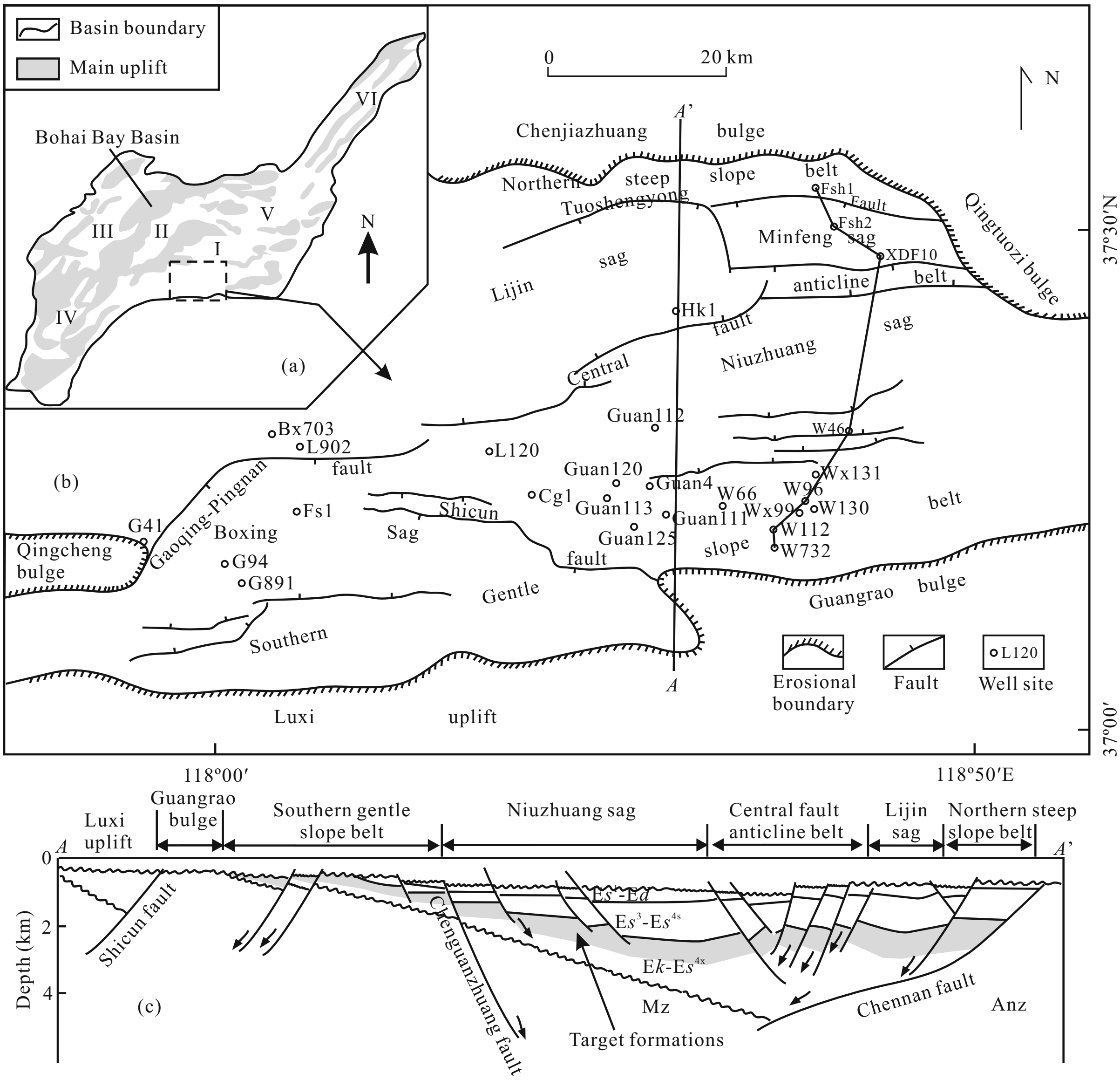

Figure 1. (a) Tectonic setting of the Dongying depression in the southern Jiyang subbasin (I) of the Bohai Bay Basin. Other subbasins in Bohai Bay Basin of North China are Huanghua subbasin (II), Jizhong subbasin (III), Linqing subbasin (IV), Bozhong subbasin (V) and Liaohe subbasin (VI). (b) Structural map of the Dongying depression with well locations and main faults of the Ek^1–Es^{4x}. (c) Section structural characteristics and target formations of the Dongying depression.

of the sporopollen found in the region corresponds mainly to the xerophilous and the medium groups. A calculation of the comprehensive humidity index indicated by the sporopollen (Wu W et al., 2012) suggests that the climate in the Dongying depression was relatively arid during the sedimentary period of the Ek^1–Es^{4x}, and there is considerable evidence of alternating dry and wet climatic variations in the vertical direction of the sedimentary formation (Fig. 2). Based on the adaptability to temperature of the parent plants, the sporopollen in the study area can be divided into the sub-tropical group, the tropical-temperate transition group, the temperate-cold transition group, and the hardy group (Kujaua et al., 2013; Li et al., 2013; Fu et al., 2003; Wang, 1999; Wang et al., 1998). The sub-tropical group primarily includes *Ephedriptes*, *Quercoidites minor*, *Taxodiaceaepollenites elongation*, and *Taxodiaceaepollenites hiatus*; the tropical-temperate transition group primarily includes *Ulmipollenites* and *Inaperturopollenites*; the temperate-cold transition group primarily includes *Abietineaepollenites* and *Pinuspollenites*; and the hardy group primarily includes *Piceaepollenites* (Fig. 2). The temperature sensitivity of the sporopollen found in the region is dominated by the sub-tropical group and the tropical-temperate transition group. A calculation of the comprehensive temperature index indicated by the sporopollen (Wu W et al., 2012) suggests that the climate in the Dongying depression was relatively hot during the sedimentary period of the Ek^1–Es^{4x}, and the features of the vertical variation of the sedimentary formation strongly correspond to the comprehensive humidity index (Fig. 2). The statistical error of sporopollen quantity may account for the converse changes between the comprehensive humidity index and temperature index at 3 060–3 120 m. Therefore, the overall paleoclimate in the Dongying depression was relatively arid and hot

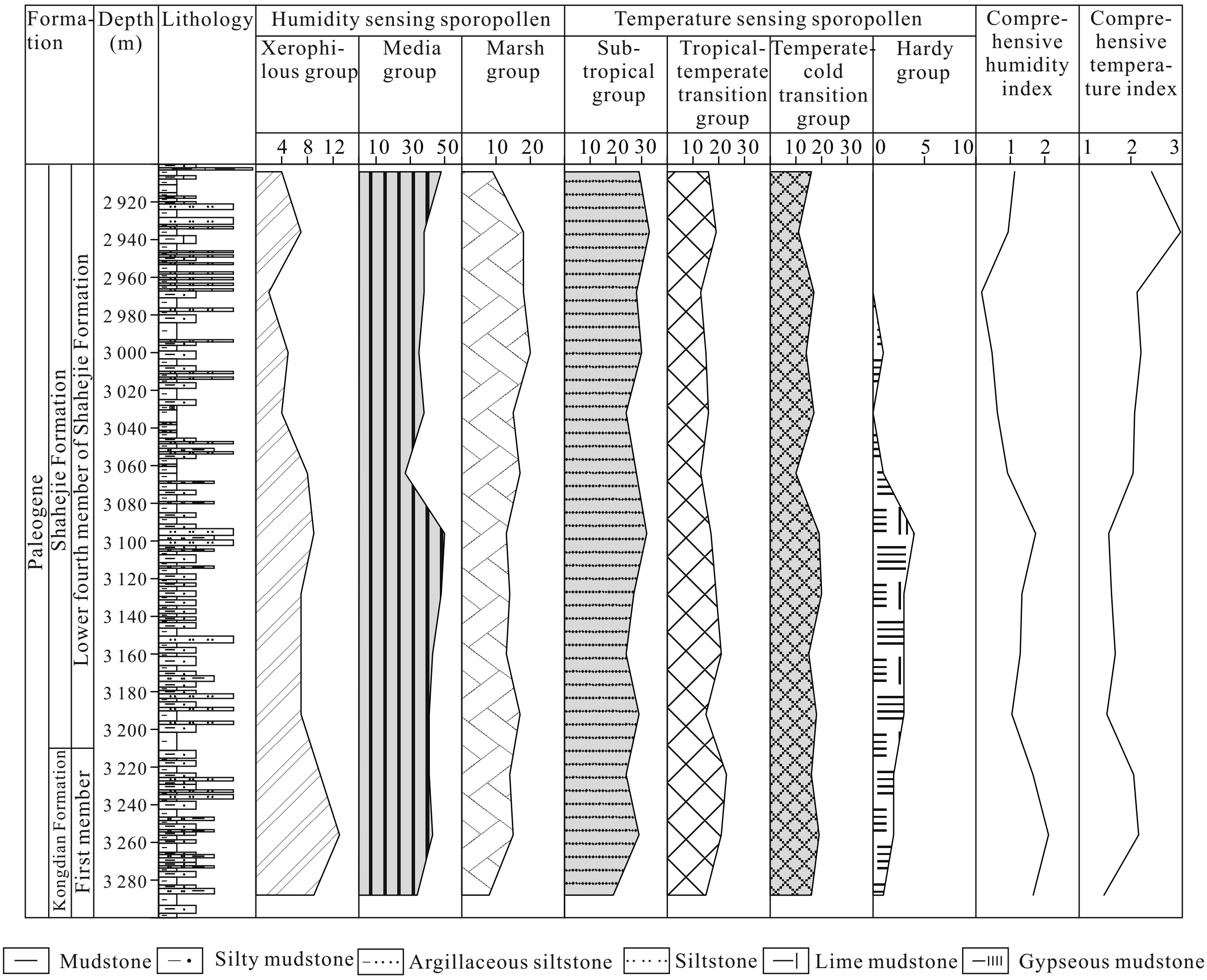

Figure 2. Characteristics of sporopollen and paleoclimate changes of the Ek^1–Es^{4x} members of Well L120 in the Dongying depression.

during the sedimentary period of the Ek^1–Es^{4x}, and large-scale features reflecting the cyclic variation of humidity and temperature are evident in the vertical direction of the sedimentary formation.

The major elements and trace elements and the ratios of certain elements in sediments have been widely used to reconstruct paleoclimates and to determine sedimentary environments (Midgley et al., 2012; Fandeur et al., 2009). On one hand, the properties of elements in rock are determined by the physical and chemical properties of the elements themselves; on the other hand, they are also affected by the paleoclimate and paleoenvironment. This phenomenon provides the scientific basis for the reconstruction of the paleoclimate based on the relative contents of characteristic elements and their ratios (Vital et al., 1999). The selection of the appropriate paleoclimate and paleosalinity indexes is the key to studying the paleoclimates and paleoenvironments of lakes.

In a continental basin, the chemical weathering under wet conditions is strong, and a large amount of Rb is separated and absorbed by clays. However, these clays do not remain at their original locations; instead, they are mostly eroded and transported into the sediments of lakes. The dissolved Sr^{2+} that enters the lake basin at the same time is generally isomorphous to carbonates and is deposited during relatively arid periods, resulting in the enhancement of the Rb/Sr ratio in humid environments (Chang et al., 2013; Chen et al., 2008). Therefore, in a continental basin, a high Rb/Sr ratio represents a relatively humid climate; a low Rb/Sr ratio represents a relatively arid climate (Xu et al., 2010; Chen et al., 1999). Most shale contains very fine sands, such as quartz and feldspar, and these relatively coarse types of debris are typically transported into a lake basin through the water flow into the lake. Over the course of a small-scale sedimentary cycle, when the content of very fine sands in the shale increases significantly, it indicates stronger water flow into the lake and better circulation of the lake water; thus, such sedimentary behavior indicates a relatively humid climate (Giovanoli, 1990).

Because the samples used in our study for Well Fsh2, Well Guan112, and Well L120 are subject to different degrees of carbonate recrystallization, the carbonate stable isotope method is not applicable (Sarg et al., 2013; Yu et al., 2002). When samples contain considerable amounts of mineral salts, such as carbonates, gypsum, and rock salts, the salinity indices (e.g., B/Ga, Sr/Ca, and Sr/Ba) do not accurately reflect the paleosalinity (Chivas et al., 1986, 1985). In studies of Quaternary ancient lakes, the carbonate content of sediments is often used as the index for the variation in the salinity (Zhang et al., 2010). In the present study, the sediments in the core sections of Well Fsh2, Well Guan112, and Well L120 generally contain varying amounts of gypsum and carbonate, and both are native. Therefore, we use the carbonate and sulfate content as an alternate indicator of the lake's paleosalinity.

The Rb/Sr ratios of the drilling core sections of Well Fsh2, Well Guan112, and Well L120 exhibit multiple cyclic increasing and decreasing variations in the vertical direction. In the vertical direction, the quartz and feldspar content, the terrigenous element Cr content, and the Rb/Sr ratio exhibit significant variations in the same direction, whereas the carbonate and sulfate content and the Rb/Sr ratio exhibit a clear inverse relationship. An increase in the Rb/Sr ratio reflects a relatively humid climate. At such times, the amount of water flow into the lake increased, the relative lake level rose, and the salinity of the water declined; the sediments that correspond to these periods are dominated by gray mudstones, shale, and silty mudstones. A decrease in the Rb/Sr ratio reflects a relatively arid climate. At such times, the amount of water flow into the lake decreased significantly, and the evaporation was strong. The relative lake level dropped rapidly, and the salinity of the water increased; the sediments that correspond to these periods are dominated by gray, purple, and mottled lime mudstones, dolomitic mudstones, dolomitic shale, argillaceous dolomites, and argillaceous rocks (Fig. 3). Therefore, the paleoclimate in the Dongying depression during the sedimentary period of the Ek^1–Es^{4x} underwent frequent, small-scale dry and wet alternations within the overall large-scale arid climatic background (Fig. 3). There are generally 4–7 small-scale dry and wet alternative cycles within 10 m strata. The thickness of one small-scale dry and wet alternative cycle is very small. During the wet period the thickness of gray mudstones, shale, and silty mudstones increased; and during the dry period the thickness of gray, purple, and mottled lime mudstones, dolomitic mudstones, dolomitic shale, argillaceous dolomites, and argillaceous rocks increased.

2.2 Paleogeomorphology

Paleogeomorphology refers to the locations where sediments accumulate and is an important characteristic of a sedimentary environment. The paleogeomorphology before the sedimentary period of the Lower Eocene Ek^1–Es^{4x} members was restored based on the analysis of residual stratum thickness, denuded strata thickness, load correction parameter, compaction correction parameter and ancient water depth parameter. An analysis of a prototype basin during the sedimentary period of the Ek^1–Es^{4x} (Wu Z P et al., 2012) indicates that because of the influence of the activity of the Chennan fault, the northern steep slope belt of the Dongying depression is a high-angle fault slope. The downthrown wall of the Chennan fault caused the formation of the NEE-trending sag and the sedimentary center. The Qingcheng uplift to the west of the Dongying depression had not yet formed at this time. Because of the influence of the activity of the Shicun fault, small-scale sub-sag formed in the Boxing area. However, the variation of the topographic slope in this region is gentle. The structural features in the southeast region of the Dongying depression are relatively simple, with simple slope features (Fig. 4). An analysis of seismic data indicates that the typical slope of the paleogeomorphology of the south region of the Dongying depression was 2º–6º during the sedimentary period of the Ek^1–Es^{4x}. From the edge to the center of the basin the slope increases gradually. The slope of the paleogeomorphology of the north sag belt was relatively steep. The gentle paleogeomorphology provided a good paleotopographic background for the development of a high-frequency oscillatory lake.

Because of the hot and arid climate, the Dongying depression was a closed lake basin during the sedimentary period of the Ek^1–Es^{4x}. Because of the frequent alternation between dry and wet climates and the gentle paleotopography, the depth of the lake water varied considerably in the gentle slope belt. During the relatively wet climatic periods, the water flow into the lake was relatively large, and the depth of the lake water increased rapidly; the relative lake level rose, and salinity of the lake water was relatively low. During the relatively arid climatic periods, the water flow into the lake significantly decreased, and the evaporation was strong; the depth of the lake water decreased rapidly, the relative lake level rapidly dropped, and the salinity of the lake water increased. Because of the frequent alternation of arid and wet climates, the depth of the lake exhibited high-frequency oscillatory expansion and shrinkage, and the relative lake level exhibited high-frequency oscillatory rising and falling. The salinity of the lake water exhibited high-frequency oscillatory increases and decreases, and the gentle slope belt of the basin was frequently and intermittently exposed. Consequently, because of the influence of the paleoclimate and paleotopography, the Dongying depression developed a high-frequency oscillatory lake environment during the Early Eocene period.

3 DEPOSITIONAL SYSTEM AND FACIES DISTRIBUTION IN THE HIGH-FREQUENCY OSCILLATORY LAKE

The variation in the relative lake level of a high-frequency oscillatory lake and the salinity of the lake water are primarily controlled by the paroxysmal water flow into the lake, which is determined by the climate, causing complex and diverse types of sedimentation. The sedimentation of both clastic rocks and chemical rocks occurred in the Dongying depression during the sedimentary period of the Ek^1–Es^{4x}. The sedimentation of clastic rocks primarily occurred in the broad gentle slope belt and in a confined area of the steep slope belt, whereas the sedimentation of chemical rocks primarily occurred in the sag belt.

3.1 Clastic Sedimentary System

The formation mechanism of the high-frequency oscillatory lake indicates that the sedimentation of clastic rocks primarily occurred during the relatively humid climatic periods. During these times, the water flow into the lake carried a large amount of clastic substances, which were deposited in the gentle slope belt and steep slope belt of the basin. Because of the arid climatic background, the water flow into the lake during the relatively humid periods primarily originated from paroxysmal floods and unstable rivers and these water sources collectively led to the formation of large-scale over-flooding lake deltas in the gentle slope belt (Fig. 5). The over-flooding lake deltas primarily developed the delta plain and the delta front. The delta plain deposits distribute between the flooding surface and the dry surface. According to the sedimentary characteristics the delta plain is classified into the upper delta plain and the lower delta plain. The sedimentation of the upper delta

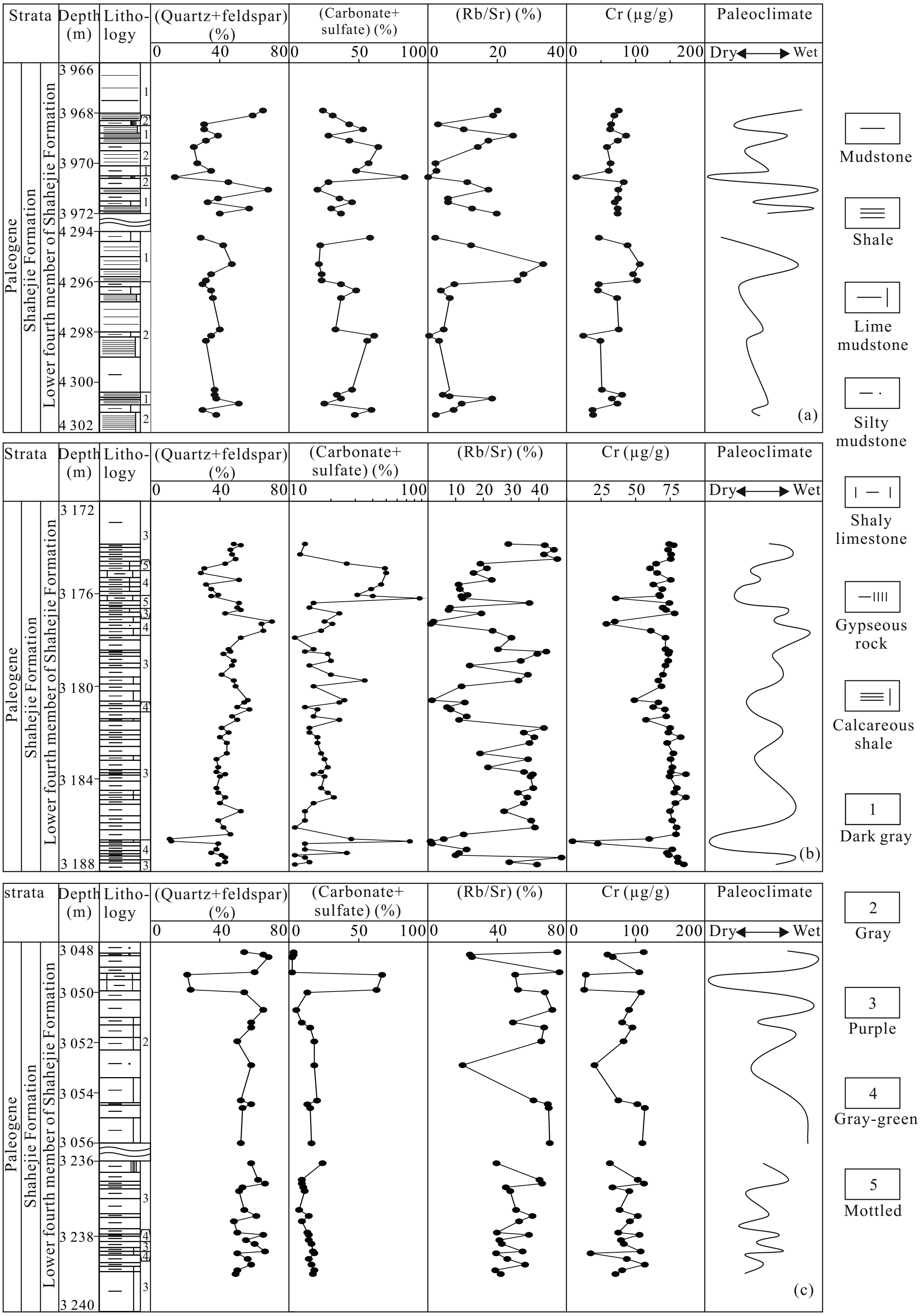

Figure 3. Characteristics of minerals, elements and paleoclimates of drilling cores of Well Fsh2 (a), Guan112 (b) and L120 (c) of the Lower Eocene Ek^1–Es^{4x} members in the Dongying depression.

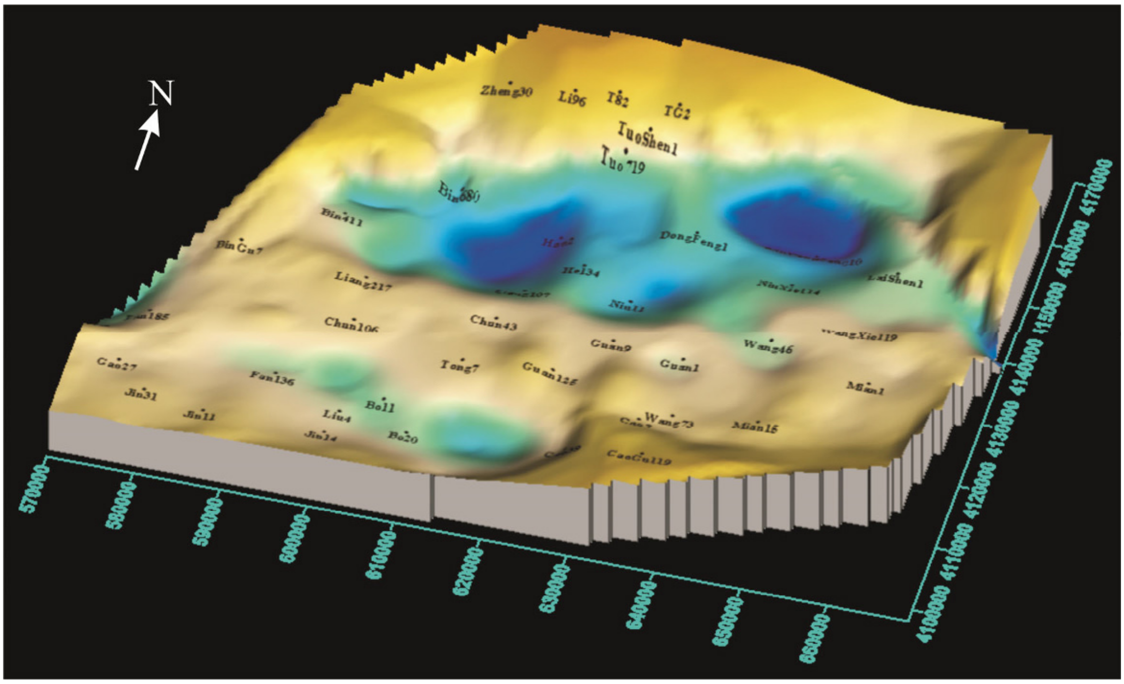

Figure 4. Characteristics of paleogeomorphology before the Early Eocene Ek^1–Es^{4x} members of the Dongying depression.

plain was dominated by flood with gravity current property; and the sedimentation of the lower delta plain was dominated by river with tractive current property. In front of the over-flooding lake deltas, certain amounts of over-flooding lake beach-bars were caused by waves. Because of the impact of floods, the steep slope belt of the basin experienced a certain amount of conglomerate deposition. The scale of the clastic deposits of the Ek^1 member is larger than that of the Es^{4x} member (Figs. 5a, 5b). The observation of drilling cores indicates that the clastic rocks of the Dongying depression that were deposited during the sedimentary period of the Ek^1–Es^{4x} primarily contain the following five types of associations of sedimentary microfacies (Fig. 6).

(1) Microfacies showing a superposition of multi-stage flood channels (Fig. 6a). This type primarily developed in the upper delta plain of the over-flooding lake delta, where the thickness of the flood channel is large and the sedimentary particles are coarse. The thickness of flood channels is generally 2–6 m. Scour surfaces were created, and gravel or clay boulders were deposited along the bottoms of these flood channels (Figs. 7a, 7b). During the relatively humid climatic periods, the water supplied by floods increased the relative lake level, and the effective accommodation space increased rapidly and migrated toward the margin of the basin, forming an ascending hemicycle of base levels. During the relative arid climatic periods, the water in the lake basin became rapidly shallower, and the base level decreased. The sediment supply was relatively insufficient, and the deposits are generally thin and composed of purplish red and red mudstones or mudstones interbedded with thin sandstones. The thickness of this kind of microfacies association is usually 4–8 m.

(2) Microfacies showing a superposition of multi-stage flood channels and distributary channels (Fig. 6b). This type of sedimentary microfacies association is dominated by flood channels and overlying distributary channels formed during periods when the relative lake level was rising, and it primarily developed in the transition zone between the upper and the lower delta plain areas. The action of floods gradually weakened from the margin to the interior of the basin, and the thickness of the flood channels in this region is relatively thin. The bottom of these beds also display scour surfaces and clay boulders. The floods gradually transformed into unstable rivers, and the thickness of the distributary channels is moderate to relatively thick with the thickness is generally 1–5 m. It is dominated by moderate and fine sandstones, and the sandbodies exhibit sedimentary structures that reflect the role of traction currents, such as cross-bedding and parallel bedding (Figs. 7c, 7d, 7e). During a relatively dry paleoclimatic period, the reduced water influx led to a rapid drop in the relative lake level, which resulted in the deposition of a set of purplish red and red mudstones and thinly bedded sandstones. The thickness of this kind of microfacies association is usually 3–8 m.

(3) Microfacies showing a superposition of multi-stage distributary channels (Fig. 6c). This type of sedimentary microfacies association consists of superposed distributary channel sediments that were deposited along the front of the lower delta plain. Compared to type 1 and 2 microfacies associations, there is less of an influence of unstable fluvial deposition at the inner part of the basin in a relatively wet paleoclimate, the distributary channel deposits are thinner and the rock types are primarily fine sandstones and siltstones. Small-scale cross and parallel bedding and vertical burrows are present in the sandstones of the distributary channels (Figs. 7d, 7e). During the relatively arid climatic periods, the relative lake level dropped, and wave action had a more significant impact in the inner region of the lake basin, which resulted in a minor amount of thinly bedded sandstones in front of the submerged distributary

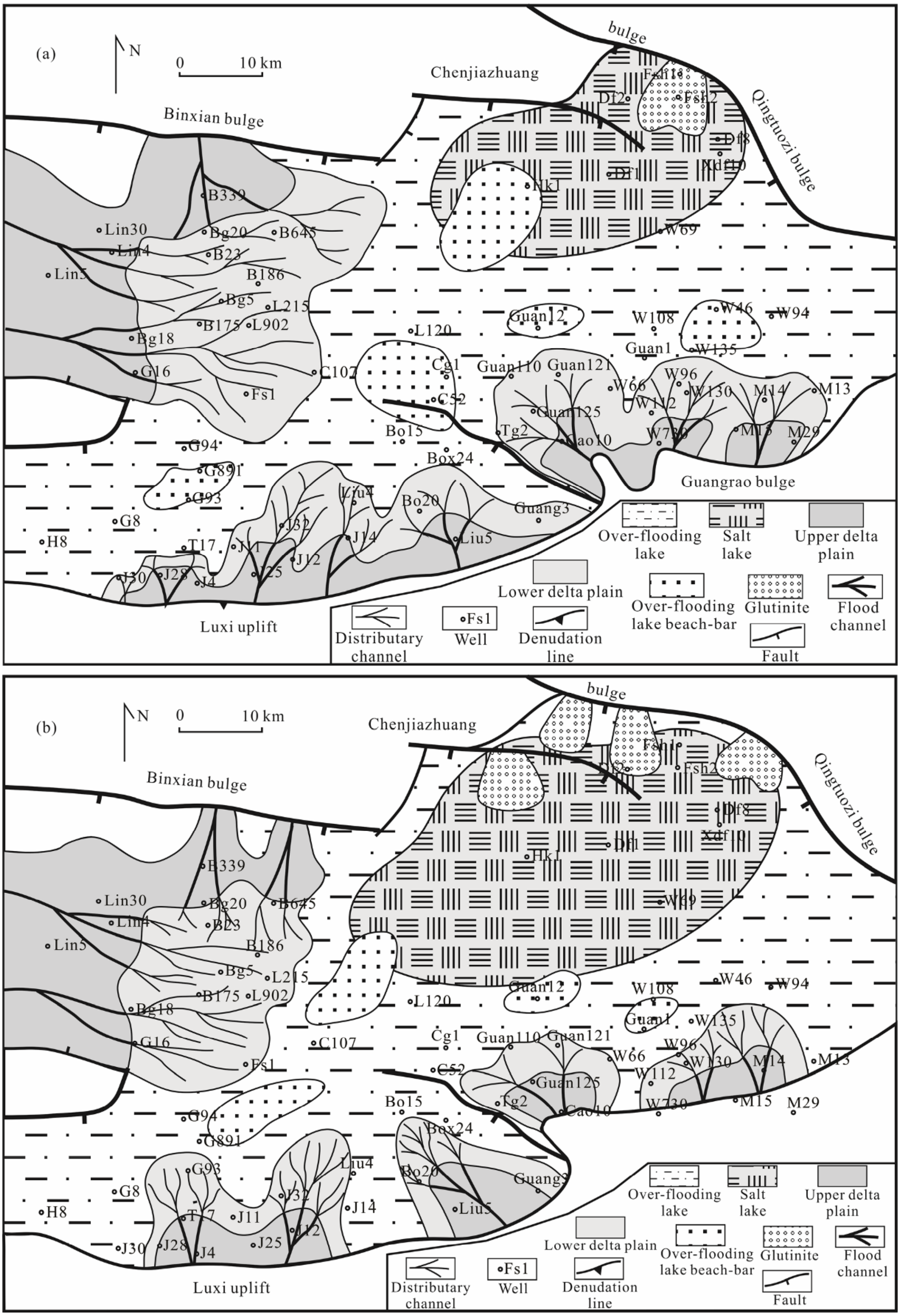

Figure 5. Planar distribution characteristics of sedimentary systems of the Lower Eocene Ek^1 member (a) and Es^{4x} member (b) in the Dongying depression.

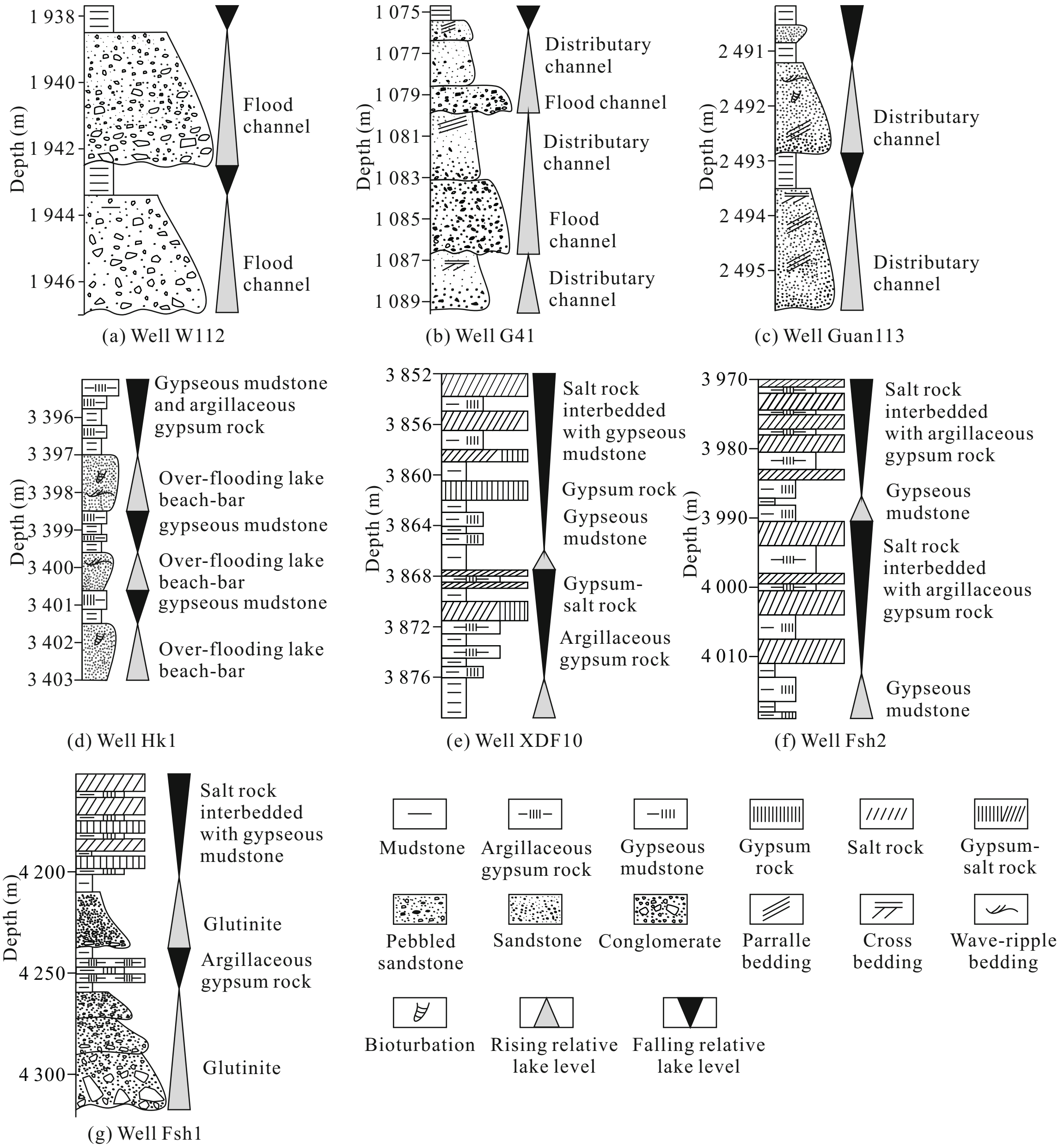

Figure 6. Types and characteristics of sedimentary microfacies associations and lithology of the Lower Eocene Ek^1–Es^{4x} members in the Dongying depression.

channels. At the top of this sedimentary unit, the rocks are mostly purplish red and red mudstones. The thickness of this kind of microfacies association is usually 2–5 m.

(4) Microfacies showing multi-stage over-flooding lake beach-bar sandbodies interbedded with oxidation color mudstones, gypseous mudstones, and argillaceous gypsum rocks (Fig. 6d). During the relatively humid climatic periods, the water of the lake was relatively deep, and wave action transported and transformed the sands of the over-flooding lake delta, forming a certain amount of over-flooding lake beach-bars with reverse-sequence features and thin fine siltstones in front of the delta. Small-scale wavy ripple cross bedding and bioturbation are the principal sedimentary structures (Figs. 7f, 7g, 7h). During the relatively arid climatic periods, the sediment supply decreased, and the energy of the lake declined. As the evaporation gradually became stronger, the salinity of the water rapidly increased, causing an enhancement of the salt or gypsum content in the sediments. The thickness of this kind of microfacies association is usually 1.5–4 m.

(5) Microfacies showing a superposition of multi-stage glutenite and gypsum-salt rocks (Fig. 6g). This type of sedimentary microfacies association primarily developed in the steep slope belt of the basin. The floods that occurred during the relatively humid climatic periods carried a large amount of mixed coarse clastic sediments across the fault and directly into the lake, leading to the multi-stage superposed sedimentation of glutenite with coarse grain and poor sorting and rounding. During the relatively arid climatic periods, the salinity of the lake water increase led to the development of overlying gypsum-salt rocks composed of gypseous mudstones, argillaceous gypsum rocks, gypsum rocks, and salt rocks. The thickness of this kind of microfacies association is usually 5–25 m.

Therefore, the clastic sediments exhibit clear and

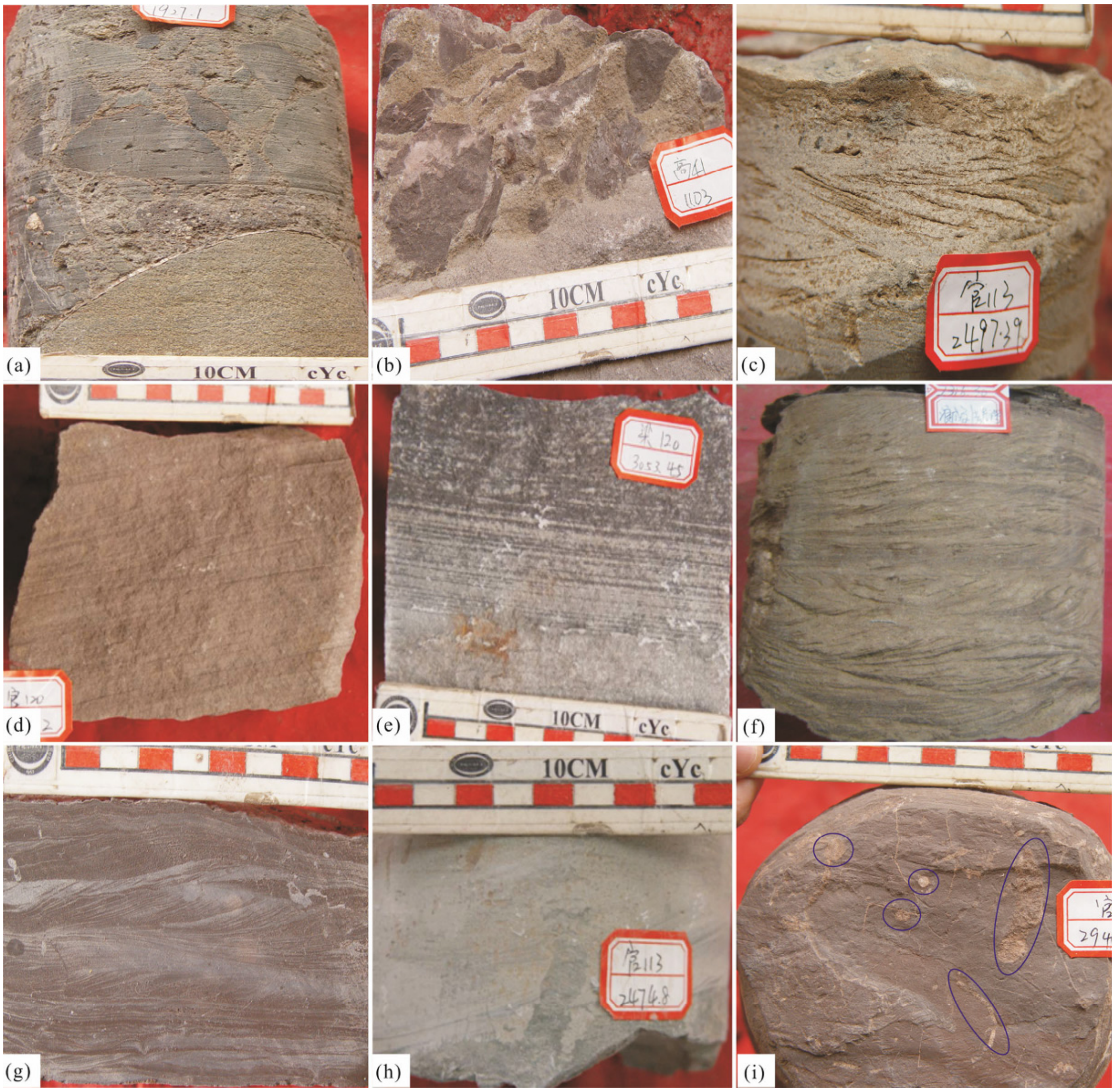

Figure 7. Sedimentary structure characteristics of the Lower Eocene Ek^1–Es^{4x} members in Dongying depression. (a) Well W112, 1 927.1 m, gravels and scour surface; (b) Well G41, 1 103 m, boulder clays and scour surface; (c) Well Guan113, 2 497.39 m, cross bedding; (d) Well Guan120, 2 950.2 m, cross bedding; (e) Well L120, 3 053.45 m, parallel bedding; (f) Well Cg1, 2 316.3 m, wave-cross bedding; (g) Well Hk1, 3 968.3 m, wave-ripple bedding; (h) Well Guan113, 2 474.8 m, bioturbation; (i) Well Guan120, 2 947.89 m, bioturbation.

regularly varying features from the edge to the interior of the basin. During the relatively humid climatic periods, seasonal floods led to the formation of flood channels with gravity currents features and gradually decreased thickness along the direction of the flow. The flood channels are isochronous in the lateral direction and can be used as a mark of the beginning of the sedimentary cycle. Toward the inner basin, the sedimentation gradually transitioned from gravity currents to traction currents, leading to the formation of a certain scale of distributary channels. The thickness of distributary channels also gradually became thinner and evolved into over-flooding lake beach-bars with reverse-sequence features. Within a certain time scale, the flood channels, distributary channels, and over-flooding lake beach-bars are laterally isochronous and comprise a transgressive cycle. During the relatively arid climatic periods, the relative lake level rapidly dropped, and the sediment supply declined, which led to the primary deposition of mudstones with oxidation colors and the gradually increase of gypsum and salt contents toward the interior of the basin.

3.2 Chemical Depositional System

Because of the nature of a high-frequency oscillatory lake, chemical deposition primarily occurs during periods of relatively arid climate. At such times, the relative lake level is low, the depth of the lake water is small, the evaporation is strong, and the salinity of the water is high, leading to considerable sedimentation of gypsum-salt rocks. There are various occurrences of salt minerals that were deposited in the Dongying depression during the sedimentary period of the Ek^1–Es^{4x}, and patchy gypsum (Fig. 8a), thin-layered gypsum or salt rocks (Fig. 8b), and thick-layered gypsum or salt rocks (Figs. 8c, 8d, 8e) can often be observed in drilling cores. The gypsum and salt rocks are often interbedded with oxidized

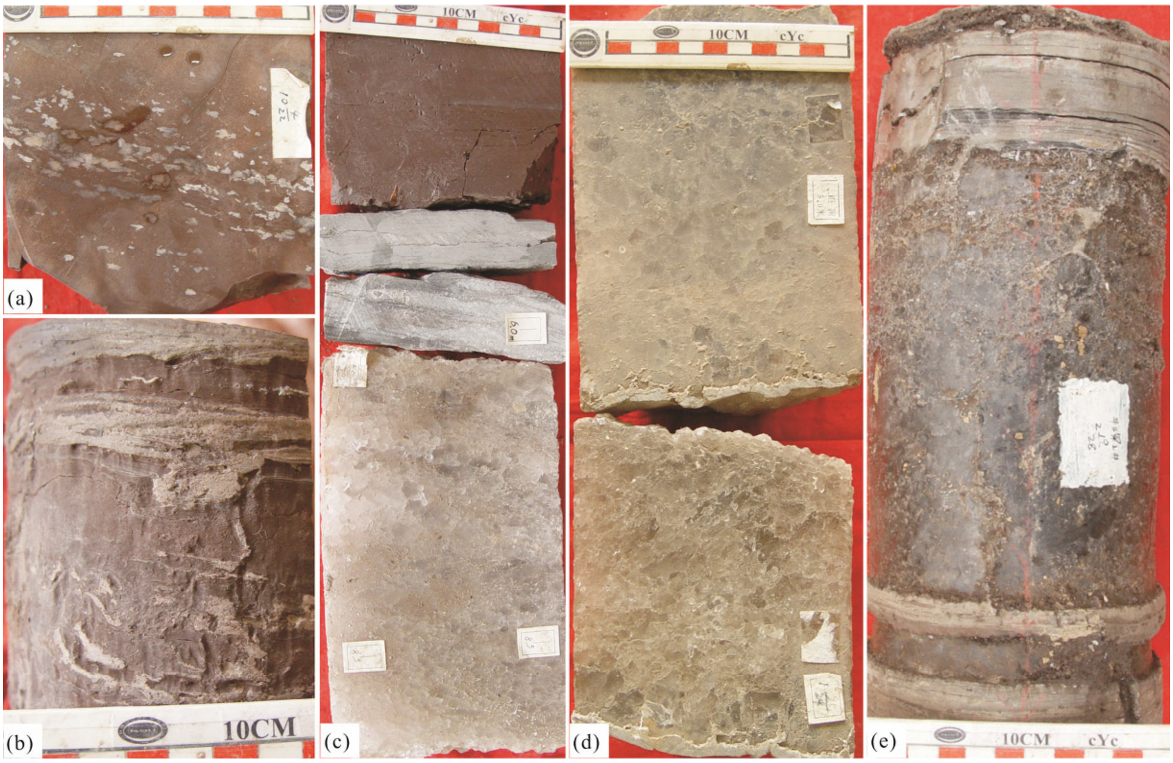

Figure 8. The occurrences of the salt minerals of the Lower Eocene Ek^1–Es^{4x} members in the Dongying depression. (a) Well Hk1, 4 498.25 m, patchy gypsum in purple silty mudstone; (b) Well Hk1, 3 762.3 m, thin gypsum interbedded with purple silty mudstone; (c) Well Hk1, 3 768.55–3 771.65 m, thick salt rock interbedded with gypseous mudstone and purple mudstone; (d) Well Hk1, 3 436.07–3 436.39 m, thick salt rocks; (e) Well Fsh2, 4 298.9 m, thick salt rock interbedded with thin gypsum and gray mudstone.

or gray mudstones in layers of unequal thickness (Figs. 8b, 8c, 8e), which reflects the oscillatory nature of the sedimentary environment.

The sedimentation of the gypsum-salt rocks exhibits different vertical evolutionary sequences depending on the location in the basin. On the margin of the gypsum-salt rock sediments, these sediments often exhibit the fourth type of sedimentary microfacies association described above. At positions relatively close to the interior of the lake, from bottom to top, there are thick layers of gray-green and gray mudstones interbedded with thin layers of gypseous mudstones, followed by argillaceous gypsum rocks interbedded with thin layers of mudstones, gypsum and salt rocks (Fig. 6e). In the center region of the gypsum-salt rock sediments, from bottom to top, there are thin layers of argillaceous gypsum rocks interbedded with thin layers of mudstones, followed by argillaceous gypsum rocks interbedded with gypseous mudstones, thick layers of gypsum rocks, and salt rocks (Fig. 6f). In the steep slope belt of the basin, the fifth type of sedimentary microfacies association discussed above is often evident in the gypsum-salt rock sediments. During the relatively humid climatic periods, the water that flowed into the lake decreased the salinity of the water in the lake to some extent, and the sediments formed during such times are dominated by mudstones, gypseous mudstones, and argillaceous gypsum rocks. During the relatively arid climatic periods, evaporation caused the salinity of the water in the lake to increase rapidly, and relatively thick sediments of gypsum and salt rocks developed. The thicknesses of these two kinds of microfacies associations are usually 8–30 m.

In the horizontal direction, the sedimentation of the gypsum-salt rocks has a very distinct zonal structure. From the edge to the center, there is a gradual transition from gypseous mudstones to argillaceous gypsum rocks, gypsum rocks, and salt rocks. The sedimentary thickness of the gypsum-salt rock gradually increases from the edge to the center (Fig. 9). Because the climate was arid, the lake water at the surface of the sag belt was affected by evaporation, generating brine of relatively high density. When the brine density became sufficiently high, it would sink and displace the relatively low-density water on the bottom of the lake. As the brine continued to sink, the high-salinity lake water in the sag belt developed salinity stratification (Romero and Philp, 2012; Kristen et al., 2007; Heydari et al., 1997). From top to bottom, such a salinity stratification is generally composed of a diluent layer, a halocline, and a brine layer (Xu et al., 2008; Heydari et al., 1997) (Fig. 10). The diluent layer is generally located above the wave base and is strongly affected by various external factors. The water of the halocline is relatively quiet, and the salinity rapidly increases between the diluent layer and this layer, with a certain density interface between the two. The brine layer is generally in dynamic equilibrium with the deposited salt minerals. When the concentration of the brine reaches the crystallization concentration of a certain salt mineral, deposition of this salt mineral will occur. During the relatively humid climatic periods, the seasonal flow of freshwater into the lake reduced the salinity of the lake, and the halocline and brine layer migrated toward the center of the

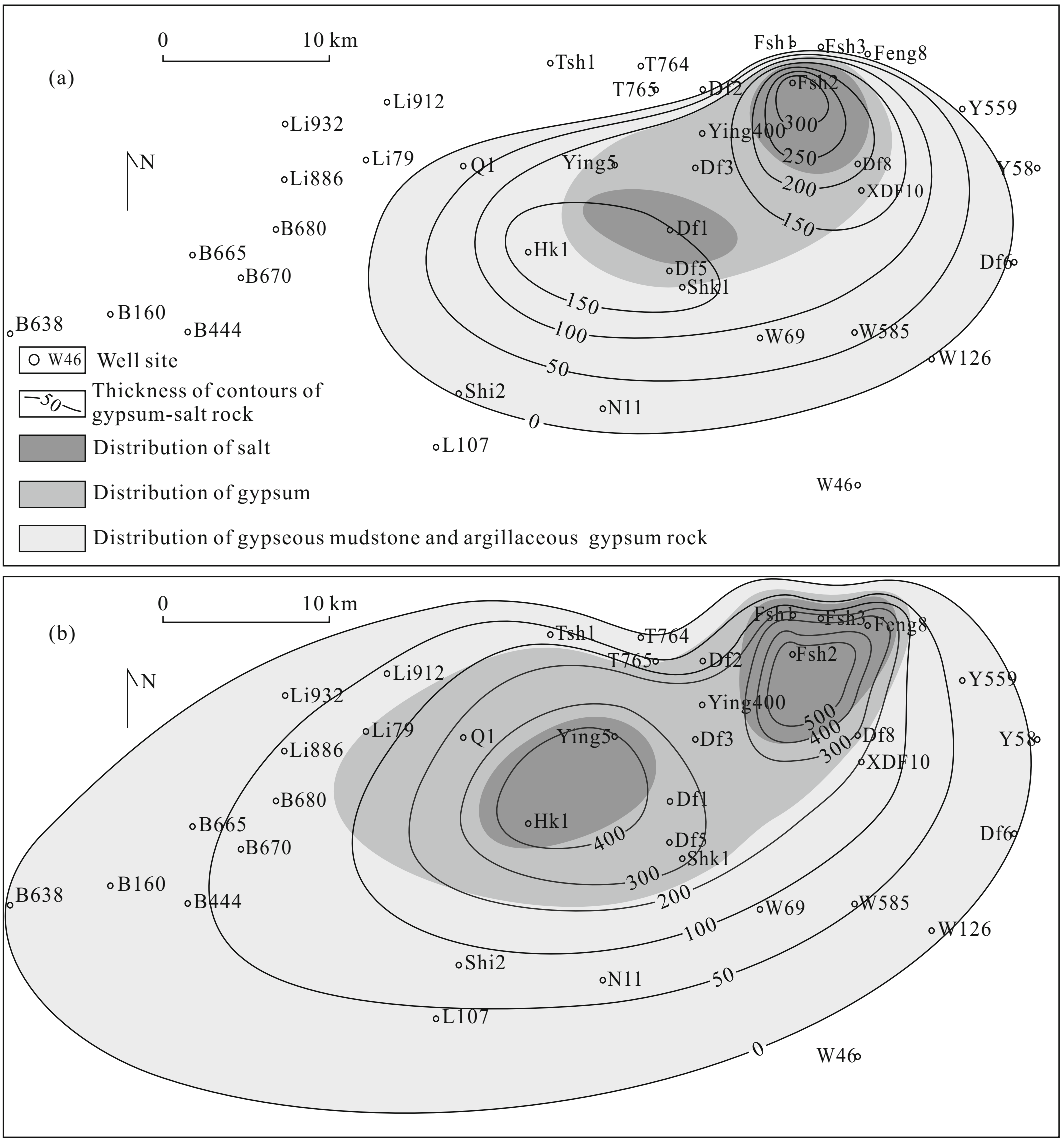

Figure 9. Thickness contours and distribution of different kinds of gypsum-salt rocks of the Lower Eocene Ek^1 member (a) and Es^{4x} member (b) in Dongying depression.

basin. These two layers became smaller in scale or perhaps even disappeared, and the sedimentation was dominated by gypseous mudstones and argillaceous gypsum rocks (Fig. 10a). During the relatively arid climatic periods, the evaporation was strong, and there was a high level of salinity stratification. The halocline and brine layer increased in size, and they migrated toward the margin of the basin (Figs. 10b, 10c). As evaporation progressed, the solute ions that were present in high levels in the brine layer were deposited in order of increasing solubility: carbonate minerals, gypsum minerals, and finally, salt minerals. Because of the salinity stratification, the salinity of the water gradually decreased from the center to the edge of the basin, leading to the formation of a zonal structure that transition from salt rocks to gypsum rocks, argillaceous gypsum rocks, and gypseous mudstones from the center to the edge of the basin.

During the relatively arid climatic periods, the sedimentation of gypsum-salt rocks that developed in the sag belt and the mudstone sedimentation that developed on the margin of the basin both reflected the descent of the relative lake level. Within a certain time scale, these sediment formations are isochronous and comparable and comprise a retrogressive clastic-chemical rock cycle (Figs. 11 and 12).

Both of the Ek^1 and Es^{4x} members of the study area are classified into 6 fourth-order sequence cycles based on the characteristics of associations of sedimentary microfacies and the lateral correlation (Figs. 11 and 12). These cycles indicate that the sedimentary characteristics of high frequency oscillatory salt lake in a relatively large scale are as same as the small scale. Thus, the sedimentary characteristics of the high frequency oscillatory salt lake are consistent in different time scales. The difference between the Ek^1 and Es^{4x} members is that the distribution area of clastic sediments of the Ek^1 member is larger than that of the Es^{4x} member. The over-flooding lake beach-bars still exist even in the sag belt of the Ek^1 member (Fig. 11). The distribution area of the chemical sediments of the Ek^1 member is smaller than that of the Es^{4x} member.

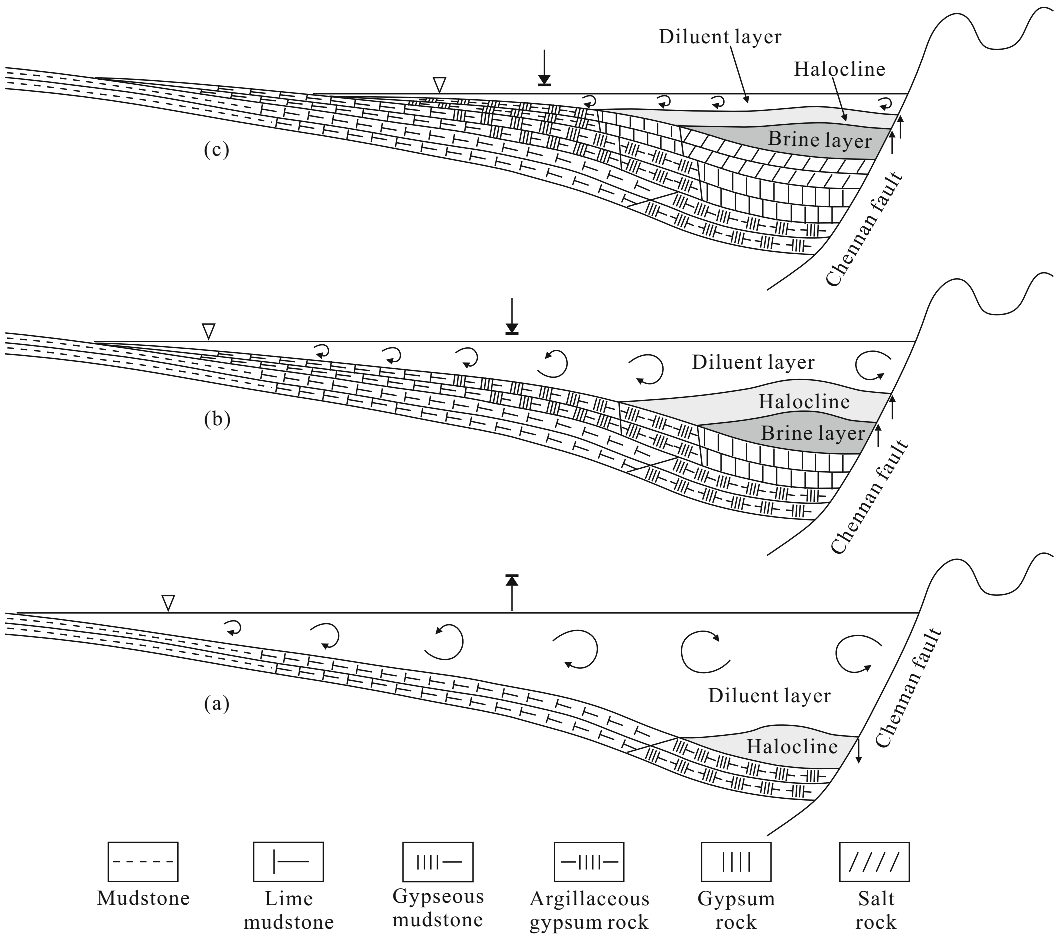

Figure 10. The schematic diagram showing the salinity stratification and formation mechanism of zonal structure of gypsum-salt rocks of the Lower Eocene E*k*^{1}–E*s*^{4x} members in the Dongying depression.

4 SEDIMENTARY FILLING MODEL OF THE HIGH-FREQUENCY OSCILLATORY LAKE

The clastic sedimentation and chemical sedimentation in the high-frequency oscillatory lake are not two separate sedimentary processes. Instead, they are one entity with mutual influence and a unified existence. The clastic sedimentation and chemical sedimentation have shifting characteristics. During the relatively humid climatic periods, the water flow into the lake carried a large amount of detrital substances into the lake. Because of the gentle paleotopography of the gentle slope belt, from the margin to the interior of the basin developed flood channels and distributary channels orderly, which drove the formation of the upper and the lower delta plains of the over-flooding lake delta respectively. Affected by waves in the lake, small scale and isolated over-flooding lake beach-bar sandbodies were formed in front of the delta. Because of the influence of the high-angle basin controlling faults in the steep slope belt, floods caused a certain amount of vertical multi-stage superposed sedimentation of glutenite. Because of water flow into the lake, the salinity of the lake water decreased, leading to the development of primarily mudstones, gypseous mudstones, and argillaceous gypsum rocks in the sag belt; the sedimentary range of the gypsum-salt rocks is relatively small, as is its thickness (Fig. 13). During the sedimentary stage of the E*k*^{1}, the sedimentary supply was relatively large. The scale of the over-flooding lake delta at the gentle slope belt was very large; even in the sag belt the over-flooding delta sandbodies and the over-flooding beach-bar sandbodies still existed (Fig. 13a). During the sedimentary stage of the E*s*^{4x}, the scales of the over-flooding lake delta and the over-flooding beach-bar were relatively small; at the sag belt there were mainly mudstones, gypseous mudstones and argillaceous gypsum rocks (Fig. 13b).

During the relatively arid climatic periods, the water flow into the lake rapidly decreased, and the sediment supply decreased significantly, causing the range of clastic sediments in the gentle slope belt to shrink rapidly. The sediments that formed during these periods are dominated by mudstones and thin-layered sandstones. Because the lake level dropped rapidly, the sediments on the margin of the gentle slope belt were gradually exposed, and sedimentation occurred only in the area of the sag belt that remained covered by water. Because of the impact of the salinity stratification, the sedimentation that occurred during these periods is characterized by the formation of gypsum-salt rocks with a planar zonal structure and particular vertical evolutionary sequences (Fig. 13). The scale of the gypsum-salt deposits of the E*k*^{1} member was smaller than that of the E*s*^{4x} influenced by the relatively stronger clastic sediment supply.

The clastic sediments that formed during the relatively humid climatic periods and the chemical sediments that formed

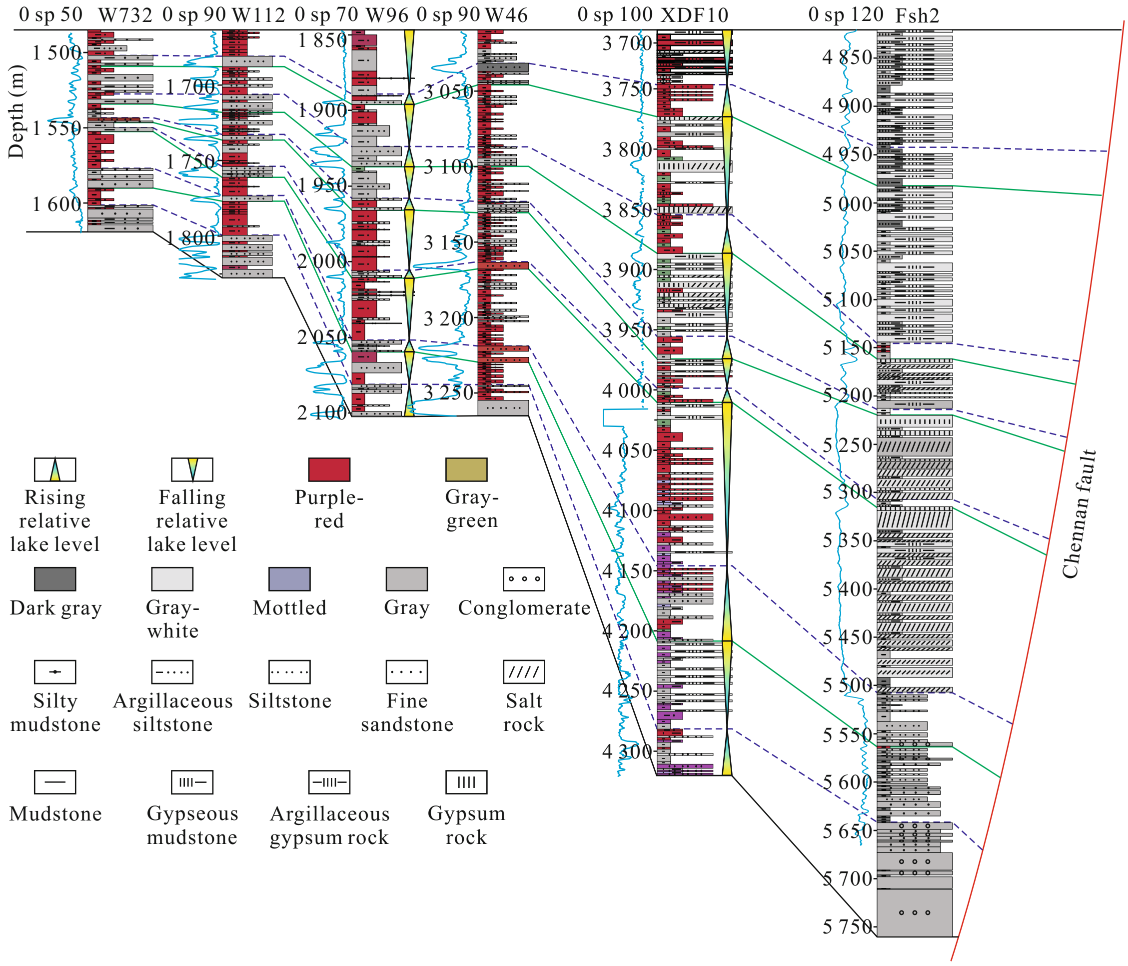

Figure 11. Sedimentary filling sequence of high frequency oscillatory salt lake of the Lower Eocene Ek^1 member in the Dongying depression. See Fig. 1b for profile location.

during the relatively arid climatic periods represent a complete sedimentary cycle of the oscillatory lake. In the horizontal and vertical directions, the sedimentary cycle of the oscillatory lake reflects the evolution from gravity currents to traction currents, from coarse debris to fine debris, and from clastic rocks to chemical rocks (Figs. 11, 12 and 13).

5 CONCLUSIONS

(1) The paleoclimate in the Dongying depression during the Early Eocene period exhibited frequent alternation between relatively dry and wet conditions within the overall arid climatic background. Because of the frequent alternation of the dry and wet paleoclimates and the gentle paleotopography, the sedimentary environment of the Dongying depression during the Early Eocene period was that of a high-frequency oscillatory lake, and the relative lake level exhibited high-frequency oscillations between rising and falling behavior. The depth of the lake water exhibited high-frequency oscillatory expansion and shrinkage, and the salinity of the water exhibited high-frequency oscillatory increases and decreases.

(2) The climate was the dominant factor that controlled the deposition in the high-frequency oscillatory lake. Because of the frequent alternation of dry and wet climates, sedimentation of both clastic rocks and chemical rocks occurred in the Dongying depression during the Eocene sedimentary period. The sedimentation of clastic rocks primarily occurred during periods with relatively wet climates, and the seasonal flows into the lake primarily originated from paroxysmal floods and unstable rivers. Under the combined action of these two hydrodynamics, the gentle slope belt developed over-flooding lake delta that are dominated by the upper and the lower delta plains. Because of the impact of waves in the lake, a certain amount of over-flooding lake beach-bars developed in front of the delta. Floods caused relatively small-scale conglomerate deposition in the steep slope belt. The deposition of chemical rocks primarily occurred during the relatively arid climatic periods. The intense evaporation that occurred during these periods resulted in the salinity stratification of the lake water, leading to the deposition of gypsum-salt rocks with regular vertical evolutionary sequences and a planar zonal structure. The scale of the clastic deposits of the Ek^1 was larger than that of the Es^{4x}, while the scale of the chemical deposits of the Ek^1 was smaller than that of the Es^{4x}.

(3) The clastic sediments with various sedimentary microfacies associations and the gypsum-salt rocks with a planar zonal structure and regular vertical evolutionary sequences represent a complete sedimentary cycle of the oscillatory lake. A typical sedimentary cycle in the oscillatory lake began with

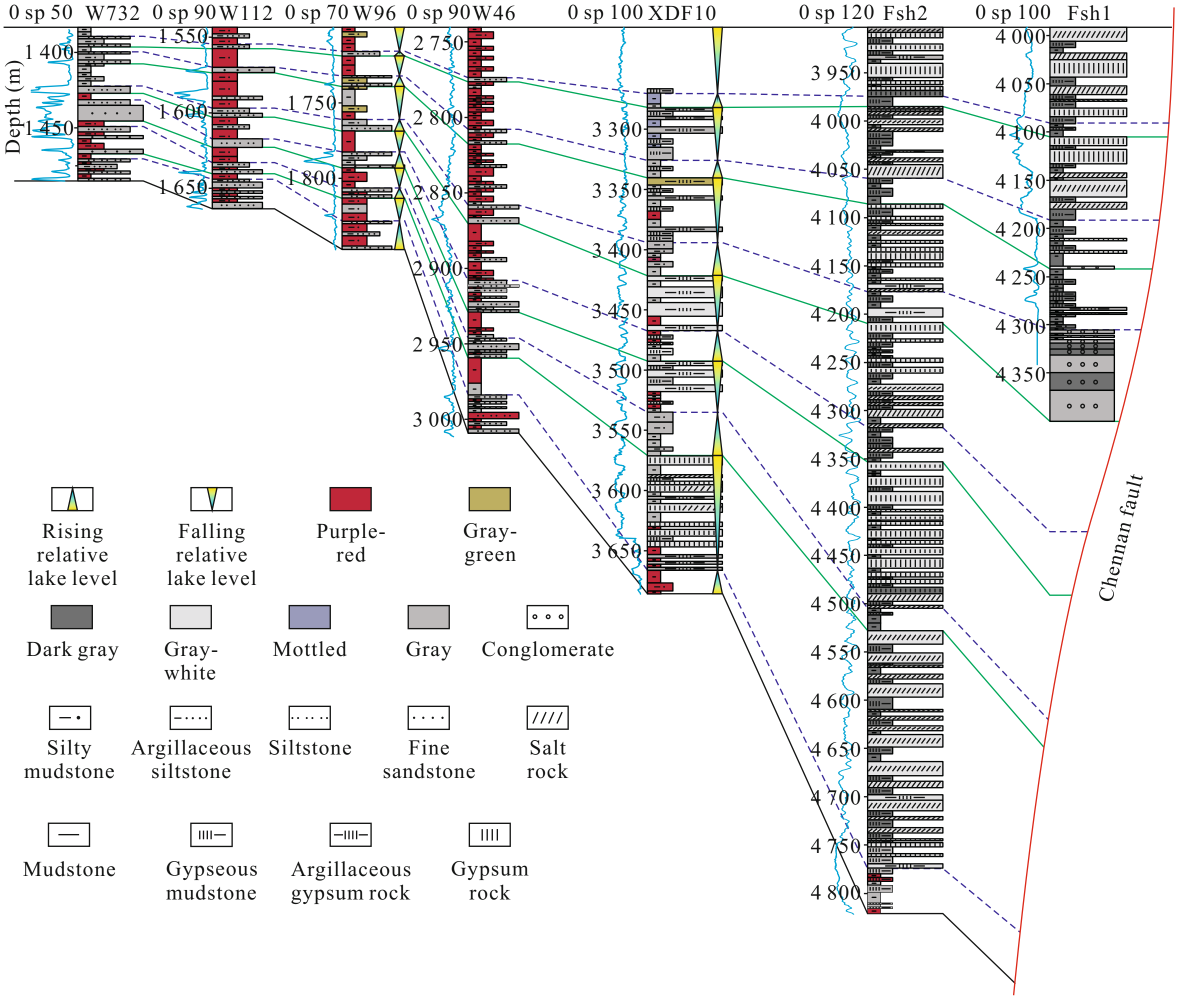

Figure 12. Sedimentary filling sequence of high frequency oscillatory salt lake of the Lower Eocene E*s*^{4x} member in the Dongying depression. See Fig. 1b for profile location.

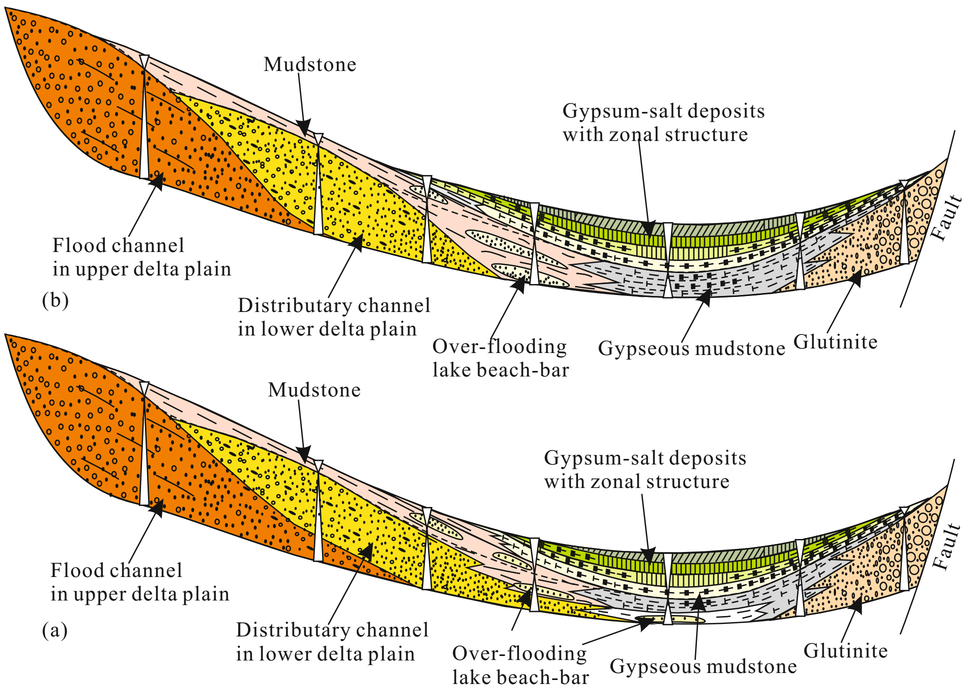

Figure 13. Sedimentary filling model of high frequency oscillatory salt lake of the Lower Eocene E*k*^{1}–E*s*^{4x} members in the Dongying depression. Legends of lithology as in Figs. 6 and 10.

the formation of isochronous flood channels and ended with the formation of gypsum rocks and salt rocks with relatively large thicknesses. The sedimentary filling model of the high-frequency oscillatory lake reveals the pattern of distribution of sediments in this continental lake basin in an arid climatic background and will provide excellent guidance for the study of the sedimentary features of other sedimentary basins with similar geological backgrounds.

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