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Eocene prevalence of monsoon-like climate over eastern China reflected by hydrological dynamics

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A B S T R A C T

Hydrological dynamics of sedimentary basins are essential for understanding regional climatic pattern in the geological past. In previous qualitative studies lithologically depending on the occurrence of featured sedimentary rocks, the Eocene climate of China had been subdivided into three latitudinal zones, with one subtropical high-controlled arid zone throughout middle China, and two humid zones respectively in the north and south. However, recent advances on mammalian fauna distribution, plant fossil-based quantitative paleoclimatic reconstruction, and modeling experiment jointly suggest that the relatively humid monsoonal climate might have prevailed over the territory. Here we examine and compare sedimentary sequences of 10 Eocene sections across eastern China, and hence the lake level fluctuations, to discuss the nature of climate type. Our results show that, instead of the categorically zonal pattern, the hydroclimate dynamics is intensified landward. This is demonstrated by the fact that, in contrast to the wide developed coal layers around the periphery, evaporites are growingly occurred endocentrically to the central part of middle China. However, although we have had assumed that all evaporites are indicator of extreme aridity, the highly oscillated climate in the central part of middle China was humid in the majority of the Eocene, distinct from permanent arid as seen in deserts or steppe along modern horse latitude. From the upcountry distribution pattern of the Eocene hydrological dynamics, it appears that the relatively dry climate in central China was caused by the impact of continentality or rain shadow effect under monsoonal, or monsoon-like climate.

1. Introduction

The Eocene represents one of the most pronounced greenhouse periods in the Cenozoic, characterized by the equably distributed hot and humid climate (Greenwood and Wing, 1995; Clementz and Sewall, 2011). The warm global temperature, as much as 5–12 °C higher than today that leading to ice-free poles for the majority of the epoch (Huber and Sloan, 2001; Bijl et al., 2009), allowed air masses holding more water vapor, and enhanced polarward moisture transportation from extremely wet tropics along a shallow gradient (Fricke, 2003; Greenwood et al., 2010; Clementz and Sewall, 2011). However, the regional hydrological dynamics distribution, and hence the climatic pattern during the Eocene, are intangibly known, especially in the vast territory of East Asia such as China, in which conflicting explanations are produced (e.g., Qiu, 1996; Tong et al., 1996; Liu, 1997; Wang et al., 1999; Sun and Wang, 2005; Lu et al., 2007; Huber and Caballero, 2012; Quan et al., 2012a).

Previous lithology-based qualitative climatic studies suggest that there were two humid zones respectively in the north and south marked by the occurrences of coal and/or oil shale, and one broad arid zone stretched throughout middle China from west to east implied by the wide spread red beds and/or evaporites (Fig. 1) (Liu, 1997; Wang et al., 1999; Sun and Wang, 2005). Because this arid zone was located around 30°N paleo-latitude, it was further identified with the Eocene subtropical high (Liu, 1997; Wang et al., 1999), probably with landscapes resembling deserts and steppes along modern horse latitudes (Zhang et al., 2012). However, latest large-scale quantitative climatic reconstruction depending on the paleobotanical assemblages (Quan et al., 2012a) and the numerical simulation experiment (Huber and Caballero, 2012) both suggest that monsoonal climate might have been more or less developed under a relatively humid environment over China during the Eocene. From a paleoclimatic perspective, these new results corroborate those of mammalian fossil investigations, which deduce that the Eocene mammalian faunas are equably distributed in a humid climate over the

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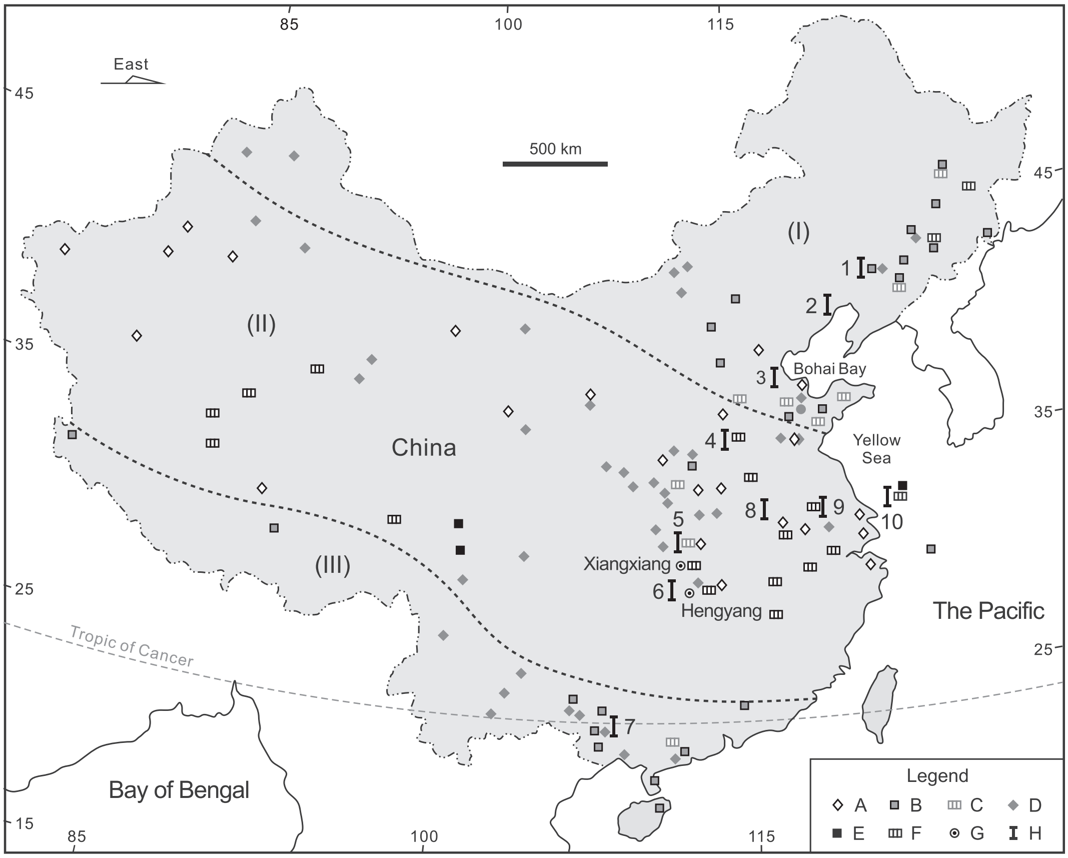

Fig. 1. Location of selected Eocene sections and associated lithological and paleontological data. Site numbers as in Table 1. Climatic zone subdivision (I–III) and related lithological data are from previous studies (Liu, 1997; Wang et al., 1999; Sun and Wang, 2005; Zhang et al., 2012). I – humid warm temperate to subtropical zone; II – middle arid zone (subtropical highs); III – tropical to subtropical zone. A – evaporites; B – coal; C – oil shale; D – mammalian fauna; E – newly found coal site; F – newly found oil shale site; G – important plant fossil or stratigraphic site; H – selected sections investigated in the present study. Mammalian data are mainly based on Tong (1989); data of newly found coal and oil shale sites are available online of data available on the website of National Geological Archives of China at http://www.ngac.cn/.

country, without an unambiguous latitudinal zonal pattern (Qiu, 1996; Tong et al., 1996). Apparently, in such a discrepancy, depicting the distribution of hydrological dynamics is crucial in understanding the Eocene climatic pattern of China.

Sedimentologically, stratigraphic succession of terrestrial deposits provides a substantial record of perturbations in lake system responding to associated climatic changes, and helps to decrypt the regional hydroclimatic dynamics in the geological past by comparing sedimentary sequences of different areas (Frakes, 1979; Janasson, 1983; Renaut and Long, 1989). In this paper, we examine profiles from several representative Eocene basins of eastern China to find out the overall distribution of lake water dynamics, which conduces to the comprehensive understanding of the Eocene climatic pattern thereof. Our results reveal that middle China, previously considered as an arid zone controlled by a subtropical high, is of high hydroclimatic dynamics in the Eocene, far from permanent arid as seen in deserts or steppe along the horse latitude. Moreover, integrated analyses further suggest that it appears without a distinguished arid zone obstructing across middle China during the Eocene, supporting that a monsoonal, or monsoon-like climate must have had dominated this vast region.

2. Method and material

2.1. Mudstone facies

Diagenetically, the mudstones, including mudrock, clay, shale, and other fine-grained rocks, give critical insight into sedimentation processes of the basin, such as the lake level changes and oxygen level identifications (Janasson, 1983; Aplin et al., 1999; Potter et al., 2005). Among various physical properties of mudstone, the rock color is basically controlled by water depth, and subsequently by the redox condition (Janasson, 1983; Parrish, 1998; Aplin et al., 1999). For a given facies, color of mudstone is decisive in environment determination, as shown by cycles of either marine or terrestrial muddy shoreline deposits (Abdul Aziz et al., 2003; Potter et al., 2005). In general, the color of mudstone tends to be darkened with deepening of the water body. Ferrous iron and organic matter are responsible to the darkened rock color, from gray, gray–green to black, under the reducing environment (Aplin et al., 1999; Abdul Aziz et al., 2003). When the lake depth turns to be shallow, ferric iron is accountable to the reddened rock color under the oxidizing environment (McBride, 1974; Parrish, 1998; Potter et al., 2005). In other words, the water depth plays the key role for redox condition, and thus the color variation of mudstone (Aplin et al., 1999; Potter et al., 2005). Therefore, we here briefly summarize the characteristics of mudstone in continental sedimentary facies, and use it as the indicator of hydrological dynamics.

Fluvial facies are deposited in oxidizing environment in most cases, in which the color of mudstone is red in either humid or arid climate (McBride, 1974; Parrish, 1998). Likewise, alluvial fan is also definitely in the oxidizing environment, where the mudstone could be red in both climate types (van Houten, 1973; Parrish, 1998). However, the mudstone is impure and occasionally comprising sandstone, conglomerate, charcoal, and fossil plant fragments in humid climate, while in arid climate, the mudstone is mainly

Table 1
Characteristics of mudstone under different terrestrial depositional environments. Mudstone characteristics of each facies were summarized from literatures (van Houten, 1973; McBride, 1974; Frakes, 1979; Janasson, 1983; Besly and Fielding, 1989; Armenteros et al., 1997; Parrish, 1998; Aplin et al., 1999; Abdul Aziz et al., 2003; Potter et al., 2005; Falcon-Lang et al., 2011; Pendleton et al., 2012). O: oxidation; R: reduction; R–O: reduction–oxidation.

Depositional environment (facies)	Humid			Arid		
	Sedimentary symbol	Main color of mudstone	Redox	Sedimentary symbol	Main color of mudstone	Redox
Floodplain						
Fluvial	Charcoal in thick sandstone	Red	O	Calcareous nodule in mudstone or siltstone	Red	O
Alluvial fan	Impure mudstone composing of sandstone or conglomerate	Red	O	Sandy mudstone, calcareous nodule	Red	O
Lacustrine						
Shore	Red mudstone	Red–brown	O	Dolomitic mudstone, muddy dolomite, gypsum mudstone	Red–gray white	O
Shallow	Mudstone, siltstone, and fine sandstone	Red–gray green	R–O	Lime- or dolomitic mudstone	Red–gray green	R–O
(Semi-)deep	Pure dark mudstone, shale	Black	R	Pure dark mudstone, shale	Black	R
Lagoon (and oxbow lake)	Coal, carbonaceous mudstone (swamp)	Black	R	Halite, gypsum (playa)	Gray white	O
Delta						
Plain	Coexistence of sandstone and brown coal	Red–gray green	R–O	Gypsum mudstone, calcareous nodule	Red–gray	O
Front	Charcoal in sandstone, channel deposit	Gray–brown	R–O	Lime mudstone	Gray–brown	R–O
Pro-delta	Dark mudstone occasionally with turbidite sandstone	Gray black	R	Dark mudstone occasionally with turbidite sandstone	Gray black	R

sandy mudstone, frequently composing of gypsum and/or calcareous nodule (Frakes, 1979) (Table 1).

For the lacustrine facies, mudstone in humid climate is red to brown in lakeshore because of the effect of oxidization, while in arid climate the sediments are characterized by dolomitic mudstone, muddy dolomite, muddy gypsum, and/or gypsum mudstone (Parrish, 1998; Abdul Aziz et al., 2003) (Table 1). And in shallow lake, the sedimentary environment varies from oxidization to weak reduction. As a result, the mudstone is red to gray green in color in both humid and arid climate. However, lime- or dolomitic mudstone might be deposited in arid climate (Table 1). For example, Abdul Aziz et al. (2003) reconstructed the evolutionary and paleoenvironmental history of the Calatayud Basin of Spain during the middle Miocene, which yields both serials of mudstone. The shallow lake facies shows a remarkable cyclical alternation of green–gray, red siliciclastic mudstone units, and white dolomites, reflecting the paleoclimate oscillation between dry and wet conditions.

The lagoon facies are characterized by coal or carbonaceous mudstone in reducing environment under humid climate (i.e., palustrine), and by gray white gypsum mudstone, gypsum, and/or halite in oxidizing environment of arid climate (Janasson, 1983; Armenteros et al., 1997). On the contrary, pure dark mudstone is formed in (semi-)deep lake under the strong reducing environment in both arid and humid climates (McBride, 1974; Janasson, 1983; Potter et al., 2005) (Table 1). Noticeably, halite layers might be precipitated in deep lake under either humid or arid climate (see below).

Three sub-facies are involved in the deltaic sedimentary environment, including delta plain, delta front, and pro-delta. In delta plain, both the mudstone with exposure signatures such as mud crack and raindrop imprint, and the mudstone between distributary channels are mainly red–gray green in color due to the redox condition changes (Besly and Fielding, 1989; Falcon-Lang et al., 2011). However, in humid climate, there might be swamp (or wetland), which is marked by terminal deposits of coal and/or carbonaceous mudstone (Pendleton et al., 2012). By contrast, gypsum mudstone and calcareous nodule are frequently occurred in arid climate (Falcon-Lang et al., 2011). In delta front with relatively shallow water, the environment is oxidizing to weak reducing, in which the color mudstone is inclined to being brownalized. However, lime mudstone is occasionally developed in delta front under the relatively dry climate (Potter et al., 2005). The mudstone color turns to be further darken, from gray, gray–black to black, with the deepening of the water body from delta front to pro-delta (Table 1).

Taken together, the rock color in various facies is mainly controlled by the redox condition where it deposited, not closely connecting to a specific climate type (Table 1). Therefore, it appears inadequate to deduce the prevalence of arid climate in a geological interval merely based on the occurrence of red beds (van Houten, 1973; Parrish, 1998; Aplin et al., 1999; Potter et al., 2005).

2.2. Section selection and climate indicator

A total of 10 sections are carefully selected from the Eocene basins over eastern China, which covers all the three inferred climate zones (Fig. 1; Table 2). Stratigraphic data are based on either literature or profile measurements by this study (Table 2). Among these, selection of Sections 1–7 from north to south is intended to find out the overall latitudinal distribution of the hydrological dynamics, while the selection of Sections 8–10 and 5 from coastal to inland are designed for the transmeridional pattern (Fig. 1). Specifically, we employ the section of Fushun coal-mine as the typical example of deposits under humid climate in the north (Section 1; Fig. 1 and Table 2), which hold important information on the development and the then enhanced monsoon during the Eocene (Quan et al., 2011, 2012b). In the south, the coal-bearing Baigang section from the Bose Basin is selected as the representative of humid climate in the low latitudes (Section 7; Fig. 1 and Table 2). Moreover, Sections 2–4 are selected respectively from the north, middle, and south of the Bohai Bay Basin to compare the hydrological dynamics in different parts of same basin (Fig. 1 and Table 2). Other 2 sections are selected from southern part of the South Yellow Sea–North Jiangsu Basin to illustrate the hydrological condition in eastern part of the supposed Eocene subtropical high across middle China (Sections 9 and 10; Fig. 1 and Table 2).

In all sections, coal bed is considered to be the product of humid climate (Besly and Fielding, 1989; Pendleton et al., 2012). Similarly, the dark mudstone is also treated as the outcome of humid climate, because it always suggests the high lake level resulted from the high water season of the drainage basin (Aplin et al., 1999; Potter et al., 2005).

Table 2
Selected Eocene sections from eastern China. Section number as in Fig. 1. SYS–NJ: South Yellow Sea–North Jiangsu Basin; Age: Eo – Eocene; E – early Eocene; M – middle Eocene; L – late Eocene.

No.	Coordinate	Section	Basin	Formation(s)	Age	Data source
1	41°39′N, 121°17′E	Fushun Coal-mine, Liaoning	Fushun	Guchangzi, Jijuntun, Xilutian, and Gengjiajie	Eo	This study
2	40°56′N, 120°45′E	Damintun Sag, Liaoning	Bohai Bay	Shahejie (Members 2–4)	Eo	This study
3	37°50′N, 117°07′E	Mid Hebei Depression	Bohai Bay	Shahejie (Members 2–4)	Eo	Tao et al. (2011)
4	35°36′N, 115°41′E	Dongpu Depression, Henan	Bohai Bay	Shahejie (Members 2–4)	Eo	Zhai and Xu (1992)
5	30°07′N, 112°49′E	Qianjiang Sag, Hubei	Jianghan	Qianjiang (Members 2–4)	Eo	Fang, 2006
6	27°08′N, 112°50′E	Xialiu, Hunan	Hengyang	Gaoling	E	Zhang (1997a,b)
7	23°52′N,106°35′E	Baigang, Bose of Guangxi	Bose	Nadu, and Fuping	L	This study
8	33°23′N, 115°24′E	Lilou, Jieshou of Anhui	Zhoukou	Jieshou	E	Li and Jiang (1997)
9	32°51′N, 119°41′E	Gaoyou Sag, north Jiangsu	SYS–NJ	Dainan	E–M	Gao et al. (2010)
10	33°13′N, 123°05′E	Southern Yellow Sea	SYS–NJ	Dainan	E–M	This study

Determination of arid climate, for example, usually depending on evaporites, is somewhat ambiguous. In principle, depositional settings of primary evaporites largely involve environments of the subaerial, subaerial–shallow water, shallow–subaqueous, and deep subaqueous, which are diagenetically corresponding to the playa, sabkha, mud flat, and deep brine, respectively (Schreiber and Tabakh, 2000; Warren, 2006). The first two sedimentary environments are usually allied to the arid climate (although not always), while the last two are equivocally related to either arid or humid climate (Yechieli and Wood, 2002; Warren, 2006; and see below). In the present study, however, because of lacking extensive geochemical data to determine the origin of specific evaporite layers, we here follow the lithological criterion of previous qualitative studies (Liu, 1997; Wang et al., 1999; Sun and Wang, 2005), and tentatively treat all evaporites, if occurred, as the indicator of arid climate in sedimentary facies analyses of each stratigraphic section, although some recent investigations argued that halite layers in most Eocene basins of eastern China are of deep brines (Chen et al., 2000; Yuan et al., 2000; Zhang et al., 2003, 2005; Fang, 2006; Du et al., 2007; Lu et al., 2007; and see below for details).

It should also be mentioned that the characteristics of sediments are highly depended on the diagenetic history, and subsequently the rock color might not be primary, especially for those of mottled clastic deposits (McBride, 1974; Janasson, 1983; Potter et al., 2005). The light colored and mottled rocks may be resulted from oxidation of organic matters or dissolution in the diagenetic process (Parrish, 1998; Potter et al., 2005). Therefore, when sediments are closely associated with neither humid nor arid indicator, the climate type was treated as unknown.

3. Results

3.1. Fushun coal-mine section of Fushun Basin

The Eocene strata in the Fushun coal-mine section composes of four formations (Fig. 2; Table 2). Each formation is marked by its distinctive lithologic association, i.e., the coal or carbonaceous mudstone of the Guchengzi Formation, oil shale and dark mudstone of the Jijuntun Formation, gray green mudstone and argillaceous limestone of Xilutian Formation, and brown shale intercalated with variegated shale-, silt-, and sandstone of Gengjiajie Formation. In this section, the color of mudstone layers are mainly gray green to black, suggesting the reducing condition in the majority of the spanning period. At the bottom of the section, development of thick coal and carbonaceous mudstone of the Gushenczi Formation indicates that the environment was lagoon/swamp under humid climate (0–26 m; Fig. 2). Oil shale of the Jijuntun Formation (26–50 m) apparently suggests a deep lake environment under a humid climate. The lake level turned to be oscillated in the stage of Xilutian Formation (50–111 m), because

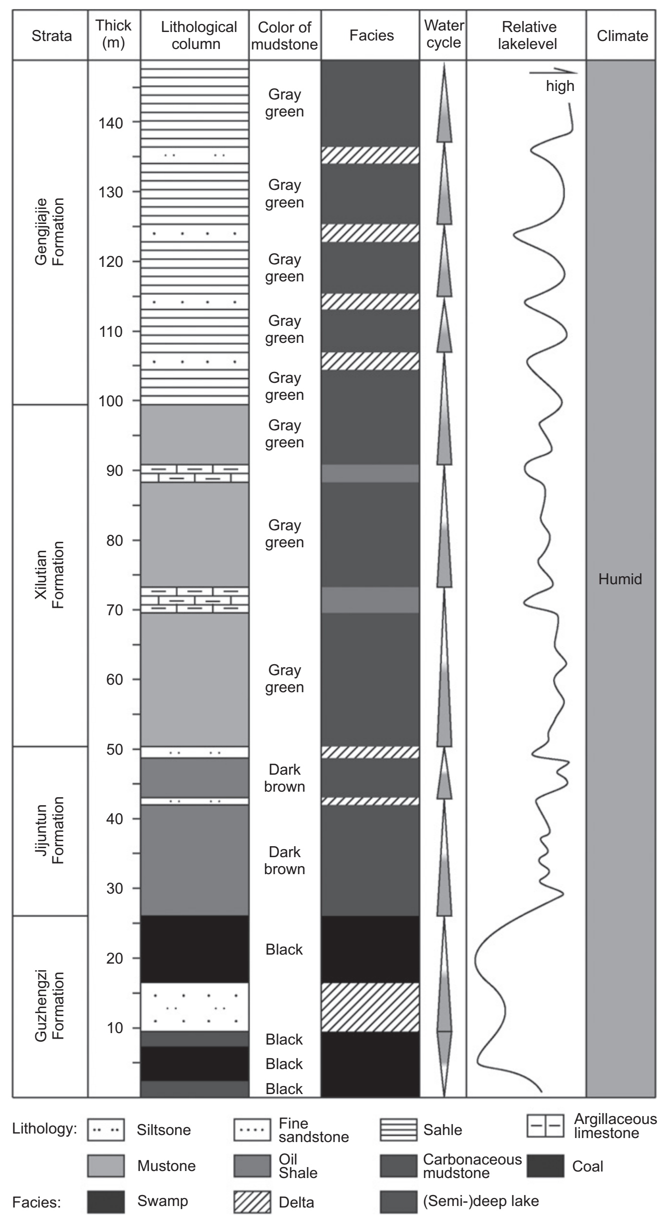

Fig. 2. Sedimentary sequence of Fushun coal-mine section (Site 1).

of the occasionally occurred argillaceous limestone in the main matrix of gray green mudstone. At the top of the section, dramatic facies variation is observed in the Gengjiajie Formation (111–149 m). However, gray white fine sandstone and gray green shale, respectively responsible for the depositional environment of delta and semi-deep lake, indicate that climate mainly was humid (Fig. 2).

3.2. Damintun Sag of Bohai Bay Basin

The Damintun Sag is located in the north of the Bohai Bay Basin (Fig. 1 and Table 2). It represents one of the examples of paradoxical hydrological statement in the same basin. In comparison to the more or less developed halite layers in the middle and southern part of the basin, evaporites are absent from the Eocene Shahejie Formation of this sag (Fig. 3). In the lower part of the section, the thick black mudstone and oil shale obviously illustrates a long period high water level of the lake because, as the type of condensed section in sedimentary sequence, they must have been deposited in a longer time interval than other rocks. From 500 m upward, the lake area shrunk and then expanded for several times, as shown by the facies alternation regularly between (semi-)deep lake and delta. More importantly, coal beds are occasionally occurred, substantially indicating the humid climate hereof (Fig. 3).

3.3. Mid Hubei depression of Bohai Bay Basin

A few evaporite layers had been found from the Eocene Shahejie Formation of mid Hubei, middle part of the Bohai Bay Basin (Figs. 1 and 4; Table 2). In the base 160 m of the section, the sedimentary sequence mainly comprises inter-bedding of grayish white medium, fine, and silty sandstone, intercalated by coal seams and carbonaceous mudstone, which suggest the facies of distributary channels in delta front to swamp under humid climate. The water body was intermittently deepened in the interval of 160–420 m, shown by facies cycles between grayish sandy stone of distributary channel and grayish white mudstone of semi-deep lake. Gypsum is deposited at 420–424 m, suggesting a short process of aridification. In 424–910 m interval, the water body backtracked to be deepened lithologically due to the inter-bedding of grayish white mudstone, medium, fine, and silt sandstone. The (semi-)deep lake retained throughout the interval of 910–1223 m, where thick gray mudstone was developed, suggests a long period of high flow period or wet season around the drainage basin. The high flow period occurred again at 1510–1780 m, after the period of lake level fluctuation at 1223–1510 m. The climate became steadily humid at 1780–2030 m because of the formation of coal seams and carbonaceous mudstone that are intercalated in the gray mudstone and fine sandstone of the delta front. Gypsum is re-occurred in the section at 2120–2150 m, with inter-bedded purple mudstone. This indicates a period of lake area shrinking that resulted in a strong oxidizing condition (Fig. 4).

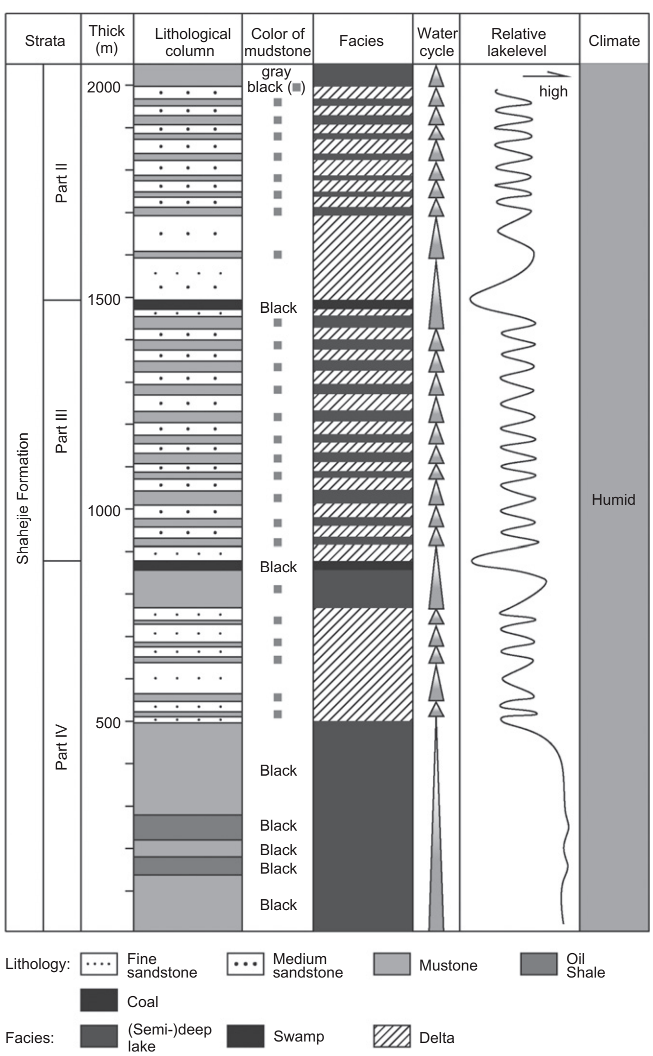

Fig. 3. Sedimentary sequence of Damintun Sag, northern Bohai Bay Basin (Site 2).

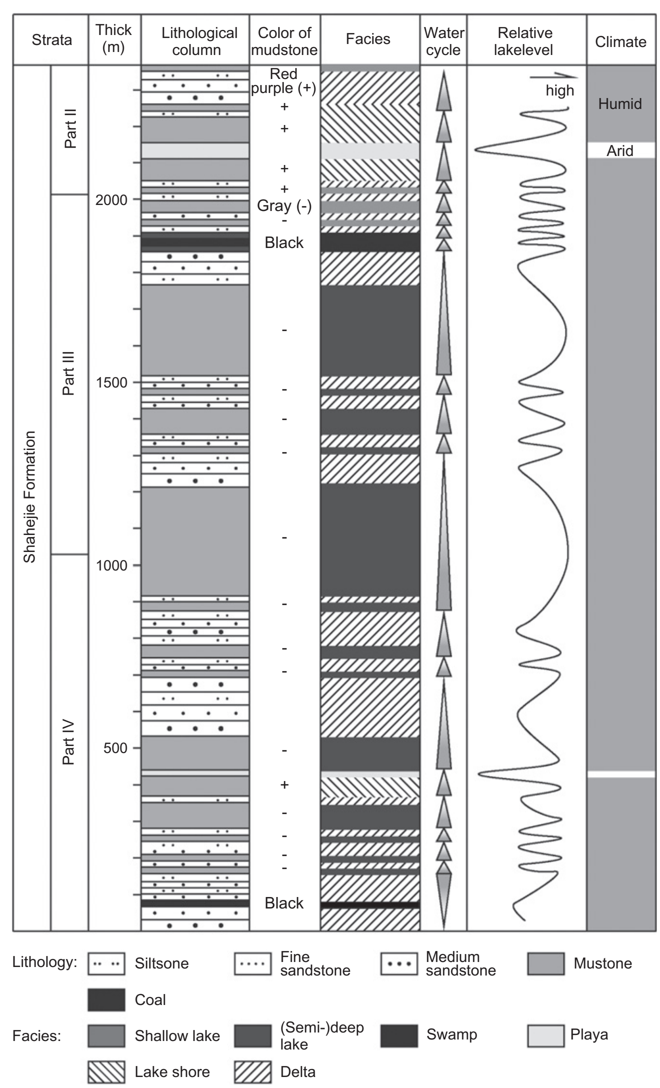

Fig. 4. Sedimentary sequence of Mid Hubei Depression, middle Bohai Bay Basin (Site 3).

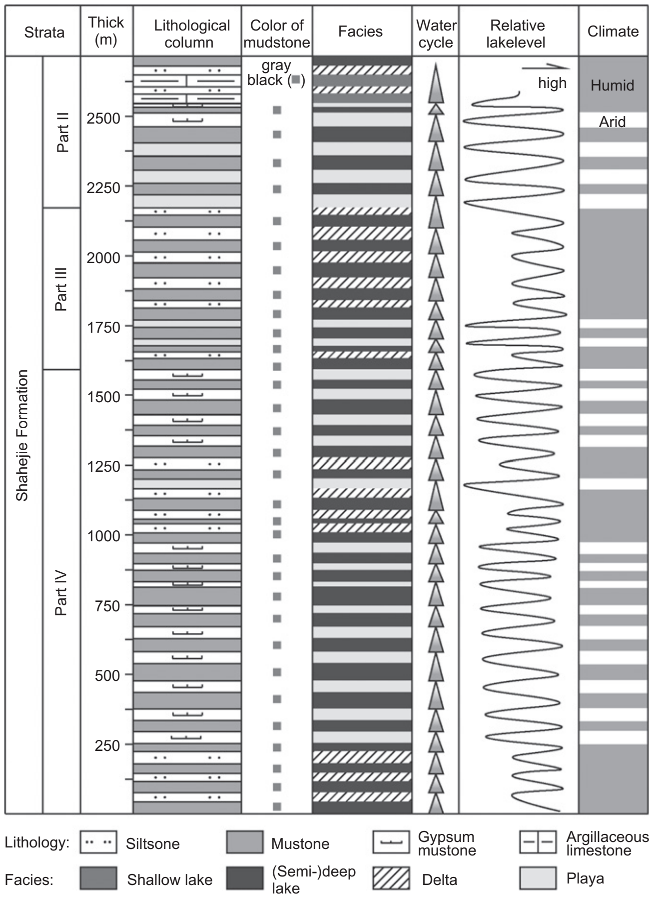

Fig. 5. Sedimentary sequence of Dongpu Depression, sourthern Bohai Bay Basin (Site 4).

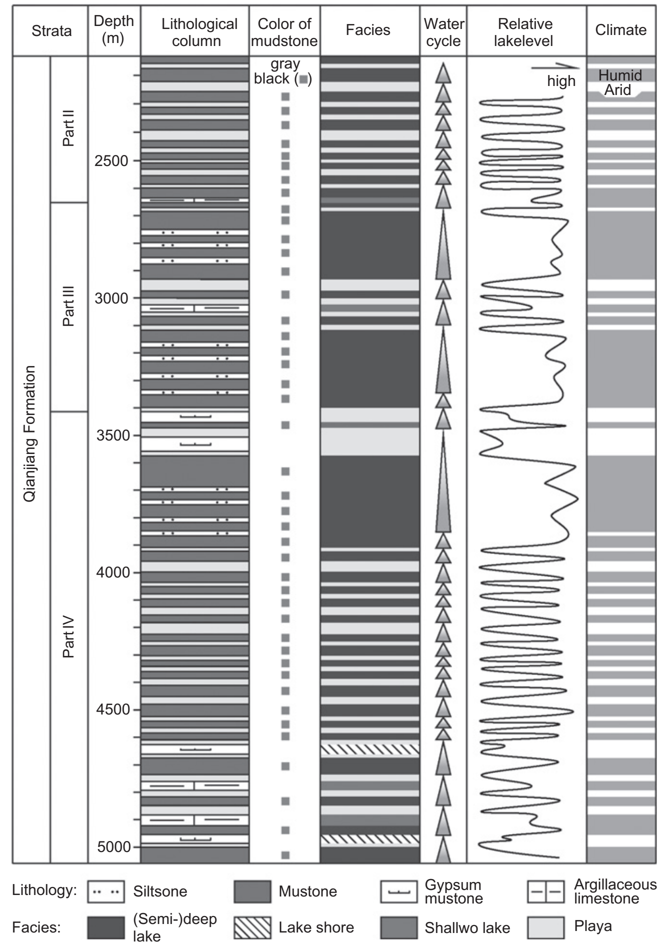

Fig. 6. Sedimentary sequence of Qianjiang Sag, Jianghan Basin (Site 5).

3.4. Dongpu Depression of Bohai Bay Basin

The Wenliu section is from the Dongpu Depression, southern part of the Bohai Bay Basin (Fig. 1 and Table 2). In contrary to those of both middle and northern parts of the basin, several layers of halite and gypsum are observed in this section (Fig. 5). The water level oscillated between (semi-)deep lake and delta under (semi-)humid climate at the lowest 240 m, implied by the inter-bedded gray–black mudstone and siltstone. The same applies to the intervals of 970–1175 m, 1240–1380 m, 1628–1680 m, and 1810–2145 m. By contrast, interval of 240–970 m represents a period frequent alternation of humid and arid climates, because of the cycles of inter-bedded gray black mudstone and gypsum. Such kind of hydrological cycles is also observed at intervals of 1380–1628 m and 2475–2680 m. However, more frequent climatic change is found in 1175–1240 m. In this interval, as also those of 1680–1810 m and 2145–2475 m, gray black mudstone and halite are alternately deposited, suggesting a sharply shifted lake level between deep and dry-out, if considering the halite as indicator of playa (see Section 2).

3.5. Qianjiang Sag of Jianghan Basin

The section is from the center of the Qianjiang Sag of the Jianghan Basin, central China (Fig. 1 and Table 2), in which the Eocene Qianjiang Formation is lithologically composed of halite, sandstone, and mudstone (Fig. 6). The sedimentary sequence is overall constituted by four megacycles that consist of several sub-cycles. From the base to about 4620 m of the section (stage 1), the stratigraphic cycles are characterized by inter-bedding of dark mudstone, argillaceous limestone, gypsum mudstone, and halite. Accordingly, the sedimentary environments varied among (semi-)deep lake, shallow lake, lake shore, and playa. This suggests a dramatically changed climate, which led the fluctuated lake levels and resulted in the redox condition varying between oxidizing and reducing. From 4620 m to 3910 m (stage 2), stratigraphic cycles are mainly involving halite and mudstone, suggesting drastic lake depth changes between (semi-)deep lake and playa. In the well section of 3910–3580 m (stage 3), the lake maintained a relatively high level for a long period, shown by dark mudstone intercalated by thin siltstone of turbidite fans. However, the lake level turned to be fluctuated again in stage 4 at 3580–3340 m. From this stage upward, cycles alike those of stages 3 and 4 repeatedly occurred two times respectively in the stratigraphic interval of 3340–3120 m and 3120–2930 m, and 2930–2690 m and 2690–2130 m (Fig. 6).

3.6. Xialiu section of northern Hengyang Basin

The Eocene Gaoling Formation in the Xialiu section of the northern Hengnyang Basin is mainly composed of brown red siltstone, fine to medium sandstone, and gray green mudstone, with absence of evaporites (Fig. 7). Sedimentary cycles of this section are relative simple, composing of 6 megacycles between inter-bedded brown red sandstone and siltstone of delta front and thick gray green mudstone of relatively deepened shallow lake. The brown red color of the sand- and siltstone is probably related to oxidizing condition or weathering of parent rock (Fig. 7).

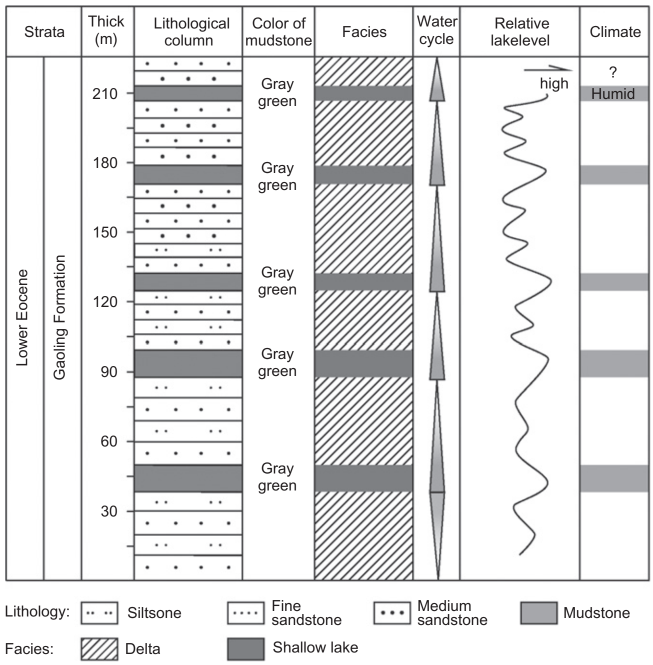

Fig. 7. Sedimentary sequence of northern Hengyang Basin (Site 6).

3.7. Baigang section of Bose Basin

The Baigang section from the Bose Basin analyzed here includes the late Eocene Nadu and Baigang formations. Lithologically, this section is mainly composed of yellow green mudstone, fine sandstone, siltstone, carbonaceous mudstone, and brown coal, representing a typical sedimentary succession under humid climate in southern China (Figs. 1 and 8). Inter-bedding of yellow green mudstone, fine sandstone, and carbonaceous mudstone in the basal 97 m of the section suggests that the facies alternated between shallow lake and delta under a reducing environment of humid climate. The facies then turns to be lagoon/swamp at the interval of 97–105 m, marked by the thick bed of brown coal. The lake level rose in 105–310 m and 350–538 m intervals and formed the shallow lake to delta facies again, forming the inter-bedded yellow green sandstone, siltstone, and carbonaceous mudstone. Shallow lake facies indicated by thick yellow green mudstone at 310–339 m is followed by coal layer at 339–350 m. On the top of the section (538–600 m), thick yellow green mudstone implies that the lake remained a relative high level under humid climate for a long period (Fig. 8).

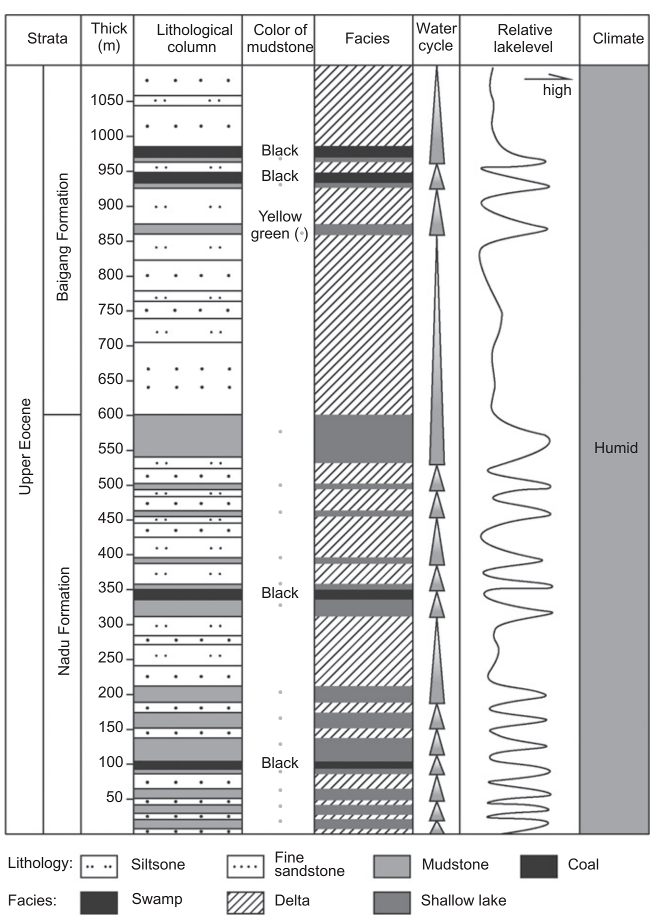

Fig. 8. Sedimentary sequence of Baigang section, Bose Basin (Site 7).

3.8. Lilou section of southern Zhoukou Basin

In this section, the Eocene Jieshou Formation is characterized by a series of cycles of brown fine sandstone, brown red siltstone, and brown red mudstone (Fig. 9). The brown–red colored rocks suggest that oxidizing condition was prevailing throughout the sedimentary stage in either delta or shallow lake. Notably, however, development of thick silty mudstone at the top of the section

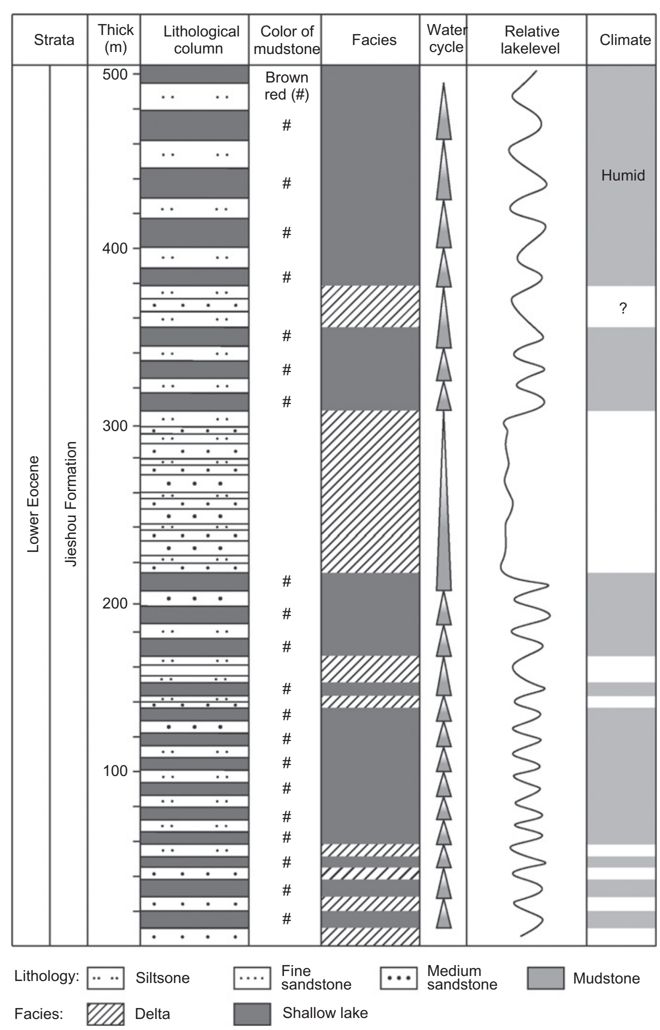

Fig. 9. Sedimentary sequence of Lilou section, southern Zhoukou Basin (Site 8).

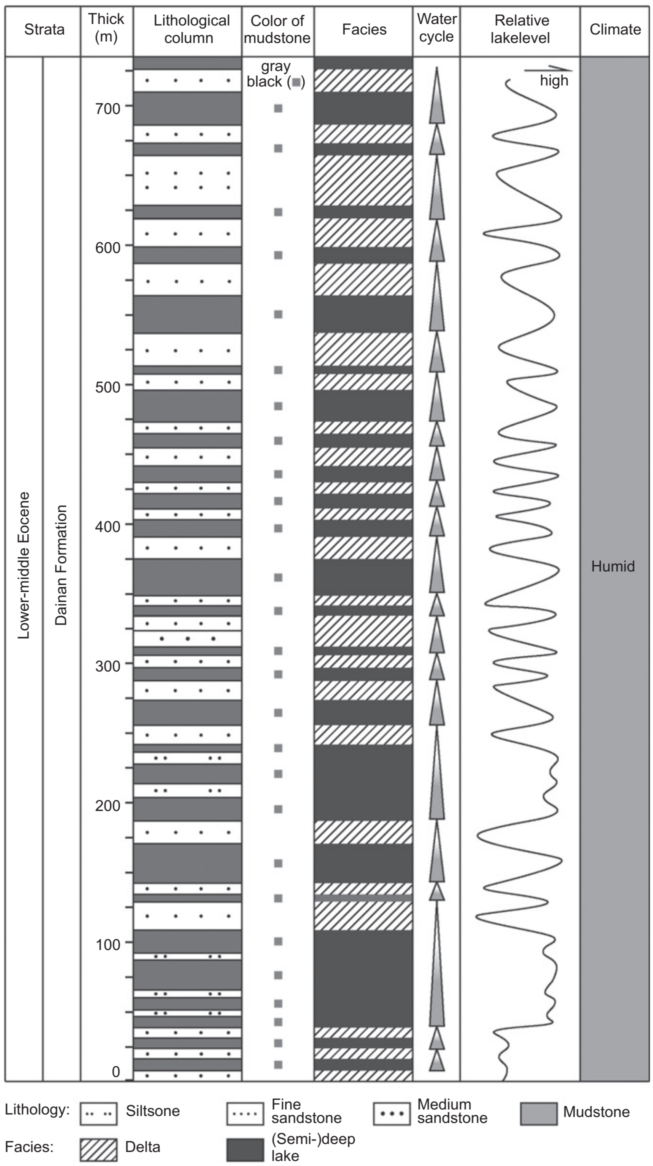

Fig. 10. Sedimentary sequence of Gaoyou Sag, South Yellow Sea–North Jiangsu Basin (Site 9).

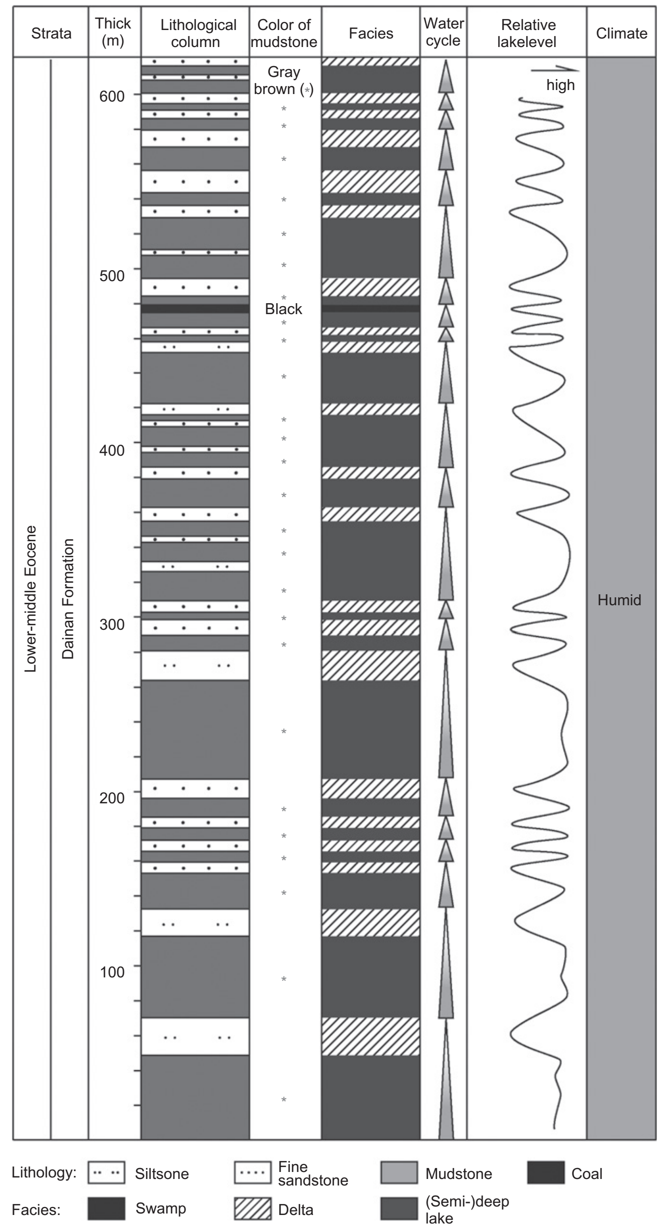

Fig. 11. Sedimentary sequence of southern South Yellow Sea, South Yellow Sea–North Jiangsu Basin (Site 10).

(378–502 m) indicates a long period of a steady, relatively high lake level.

3.9. Gaoyou Sag of South Yellow Sea–North Jiangsu Basin

Sedimentary succession of the Dainan Formation from the center of the Gaoyou Sag includes 3 megacycles of thick gray black mudstone and gray black mudstone–gray white fine sandstone inter-bedding (Fig. 10). The thick dark mudstone layers indicate a long period of high lake level under humid climate, while the inter-bedded dark mudstone and light fine sandstone sub-cycles suggest the frequent oscillations between low flow delta front and high flow (semi-)deep lake. No evaporites are observed in this section. However, gypsum mudstone is sporadically occurred at the basin margin, which is probably related to a mud flat environment.

3.10. Southern Yellow Sea depression of South Yellow Sea–North Jiangsu Basin

Sediments of the Dainan Formation in this section are characterized by gray brown mudstone, siltstone, fine sandstone to gritstone, and coal, without evaporites (Fig. 11). Deep lake stages occupy the majority of the depositional period, represented by thick gray brown mudstone respectively at the lowest 44 m, 65–119 m, 204–263 m, and 464–483 m. Other intervals that alternately stuck in two adjacent deep lake stages are mainly sub-cycles of delta front distributary channel and shallow lake, as shown by the inter-bedded gray brown mudstone and sandstone layers, which is occasionally intercalated by coal beds of paludal environment.

4. Discussion

4.1. Distribution pattern of hydrological dynamics

By considering all evaporites as the indicator of lake shrinking under arid climate, the most remarkable feature of Eocene hydroclimate distribution pattern of eastern China is the inland intensified water dynamics, instead of the categorically zonal pattern

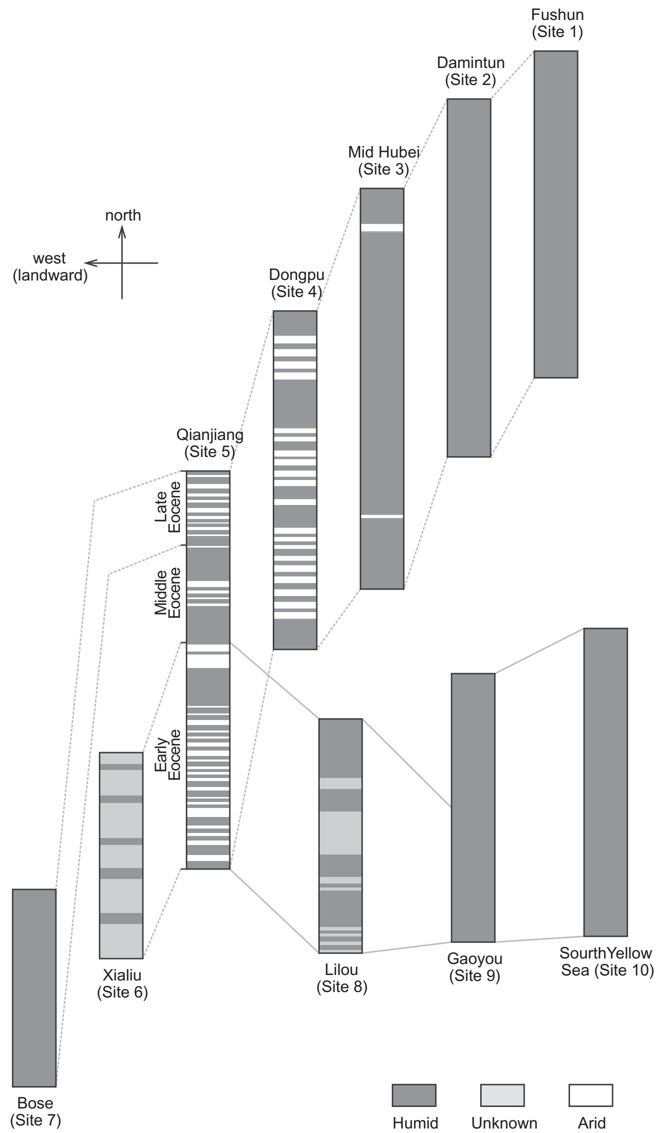

Fig. 12. Eocene hydroclimate distribution of eastern China. Schematic diagram not to scale; site number as in Fig. 1 and Table 1; legend as in sedimentary sequence chart of each site.

(Fig. 12). Evaporites are growingly developed from the surrounding areas endocentrically to central China. The Qianjiang Sag of Jianghan Basin, central China, represents the most dramatic hydrological dynamics (Fig. 6). In this depression, up to 160 beds of evaporites are observed (Fang, 2006), which are in most cases abruptly occurred between adjacent oil shale beds, with absence of transitional phase (Fig. 6). For the thickness, however, a total of ~1800 m dark mudstone and oil shale have been deposited, while only ~900 m of evaporites are developed (Fig. 6). Because the deposition rate of aridity-derived evaporites is much greater than those of dark mudstone and shale (Aplin et al., 1999; Schreiber and Tabakh, 2000; Potter et al., 2005; Warren, 2006), the evaporites at most indicate a serial of short arid periods. By contrast, the dark mudstone and oil shale, with doubled thickness to that of evaporites, substantially suggest that the lake had kept in the high lake level for the majority of the sedimentary stage, which appears to be caused by high flow period or wet season in the drainage basin.

From the northern to central part, thick beds of coal and carbonaceous mudstone of the Fushun coal-mine section strongly suggest a humid climate in the north (Sections 1; Figs. 1 and 2). Southward, however, it is notable that contradictory hydrological conditions are found in different part of the Bohai Bay Basin (Sections 2–4). In the northern part of the basin, the Damintun Sag is characterized by a long period of deep lake that is occasionally punctuated by delta plain that yields coal beds; evaporites are absent from the whole section (Fig. 3). By contrast, evaporites are sporadically occurred in the Mid Hubei Depression of the middle part of the basin, in which coal beds are also developed (Fig. 4). More evaporite beds are found from the Dongpu Depression in the south of the basin (Fig. 5). The conflicting hydrological conditions appear to suggest that the Eocene salinity is unbalanced in the basin, or that evaporites are not all always effective indicators of arid climate due to the possibility of deep brine (Warren, 2006; Chaboureau et al., 2012; and see below for details).

In the low latitudes, thick coal beds in the Baigang section obviously epitomize the humid climate in Bose of Guangxi, southern China (Figs. 1 and 8). Upward to central inland areas, however, coal beds are absent in the Xialiu section of northern Hengyang Basin (Figs. 1 and 7). Although evaporites are not observed in the present section, halite and dark gypsum mudstone are found in drill cores and limitedly outcropped Eocene strata in the center of the basin, which are inter-bedded with oil shale of a deep lake environment (Chu, 1983; Tong, 1996). From the mudstone layers, plenty of ostracods are found, including *Limnocythere*, *Ilyocypris*, *Eucypris*, *Sinocypris*, *Paraeucypris*, and *Cyrinotus* (Zhang, 1997a,b), which assemblage suggests a fresh to slightly brackish lake water.

Transmeridionally, in the eastern part of the supposed subtropical high-forced arid zone throughout middle China, the climate of the South Yellow Sea–North Jiangsu Basin was apparently humid, lithologically indicated by both coal of palustrine facies and thick dark mudstone of deep lake (Sections 9 and 10; Figs. 10 and 11). The humid climate is also suggested by water salinity in the Gaoyou Sag of the basin (Section 9), although gypsum mudstone is sometimes occurred in mud flat facies of the basin margin. Wang et al. (1985) reported isotopic data from the Eocene Dainan Formation of the sag, in which the ratio of Sr/Ba is ranging from 0.5 to 0.8, less than the threshold of 1 between terrestrial fresh water and sea water. Moreover, the values of Mn/Fe ratio from several cores are all lower than 0.1, the boundary between fresh water and slightly brackish water. Therefore, both lithological and geochemical data imply a fresh water lake under humid climate during the Eocene.

Westward, the lake depth of Zhoukou Basin remained a shallow to deepened shallow water body throughout the sedimentary stage (Section 8; Figs. 1 and 9). From the mudstone beds of the section, ostracods assemblage of *Cyprinotus–Eucypris* and charophytes assemblage of *Obtusochara–Gyrogona* are found (Li and Jiang, 1997), which largely suggest the water body was fresh to slightly brackish.

4.2. Formation of evaporites: saline lake in (sub-)humid climate?

Lithologically, it is because of the wide spread Paleogene red beds and evaporites across middle China along paleo-latitude of ~30°N that led some authors tie it to the subtropical high pressure (e.g., Liu, 1997; Wang et al., 1999). Red beds, as stated above, are indicative of the oxidizing environment, associated obligatorily with neither humid nor arid climate (Table 1). Therefore, interpreting the formation of evaporites is essential to understand the climatic pattern of eastern China. In the facies analyses of the present study, all evaporites are tentatively considered as indicator of extreme aridity because of lacking detailed data on their origin. Even by this treatment, it is clear that high lake level periods had spanned the majority of the sedimentary stages in all evaporite-bearing sections examined (Figs. 3–5), suggesting a much longer high flow period or wet season in comparison to those of arid one. On the other hand, recent advances in both limnology and petrogenesis reveal that occurrences of evaporites do not necessarily mean the arid climate (Renaut and Long, 1989; Alcocer and Hammer, 1998; Schreiber and Tabakh, 2000; Yechieli and Wood, 2002; Warren, 2006; Chaboureau et al., 2012). New studies on sedimentology, sequence stratigraphy, and basin analysis also suggest that most of the Eocene evaporites in the eastern part of middle China, although not all, are related not to the possible permanent arid or hyper-arid climate driven by the supposed subtropical high, but to the brine delamination in a deep lake environment (e.g., Chen et al., 2000; Yuan et al., 2000; Zhang et al., 2003, 2005; Fang, 2006; Du et al., 2007; Lu et al., 2007). Here we provide some modern examples that help to understand the potential mechanism of evaporites formation under humid, at least not likely permanent dry climate in the Eocene eastern China.

In modern lake distribution, freshwater lakes are generally found in (sub-)humid climate, while saline lakes are frequently formed in (semi-)arid areas (Rohli and Vega, 2008). However, saline lakes in (sub-)humid climate are not rare phenomena around the world. For instance, hundreds of saline lakes are developed in the Cariboo Plateau, British Columbia Interior of Canada, in which the climates of the majority of the region are definitely sub-humid to humid according to the Thornthwaite's (1948) climatic classification, with humidity indices ranging from 0.56 to 1.34, larger than the sub-humid/semi-arid threshold of 0.5 (data available on the website of Consortium for Spatial Information, Consultative Group on International Agricultural Research; http://www.cgiar-csi.org/; long-term mean years 1950–2000). Saline lakes in British Columbia Interior are highly diverse, including either perennial or ephemeral muddy siliciclastic and saline playas (Renaut and Long, 1989). Hydrologically, brines, recharge of groundwater through the lake-floor sediments, and/or limited runoff over the marginal clastic sediments are responsible to the high salinity of the lake by carrying solute into the closed lakes. Although most lakes retain some water throughout the year, many ephemeral saline lakes dry out periodically, leaving a low central area of exposed salts (Hardie et al., 1978).

This condition might be the analog to some of the gypsum beds occasionally developed in the center of the Qianjiang Sag, Jianghan Basin (Fig. 6). Lu et al. (2007) analyzed the salt origin and the formation of the basin based on the lithology, rhythm, and sedimentary characteristics of the Eocene deposits. Their results suggest that it was a closed inland salt lake basin, with sedimentary recharged from a northern unilateral clastic source. Some of the evaporite beds were resulted from brine and salt sources along the basin margin under a frequent climatic alternation between humid and relatively dry. Similar conclusion is drawn by Zhang et al. (2005), which further demonstrates the varves are caused, at least partially, by hydrological seasonality, as also seen in the Eocene deposits of Hengyang, Hunan of middle China (Tong, 1996). Consistently, lithological evidence from the present study demonstrates the dramatic shifts of lake depth, suggesting the drastic alternation between humid and relatively dry climates that respectively result in the high flow and low flow periods. But it is clear that the deep lake periods had spanned most sedimentary stage (Fig. 6).

Mexico represents another example that brackish–saline lakes are developed in both (semi-)arid and (sub-)humid climates. In general, more than 50% of the saline lakes are located in endorheic basins in the northern and central regions, where the climate is arid to semi-arid, such as Baja California, northwestern Sonora, and Chihuahua (Alcocer and Hammer, 1998). However, two types of brackish–saline lakes are observed in coastal areas or inland with humid climates. In coastal areas, brackish lakes do no directly communicate with the adjacent sea, such as the Camaronera and Laguna Mandinga lakes. The salinity rises with underground seawater encroachment propelled by water pressure difference and/or tidal movement (Alcocer and Escobar, 1996). This could be a possible analog to at least some of the Eocene closed drainage basins, if as some authors argued that there are saline water bodies in the coastal region in the eastern part of middle China, such as sags of the South Yellow Sea–North Jiangsu Basin.

Wang et al. (1984) investigated the sedimentary environments of some major Paleogene basins of eastern China, based on various groups of fossils, such as polycheats, ostracods, perciformes, dinoflagellates, and foraminifers. Their results show that "quasi-marine" taxa are occasionally occurred in limited beds of the whole thickness of terrestrial strata, suggesting transient ingressions of sea water. Similar results are from Tong (1999), who studied both paleoinvertebrates and paleobotanical material from the Eocene Dainan Formation of Gouyou Sag, eastern China (closely adjacent to Section 9 of the present study; Fig. 1). The ostracods are characterized by *Cypris*, *Sinocypris*, *Candona*, *Eucypris*, *Ilyocypris*, *Limnocythere*, and *Neomonceratina*, while the gastropods comprise *Mirolaminatus*, *Amnicola*, *Retinella*, *Anisus*, *Assiminea*, *Valvata*, *Pupoides*, and *Bithynia*. Apparently, these assemblages imply a slightly brackish to fresh water environment. Consistent with the invertebrate data, the charophytes, composing of *Neochara*, *Grovesihara*, *Obtusochara*, *Rhabdochara*, *Stephanochara*, *Sinochara*, *Peckichara*, *Hornichara*, and *Gyrogona*, also indicate a stagnant lake with slightly brackish to fresh water. More recently, Ma et al. (2012) comprehensively studied the sedimentary environments and facies distribution of the same locality based on paleontological, geochemical, and well-logging data. The ostracod assemblages suggest that the lake was mainly fresh water, but punctuated by slightly brackish stages that might be caused by corresponding transient marine ingressions, supported by trace elements data with ratios of $w(\mathrm{Sr})/w(\mathrm{Ba})$ ranging from 0.52 to 0.699, and $w(\mathrm{B})/w(\mathrm{Ga})$ of 5.06. However, even with the slightly brackish water body, the palynological data, mainly represented by *Magnolipollis*, *Rhoipites*, *Ostryoipollenites*, *Carpinipites*, and *Juglanspollenites*, strongly imply that the Eocene climate here is warm and humid (Tong, 1999; Ma et al., 2012).

For the other type of saline lakes in Mexico, although the annual rainfall in southern and southwestern regions is largely higher than 1,000 mm, closed inland saline lakes in (sub-)humid climate are also widely distributed (Alcocer and Escobar, 1996; Alcocer and Hammer, 1998). Some of the saline lakes are related to the Jurassic salt domes of Tehuantepec, while others are in association with widespread saline meromictic solution from sinkholes (Alcocer and Hammer, 1998). Salt is precipitated especially in the dry season by particular hydrographical condition, a situation that is more or less similar to those of the Cariboo Plateau of Canada. Analogically, it is possible that some of the aridity-driven salt layers in the Eocene inland basins of eastern China, such as the Jianghan, Hengyang, and Hefei basins (Fig 1 and Table 2), are probably formed in this way (Zhang et al., 2003; Fang, 2006), because there is no evidence so far to show that the mean annual precipitation in these inland basins are lower than 500 mm, the modern rainfall boundary between sub-humid and semi-arid climates, although the hydrological seasonality are highly dynamic (Tong et al., 2002; Quan et al., 2012a).

In the geological history, paradox of evaporites in humid climates is also encountered elsewhere. Chaboureau et al. (2012) reported modeling results on the mineralogical difference between the Cretaceous evaporites respectively in northern and southern parts of the central segment of the South Atlantic. Based on the modeling results and the latitudinal gradient of evaporite mineralogy, they conclude that evaporites deposited in the south may have had been controlled by increased climatic aridity and high saline waters. In contrast, evaporites in the north were established by hydrothermal flux and brines under a humid climate, not associated to extreme aridification. In conjunction with the modern and geological examples, it suggests that the presence of evaporites is not necessarily an indicator of arid climates (Chaboureau et al., 2012). Although aridity-driven evaporites are basically depending on the climatic conditions, such as the evapotranspiration rates and the concentration of the solutions, they are also determined by other factors, such as the isolation of the basin, water influx, underground water recharge, and brines (e.g., Renaut and Long, 1989; Alcocer and Hammer, 1998).

If taking the Cretaceous South Atlantic as an analog, similar latitudinal gradient of evaporites development is also observed in the Eocene Bohai Bay Basin, by considering the whole thickness of evaporites in each part (Sections 2–4; Figs. 3–5). In this basin, deep brine-derived salt layers are frequently formed in the Dongpu Depression in the south part (Fig. 5), and occasionally occurred in the Mid Hubei Depression in the middle part (Fig. 4). However, in the Damintun Sag in the north of the basin, the sedimentary sequence is characterized not only by the absence of evaporites, but also by the widely developed coal beds and oil shale (Fig. 3). Chen et al. (2000) investigated the formation of the Eocene salt–rock in the Dongpu Depression (Section 4 in Fig. 1 and Table 2). Depending on the stratigraphical, seimic, geochemical, paleobiological, and logging data, they proposed that the halite is originated from the deep-water hot brine under a humid climate. Consequently, occurrence of halite hereof is not the indicator of playa caused by exceeding evaporation, but is controlled by the movement of the deep fault that constrains the development of the basin. By this way, the salt resources upwelled from the deep earth. This conclusion is later corroborated by Du et al. (2007) based on geochemical, tectonic, and paleoclimatic analysis, who further pointed out that the deep-water salification in this basin is actually the marker of the maximum flooding surface, representing the highest water level of the lake, rather than drying up as the playa. Mechanism of deep-water salification is also advocated in the formation of Xiangli salt mine, Xiangxiang Basin (Fig. 1), because the mineral structure and sulfur isotope ratio of the halite indicate the salt was crystallized due to the dehydration under the pressure of closed deep lake (Chu, 1983).

4.3. Concluding remarks: prevalence of monsoon-like climate

The present study shows that middle China was more or less drier than those of both north and south during the Eocene, especially in the central part. This result corroborates a previous plant fossil-based quantitative climatic reconstruction (Quan et al., 2012a). However, the relatively dry climate appears not to be driven by the supposed subtropical high. On the one hand, neither Gobi nor serir deposit is found from any of the examined sections (Figs. 2–11), not supporting the desert landscape throughout middle China as inferred by a climatic modeling (Zhang et al., 2012). On the other hand, although all evaporites have had been considered as indicator of extremely arid climate that caused significant shrink or even dry-out of the lake, there appears without a categorically permanent arid zone throughout middle China during the Eocene, but with a landward endocentric hydrological pattern. And more importantly, the humid climate was apparently overwhelming in the majority of the period, as vividly shown by the much thicker dark mudstone in comparison to the thickness of the evaporites.

From the endocentrically distributed hydrological dynamics (Fig. 12), it appears that the relatively dry climate in central China was caused by the impact of continentality or rain shadow effect under monsoonal climate (e.g., Quan et al., 2012a). When the monsoon, or monsoon-like climate, was intensified, it might have carried more precipitation/moisture landward, resulting in high lake levels. And when it reduced, the inland climate turned to be relatively dry because of either the distance from the sea (continentality) or the rain shadow effect caused by slightly uplifted terrain along the near coastal region (e.g., Bice and Marotzke, 2002). However, despite of the inland decrease of humidity, middle China is definitely fluctuated between the humid and relatively dry climates during the Eocene (Tong, 1996), as seen in modern regime of the Eastern Asian monsoon, at least not permanent arid as in deserts driven by the subtropical high.

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