Cretaceous paleogeography and paleoclimate and the setting of SKI borehole sites in Songliao Basin, northeast China

Chengshan Wang a,b,*, Zhiqiang Feng c, Laiming Zhang a,b, Yongjian Huang a,b, Ke Cao d, Pujun Wang e, Bin Zhao a,b

a State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Beijing 100083, China
b School of the Earth Science and Resources, China University of Geosciences, Beijing 100083, China
c Institute of Exploration and Development of Daqing Oil field Company Ltd, Daqing, 163712, China
d The Key Laboratory of Marine Hydrocarbon Resources and Environment Geology, Qingdao institute of marine geology, Qingdao 266071, China
e School of Earth Sciences, Jilin University; Changchun, 130061, China

1. Introduction

In contrast to the oscillating glacial-interglacial climates of the past few million years, the Cretaceous Period was a time of long-term climate stability with warm equable climates resulting from a higher atmospheric greenhouse gas content (Skelton et al., 2003; Bice et al., 2006), punctuated by rapid climate change events related to perturbations in the global carbon cycle such as ocean anoxic events (OAEs, Schlanger and Jenkyns, 1976; Leckie et al., 2002; Bice et al., 2006) and the deposition of ocean red beds (Hu et al., 2005; Wang et al., 2005; Hu et al., 2006a, 2006b; Hu et al., 2009; Wang et al., 2009), or to global hydrological cycle disturbances such as possible glaciation in polar or mountain areas (Wang et al., 1996; Miller et al., 2005; Bornemann et al., 2008). A detailed record of Cretaceous climate change has the potential to improve our understanding of modern global warming. However, although the oceanic response to Cretaceous climate change is relatively well known from oceanic scientific drilling (DSDP, ODP and IODP), knowledge of Cretaceous terrestrial climatic change is at best fragmentary (Hasegawa, 1997; Gröcke et al., 1999; Hasegawa, 2003; Heinbofer et al., 2005). In this respect, the long-lived Cretaceous Songliao Basin, covering roughly 260,000 km² in Heilongjiang, Jilin, and Liaoning provinces of NE China (42°25′N to 49°23′N, 119°40′E to 128°24′E), and located on one of the largest landmasses of this period (Scotese et al., 1988), is an excellent candidate from which to recover a nearly complete Cretaceous terrestrial sedimentary record of basin-filling history (Chen, 1987; Chen and Chang, 1994).

In addition, the Songliao Basin contains rich petroleum reserves; the proven oil reserves are over 40 billion barrels, and proven gas over 300 billion m³ (Hou et al., 2009). Daqing oilfield, located in the Songliao Basin, is the biggest oilfield of China, with total oil...
production up to 14 billion barrels over the past 50 years. In recent years, large gas fields have been found in synrift volcanic reservoirs with proven reserves of more than 200 billion m$^3$ (Feng, 2008; Feng et al., 2010a).

In order to better understand Cretaceous continental climate, we implemented continental scientific drilling in the Songliao Basin in 2006 under the framework of the International Continental Scientific Drilling Program. This drilling was divided into two stages; the first stage drilling of the SKI has been completed and has recovered nearly 2500 m of cores (Huang et al., 2008). The purpose of this paper is to introduce the basic paleogeographic and the paleoclimatic framework during Cretaceous deposition in the Songliao Basin, and to provide an opportunity for the international earth scientific community to gain a thorough understanding of the research results (papers in this volume) based on cores acquired.

Scientific deep drilling provides unique opportunities for the geoscience community to understand the response of terrestrial environments to geological events related to the carbon cycle and greenhouse climate change, based on continuous high-resolution sedimentary records derived from core and from other Cretaceous terrestrial sedimentary and paleontological records (Wang et al., 2008). It will also address important problems, such as the identification of important stratigraphic boundaries and marine-terrestrial stratigraphic correlation (Wang et al., 2002), possible reasons for the biotic response to the terrestrial environmental change (Coolen and Overmann, 2007), terrestrial response to Cretaceous oceanic anoxic events (Herrie et al., 2003; Cohen et al., 2004; Beckmann et al., 2005; Bornemann et al., 2005), formation of terrestrial petroleum source rocks (Wan et al., 2005), and mechanisms for the Cretaceous magnetic Normal Super-Chron (CNS) (McFadden and Merrill, 2000; Hulot and Gallet, 2003).

2. Geographic location and tectonic setting

2.1. Geographic location

The Songliao Basin covers roughly 260,000 km$^2$ in Heilongjiang, Jilin, and Liaoning provinces of NE China. It is approximately 820 km long in the north–south direction and approximately 350 km wide in the east–west direction; geographically the basin is located between 119°40’E to 128°24’E, and 42°25’N to 49°23’N. The basin trends in an NNE direction and the basin floor is diamond-shaped (Wang et al., 1994; Fig. 1). Transportation conditions and geologic knowledge of the area have increased dramatically since the discovery of Daqing oilfield in the late 1950s, allowing for a well-designed scientific drilling program to be initiated and conducted here.

Geomorphologically, the area of the Songliao Basin generally coincides with the modern Songliao Plain. The Songliao Basin underlies the Songnen Plain to the north and Liaohe Plain to the south, its main area is beneath the Chinese Dongbei Plain, with an altitude generally lower than 200 m. The basin is surrounded by mountain ranges and hills, is bordered by the Zhangguangcailing Mountains to the east, the Daxinganling Mountains to the west, the Xiaoxinganling Mountains to the north, and by the mountainous lands in Liaoning province to the south (Wang et al., 1994; Hou et al., 2009; Fig. 1). Currently the basin includes large scale plains and marshes of two river systems, the Songhua River-Nen River and the Liao River. However, the Cretaceous sedimentary basin may be much larger than the Songliao Plain, therefore its measured area of 260,000 km$^2$ likely is a minimum estimate. Consequently, it would be reasonable to believe that the Songliao Basin, with an area more than fifty times that of China’s biggest lake (Qinghai Lake), played a significant role in regulating climate of East Asia during the Cretaceous.

2.2. Tectonic setting

East Asia, where the Songliao Basin is located, is a complex combination of discontinuous and amalgamated landmasses. This tectonic complex is subdivided by suture zones and fold belts, which were formed during continuous continental collisions during the Paleozoic and Mesozoic (Fig. 1) (Sengör and Natal’in, 1996; Yin and Nie, 1996; Hendrix and Davis, 2001). Hence, East Asia is an excellent area to study continental development and associated deformation processes. An extensional rift valley system as large as the Basin and Range province in North America developed in NE China and southern Mongolia from Late Jurassic to Cretaceous time.
(Graham et al., 1996, 2001; Ren et al., 2002). This rift valley system overlapped onto several interior contractile orogenic zones, leading to three groups of rift basins in the western, the central and the eastern areas. Geomorphologically, the modern western basin group is represented by the Erlian Basin and the Hailaer Basin, which are separated from the central basin group represented by the Songliao Basin by Great Khingan Mountain and Taihang Mountain. The eastern basin group is represented by the Sanjiang Basin, which is separated from the central group by the Tanlu fault (Fig. 1). These three basin groups are not only separated by mountains and structural belts, but also in terms of their developmental stages, sedimentary patterns, and subsequent intensity of tectonic deformation (Chi et al., 2002), implying that this geomorphology may have existed before the formation of the basin floors.

Extensional zones commonly develop upon the contractile orogenic belts. An important phenomenon of this environment is an older thrust–fault plane reactivated as a normal fault during extension (Gries, 1983; Williams and Powell, 1989; Axen et al., 1993) and the emergence of a high strain extensional zone characterized by a metamorphic core complex (Coney and Harms, 1984; Constenius, 1996). Gravitational collapse is considered to be the driving force for the extensional process, and this process occurred where the crust thickened simultaneously or soon afterwards, as for example in the Basin and Range province in western North America (Coney and Harms, 1984; Wust, 1986; Constenius, 1996), the Caledonian orogenic belt in Norway (Seguret et al., 1989), and Southern Tibet (Burchfiel and Royden, 1985; Royden and Burchfiel, 1987; Hodges et al., 1992). Although the three East Asia Cretaceous rift basins were developed on older orogenic belts, their origins have long been controversial, especially the mechanism for formation of the single largest and most long-lived basin, the Songliao Basin. Much evidence indicates that its origin was related to back-arc extension associated with west-directed subduction of the paleo-Pacific beneath the Asian margin, but because 2000 km separate the Songliao Basin from the Japan Island Arc, the role of plate subduction there is definitely a deformation (Chi et al., 2002), implying that this geomorphology may have existed before the formation of the basin floors.

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3. Strata and basin structure

Cretaceous deposits in China are mostly of non-marine origin; marine sediments occur only in parts of Tibet and Xinjiang (Chen, 1987; Chen and Chang, 1994). During the Cretaceous, the Songliao Basin in northeastern China was a large rift basin that hosted a long-lived deep lake (Chen, 1987). This history caused the basin to become the largest oil and gas producing basin in China, with China’s largest oilfield, Daqing, situated in the central part of the basin (Zhou and Littke, 1999). Large-scale geological investigation of the Songliao Basin for petroleum began in 1956, and on Sept. 26, 1959, the first highly productive oil well (known as the Songli-3 Gusher) was successfully drilled, initiating the history of Daqing Oilfield. Since then, extensive exploration has been conducted in the Songliao Basin. By the end of 2000, over 250,000 km of seismic reflection profiles had been completed. The block scale for the seismic network is 0.5×0.5 to 2×4 km, and some 3-D seismic reflection data have been acquired. About 50,000 wells have been drilled, with cumulative drill penetration of about 40 million meters (Wang et al., 2008). In recent years, more wells have been drilled to the Lower Cretaceous, which offer reference points for the proposed deeper drilling program, and which form the basis for detailed stratigraphic correlation and derivative reconstructions of Cretaceous paleoenvironment, and permit identification of an optimum drilling location for scientific objectives.

3.1. Strata and ages

The Songliao Basin is filled predominantly with volcaniclastic, aluvial fan, fluvial and lacustrine sediments of Late Jurassic, Cretaceous and Paleogene ages resting on a pre-Mesozoic basement (Chi et al., 2002; Figs. 2 and 3). The oldest sedimentary cover within the basin is the Upper Jurassic Huoshiling Formation (J3h). Overlying the Jurassic strata are the Lower Cretaceous Shahezi (K1sh), Yingcheng (K1y), Denglouku (K1d) and Quantou (K1q) formations; these are overlain by the Upper Cretaceous Qinshankou (K2qn), Yaojia (K2y), Nenjiang (K2n), Sifangtai (K2s), and Mingshui (K2m) formations. The sedimentary sequence is capped by an unconformity between the Cretaceous and Cenozoic, overlain by the Paleogene–Neogene Y’ian (E2–3ya), Da’an (N2da) and Taikang (N2tk) formations (Hou et al., 2009).

The age of Huoshiling Formation is still controversial, with uncertainty as to whether it spans the Jurassic–Cretaceous boundary in the Songliao Basin. We place the formation in the Late Jurassic Tithonian Stage because the majority of radiometric ages are between 150 and 155 Ma (Hou et al., 2009). The sedimentary thickness is 500–1600 m, and strata include volcanic flows (mainly andesitic) and volcaniclastics intercalated with clastic fluvial, flood-plain and swamp or mire facies (Feng et al., 2010a). Seismic horizon T5 at the base of the formation clearly demonstrates that this formation overlies the underlying basement.

With typical fossils of the Jehol Biota, the Shahezi Formation overlies the Huoshiling Formation. Because the age of this biota is still controversial, we provisionally place this formation in the Berriasian–Valanginian (Hou et al., 2009). The formation is typically 400–1500 m thick, and consists of gray to black lacustrine and flood-plain mudstone and siltstone interbedded with gray sandstone and conglomerate. A thin layer of felsic tuff and tuff breccia occurs at the base of the formation (Feng et al., 2010a).

Overlying the Shahezi Formation is the Yingcheng Formation, which comprises mainly felsic volcanics, which are the main petroleum reservoirs, and are interbedded with clastic strata and several discontinuous coal beds, and normally 500–1000 m thick (Feng et al., 2010a). The zircon U–Pb ages show that the extensive volcanic sequences found in the northern the Songliao Basin were emplaced between ca. 115 and 109 Ma in the Early Cretaceous (Zhang et al., 2011). As a result, we suggest that the age of Yingcheng Formation is Hauterivian–Barremian. Of the ten reservoir levels in the Songliao Basin from shallow to deep (Fig. 2, Hou et al., 2009), the volcanics in this formation (known as the Xingcheng gas layer) are the main target for gas exploration (Fig. 2). Notably, the top of Yingcheng formation is bounded by an unconformity, equivalent to seismic horizon T4 (Feng et al., 2010a; Figs. 2 and 3).

The Denglouku Formation unconformably overlies the Yingcheng Formation, and comprises interbedded gray to white structureless sandstone, dark sandy mudstone, mixed-color sandstone and mudstone, conglomerate and a thick argillite (Feng et al., 2010a). The thickness of this formation is typically 500–1000 m. The charophyte fossils in the formation are worldwide Aptian fossils (Hou et al., 2009), thus we suggest that the age of Denglouku Formation is Aptian. The formation can be divided into 4 members according to the lithology, and the 3rd and 4th members comprise the Changde gas layer (Fig. 2).

Above the Denglouku Formation is the Quantou Formation, which overlaps the eastern and western basin margins and extends across the whole basin. Quantou strata are characterized by red-brown, purple and purple-brown mudstone, coarse grayish-white sandstone and conglomerate of fluvial and floodplain origins deposited in arid or semi-arid conditions (Feng et al., 2010a). Although, this formation has few fossils, previous studies allocated this formation to the Albian Stage (Hou et al., 2009). The Quantou Formation is Albian–Cenomanian-lowermost Turonian in age (see Wan et al.,
The thickness of the sequence is typically 550–1200 m, with a maximum of 1650 m. It can be divided into 4 members according to the lithology, and the 3rd and 4th members belong to the Changde and Fuyu oil layers (Fig. 2), which also are called the lower oil-bearing assemblage (Hou et al., 2009).

Fig. 2. Stratigraphic column of Songliao Basin modified from Wang et al. (2008). 1, Volcanic; 2, Mudstone; 3, Muddy Siltstone; 4, Siltstone; 5, Sandstone; 6, Conglomerate.
The Qingshankou Formation consists of gray, dark gray and black mudstone interbedded with oil shale and gray sandstone and siltstone. Deltaic and shallow lacustrine facies dominate this formation. During early deposition of the Qingshankou deep-water, lacustrine, black mudstone with a thickness of 60–100 m was deposited across the entire central downwarp, forming the most important petroleum source rocks in the Songliao Basin (Feng et al., 2010a). Based on abundant aquatic fossils found in the formation, such as conchostraca, ostracode, bivalve, and fish, the most recent research determines the age to be late Turonian–Coniacian (see Wan et al., 2013–this volume; Deng et al., 2013–this volume). It can be divided into 3 members according to lithology, and the 2nd and 3rd members belong to the Gaotaizi oil layer (Fig. 2). The seismic marker T11 at the base of the Yaojia Formation (Figs. 2 and 3) is an unconformity and in the western and southeastern and central zones of the basin (Fig. 3), which shows clear evidence of long sub-aerial exposure and weathering, including mud cracks, caliche, red palaeosol, calcareous nodules and plant roots (Feng et al., 2010a). The Yaojia Formation comprises red, gray, grayish green and black mudstone, siltstone and sandstone of lacustrine, fluvial and deltaic origins (Feng et al., 2010a). Like the Qingshankou Formation, the Yaojia is also rich in fossils, and based on the regional correlation of these fossils, the age is Coniacian–Santonian (see Wan et al., 2013–this volume; Deng et al., 2013–this volume). It can be divided into 3 members according to the lithology, and the 1st member is the Putouhua oil layer (Fig. 2).

The Nenjiang Formation is dominated by deep-water lacustrine gray to black mudstone, marl, shelly limestone, and oil shale interbedded with gray siltstone and fine sandstone. During deposition of the first member of the Nenjiang Formation (K2n1), the lake expanded rapidly and reached its maximum extent of 20 × 104 km², covering almost the entire basin (Feng et al., 2010a). The Nenjiang Formation has the most abundant and diverse fossils of every kind in the Songliao Basin (see Section 5 for details). The age is Late Santonian–early-to-middle Campanian (see Wan et al., 2013–this volume; Deng et al., 2013–this volume). It can be divided into 5 members according to the lithology, and the 3rd and 4th members belong to the Hetimiao oil layer (Fig. 2), which is the shallowest oil layer in the Songliao Basin.

The Sifangtai and Mingshui formations are the uppermost Cretaceous units in the Songliao Basin, and because they have very similar biota, we discuss them together. The Sifangtai Formation consists of brick-red pebbly sandstone and shale interbedded with brown, gray and gray-green sandstone and muddy siltstone. The middle part of the formation consists of gray fine sandstone and siltsstone interbedded with brick-red and mauve shale. Fine clastics dominate the upper part of the formation and comprise red and mauve shale interbedded with gray-green mudstone. The Mingshui Formation is composed of gray-green, gray, black and brown-red shale and gray-green sandstone (Feng et al., 2010a). Various lines of new evidence, including comprehensive palynological research in SKI (Li et al., 2011), show that the Mingshui is middle Campanian–Maastrichtian, but also clearly indicate that the top of Mingshui Formation is Paleoceocene in age (see Wan et al., 2013–this volume; Deng et al., 2013–this volume). Seismic horizon T02 is a significant regional unconformity separating the Cretaceous and Cenozoic deposits (Figs. 2 and 3), indicating strong structural inversion, including folding and uplift (Feng et al., 2010a).

The drilling of the first stage of the SKI has already achieved a continuous sedimentary record from the 3rd member of Quantou Formation to the Mingshui Formation (Fig. 2). The second stage of this program is about to begin, and plans to recover a continuous sedimentary record from the basement to the 2nd member of Quantou Formation (Fig. 2).

In summary, the Songliao Basin was filled mainly with lacustrine deposits beginning about 155–150 Ma and possibly ending in the early Danian at 64 Ma, with a time span of up to 85–90 m.y.. Thus, the Songliao Basin is likely the longest-lived lacustrine-dominated sedimentary basin known in the rock record.

3.2. Basin structure

The Songliao Basin is an intra-cratonic Cretaceous rift basin, as demonstrated by an abundance of data generated by the petroleum industry, including its subsidence and geothermal history, sedimentary facies, crustal underpinnings, and structural style (Song, 1997; Khudololey and Sokolov, 1998; Einsele, 2000). The evolution of the Songliao Basin consists involves 4 stages and 5 structural units: (1) a pre-rift doming stage during the late-pre Jurassic (before 155 Ma). Uplift and erosion resulting from mantle doming precluded accumulation of Triassic to Middle Jurassic sediments. (2) A synrift stage during the latest Jurassic–earliest Cretaceous, forming the structurally deepest unit (T5–T4, Huoshiling, Shahezi and Yingcheng formations). During this time interval, over thirty isolated faulted sub-basins were formed (Feng et al., 2010a; Liu et al., 2011). (3) Downwarping was
driven by thermal subsidence during the late Early Cretaceous and Late Cretaceous. From a petroleum perspective, this is the most important stage among the four, for up to 4500 m of sediments, including two main oil-prone black shale units (the Qingshankou and Nenjiang formations), were deposited. A regional unconformity occurs near the base of Upper Cretaceous strata, equivalent to seismic horizon T2 (Figs. 2 and 3). This unconformity divides the thermal subsidence tectonostratigraphic unit into two parts, each with distinct architecture and depositional features (Feng et al., 2010a), including lower unit (T4-T2, Denglouku and Quan Tou formations) and middle unit (T2-T03, Qingshankou, Yaojia and Nenjiang formations); (4) Basin shrinkage and regional compression. After the late Late Cretaceous, regional stress became compressional. During this period the upper unit (T03-T02, the Sifangtai and Mingshui formations) formed.

Based on the structural cross section (Fig. 3) across the Songliao Basin, the basin-filling geometric pattern is a typical ‘steer’s-head’ geometry. The lower unit is limited to the grabens controlled by faults in the synrift stage, and in the upper part the Yingcheng Formation (K1yc) locally truncates underlying strata and onlaps the basin-margin faults. The middle and lower stratigraphic units typically appear to have a downwarping sedimentary pattern, their deposits overlap on all the graben basins, and the east and west sides of the basin overlap in an onlap pattern. The change from the lower to the upper stratigraphic units, which occurs between the Denglouku Formation and the Nenjiang Formation, results in extensive overlap that exceeds the present extent of the Songliao Basin. The upper stratigraphic unit only crops out at the western side of the basin, because stress from the east during this period not only led to the westward migration of depocenter, but also resulted in continuous uplift and erosion on the east.

4. Paleogeography and evolution of basins

4.1. Cretaceous paleogeography of China

Previous paleomagnetic data showed that the North China plate, the Yangtze plate and the Korean plate formed a single block beginning in the Late Jurassic (Gilder and Courtillot, 1997). According to paleomagnetic studies of fifty-five Cretaceous lavas in western Liaoning Province, this area did not move relative to Eurasia (Zhu et al., 2002), which suggests that the Songliao Basin was located at middle latitude similar to where it is now, although a previous study suggested that it moved about 2–4 degrees southward migration (Fang et al., 1988).

A paleogeographic map of China compiled by Wang et al. (1985a) reveals that eastern China and adjacent areas were dominated by extensional basins during the Mesozoic (e.g., Chen and Dickinson, 1986). The paleoclimate and paleogeography of the Songliao Basin changed over its long life as a sedimentary basin. Understanding these changes helps to realize the process of its evolution.

Early Cretaceous rift basins mainly occurred in northeastern China, viz. basin group referred in Section 2.2, many isolated half-graben basins also occurred in North China and southeastern China. They are volcano-sedimentary basins and have similar filling sequences. No sediment was deposited during the Early Cretaceous in the hinterland of South and North China, which Wang et al. (1985a) termed the North China highland and South China highland. The basin group in northeastern China obviously changed in the Late Cretaceous. The Songliao Basin entered the stage of thermal subsidence while the western basin group stopped filling and the eastern basin group rifted and was eroded. The distribution of detachment extensional structures extended westward and rift basins occurred abroad in North China and southeastern China. At the same time, westward subduction of the Izanagi plate caused a 3000–4000 m high coastal mountain chain along the eastern margin of East Asia (Yano and Wu, 1995; Chen, 1997; Okada, 1997; Yano and Wu, 1997; Okada, 2000), which influenced deposition of many distinctive types of sedimentary facies, including aeolian sandstone, gypsum and calcareous concretions (Xiang et al., 2009), in basins in the rain shadow of the coast ranges.

4.2. Sedimentary facies and environmental evolution of the Songliao Basin

During the depositional of the Huoshiling Formation through the Yingcheng Formations, the Songliao Basin entered a faulted phase. More than 30 isolated rift basins composed the Songliao Basin, all having similar filling sequences and facies combinations. Two sedimentary sequences developed, consisting of volcanic-alluvial fan facies and fan delta-shallow lake-fan delta facies. They formed the first complete cycle from lake transgression to regression. The total area of these 30 basins was 90,367 km², which included a lake area of 36,898 km² (Table 1; Zhang and Ren, 2003).

The Songliao Basin entered a fault-subsidence transition stage during the deposition period of the Denglouku Formation (Guo et al., 2005), when the basin was fully integrated and had several centers of sediment and subsidence (Feng et al., 2010a). The Denglouku Formation is the second complete cycle, which was filled base to top by a succession of alluvial plain-delta-shore to shallow lake-deeper lake – shore to shallow lake – alluvial plain deposits. Climate conditions during this period were hot, when much of the red mudstone replaced former swamp mudstone. Because of differential subsidence, a large area of the Songliao Basin was exposed at the surface, and the

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**Table 1**

Late Cretaceous lithofacies and rock colors in Songliao Basin.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Area (km²)</th>
<th>Color</th>
<th>Special rocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sifangtai-Mingshui</td>
<td>83,492</td>
<td>Western: black eastern: red</td>
<td>Oil shale and biogenic limestone</td>
</tr>
<tr>
<td>the 3rd-5th members of Nenjiang</td>
<td>89,646</td>
<td>Black and red</td>
<td>Gypsum</td>
</tr>
<tr>
<td>the 1st–2nd members of Nenjiang</td>
<td>&gt; 180,343</td>
<td>Black</td>
<td>Gypsum</td>
</tr>
<tr>
<td>Yaojia</td>
<td>144,666</td>
<td>80% of the area are red</td>
<td>Oil shale and biogenic limestone</td>
</tr>
<tr>
<td>the 2nd–3rd members of Qingshankou</td>
<td>162,458</td>
<td>Black and red</td>
<td>Coal</td>
</tr>
<tr>
<td>the 1st member of Qingshankou</td>
<td>162,458</td>
<td>Black</td>
<td>Oil shale and biogenic limestone</td>
</tr>
<tr>
<td>Quantou</td>
<td>155,663</td>
<td>Major in red sandstone, interbedded by grayish-green siltstone and mudstone</td>
<td></td>
</tr>
<tr>
<td>Denglouku</td>
<td>62,690</td>
<td>Major in grayish-green and black, and great deal of red mudstone</td>
<td></td>
</tr>
<tr>
<td>Huoshiling–Yingcheng</td>
<td>90,367</td>
<td>Gray-black conglomerate, sandstone, siltstone and mudstone</td>
<td></td>
</tr>
</tbody>
</table>

*Modified after Zhang and Ren, 2003.*
area of sediment deposition in the Songliao Basin was reduced to 62,689 km² (Zhang and Ren, 2003).

The Quantou and Qingshankou formations were deposited during the early subsidence phase. They formed the third complete stratigraphic cycle, which was a sequence of alluvial fan–alluvial plain–shore to shallow lake deposits in the Quantou Formation to deep lake–shore to shallow lake–transgressive delta–alluvial plain deposits in the Qingshankou Formation. However, marginal facies are absent in the eastern part of the Songliao Basin, which suggests that during this period the eastern boundary of the basin extended beyond the present boundary. The Quantou Formation was deposited mainly as red siltstone and mudstone, interbedded with gray greenish siltstone and mudstone. The Quantou covers 15,5662 km², including an area of lacustrine sediment of 23,150 km² (Zhang and Ren, 2003). When the first member of the Qingshankou Formation was deposited, the area of sediment extended to 162,458 km², which contained a lacustrine area of 68,134 km², with a deep water lacustrine area of 40,000 km² (Fig. 4A), may be influenced by sea-water input during deposition of this member (Xi et al., 2011). Black, gray black shale, limestone and oil shale are widespread in the middle and eastern parts of the Songliao Basin. They formed the first major hydrocarbon source rocks whose content of organic matter reached 53.2%. When the second and third members of the Qingshankou Formation were deposited, a large delta system occurred in northern and western Songliao Basin and a small area of salt-bearing mudstone occurred in the eastern area. The area of lacustrine sediment was reduced to 41,000 km² (Yang, 1985), with an area of deep-water lacustrine sediment less than 20,000 km² (Zhang and Ren, 2003).

The Yaojia and Nenjiang formations were deposited during a late subsidence phase. They formed the fourth stratigraphic cycle, which was a sequence of alluvial plain–delta-shore to shallow lake in the Yaojia to deep lake–shallow lake–delta–alluvial plain in the Nenjiang Formation. Marginal facies from the Yaojia to the first and second members of the Nenjiang Formation, missing in the eastern Songliao Basin, but they are present in the third through fifth members of the Nenjiang Formation, which indicates that the lacustrine water level fell during this period. The distribution and sediment sequence of the Yaojia Formation is similar to that of the Qingshankou, the area of which is 144,667 km², with the deep water lacustrine area reduced to 5719 km², and the area of salt-bearing mudstone enlarged to 22,041 km². The Yaojia Formation consisted of red, red-green interbedded and red-black interbedded mudstone and siltstone (Fig. 4B). Red layers occupied 43% of total thickness of the second and third members of Yaojia Formation (Zhang and Ren, 2003).

The subaerial extent of the Nenjiang Formation was much greater than is now preserved; its peak extent was during deposition of the first and second members of the Nenjiang, which may have been 260,000 km² (Fig. 4C). Both the area and depth of the Songliao Basin reached peak because of the influence of sea-water input during deposition of the first and second members of the Nenjiang Formation (Xi et al., 2011). Only deep water in the central region and shallow water lacustrine facies occurred in the marginal. Black mudstone is throughout the basin, with local mudstone and siltstone interbedded. Black shale, limestone and oil shale are widely distributed in the whole basin, with the thickest oil shale up to 650 m. The area of deep water lacustrine facies reached 96,044 km², or about 53.25% of the area of the basin. Many sub-lacustrine fans and channel systems covered the slope and base of the Songliao Basin (Feng et al., 2010b). The largest channel system is 67 km long, and the widest channel branch is 600 m, extending southward 11.5 km from its head. The eastern basin was uplifted during deposition of the third through fifth members of the Nenjiang, which caused a reduction of the lake area. The total area of sediment was reduced to 89,646 km², including deep water lacustrine facies at 2922 km², shallow water lacustrine facies at 35,925 km² and delta facies at 16,870 km² (Zhang and Ren, 2003).

The Sifangtai and Mingshui formations were deposited during the waning phase of the basin’s life, when the eastern Songliao Basin was uplifted sharply. This displaced the basin center westward and reduced its area to 83,492 km². These units formed the fifth stratigraphic cycle, which was a sequence of alluvial plain–shore to shallow lake–alluvial plain deposits across most of the basin, but alluvial plain–alluvial fan occur at the basin margin. The overall character during this period was a widespread alluvial plain. Five small but persistent shallow lakes had low accommodation space and frequently fluctuating lake levels (Han et al., 2009). Red siltstone interbedded with mudstone and sandstone divided the dark mudstone into two sub-areas (Fig. 4D).

To sum up, five complete stratigraphic cycles formed in four evolutionary stages of the Songliao Basin. Tectonic activity and water supply controlled the changing area of the basin, which controlled the distribution and character of sediment facies. During the faulted stage, the basin was in the humid and wet climate zone, and abundant organic matter yielded dark sediment and coal-bearing strata. During the fault subsidence transition stage, the basin was integrated, but many residual sediment centers still existed, where dark deep lacustrine facies were deposited while red strata formed in shallow water and subaerial environments. During the subsidence stage, the area and depth of the Songliao Basin both reached a peak. An influx of sea-water during deposition of the first member of the Qingshankou Formation and the first and second members of the Nenjiang Formation, fostering a productive ecosystem and formation of dark shale, oil shale and limestone. After the withdrawal of the ocean, residual deep water lacustrine depositional systems yielded dark mudstone and red-green interbedded strata in shore, and shallow water lacustrine facies and alluvial plain facies. During the waning stage, the area and depth of the Songliao Basin both were reduced, the sediment color was controlled by water depth, so that dark sediment formed in deep water and red sediment formed in shallow water.

5. Paleoclimate and paleoecology

The Cretaceous Period provides significant rock records of global climate changes under conditions of greenhouse climate (Skelton et al., 2003; Bice et al., 2006). The Songliao Basin offers a unique opportunity to understand Cretaceous paleoclimate of terrestrial settings because it contains a nearly complete record of lacustrine sediments deposited throughout the Cretaceous (Chen, 1987; Chen and Chang, 1994). In the following sections, we review the literature on the paleoclimate of the Songliao Basin during the Cretaceous, and reconstruct the paleoclimate in the Songliao Basin in spore/pollen and plant fossils, oxygen isotope data, paleoecology, and climatically sensitive deposits.

5.1. Spore/pollen

Fossil spore/pollen from lake deposits provides a record of local and regional vegetation, and indirectly, climate (Cohen, 2003). The large quantities and widespread distribution of spore/pollen fossils preserved in the different lithology types in the Songliao Basin provide an important proxy for paleoclimate reconstruction. Researchers always employed percent ratios of pollen and spores taxa, to estimate temperature (ratio of percent pollen from warm-climate trees to percent pollen from cool-climate trees; Liu and Leopold, 1994; White et al., 1997; Liu et al., 2002; Larsson et al., 2010), humidity (ratio of percent pollen from humid-climate trees to percent pollen from arid-climate trees; van der Zwan et al., 1985; Liu et al., 2002; Barron et al., 2006), as well as ecological environment (such as ratio of percent shrubs-plus-herbs to trees; Hubbard and Boulter, 1983; Kalkreuth et al, 1993; Larsson et al., 2010).
In this way, Gao et al. (1999) reconstructed the climate history of the Songliao Basin on the basis of more than 20,000 samples from more than 500 cores in the Songliao Basin (e.g. *Classopolis* is regarded to indicate warm climate; Parrish, 1998). The vegetation landscape of the basin in Cretaceous time was mainly conifer forest, and steppe (Fig. 5). The Cretaceous atmospheric temperature changed relatively frequently in the Songliao Basin, but was mainly humid to semihumid subtropical environments. Four cooling events were in the Early and Late Cretaceous recorded by: (1) the Huoshiling Formation and the 1st and 2nd members of the Shahezi Formation; (2) the 4th member of the Denglouku Formation; (3) the Nenjiang Formation and (4) the 2nd member of the Mingshui Formation. Three warming events were (1) the 1st and 2nd members of the Denglouku Formation; (2) the Qingshankou and Yaojia formations; and (3) the Sifangtai Formation. Three semiarid events were (1) the 3rd and 4th members of the Shahezi Formation, (2) the 4th member of the Denglouku Formation, and (3) the Sifangtai Formation.

The first two warming periods were characterized by humid and warm conditions (humid tropical) with the abundant peak of broad-leaved evergreens. The last warming event happened during deposition of the Sifangtai Formation, when the climate was arid and warm (semiarid south subtropical) with the development of herbs and low broad-leaved evergreens and conifers. The last two semiarid events both lead to an increase in herbaceous floras and a decrease in broad-leaved evergreens. During the entire sedimentary history of the Songliao Basin, intense aridity never characterized North China and South China (Boucot et al., 2009), which may reflect the intense uplift of the Yanshan orogenic belt to the south of the Songliao Basin, and climatologically separated the Songliao Basin from North China (Haggart et al., 2006). Notably, the two major petroleum source rocks in the Daqing oilfield, the 1st member of the Qingshankou Formation and the 1st and 2nd members of the Nenjiang Formation represent different climate zones because of the climate zones were shifted during that period (Fig. 5): the former was tropical-southern subtropical, whereas the latter was northern subtropical.

5.2. Oxygen isotope data

For nearly half a century, the most significant progress of Cretaceous climate reconstruction came from the reconstruction of paleotemperature (Lowenstam and Epstein, 1954; Anderson and Schneidermann, 2013–this volume). The classification of temperature zones is based on the species of spore/pollen spectra that define the tropical, tropical–subtropical, subtropical, tropical-temperate, and temperate (Appendices 1 and 2). The dryness and humidity are based on species of parent plants of spore/pollen fossils subdivided into xerophyte, mesophyte, hygrophyte, helophyte, and hydrophyte, which correspond to arid, semiarid, semihumid and semiarid, semihumid, and humid (Appendices 1 and 3). The red bar represents warming event and the blue bar represents cooling event, and the yellow bar represents the semiarid event.

![Image of Figure 5: Cretaceous paleoclimate evolution of the Songliao Basin. Spore/pollen relative abundances, paleotemperature zones and paleohumidity are derived from Gao et al. (1999), climate-sensitive rock types are derived from Wang et al. (1994). The temperature data (black curve, black dots, diamonds) are derived from Zakharov et al. (1999, 2009, 2011). The oxygen isotope data (red curve) are derived from Chamberlain et al. (2013–this volume). The classification of temperature zones is based on the species of spore/pollen spectra that define the tropical, tropical–subtropical, subtropical, tropical-temperate, and temperate (Appendices 1 and 2). The dryness and humidity are based on species of parent plants of spore/pollen fossils subdivided into xerophyte, mesophyte, hygrophyte, helophyte, and hydrophyte, which correspond to arid, semiarid, semihumid and semiarid, semihumid, and humid (Appendices 1 and 3). The red bar represents warming event and the blue bar represents cooling event, and the yellow bar represents the semiarid event.]

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### Table 1: Stratigraphy and Vegetation of the Cretaceous

<table>
<thead>
<tr>
<th>Stratigraphy</th>
<th>Vegetation</th>
<th>Rock Types</th>
<th>Temperature Zone</th>
<th>Dryness and Humidity</th>
</tr>
</thead>
<tbody>
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<td>Conifer</td>
<td>Broad-leaved evergreen</td>
<td>Arid</td>
<td>Temperate</td>
</tr>
<tr>
<td>200 Ma</td>
<td>Broad-leaved evergreen</td>
<td>Subtropical</td>
<td>Semiarid</td>
<td></td>
</tr>
<tr>
<td>150 Ma</td>
<td>Conifer</td>
<td>Tropical</td>
<td>Semihumid</td>
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### Figure 5: Cretaceous paleoclimate evolution of the Songliao Basin. Spore/pollen relative abundances, paleotemperature zones and paleohumidity are derived from Gao et al. (1999), climate-sensitive rock types are derived from Wang et al. (1994). The temperature data (black curve, black dots, diamonds) are derived from Zakharov et al. (1999, 2009, 2011). The oxygen isotope data (red curve) are derived from Chamberlain et al. (2013–this volume). The classification of temperature zones is based on the species of spore/pollen spectra that define the tropical, tropical–subtropical, subtropical, tropical-temperate, and temperate (Appendices 1 and 2). The dryness and humidity are based on species of parent plants of spore/pollen fossils subdivided into xerophyte, mesophyte, hygrophyte, helophyte, and hydrophyte, which correspond to arid, semiarid, semihumid and semiarid, semihumid, and humid (Appendices 1 and 3). The red bar represents warming event and the blue bar represents cooling event, and the yellow bar represents the semiarid event.
1973; Barrera et al., 1987; Huber et al., 1995; McArthur et al., 2007), yet there is currently no terrestrial isotopic proxy record similar to the Cretaceous marine record. Chamberlain et al. (2013–this volume) provide the first reported oxygen isotopic results from the SKI of the Songliao Basin (Fig. 5), for the most part, diagenesis did not play a major role in the isotopic results, which can be interpreted in terms of global climatic and regional hydrological changes (e.g., Carroll and Bohacs, 1999, 2001). We also collected the marine oxygen isotope data from the Far East (Zakharov et al., 1999, 2009, 2011; Fig. 5). The latitudes are approximately similar between the Far East and Songliao Basin; hence we suppose these data might reflect the trend of Cretaceous temperature in the Songliao Basin and would like to make a comparison with other paleoclimate records.

### 5.2.1. The temperature records from the oxygen isotopes of the Far East

Cretaceous climate changed relatively frequently, and mainly in temperate climate, when the temperature commonly was above 5 °C and the highest more than 25 °C, commonly the temperature range between warming events and cooling events is 5–10 °C, sometimes they ranged up to nearly 15–20 °C (Fig. 5). In the Early Cretaceous, the data show a cooling trend to as low as 5 °C in the Berriasian–Valanginian (Zakharov et al., 2009, 2011). Then the temperature increased in the Hauterivian–early Aptian (Zakharov et al., 2011). In the late Aptian–Coniacian, the temperatures were relatively stable, except the relatively low temperatures in the Aptian/Albian and the relatively high temperatures in the middle Turonian–Coniacian. Following the relative stable stage, the temperatures decreased by 5–10 °C in the early Santonian and sharply increased in the late Santonian–early Campanian. Then the temperatures remained high (20–25 °C) until the decrease in the Maastrichtian (Zakharov et al., 1999, 2011; Fig. 5). A temporary warming event in the middle Maastrichtian is also documented in the oxygen isotope data of Zakharov et al. (2011).

### 5.2.2. Oxygen isotopes of the Songliao Basin

The oxygen isotopic data are from ostracods collected from Songliao Basin that cover an interval that extends from the Qingshankou Formation through the Mingshui Formation (Chamberlain et al., 2013–this volume). These data record clearly isotopic trends and oxygen isotope shifts. There is a negative oxygen isotope shift within the Coniacian. Following the relative stable stage, the temperatures decreased by 5–10 °C in the early Santonian and sharply increased in the late Santonian–early Campanian. Then the temperatures remained high (20–25 °C) until the decrease in the Maastrichtian (Zakharov et al., 1999, 2011; Fig. 5). A temporary warming event in the middle Maastrichtian is also documented in the oxygen isotope data of Zakharov et al. (2011).

### 5.3. Paleoecology

Plants and animals can be exquisitely sensitive to climate, and fossils can be excellent paleoclimatic indicators (Parrish, 1998). The relationship of an organism to its physical and biological environment can be controlled principally by climate, and thus the study of paleoecology has proved useful (Parrish, 1998). Many significant insights derive from extensive drilling data (Zhang and Zhou, 1978; Wang et al., 1985b; Cui, 1989; Gao et al., 1992, 1999; Gu and Yu, 1999; Ye et al., 2002), especially the discovery of fossils that provide a substantial basis for the study of Cretaceous ecosystems.

Plant fossils and spore/pollen are very abundant and coal is widely distributed (Fig. 5) in deepest stratigraphic units of the Songliao Basin in Lower Cretaceous strata, indicating a relatively well-developed plant ecosystem (Wang et al., 1995; Gao et al., 1999). In addition, bi-valves, conchostraca, ostracode, and fish (Zhang and Zhou, 1978; Cui, 1989; Gu and Yu, 1999; Ye et al., 2002) signal the development of the lake system (see Section 4 in this paper for detail). The floras reflect a warm and humid temperate climate, as does the lacustrine Jehol biota represented by the ostracode Cypridea (Cypridea vitimensis, C. (Uhelmia) koskulensis, and the conchostraca Eoestheria, Dietheria, and Liaoningestheria (Huang et al., 1999).

As with the deepest stratigraphic unit, a great number of plants and spore/pollen fossils occur in the overlying stratigraphic unit (Wang et al., 1995; Gao et al., 1999).

Diverse ecosystems were best developed in the middle stratigraphic unit in the Songliao Basin. The diversity of genera and species reached a maximum. Twenty to thirty classes of fossils and 200–300 species (Zhang and Zhou, 1978; Wang et al., 1985b; Cui, 1989; Gao et al., 1992, 1999; Gu and Yu, 1999; Ye et al., 2002; Xi et al., 2011) reflect very well-developed plant and aquatic ecosystems are characteristics of Sungrabi biota. Many species of foraminifera, chlorophyta and fish first appeared in this period. Fish fossils in Nenjiang Formation are Hama macrastoma, Jilingichthys rapax, Jilingichthys, sp., Sungarichthys longicephalus, and Manchurichthys sp. in the Qing-shankou Formation and Plesiocypridopera daqingensis in the Yaohjia Formation (Kong et al., 2006).

During deposition of the upper stratigraphic unit, the Songliao depocenter migrated westward because of compression and uplift to the east (Feng et al., 2010a). The fossils are mainly chlorophyta and ostracoda (Wang et al., 1985b; Ye et al., 2002). Compared with the middle structural unit, the fossil diversity decreased greatly in numbers of classes and species, developed the Mingshui biota in the Late Cretaceous, which implies an associated shrinkage of the basin and a suppression of the whole ecosystem.

### 5.4. Climatically sensitive deposits

Many researchers have attempted to reconstruct climate zones over geological time by analyzing the distribution of climatically sensitive deposits (Strakhov, 1967; Zharkov, 1981; Bardossy, 1982). Terrestrial red beds would appear to be indicative of climates that are warm and dry or seasonal with respect to rainfall (Parrish, 1998; Du et al., 2011), and the distribution of coal indicates a range of humid climates under different temperature conditions (Meyerhoff and Teichert, 1971; Boucot et al., 2009).

Coal beds occur widely in the Shahezi and Yingcheng formations and indicate the humid climates of the Early Cretaceous in the Songliao Basin (Fig. 5). As with the deepest stratigraphic unit, coal is virtually absent (Wang et al., 1995; Gao et al., 1999), implying a less humid climate. These changes may correspond to the northward migration of arid zones in East Asia during mid-Cretaceous (Boucot et al., 2009). According to the spore/pollen data, the Cretaceous climate was mainly humid to semihumid, whereas coal beds did not occur during deposition of the Dengluokou through the Mingshui formations, indicating that the paleoenvironment of Songliao Basin changed from the fluvial facies to the lacustrine facies.

Terrestrial red beds (Fig. 5) occur widely in the middle Cretaceous to the Late Cretaceous and appear to correlate with arid climates (Wang et al., 1995; Du et al., 2011). There were four events of large
scale red beds, in the Quantou Formation, the 2nd to 3rd members of the Qingshankou and the Yaojia Formations (Du et al., 2011), the Sifangtai Formation, and the 2nd member of the Mingshui Formation, deposits in the Songliao Basin.

5.5. Discussion

Based on all the information above, we conclude that the Songliao Basin was mainly in humid to semihumid subtropical environments. The general trends of the spore/pollen data and oxygen isotope data from the Songliao Basin and Far East are similar. The temperature commonly was above 5 °C and the highest more than 25 °C; commonly the temperature range between warming events and cooling events was 5–10 °C, sometimes it ranged up to nearly 15–20 °C (Fig. 5). The global paleovegetation simulations (Upchurch et al., 1998; Sewall et al., 2007) provide the same conclusion. The major vegetation type of the Songliao Basin was a broad-leaved evergreen forest during the Cretaceous, reflecting a temperate and humid climate condition; the southern part was adjacent to arid climate areas, and had a slightly arid climate during some periods of the Cretaceous. The temperature was above 0 °C throughout the year, and rainfall was relatively abundant.

The conclusion is also supported by the global paleoclimate reconstruction of climatically sensitive deposits (Boucot et al., 2009). East Asia, including the Songliao Basin, was in the warm temperate zone during most of the Cretaceous and did not experience large changes (Boucot et al., 2009). In a greenhouse world without ice caps, ancient ocean currents became the primary controls of continental climate changes (DeConto et al., 1999; Hay, 2008, 2011). The Songliao Basin was influenced by warm currents flowing northward from the Pacific equatorial regions and cold currents flowing southward from the Arctic region (Pucet et al., 2005; Haggart et al., 2006); these currents approximately correspond to the modern Kuroshio and Oyashio currents, because of Pacific oceanic circulation patterns offshore of the Songliao Basin were broadly similar to those of today, keeping a relative stable state (Gordon, 1973; Klinger et al., 1984).

The Huoshiling Formation represents a humid temperate environment, which is also supported by the paleoecology, and this period was part of the first cooling event in the Cretaceous Songliao Basin. Because of lack of oxygen isotope data, the climate is mainly inferred from spore/pollen (Gao et al., 1999; Fig. 5). Overlying the Huoshiling Formation is the Shahezi Formation, which was more arid and was at a low temperature based on the spore/pollen and oxygen isotope data (Gao et al., 1999; Zakharov et al., 2009, 2011), with a decrease in conifers and an increase in shrubs and herbs. Furthermore, the 3rd and 4th members of the Shahezi Formation represent the first semi-arid event in the Songliao Basin (Fig. 5). However, coal beds also occurred in this period, indicating a humid condition. We suppose that the reason may be the semi-arid event was the briefest and slightest among the three events. The Yingcheng Formation was a semihumid–humid subtropical environment, and the temperature trend (mainly 15–20 °C) decreased and became more humid (Gao et al., 1999; Zakharov et al., 2009, 2011). Coal beds occur in this formation, with a decrease in conifers and increase in shrubs and herbs.

The climate of the Denglouku Formation changed rapidly and sharply. Based on the spore/pollen data, the 1st and 2nd members of the Denglouku Formation record the first warming event, while the 4th member of the formation indicates the second cooling event and the second semi-arid event (Gao et al., 1999). There was a sharp decrease in conifers and sharp increase in broad-leaved evergreens and herbs. However, the isotope data does not show the same trend, which may be due to the insufficiency of the data. Above the Denglouku Formation is the Quantou Formation, during which the temperature and humidity were relatively stable as shown by the spore/pollen data and oxygen isotope curve (Gao et al., 1999; Zakharov et al., 2011), and it was a semihumid subtropical environment. The occurrence of red beds and the absence of coal beds may indicate a more arid environment than the deepest stratigraphical unit and the transition from fluvial to lacustrine facies.

The Qingshankou Formation records part of the second warming event in the Songliao Basin, which was a humid subtropical–tropical environment. There was a sharp decrease in conifers and a sharp increase in broad-leaved evergreens and herbs in the Yingcheng Formation (Gao et al., 1999). The occurrence of the red beds suggests that the climate changed rapidly. Chamberlain et al. (2013–this volume) observe that the decrease in $\delta^{18}$O values at the base of the Turonian Qingshankou Formation is different from the marine record of the North Atlantic (Huber et al., 2002), and argue that this interval most likely reflects lake evolution as a result of global changes in the hydrologic/carbon cycle. We suggest that the same trend of the oxygen curve in the Far East (Zakharov et al., 1999, 2011) may also be the result of global changes in the hydrologic/carbon cycle and both can be used to reflect the climate of Songliao Basin approximately. The climate of the Yaojia Formation was cooler and more arid than the Qingshankou Formation, which is reflected by the spore/pollen data and oxygen iso- type curves. The Nenjiang Formation was the third cooling event of the Songliao Basin, and the temperature was about 5–10 °C (Zakharov et al., 1999).

The Sifangtai Formation was a semi-humid subtropical environment (Gao et al., 1999; Zakharov et al., 1999, 2011; Chamberlain et al., 2013–this volume), which was the last warming event and semi-arid event, with the occurrence of the red beds. The temperature was around 20 °C and we can observe a decrease in conifers and increase in broad-leaved deciduous herbs. The Mingshui Formation was a semihumid temperate environment (Gao et al., 1999; Zakharov et al., 1999, 2011; Chamberlain et al., 2013–this volume), which was the last cooling event in the Songliao Basin. The $\delta^{18}$O values in the lower portion of the 2nd member of the Mingshui Formation are much more variable than the marine record, and Chamberlain et al. (2013–this volume) attribute this difference to be the result of local drainage reorganization within the basin. The same trend of the oxygen curve in the Far East (Zakharov et al., 1999) may suggest that the more variable continental record can be used to reflect the climate of Songliao Basin approximately.

Interest in the hypothesis of Cretaceous glaciations has grown in recent years. Price (1999) summarized the evidence for polar ice sheets during the Mesozoic in detail, concluding that there were small and ephemeral glaciations in the Cretaceous. Through compiled evidence from previous publications including dropstone, tillite, glendonites, eustatic fluctuations and $\delta^{18}$O values, Chen et al. (2011) suggested 13 potential glaciation intervals in the Cretaceous. Based on spore/pollen data (Gao et al., 1999) and oxygen data (Zakharov et al., 1999, 2009, 2011; Chamberlain et al., 2013–this volume), we conclude that the four Asian cooling events are consistent with the potential glaciations periods: Berriasian–Valanginian evidenced by tillite in Australia (Alley and Frakes, 2003); Aptian–Albian evidenced by glendonites in Canada and Norway (Kemper, 1983), glacial freeze/thaw structure in Australia (Constantine et al., 1988), and $\delta^{18}$O values (Clarke and Jenkyns, 1999); early Santonian evidenced by eustatic fluctuations (Haq et al., 1987); and Campanian–Maastrichtian evidenced by eustatic fluctuations (Haq et al., 1987; Miller et al., 2005), frost and floating ice in the Arctic (Falcon-Lang et al., 2004; Davies et al., 2009). These potential glaciation events generally correspond to the cooling events, but we lack the resolution to determine the relative order of cooling between continental and marine environment. In order to work out this relationship, we need more deep-time paleoclimate research.

6. Conclusions

The long-lived Cretaceous Songliao Basin, covering roughly 260,000 km$^2$ of NE China is an excellent candidate from which to
recover a nearly complete Cretaceous terrestrial sedimentary record, which will provide unique opportunities to understand the response of terrestrial environments to geological events related to the carbon cycle and greenhouse climate change. We revised the chronostratigraphic framework of the Songliao Basin with the latest isotope chronology and biostratigraphy. The mainly lacustrine deposition began in the Songliao Basin about 155–150 Ma, and ended in 64 Ma; the 85–90 m.y. duration of continental sedimentation likely places the Songliao Basin among the longest-lived continental sedimentary basins.

In the Songliao Basin, five stratigraphic cycles formed in four evolutionary stages, which include the faunal stage, the fault-subdivision transition stage, the subsidence stage, and the waning stage. Tectonic activity and water supply controlled the changing area of the basin, which controlled the distribution and character of sediment facies. A structural cross section across the Songliao Basin reveals that the basin filling pattern forms typical ‘steer’s-head’ geometry. The lower stratigraphic unit is limited to the grabens controlled by faults in the synrift stage. The middle and lower stratigraphic units typically appear to have a downwarping sedimentary pattern, their deposits overlap all the graben basins, and the east and west sides of the basin overlap in an onlap pattern. The upper stratigraphic unit only appears at the western side of the basin, because stress from the east during this period not only led to the westward migration of depocenter, but also resulted in continuous uplift and erosion on the east.

East Asia, including the Songliao Basin, was in the warm temperate zone throughout the Cretaceous, without large changes. Based on the spore/pollen fossil data, the vegetation landscape of the Songliao Basin in Cretaceous was mainly conifer forest, steppe and arid zone throughout the Cretaceous, without large changes. Based on the field development in Daqing, the Nenjiang basin overlap in an onlap pattern. The upper stratigraphic unit only appears to have a downwarping sedimentary pattern, their deposits overlap all the graben basins, and the east and west sides of the basin overlap in an onlap pattern. The upper stratigraphic unit only appears to have a downwarping sedimentary pattern, their deposits overlap all the graben basins, and the east and west sides of the basin overlap in an onlap pattern.

Acknowledgments
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Appendix A. Supplementary data
Supplementary data to this article can be found online at doi:10.1016/j.palaeo.2012.01.030.

References


