



The palynological record from Coniacian to lower Campanian continental sequences in the Songliao Basin, northeastern China and its implications for palaeoclimate



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ABSTRACT

A palynological record recovered from successions of Coniacian to early Campanian age (89.1–83.5 Ma) was obtained from the lacustrine sequences of the SK-I south core (SK-Is) in the Songliao Basin, northeastern China. The palynoflora is dominated by bisaccate gymnosperm pollen, followed by spores of pteridophytes, and just minor amounts of angiosperm pollen. Based on the relative abundance of the different spore and pollen taxa through the core, the succession was subdivided into three palynological assemblages. The results indicate two opposite trends for climate change, a minor warming trend (from 89.1 to 85.7 Ma) followed by a rapid cooling trend (85.7–83.5 Ma). The first warming trend reached its maximum at 85.7 Ma, which is inconsistent with results from the marine realm (which instead show a minor cooling trend based on several proxy records). However, the second cooling phase is consistent with global changes from various and abundant palaeoclimate proxies from marine deposits. We interpret the climatic changes within the studied interval (89.1–83.5 Ma) as a consequence of the shifting climate from a hot/super greenhouse to a temperate greenhouse.

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1. Introduction

The Cretaceous period was characterised as a typical greenhouse due to the interaction between marine and terrestrial circulatory systems. Hence, this interval may be a shortcut to a better understanding of modern global warming (Hay, 2011). Most marine sedimentary records reveal a steady increase in palaeotemperature, lasting through the mid-Cretaceous (Albian–Cenomanian) and culminating during the Cenomanian/Turonian thermal maximum (e.g., Huber et al., 1995; Clarke and Jenkyns, 1999; Norris et al., 2002; Pucéat et al., 2003; Forster et al., 2007; Erbacher et al., 2011). After that, a rapid temperature decrease lasting from 93.5 Ma to 65 Ma did occur (Norris et al., 2002; Jenkyns et al., 2004; Friedrich et al., 2012). Cyclic black shales formed under anoxic-to-dysoxic conditions were widely distributed during the Coniacian–Santonian in the equatorial to mid-latitudinal Atlantic and adjacent basins (see Wagreich, 2012 and references therein). This

episode was defined as the OAE3 (oceanic anoxic event 3), the last of the Cretaceous OAEs. Coniacian–Santonian continental climate changes are potentially key to understanding the relationship between decreasing temperature and cyclic black shale formation. At this stage, terrestrial climatic change studies are relatively lag behind marine research. This is mainly caused by the difficulties in determining the stratigraphic ages of Upper Cretaceous continental deposits due to the lack of suitable age-diagnostic marker fossils.

The Songliao Basin in China hosts one of the thickest Cretaceous terrestrial successions in the world. Multiple tuff and/or lava layers interbedded within this extensive continental sequences provide important absolute age control (Wang et al., 2007). In 2006, the Ministry of Science and Technology of China and Daqing oilfield initiated a coring project named the “Cretaceous Continental Scientific Drilling Program of China” (CCSD-SK-I) (Wang et al., 2009b). The project resulted in two drill-cores (south core and north core) with continuous (>90%) recovery of Upper Cretaceous non-marine strata (Cheng et al., 2009), mainly consisting of lacustrine and palustrine deposits. Additionally, the cores are rich in organic matter, which makes them suitable for palynological research. The Upper Cretaceous deposits in the Songliao Basin have been well

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dated by detailed magnetostratigraphy (He et al., 2012; Deng et al., 2013). The absolute ages of rare tuff and lava interlayers (He et al., 2012) in combination with cyclostratigraphy provide an important basis to explore the continental response to major marine environmental events (Wu et al., 2013).

In this paper, we present sporopollen records from Coniacian–lower Campanian deposits from the southern core of SK-I (SK-Is). Our sporopollen analysis of the Songliao Basin drill core covers 969–1579 m and has the following objectives: (1) to reconstruct the vegetation and climate history of the Songliao Basin for most of the Coniacian–Campanian and (2) to correlate global change between terrestrial and marine records.

2. Geological setting and stratigraphic age

The Songliao Basin covers 260,000 km² and represents one of the largest and persistent Cretaceous continental petroliferous basins in the world. Deposition in the basin was controlled by paleotopography, which can be divided into a central depression, where the studied core is located, the west slope, the northeast uplift, the north plunge, the southwest and the southeast uplift (Fig. 1). The basin is filled with approximately 9000 m of continental siliciclastics of fluvial or lacustrine origin, and multiple volcanic and pyroclastic rock interlayers (Huang et al., 2011). The thick Upper Cretaceous of the Songliao Basin can be divided into several lithostratigraphic units including the Quantou, Qingshankou, Yaojia, Nenjiang, Sifangtai, and Mingshui formations. The studied section intersects Members two and three of the Qingshankou Formation (K₂Qn²⁺³) to Member two of the Nenjiang Formation (K₂N²). This sedimentary sequence formed during the expanding stage of the depositional area, and the different sub-

basins merged into a single large basin. During the Qingshankou period, the Songliao Basin exhibited the highest lake level. Deposition during this highstand interval was characterized by greyish black mudstones, black shales and small amounts of greyish dolomite and mudstone interlayers. After that, the Yaojia Formation (K₂Y) formed during the short-lived rift phase of the basin, which was characterized by purple-red, grey-green and grey mudstones and sandstones formed in fluvial and shallow lake environments. A lake transgression occurred again during the formation of the Nenjiang Formation (K₂N), particularly during Members 2 and 3. At that time, most of the basin was dominated by deep lacustrine environments with black and greyish black mudstones, interbedded shales and small amounts of dolomite. Following deposition of Member 3 (Nenjiang Formation), lacustrine regression started, which is represented by varicolored mudstones and greyish sandstones.

So far, the continental Upper Cretaceous succession of the Songliao Basin has been dated using palaeontological records (Li et al., 2011; Xi et al., 2011), magnetostratigraphic (Deng et al., 2013) and radiometric data (He et al., 2012) derived from volcanogenic rocks. The first scientific drill core in the Songliao Basin (SK-I) provides the most continuous Upper Cretaceous continental record from northeast Asia to date. Numerous high-precision biostratigraphic zonations for the SK-I core schemes exist, including twenty ostracode assemblages, ten phytoplankton assemblages, and four charophyte assemblages (see Wang et al., 2013). Li et al. (2011) established eight palynological zones for the Lower Cretaceous of SK-I, which present the most detailed palynostatigraphic framework to date. A marine foraminiferal assemblage was discovered in the Nenjiang Formation during a short-term marine transgressive event (Xi et al., 2011). These

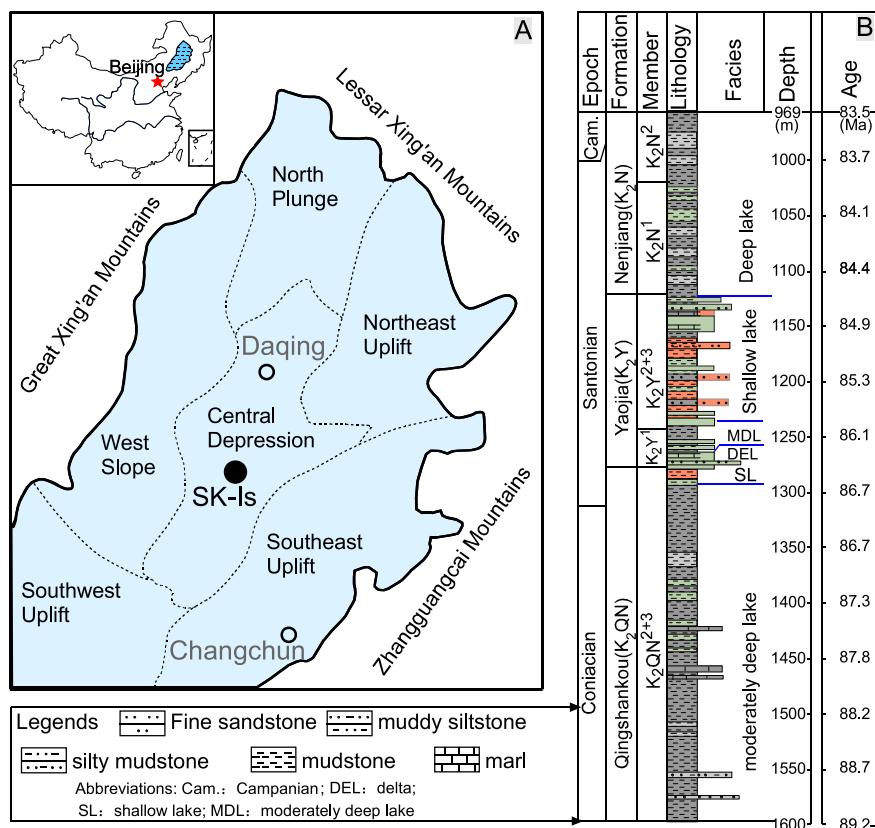


Fig. 1. A: Location of the Songliao Basin and structural subdivisions of the Songliao Basin. B: Stratigraphy and sedimentary log of the south core of SK-I.

biostratigraphic results are further synthetically calibrated by Scott et al. (2012) and Wan et al. (2013), which indicate that the studied sequence from K₂QN²⁺³ to K₂N should be Coniacian to lower Campanian.

Detailed SIMS U–Pb radiometric ages and high-resolution magnetostratigraphic data constrained the chronostratigraphic framework of the Upper Cretaceous in the Songliao Basin. He et al. (2012) reported the weighted mean ²⁰⁶Pb/²³⁸U ages from four bentonite beds in the southern core of SK-I to be 91.4 ± 0.9 Ma at 1780 m, 90.1 ± 0.9 Ma at 1705 m, 90.4 ± 0.9 Ma at 1673 m, and 83.7 ± 0.8 Ma at 1019 m. Using these absolute ages, 11 magneto-zones identified in the southern core of SK-I could be correlated to C34N to C28N (Deng et al., 2013), which constrain the stratigraphic interval covered by the Upper Quantou Formation (K₂Q) and the Mingshui Formation (K₂M) from the Turonian to Maastrichtian, respectively. Wu et al. (2013) established a floating astronomical chronology for the strata covered by the Quantou Formation (92 Ma) to the Nenjiang Formation (83.5 Ma) of the SK-I southern core (SK-Is) using the natural gamma-ray (GR) log, which accurately constrains the duration of the sedimentary sequences in the Songliao Basin.

3. Material and methods

A total of 43 samples from the southern core of SK-I were used for palynological analyses, with an average sampling resolution of 11.5 m. The sampled section stretches from Member 2 of the Nenjiang Formation (1579 m) to Member 2 of the Qingshankou Formation (969 m), with ages ranging from 89.1 to 83.5 Ma (Fig. 1). Sedimentary rock samples weighing between 30 and 80 g were processed using conventional acid treatment (e.g. Traverse, 2007). First, the samples were treated with HCl and HF acid to remove carbonates and silicates, respectively. The residues were subsequently filtered through a 10 µm nylon sieve to remove the fine fraction. Finally, the residues were mounted in glycerol for identification. All samples were studied using an Olympus CX-31 microscope at Lanzhou University (Gansu province, China). Palynomorph determination was performed according to Song et al. (1999, 2000) and Gao et al. (1999). More than 300 grains in each sample were determined to obtain statistically significant palynomorph abundances and diversities. All of the palynomorph slides are stored at the Key Laboratory of Petroleum Resources Research, Institute of Geology and Geophysics, Chinese Academy of Sciences.

In this study, we introduce a sporopollen-climate transforming methodology, which uses the percentage of drought-loving taxa and thermophilic taxa (Fig. 6) to indicate humidity and temperature stratigraphic trends, respectively. The drought taxa and thermophilic taxa have been calculated following the concept of earlier studies (Gao et al., 1999; Abbink et al., 2001; Zhang et al., 2014). *Classopolis*, *Ephedripites* and all angiosperm taxa are regarded as drought loving plants, whereas the thermophilic group is represented solely by spores.

4. Results

All 43 samples from the studied SK-Is core were palynologically productive and the palynomorphs were well preserved (low thermal alteration index = 2+; e.g., Zobaa et al., 2013). In total, 40 genera of spores (Fig. 2A), 29 genera of gymnosperm pollen (Fig. 2B) and 5 genera of angiosperm pollen were identified (Fig. 2B) and taxa are shown in Figs. 3 and 4. In general, the palynological assemblage is characterised by high abundances of conifer pollen (average 34.7%) and pteridophyte spores (average 24.5%) and an only small quantities of angiosperm pollen (2.0%). The

gymnosperm pollen are dominated by numerous bisaccate pollens, whereas the pteridophyte spores are primarily represented by *Cyathidites*. Using the quantitative distribution with stratigraphic height of the different sporopollen groups, three palynological assemblages (PA) were identified between 1579 m and 969 m, which are described below from base to top (Fig. 5).

4.1. Palynological assemblage I (PA I) (core depth 1579–1395 m, approx. 89.1–87.2 Ma)

This palynomorph assemblage is characterised by the predominance of gymnosperm pollen (82.0%) and small amounts of spores (16.3%) and angiosperm pollen (1.7%). The gymnosperm pollen are dominated by bisaccate conifer pollen (52.3%), including *Piceapollenites* sp., *Pinuspollenites* sp., *Podocarpidites* sp., *Protopinus* sp. Pollen grains of potentially taxodiaceae affinity, including *Inaperturopollenites dubius* and *Taxodiaceaepollenites hiatus*, are common and account on average for 5.3% of the total. The gymnospermous *Ephedripites* group is composed of two types, namely *Ephedripites* (*Ephedripites*) and *Ephedripites* (*Spiralipites*), and are also common (6.3%). Araucariaceae pollen (1.5%), including *Araucariacites australis* as well as *Araucariacites* sp., and monosulcate pollen (1.6%), including *Bennettiteapollenites* and *Cycadopites*, are rare in the assemblage.

The pteridophyte spores are a common element but numerically subordinate, representing only 16.3% of the total assemblage. The dominant taxon is *Cyathidites*, which accounts for an average of 8.9% of the total. *Cyathidites* consists of *Cyathidites australis*, *C. minor*, *C. punctatus*, and *C. sp.*, followed by the *Cicatricosisporites* group, which contributes between 0 and 10.2% (average 2.6%). Other common taxa, such as *Deltoidospora* sp. (average 1.0%) and *Osmundacidites* sp. (average 0.4%), are of minor importance. Some taxa occurred only occasionally in the samples (Fig. 2A).

The angiosperm pollen are not very diverse or abundant, including *Quercoidites minutus*, *Quercoidites microhenrici*, *Q. sp.*, *Retitricolpites* sp., and *Tricolpopollenites* sp..

4.2. Palynological assemblage II (PA II) (core depth 1395–1125 m, approx. 87.2–84.6 Ma)

This assemblage is characterised by a distinct increase in spore abundance (average 39.7%) compared to PA I, though still less than the gymnosperm pollen content (average 59.3%). Again, only minor occurrences of angiosperm pollen are present in this palynomorph assemblage. Bisaccate pollen of conifers (average 20.1%) show a decrease compared to the PA I but remains the major portion of the gymnosperm pollen. The content of *Classopolis* shows an average of 23.8% in this interval and increases compared to PA I. *Ephedripites* is still common in PA II without significant variation (average 4.6%). Taxodiaceae pollen account for an average of 7.7%, and show a slightly increasing trend. The Araucariaceae pollen (1.0%) and monosulcate pollen (0.9%) still are very low in abundance.

Pteridophytespores, representing 39.7% of the total abundance, show an overall increase in PA II, reaching peak values of 75.2% at 1271 m. *Cyathidites* dominate the spore assemblage and account on average for 32.7%. Other spores, such as *Deltoidospora* (2.5%) and *Cicatricosisporites* (0.2%) are rare.

4.3. Palynological assemblage III (PA III) (core depth 1125–969 m, approx. 84.6–83.5 Ma)

In PA III, the abundance of spores shows a marked decline with the lowest average levels of 9.3%. Accordingly, gymnosperm pollen are very abundant (average 86.3%). Angiosperm pollen show an

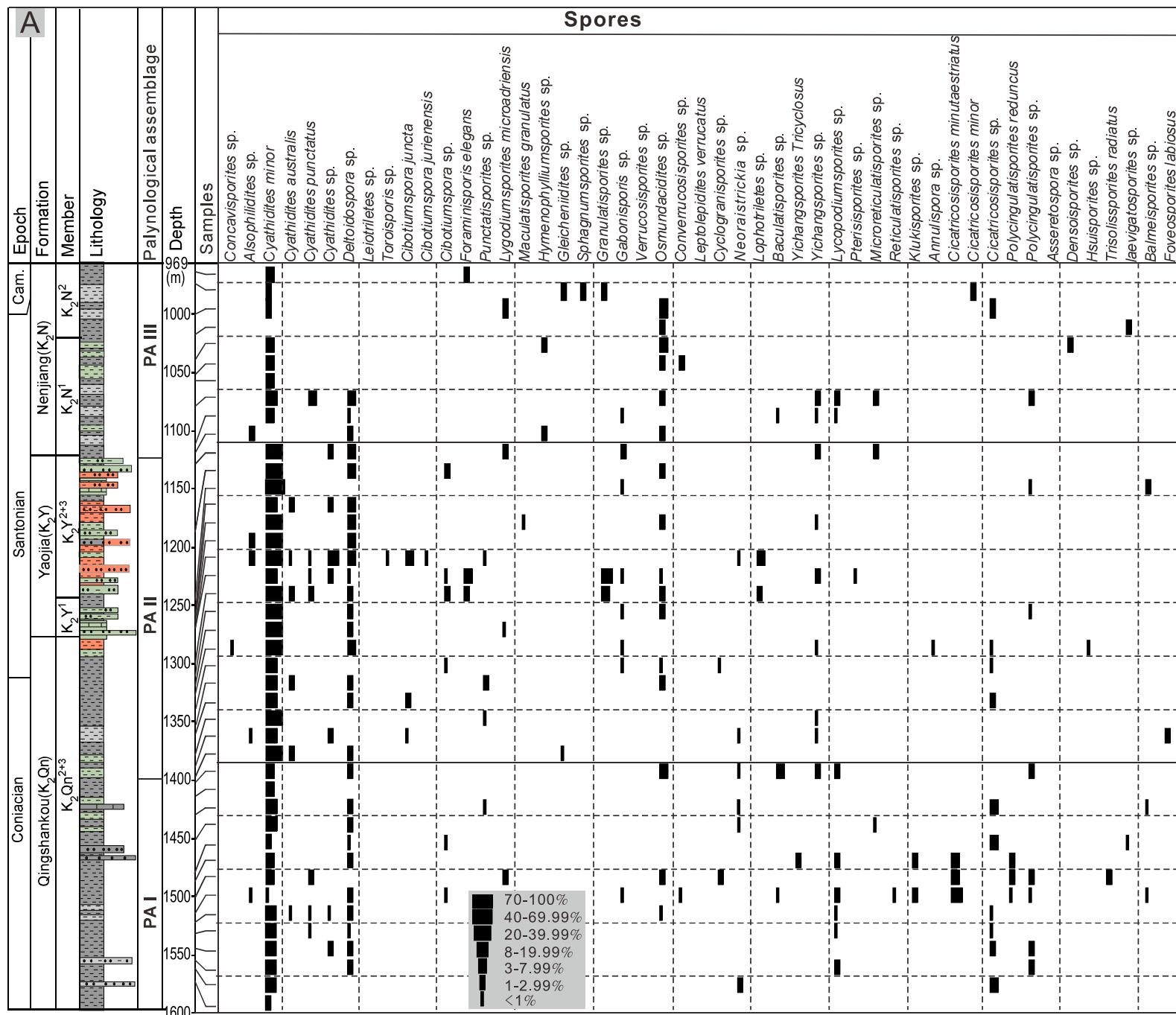


Fig. 2. (A) Quantitative stratigraphic distribution of spores and (B) pollen in the southern core of SK-I covering Coniacian to lower Campanian deposits.

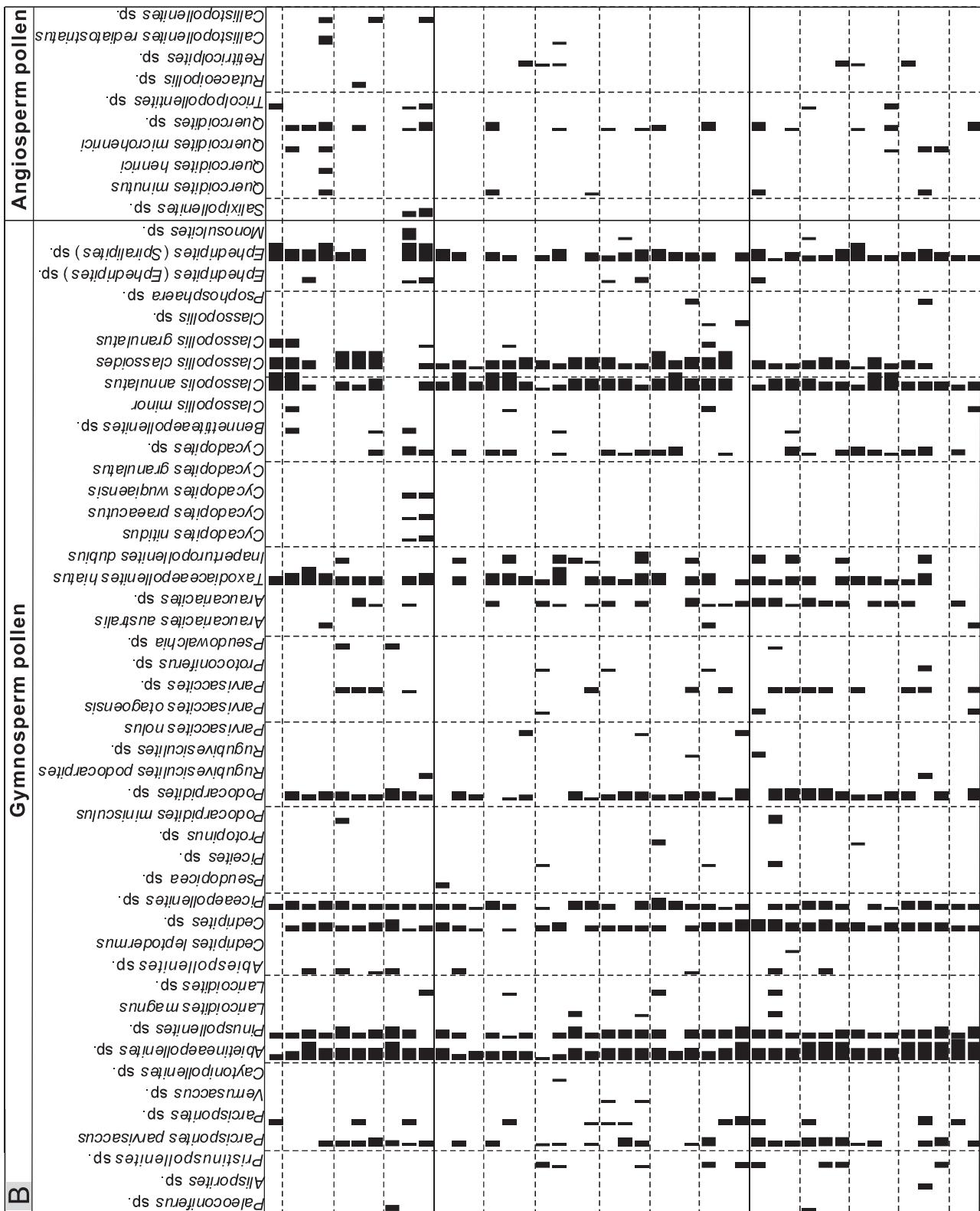


Fig. 2. (continued).



Fig. 3. Selected representative spore and pollen taxa from the southern core of SK-I. The scale bar is 20 μm . A, *Cyathidites minor*, 1258 m. B, *Sphagnumsporites* sp., 1271 m. C, *Densoisporites* sp., 1040 m. D, *Cyathidites punctatus*, 1271 m. E, *Concavissimisporites* sp., 1516 m. F, *Foveosporites labiosus*, 1383 m. G, *Cicatricosporites* sp., 1388 m. H, *Yichangsporites* sp., 1388 m. I, *Yichangsporites tricyclosus*, 1314 m. J, *Osmundacidites* sp., 1314 m. K, *Trisolissporites radiates*, 1506 m. L, *Klukisporites* sp., 1493 m. M, *Neoraistrickia* sp., 1388 m. N, *Pristinuspollenites* sp., 1337 m. O, P, *Neoraistrickia* sp., 1404 m. Q, *Reticulatisporites* sp., 1388 m. R, *Gabonisporis* sp., 1314 m. S, T, *Classopollis annulatus*, 1388 m. U, *Ephedripites (Spiralipites)* sp., 1337 m. V, *Classopollis annulatus*, 1271 m.

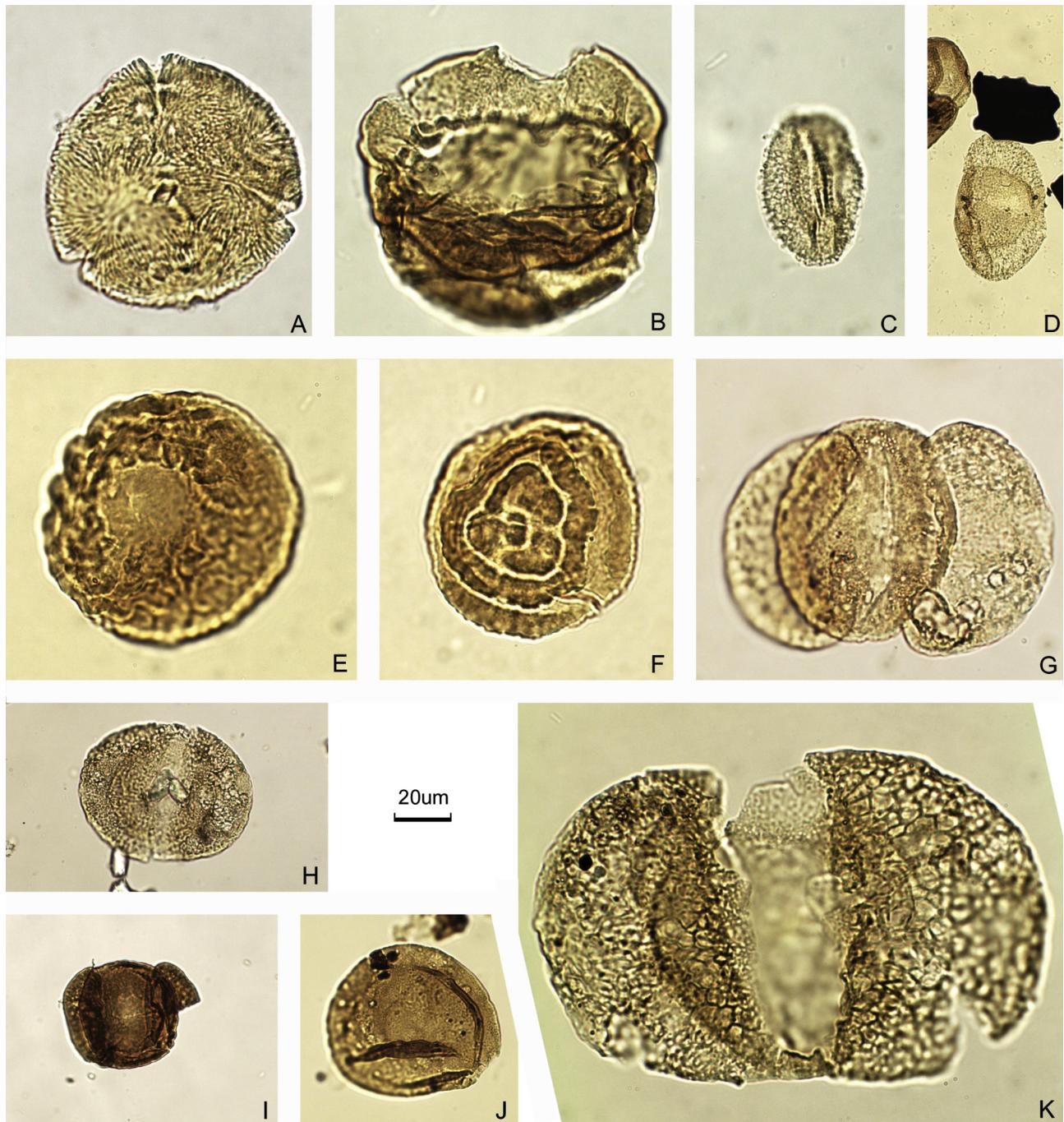


Fig. 4. Selected representative spore and pollen taxa from the southern core of SK-I. The scale bar is 20 μm . A, *Callistopollenites radiostriatus* 1036 m. B, *Jiaohepollis* sp., 1271 m. C, *Retitricolpites* sp., 1271 m. D, *Pseudowalchia* sp., 1394 m. E, *Parcisorites* sp., 1271 m. F, *Polycingulatisporites reduncus*, 1271 m. G, *Podocarpidites* sp., 1271 m. H, *Pseudowalchia* sp. 1404 m. I, *Cedripites* sp., 1388 m. J, *Araucariacites* sp., 1382 m. K, *Piceites* sp., 1388 m.

increase in abundance and diversity, with average contents reaching up to 4%.

The gymnosperm pollen assemblage is still dominated by bisaccate conifer pollen. A remarkable feature is a sharp increase in *Ephedripites* content in this assemblage, reaching 18.2% on average. The content of *Classopollis* pollen (average 21.7%) remains relatively stable compared to PA II. The Taxodiaceae pollen increased in abundance from less than 8.3% to peak values of up to 16.2%. Araucariaceaepollen (0.7%), and monosulcate pollen (2.6%) are rare, presenting slight changes compared with the two previous assemblages.

The decrease in the pteridophyte spore abundance is caused by a decline in *Cyathidites* with abundances of only 4.4%. Similarly, *Deltoidospora* decrease in PA III from peak values of 3.9% to total absence. In PA III, *Osmundacidites*, accounting for 1.4% on average, shows a slight increase. Other types, such as *Cicatricosisporites* sp., *Hymenophyllumsporites* sp., *Lycopodiumsporites* sp., *Maculatisporites granulates*, etc., remain relatively rare.

New angiosperm taxa, such as *Rutaceipollis* sp., *Callistopollenites radiostriatus*, and C. sp., occur in PA III, besides some common types known from the previous two assemblages, such as *Quercoidites* sp., *Retitricolpites* sp., *Tricolpopollenites* sp.

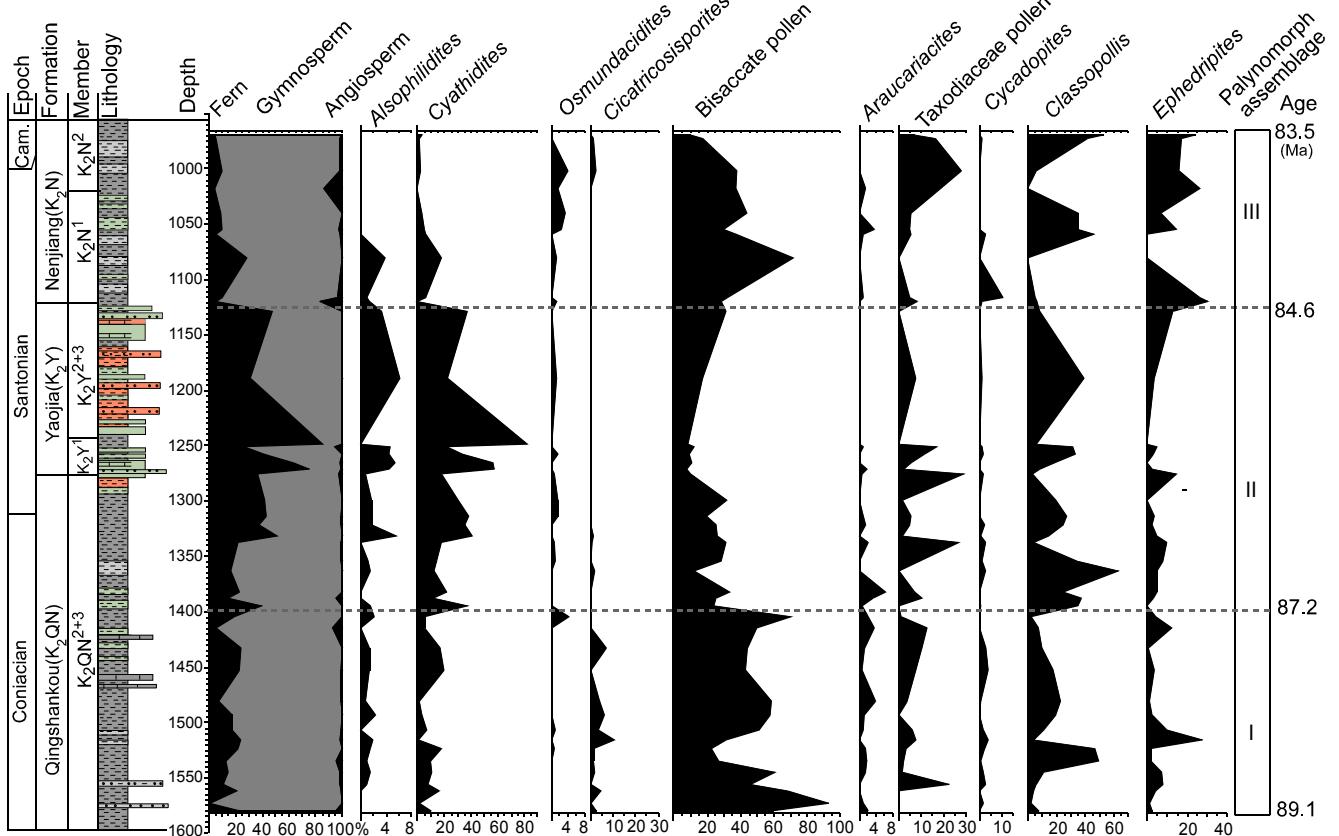


Fig. 5. Percentage sporopollen diagram of the southern core of SK-I in the Songliao Basin, northeastern China. Only selected taxa are shown.

5. Discussion

5.1. Palynoflora and palaeoclimatic change

The Late Cretaceous (Coniacian to early Campanian) palynofloras in the southern core of SK-I are produced by a variety of different plant groups. Information regarding the botanical affinities of the spore and pollen genera or categories is based on published palaeoecological data (e.g., Van Konijnenburg-van Cittert, 1971, 2002; Balme, 1995; Abbink et al., 2001; Wang et al., 2005). The climatic preferences of the various parent plants were assessed. The group of ferns is mainly composed of Cyatheaceae/Dipteridaceae (*Cyathidites*, *Deltoidosora*, *Alsophilidites*), Osmundaceae (*Osmundacitides*), Schizaeaceae (*Cicatricosporites*), and Lycophyta (*Lycopodiumsporites*). These types of ferns prefer shady and humid habitats, such as humid marshes, along river banks or grow as understory plants (Van Konijnenburg-van Cittert, 2002). The dominant conifers among the studied gymnosperms are known from a wide range of habitats. Pinaceae (*Piceapollenites*, *Pinuspollenites*), Podocarpaceae (*Podocarpidites*) and other conifer types generally grow in dry areas of upland forests and were widely distributed in warm to cold regions in the southern and northern hemispheres (Wang et al., 2005). Taxodiaceae conifers (*Inaperturopollenites* and *Taxodiaceapollenites*) are considered a vegetation type that grew in humid lowlands and cooler environments (Van Konijnenburg-Van Cittert, 1971; Pelzer et al., 1992). Cheirolepidiaceae (as indicated by *Classopollis*) are a common Mesozoic plant group that thrived in a wide range of habitats from hot equatorial regions to warm, high-latitude areas (e.g., Vakhrameyev, 1982). Additionally, these drought-resistant plants are preferred to have inhabited well-drained upland to coastal

lowland regions as well as in saline habitats (Vakhrameyev, 1982; Watson, 1988; Heimhofer et al., 2008; Mendes et al., 2010). Ephedraceae generally firstly appeared in the Early Cretaceous and flourished in the mid-Cretaceous in China. They thrived in hot and dry regions in southern China and grew in a wide range of habitats throughout China in the Late Cretaceous. Modern Ephedraceae are well adapted to warm semi-arid to arid conditions (Herschuh et al., 2004; Yang, 2002; Miao et al., 2011) and are the dominant plant group in desert regions in Asia. The high abundances of Ephedraceae is interpreted to indicate dry and relatively cooler environments. Based on the climatic preference of the different palynomorph groups, the climatic evolution of the Songliao Basin can be divided into three stages from the Coniacian to the earliest Campanian interval.

During the early Coniacian (89.1–87.2 Ma, PA I), the palynofloral community is dominated by bisaccates of pinaceous affinity, including *Cedripites*, *Piceapollenites*, *Pinuspollenites*, and *Podocarpidites*, which were the dominant floral element of the boreal realm during the Late Cretaceous. This indicates a humid and relatively cool climate (Brenner, 1976; Batten, 1984; Hochuli et al., 1999). The drought-resistant Ephedraceae show low concentrations in this interval. Abundances of *Classopollis* produced by Cheirolepidiaceae under hot and dry conditions are slightly lower than in the other two intervals (PA II and PA III). The low relative abundance of Ephedraceae and Cheirolepidiaceae indicates a humid and relatively cool climate. Hygrophytic pteridophyte ferns contributed only minor amounts with no large fluctuations which indicated a relatively cooler condition. The relative percentage of drought-adapted taxa is relatively low with a single peak at 1530 m (approximately 88.5 Ma). The percentage of thermophilic taxa is even lower and shows a stable trend. In summary, the composition

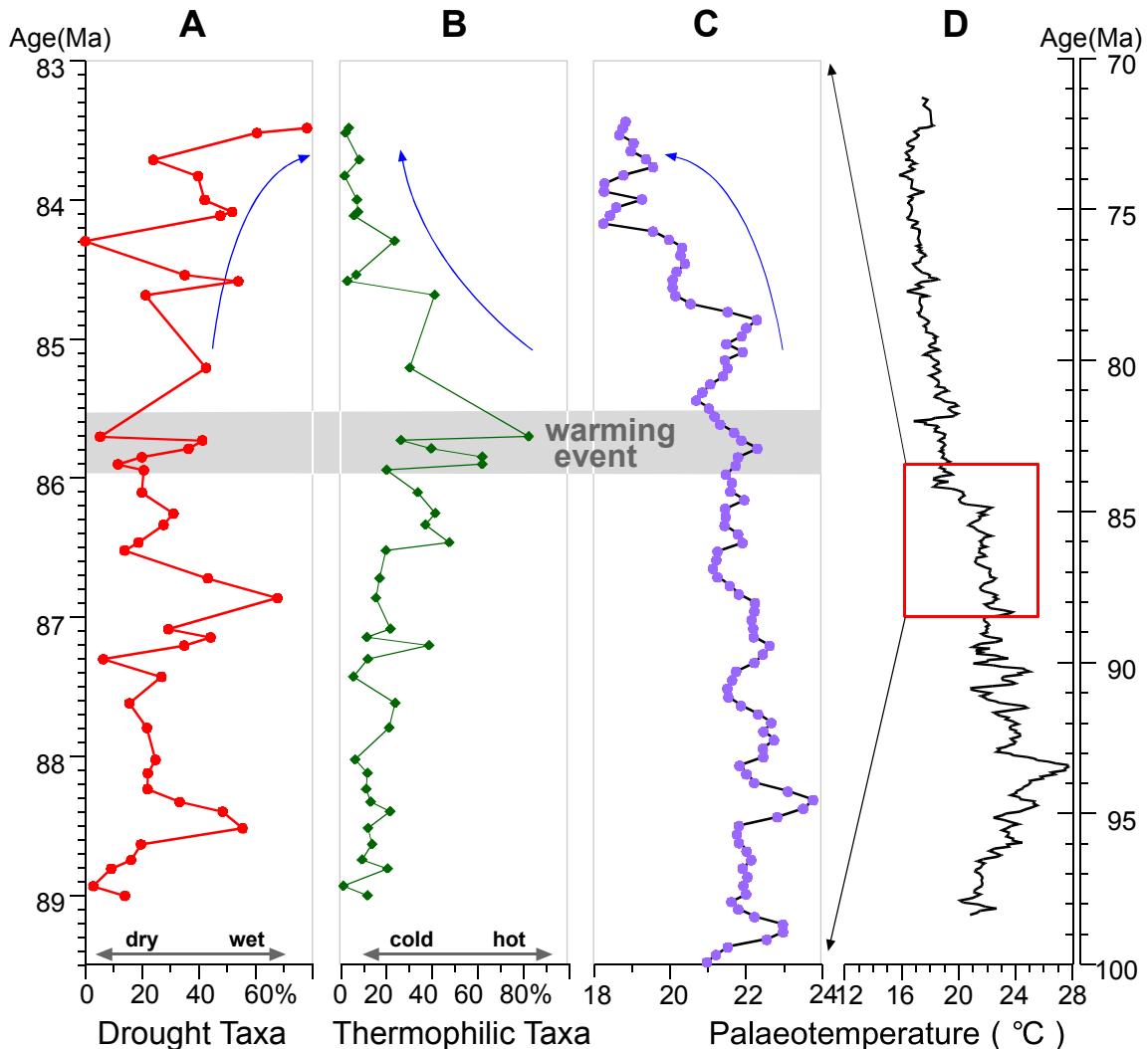


Fig. 6. Comparison between (A) drought taxa percentages, (B) thermophilic taxa percentages, (C) proxy palaeotemperature curve for the Arctic Ocean from 89.5 to 83.5 Ma (Jenkyns et al., 2004), and (D) Arctic Ocean palaeotemperature trends for the Late Cretaceous (Jenkyns et al., 2004).

of the palynoflora of PA I indicates relatively cool and humid conditions during the early Coniacian (89.1–87.2 Ma).

During PA II (Coniacian to early Santonian, 87.2–84.6 Ma), a more humid and warmer climate prevailed. This is indicated by a dramatic increase in pteridophytes (e.g., Cyatheaceae/Dicksoniaceae) in this interval. The percentages of pinaceous pollen show the lowest values. However, Cheirolepidiaceae shows minimum values at 1250 m and a subsequent rise to peak values at 1190 m and 1360 m. Ephedraceae formed a relatively rare vegetation elements in PA II. The percentage of drought loving taxa decreased, and the percentage of thermophilic taxa increased to its peak value (Fig. 6). The high abundances of pteridophytes associated with declining bisaccate abundances indicate a warm and relatively humid climate in the Songliao Basin during this interval. These conditions reached their maximum extent at around 1250 m (approximately 85.7 Ma).

A pronounced shift towards cooler and drier conditions is proposed for the late Santonian. Compared to PA II, the bisaccate pollen-producing conifers, such as the Pinaceae and Podocarpaceae, markedly increased and became the dominant plants. At the same time, the thermophilous and hygrophilous pteridophytes decrease in abundance and diversity. The drought-resistant

Ephedraceae show a significant increase during this interval. The Cheirolepidiaceae did not show marked changes. The percentage of thermophilus taxa starts to decline from 1250 m (approximately 85.7 Ma) onwards. On the other hand, the abundance of drought-adapted taxa rose slowly to reach peak values at the top of the sequence (Fig. 6). From 84.6 to 83.5 Ma, a drought-resistant and cold-loving flora grew in the basin, probably indicating a change in climate to dry and cooler condition.

In summary, the palynoflora recovered from 969 to 1579 m in the south core of SK-I indicates that a temperate and sub-humid climate existed in the Songliao Basin during the Coniacian to the early Campanian (89.1–83.5 Ma). A distinct warming event occurred at around 1250 m (approx. 85.7 Ma). Subsequently, the climate then became drier and colder.

5.2. Comparison with global climate change

The Coniacian to early Campanian was characterised by cyclical fluctuations in climate. These periodic climatic fluctuations resulted in cyclical organic carbon burial and are interpreted to have been controlled by variations in orbital parameters (Hofmann et al., 2003). Besides, this interval can be considered as a key interval

covering the transition from the mid-Cretaceous super-greenhouse state to the Late Cretaceous temperate greenhouse conditions (e.g., Norris et al., 2002; Friedrich et al., 2012). Additionally, deposition of black organic-rich shales was associated with a carbon isotope excursion, defined as oceanic anoxic event 3 (OAE3) (Ryan and Cita, 1977; Arthur and Schlanger, 1979; Jenkyns, 1980; Hofmann et al., 2003).

Based on the trends of palaeoclimatic changes assessed by the palynoflora in this sequence, the interval can be divided into three stages: (I) a stable cool and wet stage during the Coniacian (89.1–87.2 Ma); (II) a distinct warming period between 87.2 and 84.6 Ma; (III) an obvious cooling stage from the late Santonian to the early Campanian (after 84.6 Ma).

From the stage I to early stage II, the palynoflora from the terrestrial Songliao Basin indicates a relatively stable climate accompanied by gradual warming trends. In contrast, marine organic geochemical proxy (TEX_{86}) records from Ocean Drilling Program Leg 207 Sites 1258 and 1259 on Demerara Rise in the western Atlantic Ocean indicate gradually cooling sea surface temperatures (Forster et al., 2007), unlike the terrestrial records. Similarly, marine palaeotemperature curves based on proxy data derived from oxygen-isotope ratios of the chalk from southern England show a gradually cooling temperature (Jenkyns et al., 2004) (Fig. 6).

In the middle stage II, a distinct climate warming seized by this study occurred at about 85.7 Ma (1250 m), named “warming event”. During the same time, the terrestrial carbon isotope record based on ostracods from the SK-I core shows a major carbon isotope excursion (Chamberlain et al., 2013), eventually corresponding to a warming event. The carbon isotope composition of n-alkanes show minor changes from the same interval of this core in the Songliao Basin (Yin, 2013). Contemporaneous carbon isotope curves from marine records were not consistent with the continental sedimentary record from the Songliao Basin (see Chamberlain et al., 2013). During the same time, the widespread deposition of black shales rich in organic matter (OAE3) occurred in the equatorial to mid-latitudinal Atlantic and adjacent basins (see Wagreich, 2012). On the other hand, the red deep-marine CORBs (Cretaceous Oceanic Red Beds) were widely distributed in the Tethys, indicating widespread oxic deep-water environments (Wagreich et al., 2009; Wang et al., 2009a, 2011). We speculated that this interval represents the transition from a super-greenhouse to a temperate greenhouse climate state, during which the global atmosphere-land-ocean circulatory system was disturbed.

After approximately 85.7 Ma (1250 m), the palynoflora suddenly indicates cooler and drier conditions in the Songliao Basin (Fig. 6). For the same interval, the hydrogen isotopic composition of n-alkanes records a distinct negative excursion (Yin, 2013). The cooling event observed in the sporopollen data can also be identified in various marine proxy-based paleotemperature records from different sites. The TEX_{86} records of sedimentary deposits recovered from the western equatorial Atlantic revealed a drop in sea surface temperatures (SSTs) of 2 °C (Forster et al., 2007). Oxygen-isotope ratios of bulk chalk from southern England increased by nearly 1‰, interpreted about 4 °C decreasing (Jenkyns et al., 2004). Similarly, oxygen isotope records from the Pacific Exmouth Plateau located at mid-latitudes in the Southern Hemisphere show a sharp positive excursion, which can be interpreted to reflect decreasing temperatures (Clarke and Jenkyns, 1999). However, the cooling trends observed on the continents and in the oceans are not consistent (see Fig. 6). According to the palynological data presented here, cooling on the continents was more rapid than in the oceans. However, the climatic cooling during the Santonian–Campanian was a global process. The Earth then rapidly entered temperate greenhouse conditions in the Late Cretaceous.

6. Conclusions

We reconstructed the vegetation history and climatic changes of the Songliao Basin from 89.1 to 83.5 Ma. The observed changes can be divided into two phases. A first phase is characterized by a constant increase in the relative abundance of thermophilic taxa, which reach peak abundance at 85.7 Ma. This is indicative of a warming climate in East Asia and is not consistent with global climate patterns. The second stage began at around 85.7 Ma. During this stage, the palynoflora was characterised by declining percentages of thermophilic taxa and with an increase in the relative abundance of drought-adapted taxa, suggesting a rapid cooling process and aridification. Climatic cooling did not occur on the continent, but various marine palaeoclimate proxies indicate subsequent cooling. The transition from the first to second phase during the studied time periods (89.1 to 83.5 Ma) may have served as a prelude to the climate shift from hot/super greenhouse to a temperate greenhouse.

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