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Climate characteristics of the eastern Mongolian Plateau, China during the early Early Cretaceous (145–132 Ma): Palynological evidence from the Tongbomiao Formation in Well Hong-6, Hailar Basin

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A B S T R A C T

This study identified two palynological assemblages, namely *Bayanhuasporites-Cycadopites-Protoconiferus* and *Cicatricosisporites-Cedripites-Perinopollenites,* in the Tongbomiao Formation in the Hongqi Sag in the Hailar Basin, Inner Mongolia, China for the first time. The former is distributed in the lower part of the Tongbomiao Formation and is characterized by abundant gymnosperm pollen and diverse fern spores. Among them, the gymnosperm pollen is dominated by Paleoconifer (4.98%–31.62%) and *Cycadopite* (8.55%–25.23%) pollen grains and also includes other pollen grains such as *Classopollis*, *Parcisporites*, *Erlianpollis*, *Callialasporites*, and *Jiaohepollis*. The fern spores in the former palynological assemblage contain *Bayanhuasporite* (0–8.96%), *Granulatisporites* (0.93%–6.97%), and some important Cretaceous genera, such as *Cicatricosisporites*, *Concavissimisporites*, *Densoisporites*, *Hsuisporites*, *Foraminisporis,* and *Leptolepidites*. The *Cicatricosisporites-Cedripites-Perinopollenites* palynological assemblage is distributed in the upper part of the Tongbomiao Formation. Gymnosperm (77.30%), Pinaceae (31.9%), and *Paleoconiferus* (19.02%) pollen predominate this palynological assemblage, and *Quadraeculina*, *Erlianpollis,* and *Jiaohepollis* pollen are also common in this assemblage. The fern spores in this palynological assemblage include abundant *Cicatricosisporites* (4.29%). Besides, *Concavissimisporites*, *Aequitriradites,* and *Leptolepidites* are also common in this palynological assemblage. No angiosperm pollen has been found in both palynological assemblages. The identification of both palynological assemblages provides important evidence for the biostratigraphic correlation between the Hailar Basin and its adjacent areas. It also enables the reconstructions of the Berriasian-Valanginian (Early Cretaceous) vegetation and the paleoclimate on the eastern Mongolian Plateau during 141–132 Ma. The vegetation reconstructed on the palynological data of the represented by Hailar Basin in eastern Mongolian Plateau (141.6–141.4 Ma), form conifer forest or conifer broad-leaved mixed forest to conifer forest with shrubs and grassland, the climate belongs to warm temperate and warm-subtropicalt, the highest temperature is estimated to reach 35–38℃. Form 132.3 Ma, the vegetation type is conifer forest, and its paleoclimate is sub-humid warm temperate, the highest temperature is estimated to reach 24–29℃.

1. Introduction

The Hailar Basin, which lies in the southwestern part of Hulunbuir League, the Inner Mongolia Autonomous Region, China, is a fault basin, and its sedimentary cap rock has a maximum thickness of more than 6000 m. The Hongqi Sag is a second-order negative tectonic unit located in the northern part of the Beier Sag, covering an area of 840 km^2. Well Hong-6 was drilled in the Ganggangtu Subsag in the southern part of the Hongqi Sag (Fig. 1). The Hongqi Sag consists of the Middle-Upper Jurassic Tamulangou Formation, the Lower Cretaceous Tongbomiao and Nantun formations of the Xing'anling Group, the Lower Cretaceous Damoguaihe and Yimin formations of the Jalainur Group, the Upper Cretaceous Qingyuangang Formation of the Beierhu Group, the Upper Neogene Huzhashan Formation, and the Quaternary from bottom to top.

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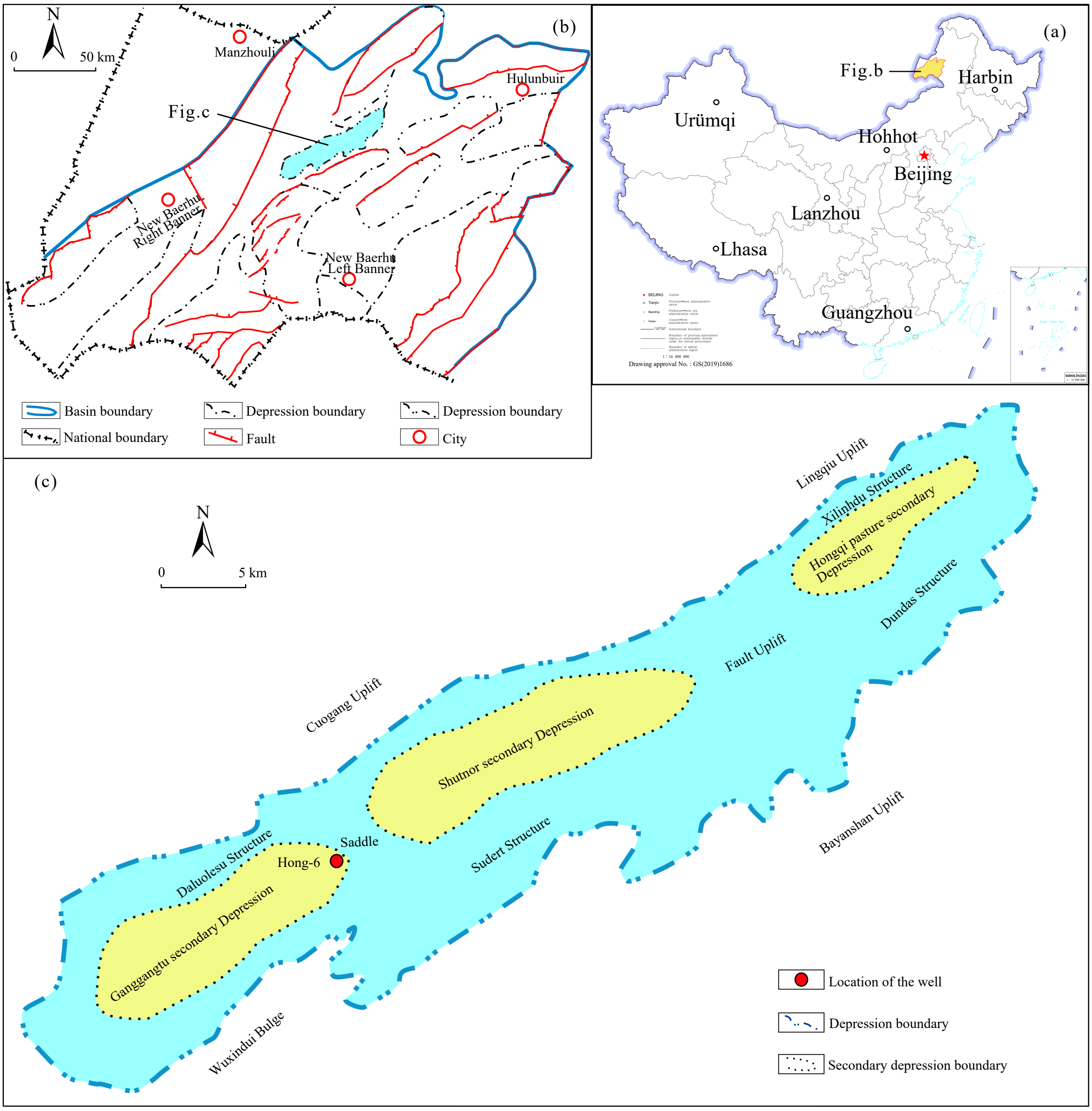

Fig. 1. Geological map of the study area. a–Location of the Hailar Basin; b–location of the Hongqi Sag; c–division of tectonic units in the Hongqi Sag.

Since 1865, both Chinese and foreign geologists have carried out geological surveys in the Hailar Basin (Ye DQ et al., 1995). Since the 1980s, studies on fossil spores and pollen in the Hailar Basin have been successively reported. Palynological researchers Pu RG and Wu HZ (1985a) studied the outcrops in the Yimin and Chenqi coal mines in the eastern Hailar Basin and the Zhalai Nuur Coal Mine in the northwestern Hailar Basin. Wan CB and Zhang Y (1990), Wan CB (1992, 1997, 2000, 2005) from the Exploration and Development Research Institute of the Daqing Oilfield Company Limited studied the Cretaceous-Tertiary palynological assemblages and the Cretaceous algal assemblages in the Hailar Basin. Meng QA et al. (2003) reported palynological assemblages in the Damoguaihe Formation in the Beier Sag. Huang QH et al. (2004, 2006) reported Early Cretaceous palynological assemblages in the Orxon and Beier sags. Li CB et al. (2007) studied the palynological assemblages in the Yiming Formation revealed in Well Haican-6 in the Orxon Sag. Shao HJ et al. (2007) studied the Early Cretaceous palynological assemblages revealed in Well Bei-16 in the southern Beier Sag. Wang LY et al. (2008, 2014) studied the Cretaceous paleovegetation and climate characteristics in the Tamutsag and Hailar basins. Liu JY (2011) and Xue YF (2017) studied the palynological assemblages and paleoclimates in the Damoguaihe and Yimin formations in the Chaganore Sag in the western Hailar Basin. Chen JH and Shang YK (2015) studied the palynological assemblages in the Damoguaihe Formation in the Jalainur Coal Mine in the northwestern Hailar Basin. Han G et al. (2018, 2019) studied the palynological assemblages in the Damoguaihe Formation revealed in wells Bei-27 and Bei-32 in the Beier Sag. Wan CB et al. (2000) and Huang QH et al.

(2004) reported the characteristics of palynological assemblages in the Tongbomiao Formation in the Beier Sag. However, no study has been reported on the palynological assemblages (e.g., palynological percentages), palaeovegetation, and palaeoclimate in the Tongbomiao Formation in the Hailar Basin until now.

In this study, 12 black mudstone samples were systematically collected from the Tongbomiao Formation for palynological analysis. Six of them are rich in pollen and spores and enabled the establishment of two palynological assemblages. This achievement contributes to the determination of the palynological assemblage sequence of the Tongbomiao Formation in the central part of the Hongqi Sag and the quantitative analysis of the types of paleovegetation, paleotemperature zones, and paleohumidity. This study of the palynological assemblages in the Hongqi Sag is significant for conducting stratigraphic correlation between the whole Hongqi Sag and its adjacent sags and for reconstructing paleovegetation and climate.

2. Stratigraphy

Well Hong-6, which was drilled in the southwestern part of the Hulunbuir League, is about 28.5 km northwest of New Baolige Sumu, New Baerhu Left Banner, Inner Mongolia, China. It lies in the Ganggangtu structure group in the Hongqi Sag.

In 1990, the horizon at a depth of 2061.0–2936.0 m in Well Haican-3 was designated as the downhole stratotype section of the Tongbomiao Formation (K_1t) named by the Association of Stratigraphy. This section was subdivided into three members, but no description was provided. Moreover, they also divided this formation into three members and provided a detailed description. The Tongbomiao Formation mined by the Daqing Oilfield Limited has been enlarged in terms of lithology. Specifically, it includes tuffs, tuffaceous rocks, and rapidly accumulated coarse rocks such as conglomerates and sandy conglomerates, as stated in its original definition. Besides, it also includes deep-water lacustrine sedimentary rocks with a certain thickness (e.g., dark mudstones, sandy mudstones, and even oil shale) and acidic volcanic rocks (e.g., rhyolites and dacites).

The Tongbomiao Formation in Well Hong-6 is 963 m thick (Fig. 2). It is composed of unevenly thick interbeds consisting of gray glutenites and black grayish mudstones and lies between seismic reflection surfaces T_3 and T_4. This formation is in parallel unconformable contact with the underlying Tamulangou Formation and conformable contact with the overlying Nantun Formation. The representative well horizons covering the Tongbomiao Formation are as follows (Fig. 2).

Overlying strata: The Nantun Formation

- - - - - - parallel unconformity- - - - - -

The Tongbomiao Formation (well depth 1579.0–2542.0 m) 963.0 m

17. Gray glutenite interbedded with black gray mudstone, argillaceous siltstone. 22.0 m

16. Black gray argillaceous siltstone with gray glutenite, gray siltstone is intercalated with black gray mudstone. 23. 0 m

15. Gray glutenite interbedded with black gray mudstone and silty mudstone. 20.0 m

14. Black gray mudstone with gray silty mudstone and glutenite, gray glutenite is intercalated with black gray silty mudstone. 31.0 m

13. Black gray mudstone interbedded with argillaceous siltstone, gray siltstone, silty mudstone, glutenite. 67.0 m

12. Gray glutenite interbedded with black gray mudstone, silty mudstone. 54.5 m

11. Gray glutenite interbedded with black gray mudstone. 41.5 m

10. Interbedded gray glutenite, black gray silty mudstone, mudstone. 57.5 m

9. Pied glutenite interbedded with black gray silty mudstone, a layer of coal in the upper. 79.0 m

8. Gray glutenite interbedded with black gray mudstone, a layer of coal. 92.0 m

7. Gray glutenite interbedded with black gray mudstone. 62.5 m

6. Black gray silty mudstone interbedded with gray glutenite, black gray mudstone, gray mudstone conglomerate. 106.0 m

5. Gray glutenite interbedded with amaranth mudstone. 56.0 m

4. Green gray silty mudstone interbedded with gray glutenite, black gray mudstone. 41.5 m

3. Gray glutenite interbedded with black gray mudstone, silty mudstone. 110.5 m

2. Gray glutenite interbedded with packsand, green-gray siltstone, and black gray mudstone. 74.5 m

1. Gray glutenite interbedded with black gray mudstone, black gray silty mudstone. 24.5 m

- - - - - - parallel unconformity - - - - - -

Underlying strata：The Tamulangou Formation

3. Characteristics of palynological assemblages

The palynological percentages of the Tongbomiao Formation in Well Hong-6 in the Hongqi Sag are shown in Table 1. Two palynological assemblages have been identified in this formation, namely *Bayanhuasporites-Cycadopites-Protoconiferus* (BCP) in the lower part Fig.3 and *Cicatricosisporites-Cedripites-Perinopollenites* (CCP) in the upper part Fig.4. The identification of both palynological assemblages provides some important biomarkers for the stratigraphic division in the southern Hongqi Sag and its adjacent areas and is an important basis for paleoclimate analysis.

3.1. Palynological assemblage BCP

3.1.1. Taxonomic composition and percentages of palynological assemblage BCP

a. Ferns spore	13.08%–57.71%
Stereisporites	0–1.49%
Undulatisporites	0–1.71%
Baculatisporites	0–0.50%
Deltoidospora	0–1.03%
Granulatisporites	0.93%–6.97%

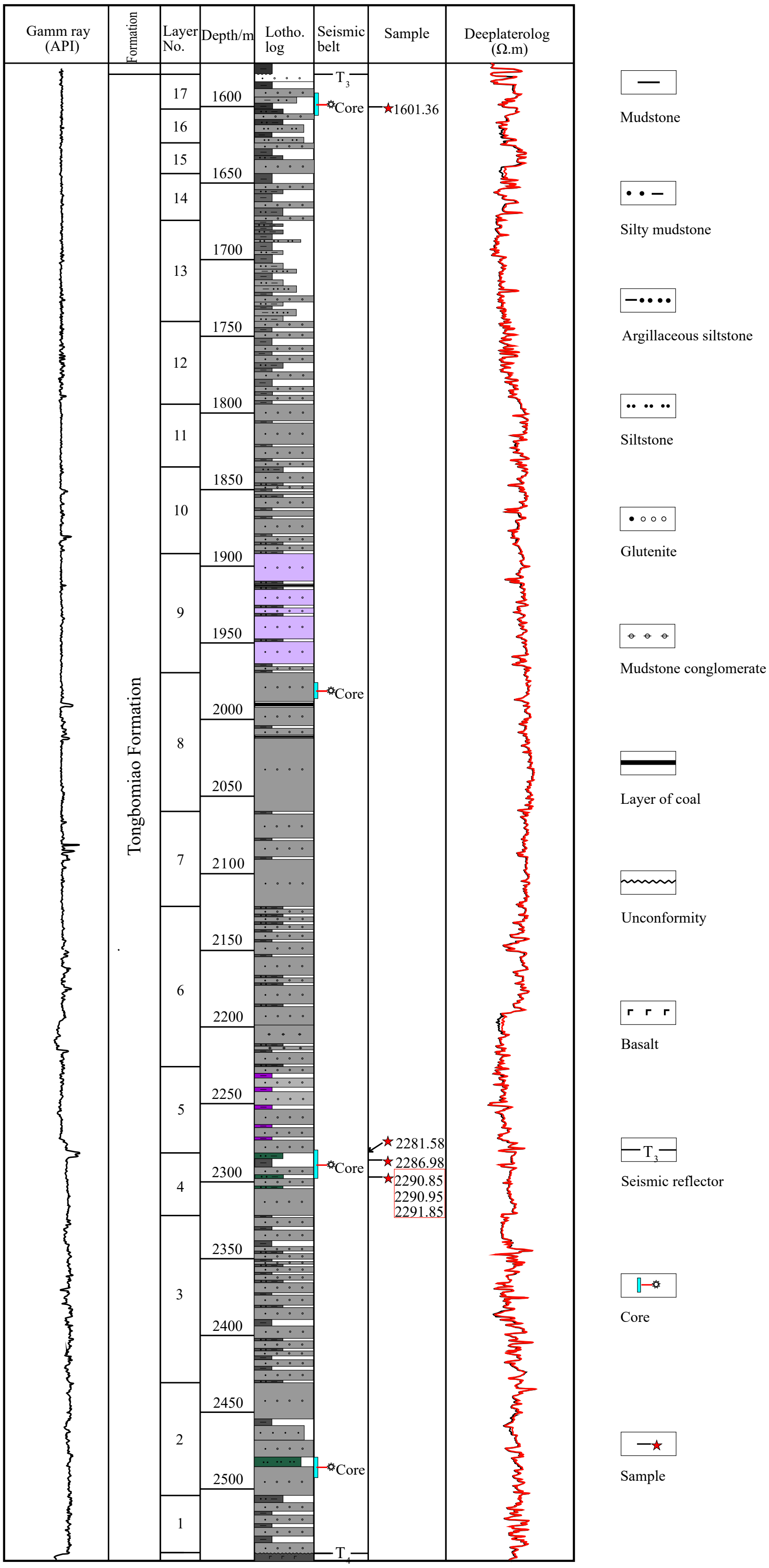

Fig. 2. Locations and stratigraphic horizons of palynological samples in Well Hong–6 in the Hongqi Sag of the Hailar Basin.

Dictyotriletes	0–1.87%	*Apiculatisporites*	0–2.94%
Leiotriletes	1.71%–5.47%	*Cyathidites*	0–0.50%
Lophotriletes	0–2.94%	*Concavissimisporites*	0–0.50%
Acanthotriletes	0–1.00%	*Osmundacidites*	0–6.97%

Table 1. The palynomorph counted in the percentage of the Tongbomiao Formation in the Well Hong-6.

Sample No.	No.7w	No.4z	No.8w	No.9w	No.23w	No.24w
Depth/m	1601.36 m	2281.58 m	2286.98 m	2290.85 m	2290.95 m	2291.85 m
Ferns spore	22.7	29.9	57.71	22.06	18.8	13.08
Stereisporites	0.61		1.49			
Undulatisporites			1		1.71	
Gleicheniidites	0.61					
Baculatisporites			0.50			
Deltoidospora	1.23	1.03				
Granulatisporites	1.84	6.19	6.97	1.47	4.27	0.93
Dictyotriletes						1.87
Leiotriletes	1.84	3.09	5.47	2.94	1.71	1.87
Lophotriletes	0.61		0.50	2.94		
Acanthotriletes			1		0.85	
Apiculatisporites				2.94		
Cyathidites	1.84		0.50			
Concavissimisporites	0.61		0.50			
Osmundacidites	2.45	1.03	6.97		3.42	
Cicatricosisporites	4.29		0.50	1.47	1.71	
Lycopodiumsporites		3.09	3.98			
Laevigatosporites			1			
Aequitriradites	1.23					
Cibotiumspora			1	4.41	0.85	0.93
Biretisporites	1.23		2.49	1.47	1.71	0.93
Punctatisporites	1.23	1.03				
Cingulatisporites			0.50	1.47		
Cyclogranisporites		1.03				0.93
Densoisporites		2.06	4.48	1.47	1.71	1.87
Hsuisporites		3.09	1.99			
Foraminisporis		1.03	1			
Abdiverrucospora	1.23		0.50			
Echinatisporis			1.49			
Leptolepidites	1.23		1			
Helioporites		1.03	0.50			
Coptospora	0.61					
Toroisporis		1.03	0.50			0.93
Bayanhuasporites		2.06	8.96			
Todisporites			0.50	1.47		
Tripartina			0.50			
Annulispora?		3.09	1.99		0.85	1.87
Calamospora						0.93
b.Gymnosperms pollen	77.30	70.10	42.29	77.94	81.2	86.92
Pinaceae		1.03		1.47		
Podocarpidites	1.23	4.12	1	7.35	3.42	4.67
Dacrycarpites			0.50			
Pinuspollenites	6.75	2.06	1.49	1.47	1.71	4.67
Abietineaepollenites	9.20	6.19	4.98	17.65	8.55	6.54
Classopollis	1.84	2.06	1.49	7.35		1.87
Abiespollenites	3.68					
Piceaepollenites	1.84	1.03			0.85	
Cedripites	10.43	5.15	0.50		1.71	2.80
Piceites	1.23	1.03	3.98	1.47	5.98	1.87
Protopinus		1.03	0.50			0.93
Paleoconifer		2.06			12.82	3.74
Paleoconiferus	6.75	5.15	1.49	1.47	6.84	1.87
Protoconiferus	8.59	4.12	1	1.47	10.26	3.74
Protopodocarpus				1.47		
Protopicea						0.93

Table 1. (*Continued*)

Sample No.	No.7w	No.4z	No.8w	No.9w	No.23w	No.24w
Pseudowalchia	0.61	1.03			0.85	0.93
Pseudopicea	1.23	2.06	1.49	1.47		1.87
Pseudopinus	0.61	1.03	0.50		0.85	1.87
Psophosphaera	3.68		0.50			0.93
Araucariacites	2.45	1.03				0.93
Inaperturopllenites	2.45	2.06	1		2.56	4.67
Chasmatosporites		1.03	0.50		2.56	0.93
Caytonipollenites	0.61		0.50			
Perinopollenites	6.13		2.49		0.85	
Cycadopites	1.23	9.28	9.95	22.06	8.55	25.23
Ginkgoretectina		7.22	4.98	8.82	0.85	6.54
Jiaohepollis	3.68	1.03	1	1.47		
Callialasporites		1.03	0.50			
Erlianpollis	1.23	4.12	0.50	1.47	3.42	0.93
Parcisporites			1			
Monosulcites		2.06			4.27	5.61
Concentrisporites	0.61					
Cerebropollenites	0.61		0.50			
Quadraeculina	0.61					
Eucommiidites				1.47		
Spheripollenties		2.06			3.42	2.80
Spinivelipollis					0.85	
Counted grains in each sample	163	97	201	68	117	107

Cicatricosisporites	0–1.71%
Lycopodiumsporites	0–3.98%
Laevigatosporites	0–1.00%
Cibotiumspora	0–4.41%
Biretisporites	0–2.49%
Punctatisporites	0–1.03%
Cingulatisporites	0–1.47%
Cyclogranisporites	0–1.03%
Densoisporites	1.47%–4.48%
Hsuisporites	0–3.09%
Foraminisporis	0–1.03%
Abdiverrucospora	0–0.50%
Echinatisporis	0–1.49%
Leptolepidites	0–1.00%
Helioporites	0–1.03%
Toroisporis	0–1.03%
Bayanhuasporites	0–8.96%
Todisporites	0–1.47%
Tripartina	0–0.50%
Annulispora	0–3.09%
Calamospora	0–0.93%
b. Gymnosperms pollen	42.29%–86.92%
Pinaceae	0–1.47%
Podocarpidites	1.00%–7.35%
Dacrycarpites	0–0.50%
Pinuspollenites	1.47%–4.67%
Abietineaepollenites	4.98%–17.65%
Classopollis	0–7.35%
Piceites	1.47%–5.98%
Piceaepollenites	0–1.03%
Cedripites	0–5.15%
Protopinus	0–1.03%
Paleoconifer	0–12.82%
Paleoconiferus	1.47%–6.84%
Protoconiferus	1.00%–10.26%
Protopodocarpus	0–1.47%
Protopicea	0–0.93%
Pseudowalchia	0–1.03%
Pseudopicea	0–2.06%
Pseudopinus	0–1.87%
Psophosphaera	0–0.93%
Araucariacites	0–1.03%
Inaperturopllenites	0–4.67%
Chasmatosporites	0–2.56%
Caytonipollenites	0–0.50%
Perinopollenites	0–2.49%
Cycadopites	8.55%–25.23%
Ginkgoretectina	0.85%–8.82%
Jiaohepollis	0–1.47%
Callialasporites	0–1.03%
Erlianpollis	0.50%–4.12%
Parcisporites	0–1.00%
Monosulcites	0–5.61%
Cerebropollenites	0–0.50%
Eucommiidites	0–1.47%
Spheripollenties	0–3.42%
Spinivelipollis	0–0.85%

3.1.2. Characteristics of palynological assemblage BCP

(i) The BCP palynological assemblage is dominated by gymnosperm pollen (42.29%–86.92%) while including rare fern spore (13.08%–57.71%) and no angiosperm pollen.

(ii) The gymnosperm pollen in the BCP palynological assemblage is dominated by Paleoconifer pollen (4.98%–31.62%), followed by *Cycadopites* (8.55%–25.23%) and *Abietineaepollenites* (4.98%–17.65%). Eight Paleoconifer genera are visible in the gymnosperm pollen. Among these Paleoconifer genera, *Protoconiferus* has the highest content (1.00%–10.26%), followed by *Ginkgoretectina* (0.85%–8.82%), *Podocarpidites* (1.00%–7.35%), and *Classopollis* (0–7.35%). Other important types of gymnosperm pollen grains include *Eucommiidites, Parcisporites, Erlianpollis, Callialasporites, Chasmatosporites,* and *Jiaohepollis*.

(iii) Among the fern spores in the BCP palynological assemblage, *Bayanhuasporite* (0–8.96%) is most abundant, followed by *Granulatisporites* (0.93%–6.97%) and *Osmundacidites* (0–6.97%). Besides, other important types of fern spores include *Concavissimisporites, Cicatricosisporites, Cingulatisporites, Densoisporites, Hsuisporites, Foraminisporis, Leptolepidites,* and *Helioporites*.

3.2. Palynological assemblage CCP

3.2.1. Taxonomic composition and percentages of palynological assemblage CCP

a. Ferns spore	22.70%
Stereisporites	0.61%
Gleicheniidites	0.61%
Deltoidospora	1.23%
Granulatisporites	1.84%
Leiotriletes	1.84%
Lophotriletes	0.61%
Cyathidites	1.84%
Concavissimisporites	0.61%
Osmundacidites	2.45%
Cicatricosisporites	4.29%
Aequitriradites	1.23%
Biretisporites	1.23%
Punctatisporites	1.23%
Abdiverrucospora	1.23%
Leptolepidites	1.23%
Coptospora	0.61%
b. Gymnosperms pollen	77.30%
Podocarpidites	1.23%
Pinuspollenites	6.75%
Abietineaepollenites	9.20%
Classopollis	1.84%
Piceites	1.23%
Abiespollenites	3.68%
Piceaepollenites	1.84%
Cedripites	10.43%
Paleoconiferus	6.75%
Protoconiferus	8.59%
Pseudowalchia	0.61%
Pseudopicea	1.23%
Pseudopinus	0.61%
Psophosphaera	3.68%
Araucariacites	2.45%
Inaperturopllenites	2.45%
Caytonipollenites	0.61%
Perinopollenites	6.13%
Cycadopites	1.23%
Jiaohepollis	3.68%
Erlianpollis	1.23%
Concentrisporites	0.61%
Cerebropollenites	0.61%
Quadraeculina	0.61%

3.2.2. Characteristics of palynological assemblage CCP

(i) The CCP palynological assemblage is dominated by gymnosperm pollen (77.30%), while including rare pores (22.70%) and no angiosperm pollen.

(ii) The gymnosperm pollen in the CCP palynological assemblage is dominated by Pinaceae (31.9%), followed by Paleoconifer (19.02%). The most abundant three types of the Pinaceae pollen are *Cedripites* (10.43%), *Abietineaepollenites* (9.20%), and *Pinuspollenites* (6.75%). The Protoconifer pollen is dominated by *Protoconiferus* (8.59%), followed by *Perinopollenites* (6.13%), *Cycadopites* (1.23%), and *Classopollis* (1.84%). Other important types of gymnosperm pollen grains include *Quadraeculina, Erlianpollis,* and *Jiaohepollis*.

(iii) Among the fern spores in the CCP palynological assemblage, *Cicatricosisporites* (4.29%) is abundant, and other important types of fern spores include *Concavissimisporites, Aequitriradites,* and *Leptolepidites*.

4. Geological era of the Tongbomiao Formation in Well Hong-6

Palynomorphs were found in the samples from the Tongbomiao Formation in Well Hong-6. These sporomorphs can be divided into two palynological assemblages according to their vertical distributions, namely the BCP and CCP, as described above. Except for the important pollen or spore types such as *Bayanhuasporites*, *Cicatricosisporites*, *Cycadopites,* and *Ginkgoretectina,* whose contents differ greatly between two palynological assemblages, the fern spores, and gymnosperms pollen have similar contents in the two palynological assemblages. Therefore, the geological ages of the two palynological assemblages of the Tongbomiao Formation were discussed together.

The palynological assemblages of the Tongbomiao Formation in Well Hong-6 are characterized by abundant gymnosperm pollen (42.26%–86.92%) and diverse fern spores (13.08%–57.71%), including 36 genera of gymnosperm pollen and 37 genera of fern spores, such as *Stereisporites*, *Undulatisporites*, *Gleicheniidites*, *Baculatisporites*, *Deltoidospora*, *Granulatisporites*, *Dictyotriletes*, *Leiotriletes*, *Lophotriletes*, *Acanthotriletes*, *Apiculatisporites*, *Cyathidites*, *Osmundacidites*, *Lycopodiumsporites*, *Laevigatosporites*, *Cibotiumspora*, *Biretisporites*, *Punctatisporites*, *Cyclogranisporites*, *Cingulatisporites*, *Abdiverrucospora*, *Echinatisporis*, *Coptospora*, *Toroisporis*, *Todisporites*, *Tripartina*, *Calamospora*, *Podocarpidites*, *Dacrycarpites*,

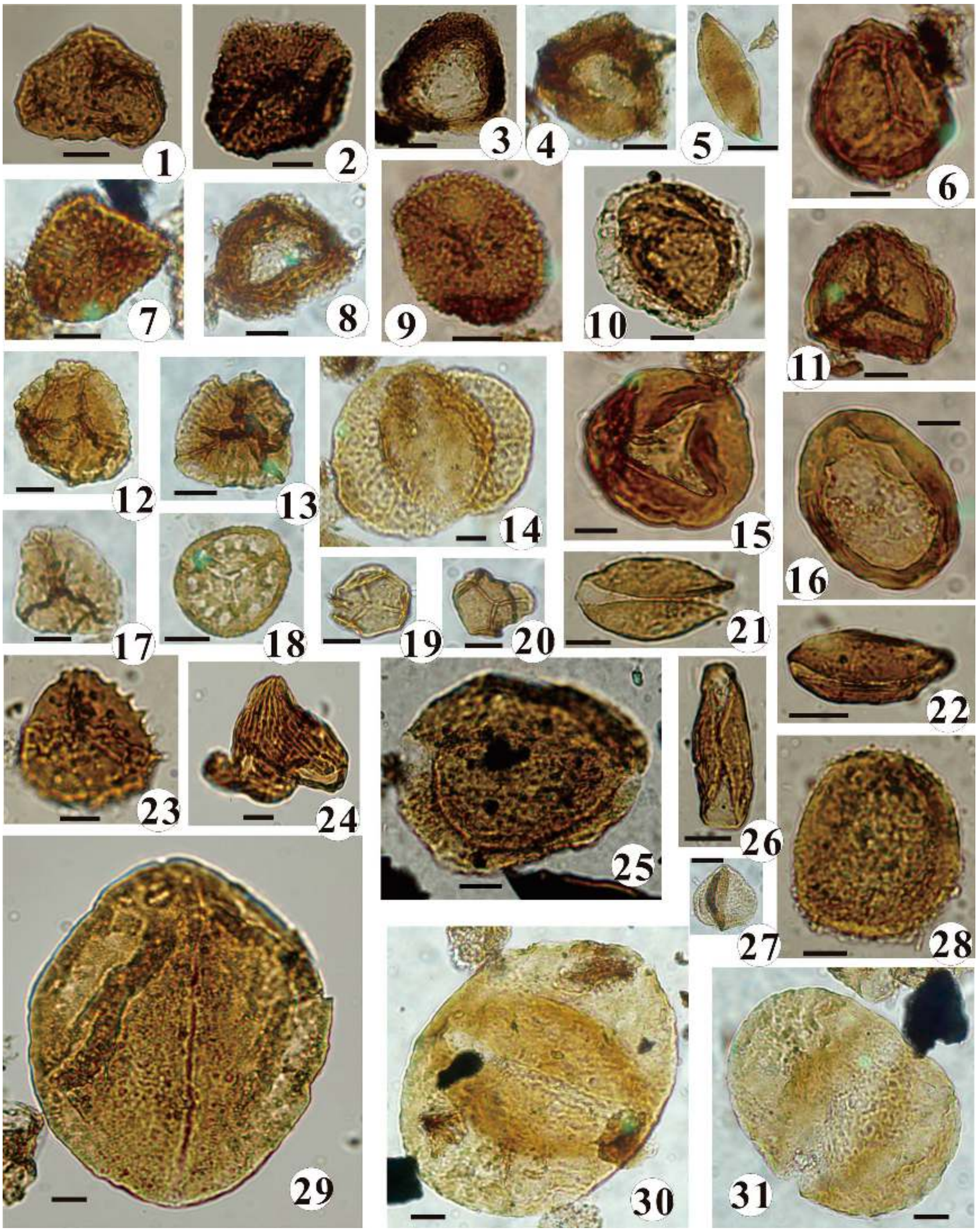

Fig. 3. Typical palynological fossils in the lower of Tongbomiao Formation. 1 –2,7 – *Foraminisporis*; 3 –4, 8 – *Bayanhuasporites*; 5–*Ginkgoretectina*; 6, 11–*Densoisporites*; 9–*Baculatisporites*; 10–*Perinopollenites*; 12, 13–*Hsuisporites*; 14–*Podocarpidites*; 15–*Toroisporis*; 16–*Chasmatosporites*; 17–*Undulatisporites*; 18–? *Annulispora*; 19, 20–*Cibotiumspora*; 21, 22, 26–*Cycadopites*; 23–*Acanthotriletes*; 24–*Cicatricosisporites*; 25–*Pseudowalchia*; 27–*Granulatisporites*; 28–*Spinivelipollis*; 29–*Protoconiferus*; 30–*Piceites*; 31–*Pseudopinus* (Bar=10 μm).

Pinuspollenites, *Abietineaepollenites*, *Abiespollenites*, *Piceaepollenites*, *Cedripites*, *Psophosphaera*, *Araucariacites*, *Inaperturopllenites*, *Caytonipollenites*, *Perinopollenites*, *Cycadopites*,*Ginkgoretectina*,*Monosulcites*,*Concentrisporites*, *Cerebropollenites*, *Spheripollenties*, and *Spinivelipollis*. Many of these genera are common in Jurassic and Early Cretaceous strata (Fig.3; Fig.4).

Cicatricosisporites is widely recognized as an important marker of the beginning of the Cretaceous. This genus appeared in North America, Australia, and China during the Late Berriasian. It increased in quantity from the Valanginian and bloomed during the Barremian (Li WB, 1984; Zhao CB, 1985; Zhang WP, 1989; Shang YK, 1997; Gao RQ et al., 1999; Li JG et al., 2016; Han G et al., 2018). *Cicatricosisporites* is sporadically distributed in the BCP palynological assemblage in the Tongbomiao Formation, with a percentage of 0–1.23%. By contrast, its percentage increases to 4.29% in the CCP palynological assemblage. Although it appears in increasing quantities from bottom to top in the Tongbomiao Formation, it is far from luxuriance. Therefore,

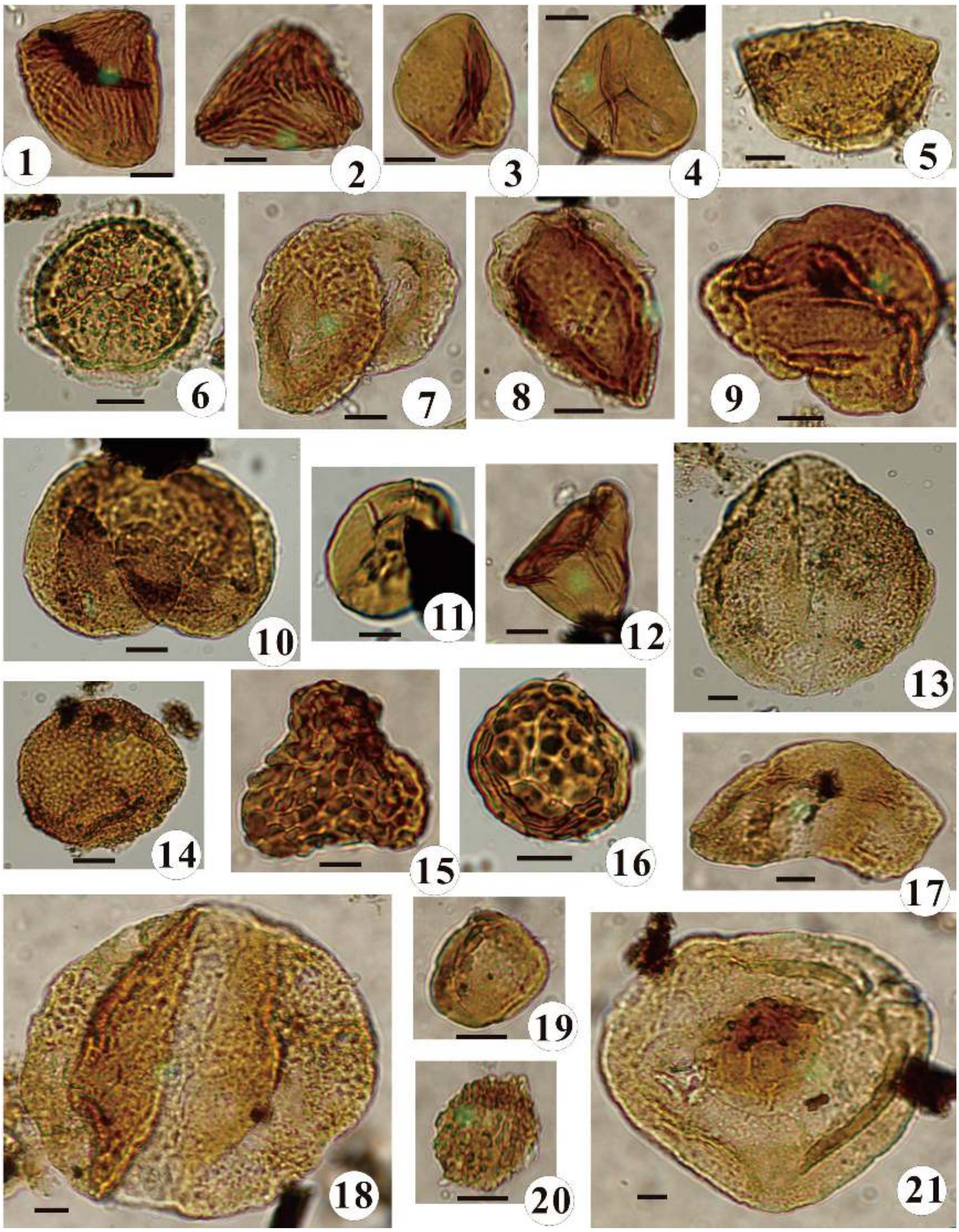

Fig. 4. Typical palynological fossils in the upper of Tongbomiao Formation. 1, 2–*Cicatricosisporites*; 3–*Leiotriletes*; 4–*Deltoidospora*; 5–*Erlianpollis*; 6−*Aequitriradites*; 7−*Quadraeculina*; 8−*Perinopollenites*; 9−*Jiaohepollis*; 10−*Cedripites*; 11−*Inaperturopllenites*; 12−*Biretisporites*; 13−*Protoconiferus*; 14−*Osmundacidites*; 15−*Concavissimisporites*; 16−*Leptolepidites*; 17−*Pinuspollenites*; 18−*Pseudopicea*; 19−*Classopollis*; 20–*Cerebropollenites*; 21–*Paleoconiferus* (Bar=10 μm).

Cicatricosisporites in the Tongbomiao Formation is thought to have formed during the Early Cretaceous.

Aequitriradites emerged during the Berriasian, bloomed during the Valanginian-Albian, declined during the Cenomanian, and went extinct during the Maastrichtian. In China, this genus occurs in the upper part of the Shahezi Formation in the Songliao Basin (Zheng YJ et al., 2019). *Aequitriradites* is rarely found in the CCP palynological assemblage of the Tongbomiao Formation, with a percentage of 0–1.71%, and thus is thought to be from the Early Cretaceous.

Leptolepidites is common in the Chengzihe and Mulin formations in eastern Heilongjiang Province (Pu RG et al., 1982), the Damoguaihe Formation in the Da Hinggan Mountains (Pu RG and Wu HZ, 1985a), the Saihantala Formation in the Erlian Basin (Song ZC et al., 1986a), and the Baihedong and Sanshui formations in the Sanshui Basin (Song ZC et al., 1986b). Therefore, *Leptolepidites* in the

Tongbomiao Formation is from the Early Cretaceous.

Hsuisporites, which is a new genus established by Zhang CB (1965), has been widely discovered in the Lower Cretaceous strata in northeast China and Inner Mongolia. Although this genus contributes less than 2% of fern spores in the Damoguaihe Formation in the Chaganore Sag, it occurs frequently in this formation (Xue YF and Wang LY, 2010).

Concavissimisporites first emerged during the Jurassic, diversified during the Berriasian and Valanginian, and bloomed during the Valanginian (Pu RG and Wu HZ, 1985a). This genus is sporadically distributed in the CCP palynological assemblage of the Tongbomiao Formation, with a percentage of 0–0.61%. Therefore, its geological era is the Early Cretaceous.

Foraminisporites first emerged during the Early Cretaceous and bloomed during the Barremian-Albian in the Far Eastern and Siberia in Russia, England, Canada, USA, and Australia (Pu RG and Wu HZ, 1982). It has also been found in the Chengzihe and Muling formations in Heilongjiang, China (Pu RG and Wu HZ, 1982; Li WB, 1992). *F. asymmetricus* first appeared during the Berriasian, bloomed during the Barremian-Albian, and survived during the Cenomanian in Australia. In addition, it has also been found in the coal-bearing horizons of the Yingcheng Formation in Jiutai County, Jilin Province, China (Wang SY, 1989). *F. wonthaggiensis* first appeared during the Berriasian and survived during the Turonian in Australia, Canada, France, and Siberia. It has also been found in the Damoguaihe and Yimin formations in Xinbaerhu Right Banner, (Han G et al., 2018), the Guyang Formation in Guyang County, and the Saihantala and Hadatu formations in the Erlian Basin (Song ZC et al., 1986a) in Inner Mongolia; the Sunjiawan and Yixian formations, Fuxin District, Liaoning Province; and the Qingshan Formation in Huangxian County, Shandong Province (Song ZC et al., 2000). All of these formations are Early Cretaceous strata.

Densoisporites appeared across the world during the Triassic –Late Cretaceous and bloomed during the Early Cretaceous. *Helioporites* is mainly distributed in Mesozoic strata in the Northern Hemisphere. In China, it has been recorded in the Damoguaihe and Jiufengshan formations in eastern Inner Mongolia and in the Shihebei Formation in western Heilongjiang (Pu RG and Wu HZ, 1982; Song ZC et al., 2000).

Bayanhuasporites is widely distributed in the Early Cretaceous strata in Inner Mongolia and northeast China (Pu RG and Wu HZ, 1985b; Yu JX, 1989). This genus frequently occurs in the Early Cretaceous Bayanhua Group in the Sonid Right and Abaga banners, Inner Mongolia, and the Early Cretaceous strata in the Hailar Basin. The percentage of *Bayanhuasporites* in the lower part of the Tongbomiao Formation in Well Hong-6 is high (8.96%), indicating that *Bayanhuasporites* in the Tongbomiao Formation is from the Early Cretaceous.

Classopollis generally emerged during the Late Triassic –Tertiary and bloomed during the Late Jurassic and Early Cretaceous. However, its evolutionary process differed in various places (Gao RQ et al., 1999). The percentage of *Classopollis* is generally low (0–5%) in the Damoguaihe Formation in the Da Hinggan Mountains region (Meng QA et al., 2003) and is also low in the Damoguaihe Formation in the Chaganore Sag (Xue YF and Wang LY, 2010). Moreover, it is low in the lower part (0–7.35%) and is high in the upper part (1.84%) in the Tongbomiao Formation in Well Hong-6.

Paleoconifer pollen was widely distributed in northern China and Siberia during the Late Jurassic and Early Cretaceous. As shown by a large amount of data, Paleoconifer pollen emerged during the Pre-Jurassic, bloomed during the Late Jurassic and Early Cretaceous, and went extinct during the Aptian and Albian in the Late Cretaceous (Gao RQ et al., 1999; Wan CB, 2006). The percentage of Paleoconifer is 6.4%–12.3% in the Baiyinkundi Formation of Zhaowuda League, Inner Mongolia, 2.1%–3.2% in the Bayanhua Group in the Erlian Basin, 13.4%–15.3% in the Yixian Formation in western Liaoning Province, and 20%–30% in the Huoshilin-Yingcheng formations in the Songliao Basin. All these strata date back to the Early Cretaceous. In this study, nine genera of Paleoconifer have been discovered in the palynological assemblages in the Tongbomiao Formation in Well Hong-6, namely *Piceites*, *Protopinus*, *Paleoconiferus*, *Protoconiferus*, *Protopodocarpus*, *Protopicea*, *Pseudowalchia*, *Pseudopicea*, and *Pseudopinus*. The high percentages of Paleoconifer pollen (7.35%–37.6%) in the Tongbomiao Formation indicate that Paleoconifer pollen in this formation is from the Early Cretaceous.

Jiaohepollis first appeared in the Wulin and Naizishan (Changcai) formations in the Jiaohe Basin in Jilin Province, with a geological era of the Berriasian-Barremian in the Early Cretaceous. This genus has been discovered in the Jurassic and Cretaceous strata in Gansu (Jiang DX and Yang HQ, 1978), Ningxia (Liu ZS, 1983), Inner Mongolia (Guo ZY, 1982; Song ZC et al., 1986b; Deng CL, 1987), Hebei (Wang XZ and Yu YQ, 1987), western Liaoning (Pu RG and Wu HZ, 1982, 1985b; Liu ZS and Guan BL, 1987), eastern Jilin (Li WB, 1984; Shang YK and Wang SY, 1991a, b), southeastern Hubei (Zhang ZL, 1984), and Hainan (Dong BL, 1991) provinces. However, it is more common in Early Cretaceous strata. This genus, together with *Cicatricosisporites,* is distributed in the Tongbomiao, Nantun, Damoguihe, and Yimin formations in the Hailar Basin. Therefore, *Jiaohepollis* is one of the most important indicators of the Early Cretaceous.

Erlianpollis is widely distributed in north and northeast China. In Well Hong-6 in the Hailar Basin, this genus is visible in the lower part of the Early Cretaceous Tongbomiao Formation but is absent in the underlying Middle –Late Jurassic Tamulangou Formation (Zhao CB, 1987).

Parcisporites is distributed in the Mesozoic and Cenozoic strata in the Northern Hemisphere. The *Parcisporites* in the Tongbomiao Formation in Well Hong-6 is quite different from the *P. scabratus* in the Upper Permian Xilin Formation in Mangniuhai, Tuquan County, Inner Mongolia, which has a wide air pocket with two almost closed ends (Zhang DJ et al., 2020). It is also different from *P. cacheutensis* occurring in the Triassic Heshanggou Formation in Xingxian County, Shanxi Province, which has an air pocket that tilts toward the distal pole. It is also different from *P. rarus* occurring in the Triassic Liujiagou Formation in Jiaocheng County, Shanxi Province, whose air pocket is slightly larger than the genus itself. By contrast, it is the same as *P. plicatus* appearing in the Cretaceous Bayan Group in Siziwang Banner, Inner Mongolia (Song ZC et al., 2000) and *P.* spp appearing in the Valanginian Dabeigou Formation in the Luanping Basin, northern Hebei Province (Lin MQ and Li JG, 2021). Therefore, the *Parcisporites* in the Tongbomiao Formation in Well Hong-6 is also one important indicator of the Early Cretaceous.

Quadraeculina is widely distributed in the Jurassic strata in China. Most especially, it bloomed during the Middle-Late Jurassic, its quantity gradually decreased during the Late Jurassic, but it still survived during the Early Cretaceous. The percentages of *Quadraeculina* are 0–2.67% in the Late Jurassic Tamulangou Formation in Well Hong-6 (Wan CB et al., 2020) and decrease to 0–0.61% in the Tongbomiao Formation in this well. The sporadic distribution of the genus *Quadraeculina* in the Tongbomiao Formation indicates that this genus is from the Early Cretaceous. *Callialasporites* and *Chasmatosporites* have characteristics similar to those of *Quadraeculina*. In other words, they are also widely distributed in Jurassic strata but are rare in Cretaceous strata. Therefore, *Callialasporites* and *Chasmatosporites* are from the early stage of the Early Cretaceous.

Professor Zhao CB (1987) described the genetic relationship and stratigraphic distribution of *Eucommiidites* in detail. He believes that *Eucommiidites* belongs to gymnosperm pollen rather than angiosperm pollen and that it existed from the Triassic to the Cretaceous and were common during the Jurassic and the Early Cretaceous.

In sum, the palynological assemblages in the Tongbomiao Formation in Well Hong-6 have abundant diverse Paleoconifer but rare Lygodiaceae of few types. These results indicate that the geological era of these palynological assemblages is the Early Cretaceous.

5. Stratigraphic parameters of the paleoclimate in the Tongbomiao Formation in Well Hong-6, Hongqi Sag

The Cretaceous climate might be supper greenhouse (Barron EJ and Washington WM, 1982). The Arctic region might be ice-free and forests were found even there (Spicer RA and Herman AB, 2010). These may be caused by the Cretaceous atmospheric CO_2 concentration, which was much higher than the present level and led to global warming, sea-level rise, oceanic anoxic events, and the deposition of black shales (Lloyd CR, 1982; Haq BU et al., 1987; Royer DL, 2006; Wang YD et al., 2014; Sun YW et al., 2016). However, the warm climate and anoxic environment during the Cretaceous were episodic (Föllmi KB, 2012), which enabled the life on the Earth to survive and evolve into many new paleontological taxa, such as flowering plants (Sun G et al., 1998).

Palynological and paleobotanic data are commonly used to qualitatively reconstruct Early Cretaceous vegetations and climates (Wan CB, 2006; Liu JY, 2011; Wang LY et al., 2014; Cheng JH and Shang YK, 2015; Xue YF, 2017; Han G et al., 2018). However, no previous study has involved the Tongbomiao Formation in the Hongqi Sag. In this study, cores were drilled from multiple parts of the Tamulangou and Tongbomiao formations in Well Hong-6. As a result, palynological fossils were only obtained from 12 mudstone samples in the Tongbomiao Formation. Six of the 12 samples contain rich palynological fossils, providing important information on the paleovegetation and paleoclimate evolution in the southern part of the Hongqi Sag. This study reconstructed the vegetation (Table 2), humidity (Table 3), and climatic zones of both the lower part and the top of the Tongbomiao Formation in their sedimentary periods based on the ecological characteristics of the parent plants indicated by palynology (Fig.5).

5.1. Vegetation reconstruction

During about 141.6–141.4 Ma, the parent plants of sporomorphs in the lower part of the Tongbomiao Formation (depth: 2281.58–2291.85 m) can be divided into coniferous forests, evergreen broad-leaved forests, deciduous broad-leaved forests, shrubs, and herbs. The coniferous forests

Table 2. Vegetation reconstruction for the Tongbomiao Formation of Well Hong-6 in the Hongqi Sag.

Strata	Depth/m	The palynological percentage of each vegetation type/%						Vegetation
		Conifers	Ever-gree broad-leaf	Deciduous broad-leaf	Shrubs	Herbaceous	Undetermined	
The top of Tongbomiao Formation	1601.36 m	75.46	3.07	0	4.91	10.43	6.13	Conifer forest
The lower of Tongbomiao Formation	2281.58 m	50.52	10.31	9.28	0	14.43	15.46	Conifer forest with grassland
	2286.98 m	26.87	11.94	4.98	1.49	32.34	22.39	Grassland with conifer forest
	2290.85 m	45.59	26.47	8.82	1.47	8.82	8.82	Conifers with broad-leaf
	2290.95 m	64.1	11.97	5.13	1.71	11.11	5.98	Conifer forest
	2291.85 m	48.6	27.1	12.15	0.93	5.61	5.61	Conifers with broad-leaf

Table 3. Humidity reconstruction for the Tongbomiao Formation of Well Hong-6 in the Hongqi Sag.

Strata	Depth/m	The palynological percentage of each humidity type/%						Humidity-aridity zone
		Xerphyte	Mesophyte	Hygrophyte	Pelophyte	Aquatic	Undertermined	
The top of Tongbomiao Formation	1601.36	3.07	46.01	33.74	2.45	0.61	14.11	Semi-humid
The lower of Tongbomiao Formation	2281.58	3.09	39.18	34.02	1.03	0	22.68	Semi-humid
	2286.98	2.99	29.85	26.37	8.46	1.99	30.35	Semi-humid
	2290.85	7.35	51.47	26.47	1.47	1.47	11.76	Semi-humid
	2290.95	0	29.06	52.99	3.42	0	14.53	Humid
	2291.85	1.87	57.94	29.91	0	0	10.28	Semi-humid

predominated (26.8%–64.1%), followed by broad-leaved forests (10.31%–27.1%). The herb plants mainly contributed 5.61%–14.43% of parent plants in this part, which sharply increased to 32.34% at a depth of 2286.98 m. Deciduous broad-leaved trees (4.98%–12.15%) and shrubs (0–1.71%) accounted for lower percentages. The above results indicate that the vegetation evolved from coniferous forests or mixed coniferous and broad-leaved forests (also referred to as the mixed forests) into coniferous forests and grasses from bottom to top. At a depth of 2286.98 m, the percentages of coniferous spores decreased from 45.59%–64.1% to 26.87%, while those of sporomorphs of herb plants increased from 5.61%–14.43% to 32.34%, indicating an obvious change in vegetation type from coniferous forests to typical herbs. However, the distances from the sample at a depth of 2286.98 m to the sample above at a depth of 2281.58 m and the sample below at a depth of 2290.85 m were only 5.4 m and 3.87 m respectively, indicating that a short cataclysmic event occurred. This event, likely a forest fire (Bowman DMJS et al., 2009; Brown SAE et al., 2012), caused the vegetation to have changed from mixed forests into grasses and coniferous forests from bottom to top and then quickly recovered to the landscape of coniferous forests and grasses dominated by coniferous forests.

At about 132.3 Ma, coniferous trees (75.46%) predominated the parent plants of sporomorphs at the top of the Tongbomiao Formation (depth: 1601.36 m) in Well Hong-6. Parent plants encountered in this formation also included rare evergreen broad-leaved forests (3.07%), shrubs (4.91%), and herbaceous plants (10.43%). Deciduous broad-leaved forests are absent in this formation. Therefore, the vegetation in this period reconstructed based on palynological data was coniferous forests.

5.2. Paleohumidity reconstruction

During about 141.6–141.4 Ma, the parent plants of sporomorphs in the lower part of the Tongbomiao Formation (depth: 2281.58–2291.85 m) can be divided into five ecologic types, namely xerophytic, mesophytic, hygrophytic, pelophytic, and aquatic plants. The mesophytic (29.06%– 57.94%) and hygrophytic plants (26.37%–52.99%) predominated, followed by the xerophytic (0–7.35%), pelophytic (0–8.46%), and aquatic plants. These findings show that a sub-humid climate was dominant at that time. At a depth of 2290.95 m, however, the percentage of hygrophytic plants (52.99%) was much higher than that of mesophytic plants (29.06%), and the sporomorphs of xerophytic and aquatic plants were entirely absent. These findings demonstrate that the lower part of the Tongbomiao Formation was semi-humid or humid at that time.

At about 132.3 Ma, mesophytic (46.01%) and hygrophytic (33.74%) plants predominated the parent plants of sporomorphs at the top of the Tongbomiao Formation (depth: 1601.36 m) in Well Hong-6. Parent plants encountered in this part also included rare xerophytic (3.07%), pelophytic (2.45%), and aquatic (0.61%) plants. Therefore, the top of the Tongbomiao Formation was semi-humid at that time.

5.3. Paleoclimate reconstruction

During about 141.6–141.4 Ma, the parent plants of the sporomorphs in the lower part of the Tongbomiao Formation (depth: 2281.58–2291.85 m) can be divided into five types (Table 2). The palynological percentages of plants that could grow in both the temperate and the tropical-temperate zones (40.8%–62.39%) were much higher than those of plants that could grow in both the tropical-subtropic and the tropical-temperate zones (21.36%–45.59%). Therefore, it can be inferred that the lower part of the Tongbomiao Formation had a warm temperate climate at that time (Table 4). At a depth of 2290.85 m, the palynological percentage of the plants that could grow in both the temperate and the tropical-temperate zones (35.29%) was much lower than that of the plants that could grow in both the tropical-subtropical and the tropical-temperate zones (45.59%). Therefore, it can be inferred that the horizon at this depth had a subtropical climate. In the sedimentary period of horizons at a depth of 2281.58–2286.98 m, the palynological percentages of plants that could grow in both the temperate and the tropical-temperate zones (39.17%–42.29%) were slightly higher than those of plants that could grow in both the tropical-subtropical and the tropical-temperate zones (35.04%–41.80%). These findings indicate that the horizons at this depth had a warm subtropical climate at this time. Therefore, the lower part of the Tongbomiao Formation experienced a temperate-subtropical temperature - subtropical climate from bottom to top.

At about 132.3 Ma, at the top of the Tongbomiao Formation of Well Hong-6 (depth: 1601.36 m), the palynological percentage of the parent plants that could grow in both the temperate and the tropical-temperate zones (60.74%) was much higher than that of plants that could grow in both the tropical-subtropical and the tropical-temperate zones (39.88%). This indicates that the top of the formation had a warm temperate climate at that time.

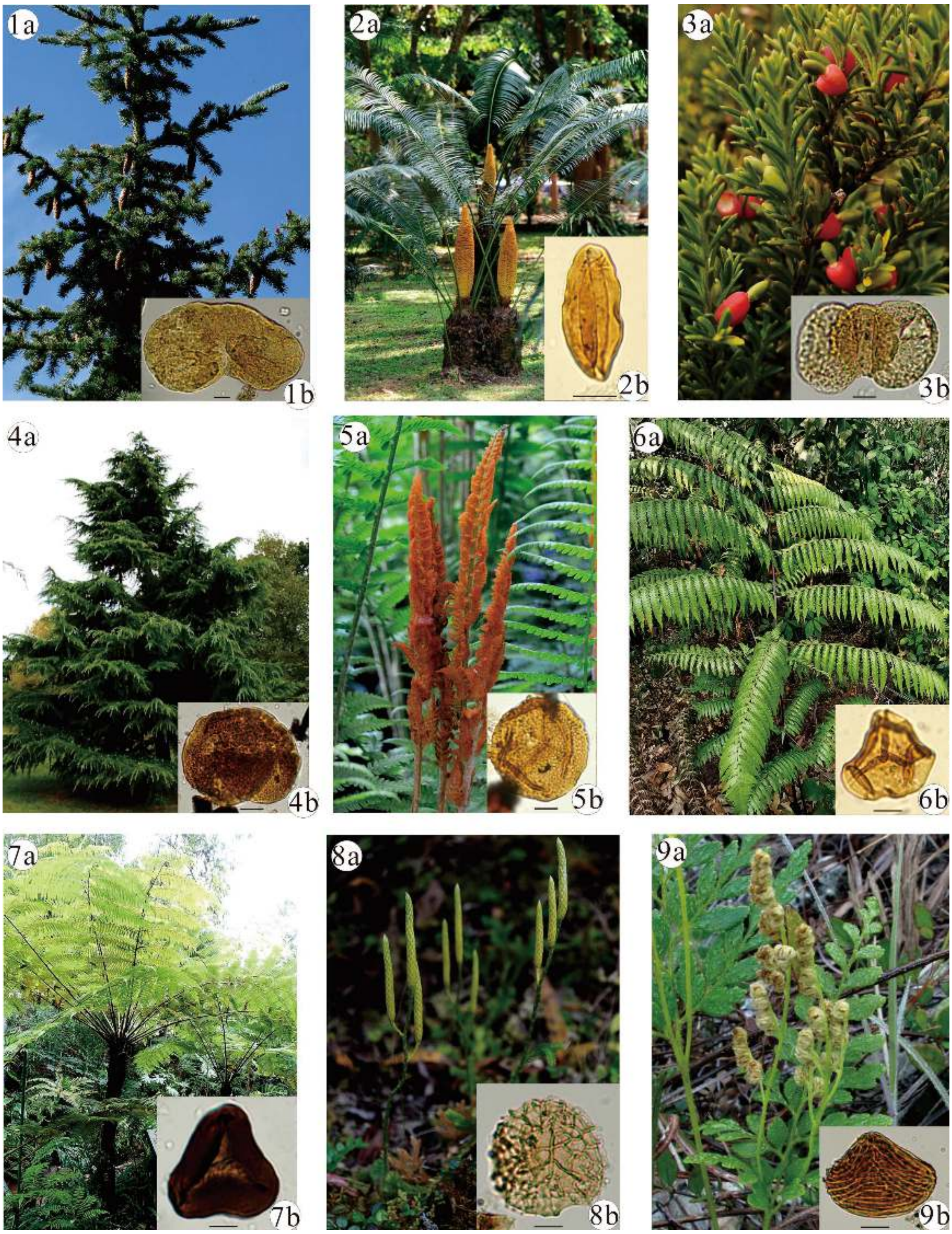

Fig. 5. Some palynological fossils of Tongbomiao Fm and their present mather plants. 1–4–Gymnosperms and their fossil reproductive organs; 5–9–Pteridophytes and their fossil reproductive organs. 1–*Picea* and its fossil reproductive organs: 1a–*Picea*, 1b–*Piceaepollenites*; 2–*Cycas* and its fossil reproductive organs: 2a–*Cycas*, 2b–*Cycadopites*; 3–*Podocarpus* and its fossil reproductive organs: 3a–*Podocarpus*, 3b–*Podocarpidites*; 4–*Cedrus* and its fossil reproductive organs: 4a–*Cedrus*, 4b–*Cedripites*; 5–*Osmunda* and its fossil reproductive organs: 5a–*Osmunda*, 5b–*Osmundacidites*; 6–*Cibotium* and its fossil reproductive organs: 6a–*Cibotium*, 6b–*Cibotiumspora*; 7–*Alsophila* and its fossil reproductive organs: 7a–*Alsophila*, 7b.*Cyathidites*; 8–*Lycopodium* and its fossil reproductive organs: 8a–*Lycopodium*, 8b–*Lycopodiumsporites*; 9–*Anemia* and its fossil reproductive organs: 9a–*Anemia*, 9b–*Cicatricosisporites*. Pictures of present mother plants quote to www.cubg.cn. (Bar=10 μm).

In sum, the lower part of Tongbomiao Formation in Well Hong-6 (depth: 2281.58–2291.85 m) had vegetation that was changed from coniferous forests or mixed forests into coniferous forests and grasses from bottom to top and a semi-humid to warm-subtropical climate during its sedimentary period, the highest temperature is estimated to reach 35–38℃ (Gao RQ et al., 1999). The top of the Tongbomiao Formation (depth: 1601.36 m) had the vegetation of coniferous forests and a semi-humid warm temperate climate during its sedimentary period, the highest temperature is estimated to reach 24–29℃ (Gao RQ et al., 1999).

Samples were obtained from only the top (depth:

Table 4. Climatic zone reconstruction for the Tongbomiao Formation of Well Hong-6 in the Hongqi Sag.

Strata	Depth/m	The palynological percentage of each climatic zone type/%						Climatic zone
		Tropic	Tropic-Subtropic	Subtropic	Tropic-temperate	Temperate	Undertermined	
The top of Tongbomiao Formation	1601.36 m	11.66	5.52	10.43	23.93	36.81	11.66	Warm temperate
The lower of Tongbomiao Formation	2281.58	15.46	14.43	5.15	15.46	23.71	25.77	Warm-subtropical
	2286.98	16.42	12.44	0.50	28.86	13.43	28.36	Warm-subtropical
	2290.85	35.29	19.12	0	26.47	8.82	10.29	Subtropic
	2290.95	16.24	2.56	1.71	17.09	45.30	17.09	Warm temperate
	2291.85	31.78	12.15	2.8	14.95	25.23	13.08	Warm temperate

1594.76–1604.98 m) and lower part (depth: 2281.38–2297.20 m) of the Tongbomiao Formation in Well Hong-6. Therefore, the palynological data obtained only reflect the characteristics of palynological fossils in these two parts. Whether these data can represent the paleovegetation and paleoclimate characteristics of the whole Tongbomiao Formation is yet to be confirmed using data from more horizons of the Tongbomiao Formation in other wells.

6. Palynological implications concerning the paleoclimate in northeastern Inner Mongolia during 145–132 Ma

The Hailar Basin is located at 115°30'–120°00'E and 46°00'–49°40'N, with an elevation of 540–60 m. It has an average annual precipitation of 239 mm, average annual evaporation of 1521 mm, and an average annual temperature of −0.3–2.0°C. It has a temperate steppe climate and lies in a transition zone between a temperate and a cold temperate climate. In terms of soil, this basin belongs to the mid-temperate dark chestnut soil subzone in the Hulunbuir-Duolun hilly plains. However, the climate in the Hailar Basin during the Early Cretaceous might be quite different from its present climate. Based on the palynological data obtained from the Hongqi and Beiersags in the Hailar Basin, the paleoclimate characteristics of the Hailar Basin were explored in this study. Moreover, these characteristics were compared with the paleoclimate characteristics of the Erlian and Kailu basins in Inner Mongolia and the Songliao Basin in northeast China.

6.1. Climate in the Hailar Basin during 145–132 Ma based on palynological data

Paleovegetation is widely used in paleogeographic and paleoclimatic reconstructions. Although some quantitative paleoclimatic reconstruction has been conducted for the Beier Sag in the Hailar Basin, this study of the Hongqi Sag is significant for understanding the paleoclimate on the eastern Mongolian Plateau during 145–132 Ma. Previous studies show that the vegetation in the Beier Sag (corresponding to the deposition of the Tongbomiao Formation) changed from mixed forests and grasses to grassland and shrubs from bottom to top. This finding indicates that the Beier Sag had warm temperate and southern subtropical climates (Wan CB, 2006). The results of this study show that the vegetation in the Hongqi Sag, located 120 km northeast of the Beier Sag, changed from mixed forests to grasses and shrubs and, finally, recovered to coniferous forests. Overall, the paleovegetation in the two sags closely resembled each other, indicating the basic characteristics of a warm temperate climate and mixed forests in the Hailar Basin. Meanwhile, the climate likely became cool during 145–132 Ma, as evidenced by the fact that the number of evergreen broad-leaved trees decreased and the coniferous trees became more common. As for humidity, the vegetation in the Beier Sag was a little wetter than that in the Hongqi Sag, which might have a semi-humid climate. The above findings reflect the basic characteristics of the paleoclimate and paleovegetation evolvement on the eastern Mongolian Plateau during the Early Cretaceous.

6.2. Climate in other basins on the eastern Mongolian Plateau and adjacent areas during 145–132 Ma based on Palynological data

The Erlian Basin is located southwest of the Hailar Basin. In this basin, the Early Berriasian Arshan Formation and the lower part of the Late Berriasian-Valanginian Saihantala Formation have the same geological era as the Tongbomiao Formation in the Hailar Basin. Two palynological assemblages, namely *Klukisporites-Biretisporites-Quadraeculina* and *Concavissimisporites-Aequitriradites-Cycadopites*, have been identified in the Arshan Formation and the lower part of the Saihantala Formation, respectively. The paleovegetation in the Erlian Basin was mainly composed of *Cycadaceae*, *Ginkgoaceae*, *Podocarpidites*, and Pinaceae, indicating a humid southern subtropical climate (Song ZC et al., 1986a). The records in the Hailar Basin show that the paleovegetation remained roughly unchanged and the paleoclimate might become warmer (±4–6°C) and more humid in the Erlian Basin during 145–132 Ma (Gao RQ et al., 1999).

The Yixian Formation in western Liaoning Province and the Tongbomiao Formation in the Hailaer Basin has the same geological era and both are the Early Cretaceous strata of 145–132 Ma. As shown by the analysis of the palynological assemblage characteristics, the Yixian Formation in Jinjiagou Village, Yixian county, western Liaoning Province had warm humid paleoclimate (Li WB, 2010). In contrast, the Yixian Formation in Piaoxian County, northwest Liaoning Province had a humid subtropical climate (Ding QH et al., 2004).

Compared with the paleoclimate characteristics of eastern Inner Mongolia represented by the Hailar Basin during 145 –132 Ma, western Liaoning Province and eastern Inner Mongolia belonged to the same temperature zone.

The Kailu Basin is located in the southwestern Songliao Basin. The palynological assemblage *Cyathidites–Pinuspollenites–Protoconiferus* discovered in the Yixian Formation in the Kailu Basin reveals the following palaeovegetation. Tall pine trees, together with Podocarpaceae, Taxodiaceae, and rare Cycadaceae, Araucariaceae, and Cheirolepidiaceae grew in mountains around ancient lake basins. Meanwhile, fern plants including Cyatheaceae, Osmundaceae, and Schizaeaceae grew in the understory and lakeshore areas. Therefore, the Kailu Basin had a warm humid climate (Xu ZL, et al., 2021), which is roughly consistent with the paleoclimates in eastern Inner Mongolia and western Liaoning.

The Huoshiling Formation in the Songliao Basin has the same geological age (145– 132 Ma) as the Tongbomiao Formation in eastern Inner Mongolia. Palynological assemblages *Inaperturopllenites-Classopollis-Cicatricosisporites and Piceites-Piceaepollennites-Cyathidites* have been discovered from the Huoshiling Formation in the southern and northern Songliao Basin, respectively. According to the analysis of the former palynological assemblage, the paleovegetation in the southern Songliao Basin was dominated by true ferns and coniferous trees, followed by rare lycophytes and mosses; the climate in the southern Songliao Basin was humid - sub-humid, with occasional seasonal drought events having occurred (Song LB, et al., 2021). As inferred from the latter palynological assemblage, the northern Songliao Basin had coniferous forests and a humid climate in its sedimentary period. Therefore, the northern and southern parts of the Songliao Basin had different vegetation at 145 –132 Ma. Meanwhile, the northern part was more humid and colder than the southern part, with a temperature difference of 8–12°C. During 145–132 Ma, the paleoclimate characteristics of the Songliao Basin were significantly different from those of eastern Inner Mongolia. Specifically, the vegetation in eastern Inner Mongolia was close to that in the northern Songliao Basin but different from that in the southern Songliao Basin, and the humidity in eastern Inner Mongolia was close to that in the southern Songliao Basin but different from that in the northern Songliao Basin. In terms of paleoclimate, the temperature in eastern Inner Mongolia was slightly lower than that in the southern Songliao Basin but higher than that in the northern Songliao Basin.

In sum, eastern Inner Mongolia represented by the Hailar Basin had coniferous and forest-grass vegetation and a humid - sub-humid subtropical climate at 145–132Ma. Compared with the central part of Inner Mongolia represented by the Erlian Basin, eastern Inner Mongolia was more humid and had a higher temperature. The paleovegetation in eastern Inner Mongolia was close to that in the northern Songliao Basin and different from that in the southern Songliao Basin. By contrast, the paleohumidity in eastern Inner Mongolia was close to that in the southern Songliao Basin and was different from that in the northern Songliao Basin. In terms of paleoclimate, the temperature in eastern Inner Mongolia was slightly lower than that in the southern Songliao Basin and higher than that in the northern Songliao Basin.

6.3. Palynological implications of paleoclimate evolvement on the eastern Mongolian Plateau during 145–132 Ma

In the lower part of the Tongbomiao Formation in Well Hong-6, the palynological percentages of coniferous trees sharply decrease from 45.59%–64.1% to 26.87% but the palynological percentages of herbaceous plants sharply increase from 5.61%–14.43% to 32.34% from bottom to top (Table 2). The vegetation type greatly changed, showing the characteristics of typical vegetation consisting of grasses-coniferous forests. The distances from the sample at a depth of 2286.98 m to the sample above at a depth of 2281.58 m and the sample below at a depth of 2290.85 m were only 5.4 m and 3.87 m, respectively, indicating that a short cataclysmic event occurred. This event, likely a forest fire, caused the vegetation to have changed from mixed forests into shrubs and coniferous forests from bottom to top and then quickly recovered to the vegetation of coniferous forest and herbaceous plants dominated by coniferous forests.

The Tongbomiao Formation in Well Hong-6 was deposited during 145–132.6 Ma. That is, it took about 12.4 Ma for the Tongbomiao Formation with a thickness of 963 m to be deposited, and thus it took about 12.88 ka for every 1 m of the formation to be deposited. Based on this, it can be estimated that it took 49.83 ka for the vegetation to have changed from mixed forests at a depth of 2290.85 m into grasses at a depth of 2286.98 m and it took about 69.53 ka for grasses at a depth of 2286.98 m to transform into coniferous forests at a depth of 2281.58 m. In other words, it took about 119.36 ka from the destruction to the recovery of the vegetation. The time that nature requires to repair itself is only a moment on the geological time scale but is extremely long on the human time scale. As Table 2 shows, the paleovegetation in the Tongbomiao Formation in Well Hong-6 should have experienced the alternation between mixed forests and coniferous forests for 12.4 Ma if it was not disturbed by external factors such as forest fires.

As estimated according to the law of change in glacial-interglacial cycles, the Earth 's climate will enter the next glacial period soon (Wang SW, 2011; Kukla G J et al., 1972), and the current interglacial period will last for about 10–30 ka (Li XZ and Liu XD, 2020). If humans do not protect the Earth's environment and control carbon dioxide emissions, the rise in global temperature will accelerate. Furthermore, the resulting global warming will lead to an increase in the number of diseases and insect pests on the Earth and an increase in the frequency of disasters such as sea-level rise and desertification. Once anthropogenic forcing surpasses natural forcing in terms of the global climate, the natural environment will become unsuitable for human beings to survive. The anthropogenic forcing factors mainly include greenhouse gas emissions (Li XZ and Liu XD, 2020), which make the natural forcing factors unable to repair the damage to the natural environment caused by human beings. The study of the paleoclimatic changes in eastern Inner Mongolia during 145–132 Ma based on palynological data underlines the need for human beings to control global warming today.

7. Conclusions

(i) Two palynological assemblages, namely *Bayanhuasporites-Cycadopites-Protoconiferus* and *Cicatricosisporites-Cedripites-Perinopollenites,* have been identified from the Tongbomiao Formation in Well Hong-6 in the Hailar Basin, Inner Mongolia, China. The *Bayanhuasporites-Cycadopites-Protoconiferus* palynological assemblage, which is distributed in the lower part of the formation, contains abundant gymnosperm pollen (42.29% –86.92%) and less abundant diverse fern spores (13.08%–57.71%). Meanwhile, *Cycadopites* and *Bayanhuasporites* predominate this palynological assemblage. Other important genera encountered in this palynological assemblage include *Densoisporites*, *Hsuisporites*, *Foraminisporis*, *Leptolepidites*, *Classopollis*, *Parcisporites*, *Erlianpollis*, *Callialasporites,* and *Jiaohepollis*. The *Cicatricosisporites-Cedripites-Perinopollenites* palynological assemblage, which is distributed in the upper part of the Tongbomiao Formation, contains abundant gymnosperm pollen (77.30%) and fern spores (22.70%) and is characterized by the increase in *Cicatricosisporites* and the emergence of *Aequitriradites* and *Quadraeculina*.

(ii) The Tongbomiao Formation in Well Hong-6 was deposited during the Berriasian-Valanginian in the Early Cretaceous according to the palynological information that palynological assemblages in this formation contain abundant diverse *Paleoconiferus* but rare Lygodiaceae spores.

(iii) During 141.6-141.4 Ma, the vegetation reconstructed on the palynological data of the represented by Hailar Basin in eastern Mongolian Plateau form conifer forest or conifer broad-leaved mixed forest to conifer forest with shrubs and grassland, the climate belongs to warm temperate and warm-subtropicalt, the highest temperature is estimated to reach 35–38℃ (Gao RQ et al., 1999). Form 132.3 Ma, the vegetation type is conifer forest, and its paleoclimate is sub-humid warm temperate, the highest temperature is estimated to reach 24–29℃ (Gao RQ et al., 1999). Eastern Inner Mongolia is located in the same temperature zone as western Liaoning Province and the Kailu Basin. Compared with the central part of Inner Mongolia represented by the Erlian Basin, eastern Inner Mongolia was more humid and had a higher temperature. The vegetation in eastern Inner Mongolia was close to that in the northern Songliao Basin and different from that in the southern Songliao Basin. By contrast, the humidity in eastern Inner Mongolia was close to that in the southern Songliao Basin and different from that in the northern Songliao Basin. In terms of paleoclimate, the temperature in eastern Inner Mongolia was slightly lower than that in the southern Songliao Basin and higher than that in the northern Songliao Basin.

(iv) As indicated by the study of the paleoclimate changes in eastern Inner Mongolia at 145−132 Ma, once the natural environment is destroyed by sudden natural forcing factors (such as forest fires), it is possible to restore the normal environment via the action of long-term regular natural forcing. It takes only a moment for nature to repair itself on the geological time scale. However, this moment corresponds to thousands to hundreds of thousands of years on the human time scale. This understanding underlines the need for human beings to prevent the impacts caused by anthropogenic forcing factors (greenhouse gas emissions) from surpassing the impacts caused by natural forcing factors on global climate. The purpose is to avoid the occurrence that natural forcing factors cannot repair the natural environment damaged by human beings and to keep the Earth livable.

CRediT authorship contribution statement

Yan Zhang designed the research plan, collected and interpreted the data, wrote and finalized the manuscript. Yun-fei Xue verified the analytical methods, Chun-yang Bu, Ti Li, Xin Zhang and Yu-dong Jin carried out the experiment. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The author declares no conflict of interest.

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References

Barron EJ, Washington WM. 1982. Cretaceous climate: A comparison of atmospheric simulations with the geologic record. Palaeogeography, Palaeoclimatology, Palaeoecology, 40, 103−133. doi: 10.1016/0198-0254(83)90118-8.

Bowman DMJS, Balch JK, Artaxo P, Bond WJ, Carlson JM, Cochrane MA, D'Antonio CM, DeFries RS, Doyle JC, Harrison SP, Johnston FH, Keeley JE, Krawchuk MA, Kull CA, Marston JB, Moritz MA, Prentice IC, Roos CI, Scott AC, Swetnam TW, van der Werf GR, Pyne SJ. 2009. Fire in the Earth System. Science, 324, 481–484. doi: 10.1126/science.1163886.

Brown SAE, Scott AC, Glasspool IJ, Collinson ME. 2012. Cretaceous wildfires and their impact on the Earth system. Cretaceous Research, 36, 162–190. doi: 10.1016/j.cretres.2012.02.008.

Cheng JH, Shang YK. 2015. Sporopollen Assemblages and paleoclimate of early Cretaceous in Jalainur Coal-mine, Manzhouli, Inner Mongolia. Acta Palaeontologica Sinica, 54(3), 316–341 (in Chinese with English abstract). doi: 10.19800/j.cnki.aps.2015.03.003.

Deng CL. 1987. Early Cretaceous palynological assemblages in western Inner Mongolia. Proceedings of the Petroleum Stratigraphy paleontology Conference. Beijing, Geological Publishing House, 217–225.

Dong BL, Lu HJ, Pang XN, Hua RH. 1991. Sporo-pollen assemblage and its geological significance of early Cretaceous in Baisha Basin, Hainan. Acta Micropalaeontologica Sinica, 8(2), 171–181 (in Chinese with English abstract).

Ding QH, Zhang LD. 2004. Spore-pollen Flora as the indicator of Paleoclimate condition in the Yixian Fomation, western Liaoning province. Acta Micropalaeontologica Sinica, 21(3), 332–341 (in Chinese with English abstract).

Föllmi KB. 2012. Early Cretaceous life, climate and anoxia. Cretaceous Research, 35, 230–257. doi: 10.1016/j.cretres.2011.12.005.

Guo ZY. 1982. Sporopollen study of the Cretaceous Zhaganlimennuoer Formation in the Abagaqi of Xilinguolemen, Inner Mongolia, China. Earth Science-Journal of Wuhan college of Geology, 18(3), 107–120 (in Chinese with English abstract).

Gao RQ, Zhao CB, Qiao XY, Zheng YL, Yan FY, Wan CB. 1999. Palynology of Cretaceous Oil Stratum in Songliao Basin. Beijing, Geological Publishing House, 1–373.

Haq BU, Hardenbol J, Vail PR. 1987. Chronology of fluctuating sea levels since the Triassic. Science, 235, 1156–1167. doi: 10.1126/science.235.4793.1156.

Huang QH, Li CB, Kong H, Zhang M. 2004. Early Cretaceous strata and palynological assemblages in southern Hailar Basin. Acta Micropalaeontologica Sinica, 21(4), 431–438 (in Chinese with English abstract).

Huang QH, Zhao LS, Lu ZW, Dang YM, Wang LQ, Kong H. 2006. Palynological fossils of Damoguaihe Formation in Hailar Basin, Inner Mongolia and Geological age. Geological Science and Technology Information, 25(1), 19–26 (in Chinese with English abstract).

Han G, Zhang WJ, Xue YF. 2018. Early Cretaceous palynological assemblages of Well Bei-27 in the Buir Sag in the Hailar Basin. Acta Micropalaeontologica Sinica, 35(1), 74–89 (in Chinese with English abstract). doi: 10.16087/j.cnki.1000-0674.2018.01.007.

Han G, Cao Y, Zhang WJ, Wang JY, Xue YF, Bao L. 2019. Early Cretaceous palynological assemblages from Nantun Formation in the Well Bei-32 in the Buir Sag in the Haihar Basin, Inner Mongolia. The Geological Report, 38(6), 916–921 (in Chinese with English abstract).

Jiang DX, Yang HQ. 1978. Early Cretaceous palynological assemblages in Huahai Basin, Gansu Province. Journal of Lanzhou University, (2), 116–135 (in Chinese with English abstract). doi: 10.13885/j.issn.0455-2059.1978.02.011.

Kukla GJ, Matthews RK, Mitchell JM. 1972. The end of the present interglacial. Quaternary Research, 2(3), 261–269. doi: 10.1016/0033-5894(72)90046-4.

Lloyd CR. 1982. The mid-Cretaceous earth: paleogeography; ocean circulation and temperature; atmospheric circulation. The Journal of Geology, 90, 393–413. doi: 10.1086/628693.

Li CB, Wan CB, Qiao XY, Shan XL, Wang LY, Shao HJ, Chi HY, Liu TY. 2007. Sporopollen assemblages and its Stratigraphic Significance of the Yimin Formation in the Well Haican-1 in the Hailar Basin. Journal of Stratigraphy, 31(1), 23–34 (in Chinese with English abstract).

Li JG, Peng JG, Zhang QQ. 2016. Early Cretaceous sporopollen assemblages from the Gambachachala section of the Xizang, China. Acta Palaeontologica Sinica, 55(3), 346–366 (in Chinese with English abstract). doi: 10.19800/j.cnki.aps.2016.03.007.

Li WB. 1992. Early Cretaceous sporopollen assemblages from eastern Heilongjiang. Acta Palaeontologica Sinica, 31(2), 178–189 (in Chinese with English abstract). doi: 10.19800/j.cnki.Aps.1992.02.003.

Li WB. 2010. Palynological assemblage form the Zhuanchrngzi Beds of Yixian Formation in Jinjiagou, Yixian. Acta Palaeontologica Sinica, 49(1), 44–53 (in Chinese with English abstract). doi: 10.19800/j.cnki.Aps.2010.01.004.

Li WB. 1984. Palynology of Early Cretaceous of Jiaohe Basin, Jilin Province. Memoirs of Nanjing Institute of Geology and Palaeontology, Academia Sinica, 19, 67–142.

Li XZ, Liu XD. 2020. A comparative study of climate change in East Asia during the Early Holocene and 10000 years after present: Roles of natural forcing and human activities. Quaternary Sciences, 40(6), 1611–1621 (in Chinese with English abstract). doi: 10.11928/j.issn.1001-7410.2020.06.20.

Liu JY. 2011. Sporopollen assemblage and its Geological Significance of Damoguaihe Formation in Chagannuoer Sag in Hailar Basin. Petroleum Geology & Oilfield Development in Daqing, 30(3), 51–58 (in Chinese with English abstract). doi: 10.3969/J.ISSN.1000.3754.2011.03.010.

Lin MQ, Li JG. 2021. Sporopollen assemblage and its significance of Tuchengzi and Dabeigou Formation in Sanchazi section, Luanping Basin, northern Hebei province. Acta Palaeontologica Sinica, 60(2), 263–280 (in Chinese with English abstract). doi: 10.19800/j.cnki.aps.2020072.

Liu ZS. 1983. Early Cretaceous sporopollen assemblage from Liupanshan of Ningxia and their bearing on paleovegetation and paleoclimatology. Acta Palaeontologica Sinica, 22(5), 517–526 (in Chinese with English abstract). doi: 10.19800/j.cnki.aps.1983.05.005.

Liu ZS, Guan B. 1987. Early Cretaceous sporopollen assemblage from Fuxin Formation in Liaoning province bearing on paleovegetation and paleoclimatology. Series of Nanjing Institute of Geology and Palaeontology, Academia Sinica, 12, 135–190.

Meng QA, Wan CB, Qiao XY, Sun YW, Shan XL, Xu YB, Ren YG, Zhao CB. 2003. Palynologiacal assemblages from the Damoguaihe Formation in the Haihar Basin, Inner Mongolia. Journal of Stratigraphy, 27(3), 173–184 (in Chinese with English abstract).

Pu RG, Wu HZ. 1982. Sporo-Pollen from the Late Mesozoic Beds in Eastern Heilongjiang Province. Bulletin of the Shenyang Institute of Geology and Mineral Resuorces, Chinese Academy of Geological Sciences, 5, 338–456.

Pu RG, Wu HZ. 1985a. Sporopollen Assemblages and their stratigraphical significance of the Hingganling and Zhalainuoer Groups in Hingganling Region, Northeast China. Bulletin of the Shenyang Institute of Geology and Mineral Resuorces, Chinese Academy of Geological Sciences, 11, 47–113.

Pu RG, Wu HZ. 1985b. Mesozoic Sporopollen Assemblages and Their Stratigraphic Significance in Western Liaoning. Mesozoic Stratigraphy and Palaeontology of Western Liaoning, 2. Beijing, Geological Publishing House, 121–212.

Royer DL. 2006. CO2-forced climate thresholds during the Phanerozoic. Geochimica et Cosmochimica Acta, 70, 5665–5675. doi: 10.1016/j.gca.2005.11.031.

Shang YK, Wang SY. 1991a. Palynomorph Assemblages from the Yingcheng Formation, Jiutai, Jilin. Acta Micropalaeontologica Sinica, 8(1), 91–110 (in Chinese with English abstract).

Shang YK, Wang SY. 1991b. Discovery of early Cretaceous palynological fossils from Luozigou Basin, Wangqing, Jilin. Acta Micropalaeontologica Sinica, 8(4), 406–422 (in Chinese with English abstract).

Shang YK. 1997. Palynology of the angiospermous fossil-bearing bed of the Chengzihe Formation, Jixi, Heilongjiang Province. Acta Micropalaeontologica Sinica, 14(2), 161–174 (in Chinese with English abstract).

Shao HJ, Wan CB, Ren YG, Qiao XY, Jin YD, Lin YB, Wang LY. 2007. Division and correlation of oil-bearing strata of Well Bei 16 in Hailar Basin. Global Geology, 26(2), 230–239 (in Chinese with English abstract).

Song LB, Cong S, Wang CL, Zhao ZY, Wan CB. 2021. Sporopollen assemblage of Member-2 of Huoshiling Formation in Dehui Rift of Songliao Basin and its geological significances. Petroleum Geology & Oilfield Development in Daqing, https://kns.cnki.net/kcms/detail/

23.1286.TE.20211026.1627.001.html (online) (in Chinese with English abstract). doi: 10.19597/J.ISSN.1000-3754.202105053.
Song ZC, Liu GW, Li WB, Jia BL, Hua RH. 1986a. Early Cretaceous Palynological Assemblages from Eren Basin, Inner Mongolia, China. Cretaceous Ostracod and Sporo-Pollen Fossils of Eren Basin, Inner Mongolia, China. Hefei, Anhui Science and Technology Publishing House, 106–334.
Song ZC, Li MY, Zhong L. 1986b. Cretaceous and Early Tertiary Sporopollen Asemblages from the Sanshui Basin, Guangdong Province. Paleontologia Sinica, NewSeriesA(10), SciencePress,1–69.
Song ZC, Shang YK, Liu ZS, Huang P, Wang XF, Qian LJ, Du BA, Zhang DH. 2000. Mesozoic spores and pollen. In:Fossil spores and pollen of China, Ⅱ., –710.
Spicer RA, Herman AB. 2010. The Late Cretaceous environment of the Arctic: Aquantitative reassessment based on plant fossils. Palaeogeography, Palae-oclimatology, Palaeoecology 295, 423–442. doi: 10.1016/j.palaeo.2010.02.025.
Sun G, Dilcher DL, Zheng S, Zhou Z. 1998. In search of the first flower: A Jurassic angiosperm, Archaefructus, from Northeast China. Science, 282, 1692–1695. doi: 10.1126/science.282.5394.1692.
Sun YW, Li X, Zhao GW, Liu H, Zhang YL. 2016. Aptian and Albian atmospheric CO2 changes during oceanic anoxic events: Evidence from fossil Ginkgo cuticles in Jilin Province, Northeast China. Cretaceous Research 62, 130–141. doi: 10.1016/j.cretres.2015.12.007.
Wan CB, Zhang Y. 1990. Discovery and significance of dinoflagellates and acritarchs in the early Cretaceous in the Hailar Basin. Petroleum Geology & Oilfield Development in Daqing, 9(3), 1–14 (in Chinese with English abstract). doi: 10.19597/j.issn.1000-3754.1990.03.002.
Wan CB. 1992. Discovery of algal fossils in the Hailar basin and its significance. Acta Botanica Sinica, 34(2), 140–145 (in Chinese with English abstract).
Wan CB, Qiao XY, Wang RH, He CQ. 1997. Cretaceous Nonmarine Microphytoplankton from the Hongqi Depression in the Hailar Basin, NE China. Acta Micropalaeontologica Sinica, 14(4), 405–418 (in Chinese with English abstract).
Wan CB, Ren YG, Chi YL, Sun XM, Zhang MS, Sun YW, Shan XL. 2000. Palynological assemblage and stratigraphic age of Hailar Basin. Journal of Changchun University of Science and Technology, 30 (Comprehensive geology and geophysics album), 60 –65 (in Chinese with English abstract).
Wan CB, Qiao XY, Xu YB, Sun YW, Ren YG, Jin YD, Gao P, Liu TY. 2005. Sporopollen assemblages from the Cretaceous Yimin Formation of the Hailar Basin, Inner Mongolia, China. Acta Geologica Sinica, 79(4), 459–470 (in Chinese with English abstract). doi: 10.1111/j.1755-6724.2005.tb00912.x.
Wan CB. 2006. Cretaceous palynological flora of Hailar Basin. Changchun, College of Earth Sciences, Jilin University, Ph. D thesis, 1–220 (in Chinese with English abstract).
Wan CB, Xue YF, Sun YW, Hou YP, Jin YD, Zhang X, Li T. 2020. Discovery of Late Jurassic sporopollen assemblage from the Tamulangou Formation in the Hongqi Sag of the Hailar Basin, Inner Mongolia, China. Acta Geologica Sinica (English Edition), 94(5), 1718–1720. doi: 10.1111/1755-6724.14590.
Wang LY, Sun YW, Qiao XY, Xue YF, Jin YD. 2008. Early Cretaceous of Palynological paleoclimate of Hailar Basin. Petroleum Geology & Oilfield Development in Daqing, 27(5), 39–42 (in Chinese with English abstract).
Wang LY, Wan CB, Sun YW. 2014. A Sporo-pollen Assemblages from the Damoguaihe Formation in the Tamutsag Basin, Mongolia and Its Geological Implication. Acta Geologica Sinica (English Edition), 88(1), 46–61. doi: 10.1111/1755-6724.12182.
Wang SY. 1989. Sporopollen assemblage of Yingcheng Formation, Jilin Province. Journal of Stratigraphy, 13(1), 34–39. doi: 10.19839/j.cnki.Dcxzz.1989.01.004.
Wang SW. 2011. When will the earth enter the next glacial period? Advances In Climate Change Research, 7(1), 77 –78 (in Chinese). doi: 1673-1719(2011)01-0077-02.
Wang XZ, Yu YQ. 1987. Early Cretaceous Spores-Pollen Assemblages in Beijing, Tianjin and Central Hebei. In: Editorial Committee of Stratigraphy and Paleontology of Oil and Gas Bearing Areas in China (eds.), The Symposium on Stratigraphy and Paleontology of Oil and Gas Bearing Areas in China (1). Beijing, Petroleum Industry Press, 73–93.
Wang YD, Huang CM, Sun BN, Quan C, Wu JY, Lin ZC. 2014. Paleo-CO2 variation trends and the Cretaceous greenhouse climate. Earth-Science Reviews, 129, 136–147. doi: 10.1016/j.earscirev.2013.11.001.
Xu ZL, Li JG, Zhu Q, Li HL, Zeng H, Wei JL, Zhang B, Cao MQ, Hong B. 2021. Early Cretaceous spore and pollen assemblage from the Yixian Formation in the Qianjiadian Depression, Kailu Basin and its paleoclimate implications. Geology in China, https://kns.cnki.net/kcms/detail/11.1167.p.20210104.1852.004.html (online) (in Chinese with English abstract).
Xue YF, Wang LY. 2010. Palynological assemblages of Jalainur group in Chaganur Sag, Hailar Basin. Coal geology of China, 22(1), 6–14 (in Chinese with English abstract). doi: 10.3969/j.issn.1674-1803.2010.01.02.
Xue YF. 2017. Palynological assemblage and its geological significance of Yimin Formation in Chaganur Sag, Hailar Basin. Petroleum Geology & Oilfield Development in Daqing, 36(2), 52–59 (in Chinese with English abstract). doi: 10.3969/J.ISSN.1000-3754.2017.02.008.
Ye DQ, Zhao CB, Wan CB. 1995. Stratigraphic Division and Comparison of Hailar Basin. Proceedings of Exploration and Development Research in Daqing Oilfield. Beijing, Petroleum Industry Press, 84–95.
Yu JX. 1989. Early Cretaceous Sporo-pollen Assemblages in Northern Hebei and Western Liaoning Provinces. In: Stratigraphical Group Institute of Geology Chinese Academy of Sciences (eds.), Tectonic-Magmatic Evolution and Metallogeny of Eastern China, No. 2, The Palaeontology and Stratigraphy of The Jurassic and Cretaceous in Eastern China. Beijing, Geological Publishing House, 21–51.
Zhao CB. 1985. Palynological index for defining Jurassic-Cretaceous boundary. Petroleum Geology & Oilfield Development in Daqing, 4(4), 1–9 (in Chinese with English abstract). doi: 10.19597/j.issn.1000–3754.1985.04.002.
Zhao CB. 1987. Early Cretaceous sporopollen assemblage in Erlian. Beijing, Petroleum Industry Press, 1–62.
Zhang CB. 1965. Spores in the Muling Formation of Jixi, Heilongjiang Province and its significance. Memoirs of Nanjing Institute of Geology and Palaeontology, Academia Sinica, 4, 163–198.
Zhang DJ, Zhang J, Zheng YJ, Chen SW, Su F, Huang X, Zhang HH, Zhen Z. 2020. Discovery of late Permian sporopollen in well TD-2, Tuquan Basin, Xingan League, Inner Mongolia and its petroleum geological significance. Geology in China, 47(3), 798–809 (in Chinese with English abstract). doi: 10.12029/gc20200317.
Zhang WP. 1989. Jurassic sporo-pollen assemblages from some parts of eastern China. In: Stratigraphical Group Institute of Geology, Chinese Academy of Sciences (eds.), Tectonic-magmatic evolution and metallogeny of eastern China, No. 2, The palaeontology and stratigraphy of the Jurassic and Cretaceous in eastern China. Beijing, Geological Publishing House, 1–20.
Zheng YJ, Chen SW, Zhang DJ, HX. 2019. Sporopollen assemblage characteristics of upper Shahezi Formation of Early Cretaceous in Well SK-2. Geology in China, 46(5), 1245–1246 (in Chinese with English abstract). doi: 10.12029/gc20190527.
Zhang ZL. 1984. Early Cretaceous spores-pollen assemblage from Lingxiang Group in southeastern Hubei. Acta Botanica Sinica, 26(6), 653–663 (in Chinese with English abstract).