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Palynomorph assemblages and paleoclimate records from the Zhuanchengzi Bed of the Yixian Formation, western Liaoning Province, China

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We collected, processed, identified, and analyzed the spores and pollen samples from the Zhuanchengzi Bed of the Yixian Formation in the Yingwoshan area of western Liaoning. As a result, we confirm a palynomorph assemblage of *Cicatricosisporites-Protoconiferus*. The pollen was primarily from gymnosperms, dominated especially by conifer pollen. Pteridophyte spores were less common and some questionable angiosperm pollen occurred occasionally. The age of the palynomorph assemblage is dated as the late Valanginian or Hauterivian-Barremian stage, the Early Cretaceous. The study applies the concept of Palynological Vegetation based on palynological spectra and the paleoecological characteristics of palynological taxa for the first time. Palynological vegetation type, climatic zone type, and humidity type are divided quantitatively for the Zhuanchengzi Bed in the Yixian Formation of western Liaoning. We then obtained the evolutionary trends. The results showed that the overall climate was warm and humid during the deposition period of the Zhuanchengzi Bed in the Yixian Formation. Palynological vegetation types are various and include coniferous forest, deciduous broadleaf forest, evergreen broad-leaved forest, grass, and shrubs. The local temperature changed from warm to much warmer and from a semi-humid to humid climate. Palynological vegetation types are always dominated by coniferous forest. The coexistence of deciduous broad-leaved forest, evergreen broad-leaved forest, shrubs, grass, and some xerophytic plants indicates vertical zonation and seasonal climate change The vertical vegetation types and the warm humid climate may imply a large geomorphological contrast in the Yixian Formation of western Liaoning.

palynomorph assemblage, paleoclimate, vertical zonation of vegetation, Zhuanchengzi Bed, Yixian Formation

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The Yixian Formation of western Liaoning Province is well known for yielding a large number of high quality and rare Jehol Biota fossils from the lower Cretaceous. The Yixian Formation is composed of basic-intermediate-intermediate acidity rocks resulting from continental volcanic eruption. The intermittent eruptions formed six lacustrine sedimentary beds, which are, in ascending order, the Laogonggou Bed, Yenangou Bed, Zhuanchengzi Bed, Dakangbao Bed, Zhujiagou Bed, Jingangshan Bed, and the Huanghuashan Bed. Among them, the Zhuanchengzi Bed and Dakangbao Bed are the main fossil-producing layers and hence the significant targets for research.

Since the first two decades of the 20th century, many paleontologists have conducted extensive research on the Yixian Formation. The feathered dinosaurs, the bird *Confu-*

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ciusornis, and other rare fossils have been found there (Hou et al., 1995; Ji et al., 1996, 1997; Chen et al., 1998; Wang et al., 1998). Researchers have also done much work on spores and pollen fossils (Pu and Wu, 1985; Yu, 1989; Li and Liu, 1999; Ding et al., 2003a, 2003b, 2004; Wang et al., 2000; Li and Batten, 2007; Li, 2010), such as establishing sequences of spores and pollen to address age assignment problems of the Yixian Formation. Wang et al. (2000), Ding et al. (2003a, 2003b 2004), Li and Batten (2007), Li (2010), and others have also carried out detailed research on Member 2 of the Yixian Formation (equivalent to the Zhuanchengzi Bed). However, there have been few updated research reports on this topic in recent years. The currently available data appear slightly outdated, and the datasets are already insufficient for the needs of the geological work in western Liaoning.

Most early researchers dated the Zhuanchengzi Bed to the Early Cretaceous Berriasian age (Po and Wu, 1985; Yu, 1989; Li and Liu, 1999; Ding et al., 2003a, 2003b, 2004; Li, 2010). Li and Batten (2007) studied spores and pollen from the bottom of the Yixian Formation in the Sihetun area, and concluded that the palynomorph assemblage was not older than the Valanginian-Hauterivian or Barremian stages. In recent years, more researchers have applied isotopic dating methods to the Yixian Formation, and their results correspond roughly to the Barremian-early Aptian stages. This conclusion has been widely accepted.

Swisher et al. (1999) suggested that the sanidine laser Ar-Ar age is 124.6±0.3 Ma in the tuff of the fossil layers from the Sihetun area. Wang et al. (2001a) obtained a zircon U-Pb age of 125.2±0.9 Ma in the tuff of vertebrate fossils layers from the Sihetun area. Wang et al. (2001b) conducted age dating of basaltic andesite in Huangbanjigou fossil layers and subvolcanic rock in the Sihetun profile. They reported an andesite K-Ar age of 129.0±2.6 Ma with an Ar-Ar isochron age of 128.4±0.2 Ma, and they also reported a diabase Ar-Ar age of 122.3±0.5 Ma with an Ar-Ar isochron age of 121.8±1.3 Ma. He et al. (2006) measured feldspar $^{40}Ar/^{39}Ar$ ages of 123.2±1.0 Ma in the tuff of fossil layers in the Lujiatun area.

Because of volcanic action, the sedimentary environment in the Yixian Formation is alkaline. Most of the sediment is tuffaceous rocks, which are not conducive to the preservation of spores and pollen. Fossils of spores and pollen are scarce and of poor quality, and there has been little recent progress in biochronological research of the area. Biostratigraphic age and isotope stratigraphy have not been unified and this represents a serious problem.

The Zhuanchengzi Bed in the Yixian Formation is rich in rare animal and plant fossils. It is one of the main strata that produce fossils in the Yixian Formation. Scholars have done some research on its paleoclimatology from palynological and sedimentological perspectives. Most think that climate in the Yixian Formation was warm and humid (Wang et al., 1999; Yan et al., 2003; Ding et al., 2003a, 2003b, 2004; Li, 2010), but detailed research on vegetation types and paleoclimate evolution trends has not been done for the Zhuanchengzi Bed in the Yixian Formation.

Based on the identification and analysis of spore and pollen fossils in the Zhuanchengzi Bed of the Yixian Formation in the Yingwoshan area, this paper precisely divides and characterizes the spore and pollen assemblage in the Zhuanchengzi Bed, infers the stratigraphic age of the assemblage, and discusses the vegetation type and paleoclimate evolution trends.

1 Regional geological background

The study area is located in the northeast of the North China Platform within the western Liaoning depression area of the Yanshan platformal fold belt. The Shanhai Pass uplift is to the south, the Inner Mongolia axis is to the north, and the Yiwulü Mountain Uplift is to the east. The area is a part of the Mesozoic circumpacific continental margin mobile belt. In the Mesozoic, the area has obvious structural "activation". This formed a series of volcanic sedimentary basins, including Beipiao Basin, Jinlingsi-Yangshan Basin, and Yixian Basin. There are NE trending Middle Proterozoic uplifts between the basins for an interval, and the Yixian Basin is a rift basin. The Lower Cretaceous layers in the Yixian Formation are exposed mainly in the Jinlingsi-Yangshan Basin (Jin-Yang Basin) and Yixian Basin (Figure 1).

Because of the apparent separation of the basins, the distribution of volcanic rocks is constrained obviously by the faults and volcanic mechanism. And the volcanic eruption times and volcanic eruption intermittent periods varied in the lengths of time in different basin, and sometime even with the different parts of the same basin. Consequently, the volcanic-sedimentary strata in the Yixian Formation show dramatic vertical and horizontal changes, which lead to a variety of proposals for the division and correlation of the Yixian Formation by different scholars (Table 1).

The study area is located in the Yixian Basin where the Yixian Formation lies unconformably on the Tuchengzi Formation. The Yixian Formation is composed of basic-intermediate-basic-neutral rocks of continental volcanic eruption. During intermittent periods of the eruptions, seven lacustrine sedimentary beds of varying thickness developed. In ascending order, these layers are the Laogonggou Bed, Yenangou Bed, Zhuanchengzi Bed, Dakangbao Bed, Zhujiagou Bed, Jingangshan Bed, and Huanghuashan Bed. Among these, the Zhuanchengzi Bed and the Dakangbao have produced important rare animal fossils and abundant plant fossils of the Jehol Biota, and thus are of great significance.

2 Material and methods

In this study, 73 spore and pollen samples were collected from the Yixian Formation outcrops. Similar collections have

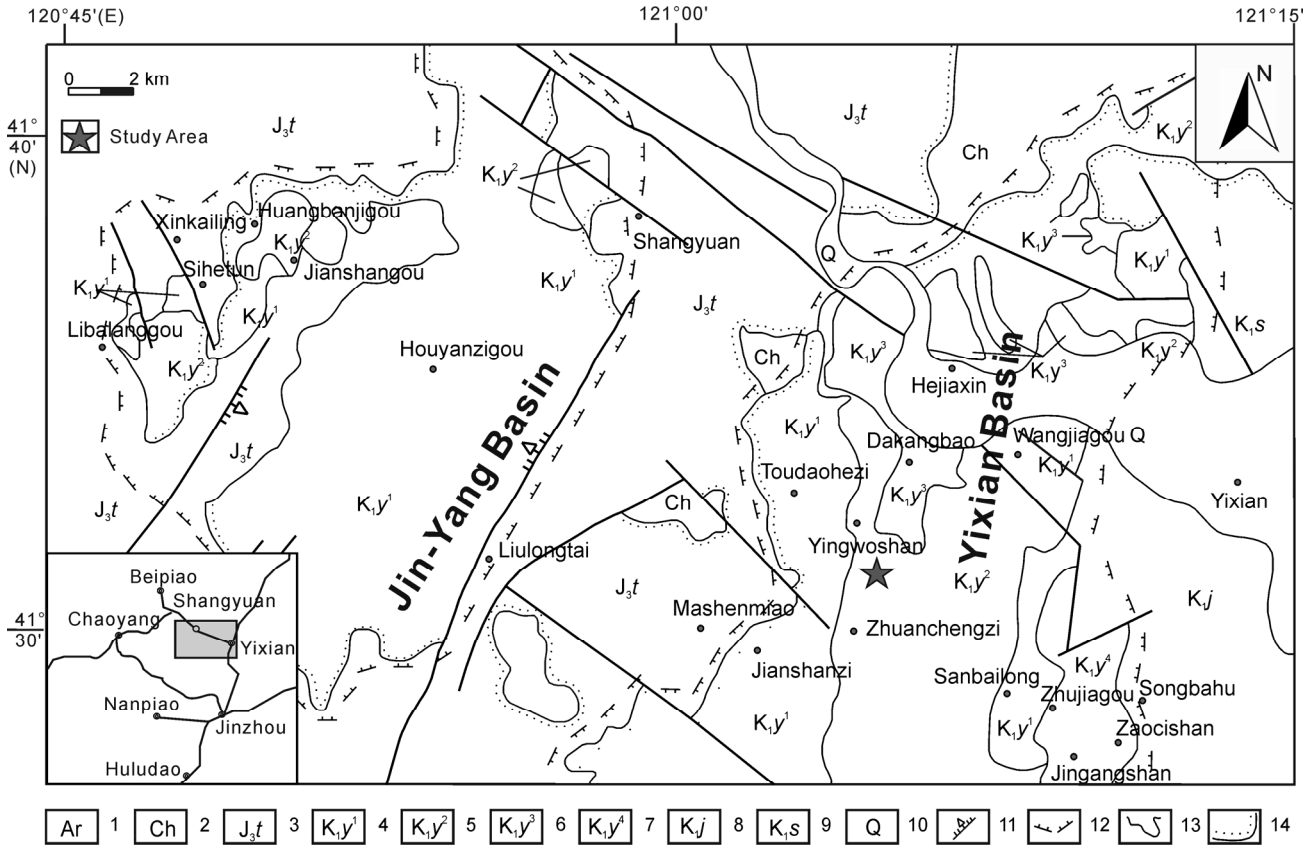

Figure 1 Geological sketch showing the Yixian Formation distribution in the Yixian and Jin-Yang Basins, western Liaoning (modified from Zhang, 2004). 1. Andesitic porphyrite; 2. basaltic porphyrite; 3. Tuchengzi Fm.; 4. Member 1 of Yixian Fm.; 5. Member 2 of Yixian Fm.; 6. Member 3 of Yixian Fm.; 7. Member 4 of Yixian Fm.; 8. Jiufotang Fm.; 9. Shahai Fm.; 10. Quaternary; 11. fault; 12. volcanic tectonic depression; 13. geologic borderline; 14. disconformity/angular unconformity.

previously been made in the Laogonggou, Yenangou, Yingwoshan, Wangjiagou, and Zaocishan. The sample spacing is 0.1–0.2 m, and most samples are black shale, gray and black shale, shale, gray dolomite, and shale containing plant debris fossils and chert nodules. Each sample weighs approximately 500 g.

There were 24 samples collected from the Zhuanchengzi Bed of Yingwoshan, and 9 of the 24 samples were selected for analytical processing. Spores and pollen were found in 6 samples, among which 3 were rich in spores and pollen. Spores and pollen sample collections were made by the group members. Spore and pollen samples were obtained via the acid treatment method.

As seen in Figure 2, spores and pollen fossils were found mainly in YW-5-S, YW-20, and YZ-17-3C samples, with very rich content. There were also fossils in the YW-6 and YW-21 samples and fewer still in the YW-14 sample. No spore or pollen fossils were found in the other samples.

3 Palynomorph assemblage: *Cicatricosisporites-Protoconiferus*

The overall palynomorph assemblage characteristics in the Zhuanchengzi Bed are dominated by gymnosperm pollen, especially bisaccate conifer pollens (88%–94%). Pteridophyte spores are less abundant (2%–12%), and there were a few instances of potential angiosperm pollen (0–1%) (Figures 3–5).

Specific assemblage characteristics are as follows.

(1) Pteridophyte spores are represented by 18 genera and 24 species, of which most are monotonous species, constituting a low proportion of the assemblage with the content of no more than 1% but of great significance nonetheless. They possess typical characters of the Early Cretaceous elements such as *Cicatricosisporites*, *Lygodiumsporites*, *Aequitriradites*.

(2) The total gymnosperms include 28 genera and 37 species. The bisaccate conifers pollen are most abundant, accounting for up to 77%–90% of the assemblage. The samples were dominated by ancient pollen types with imperfect differentiation of the bodies and their airbags, such as *Protoconiferus*, *Protopinus*, *Protopicea*, *Protopinus*, *Pseudopicea*, *Piceites*. There were also some pollens with perfect differentiation of the bodies and their airbags, such as *Picepaepollenites*, *Pinuspollenites*, *Abietineaepollenites*, *Cedripites*, *Podocarpidites*. In addition, single ditch pollens were present, such as in *Cycadopites*, *Ginkgoites*, and

Table 1 Stratigraphic classification scheme of the Yixian Formation, western Liaoning

Gu, 1962	Chen et al., 1980		Mi et al., 1980	Liaoning Bureau of Geology and Mineral Resources Exploration, 1989		Ren et al., 1997	Lu, 2000	Zhang et al., 2002		Wang et al., 2004		This study	
Tuhulu Fm.	Huanghuashan breccia layer (Fm.)	Yixian Fm.	Lower Jiufotang Fm.		Yixian Fm.	Sixth Mem.	Yixian Fm.	Forth Mem.	Yixian Fm.	Huanghuashan Layer	Yixian Fm.	Huanghuashan Bed	Yixian Fm.
Jingangshan Fm.	Jingangshan Fm.			Jingangshan Fm.		Fifth Mem.				Jingangshan Layer		Jingangshan Bed	
Yixian Fm.	Volcanics		Yixian Fm. (Sunjiawan Fm.)	Volcanics		Forth Mem.				Volcanics		Volcanics	
										Zhujiagou Layer		Zhujiagou Bed	
	Dakangbao Fm.			Dakangbao Fm.			Yaolugou Fm. (Weijialing Fm., Jianshangou Fm., Xiguayuan Fm.)	Third Mem.		Volcanics		Volcanics	
								Second Mem.		Dakangbao Layer		Dakangbao Bed	
	Volcanics			Volcanics		Third Mem.				Volcanics		Volcanics	
	Shangyuan Fm.			Shangyuan Fm.						Zhuanchengzi Layer		Zhuanchengzi Bed	
	Volcanics			Volcanics		Second Mem.		First Mem.		Volcanics		Volcanics	
	Jianshangou Fm.			Jianshangou Fm.		First Mem.				Yenangou Layer		Yenangou Bed	
										Volcanics		Volcanics	
										Laogonggou Layer		Laogonggou Bed	

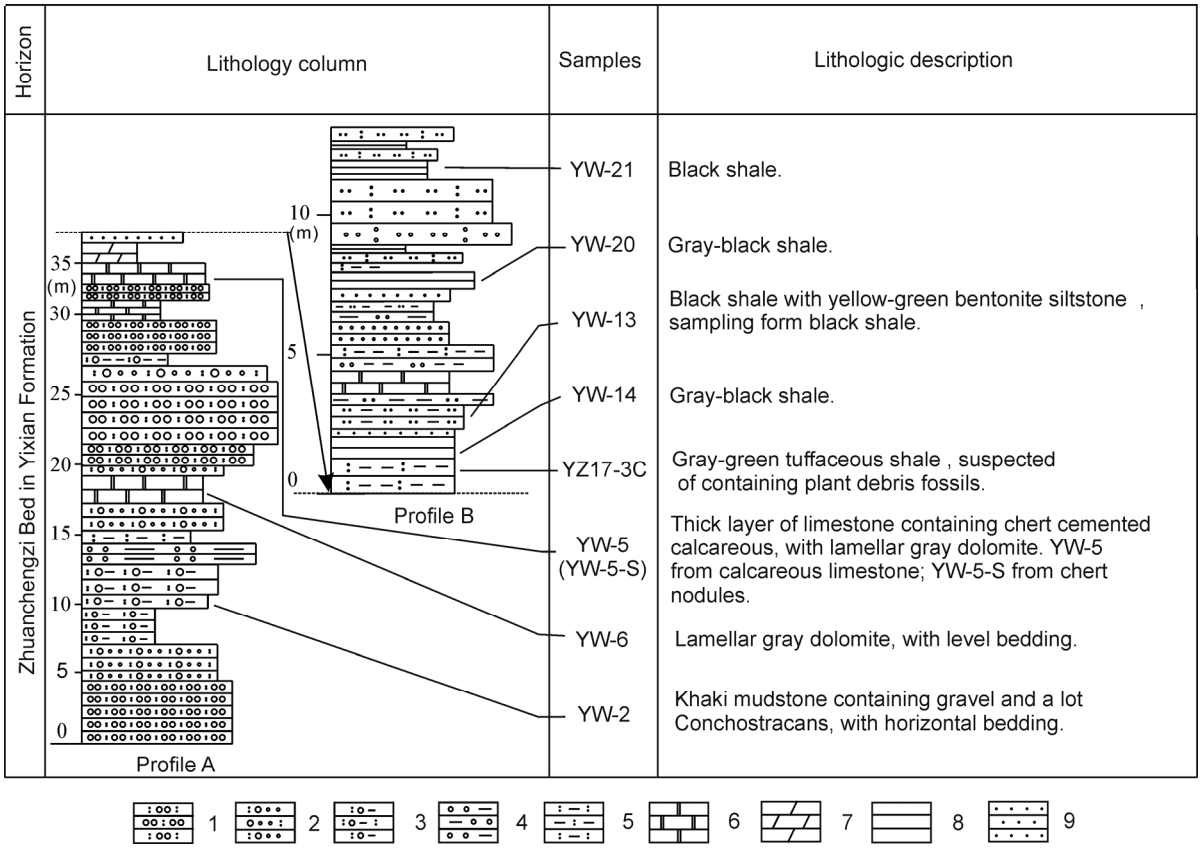

Figure 2 Lithologic description of spore and pollen samples in Zhuanchengzi Bed. 1. sand tuff; 2. tuffaceous glutenite; 3. tuffaceous gompholite; 4. pelitic siltstone; 5. tuffaceous shale; 6. dolostone; 7. marlstone; 8. shale; 9. sandstone.

Monosulciles. *Classopollis* pollen reflecting an arid environment appears only sporadically in individual samples, and *Psophosphaera* pollen reflecting an arid environment was also present.

(3) It should be mentioned that three genera of suspected angiosperm pollen were found in YW-5-S and YW-20 samples. They were identified as possible ?*Liliacidites*, ?*Magnolipollis*, and ?*Tricolpopollenites*, respectively. Unfortunately the resolution of the photographs is not as good as that of the images from the microscope, and these few samples, only 3, were 20 μm or less in size. We attempted to take photographs in the scanning electron microscope, but we failed to obtain ideal images. Although the attribution of angiosperm pollen is uncertain, potentially this represents a new discovery. More samples in many other sections of the Zhuanchengzi Bed should be collected in the future to gather additional evidence and to allow further discussion of its stratigraphic significance.

4 Paleoclimate and paleoenvironment determination based on spore and pollen fossils

Gao et al. (1999) have applied the concept of "Palynological Vegetation" to determine Cretaceous paleovegetation in the Songliao Basin. There is a small difference in latitude and longitude between western Liaoning and Songliao Basin. They are within the areas of Laurasia and north Laurasia palynoflora at the worldwide scale (Brenner, 1976), and on the scale of China, they are both characterized by Huabei spore-pollen floras in the Early Cretaceous (Li et al., 1994). Thus, this method is applied in this study because of the similar paleoclimate and paleoenvironment. On the basis of the previous studies, we combine the type of palynological species in the Yixian Formation of western Liaoning to obtain the palynological vegetation type, climate zone type, and humidity type.

The division of palynological vegetation types is based mainly on sporopollen spectra and referred to the paleoecological characteristics of palynological taxa. Each genus of spores and pollen is classified into five categories: coniferous forest, evergreen broad-leaf forest, deciduous broad-leaf forest, shrub, and herb (Table 2). Through statistically analyzing the data and referring to the modern vegetation data, we determined the palynological vegetation types. The partitioning principle is that: the number of palynological vegetation types in the class name must be more than 20%. Large classes are where more than 60% can be individually named, and groups with less than 20% of individuals identified generally do not participate in the naming. Due to the

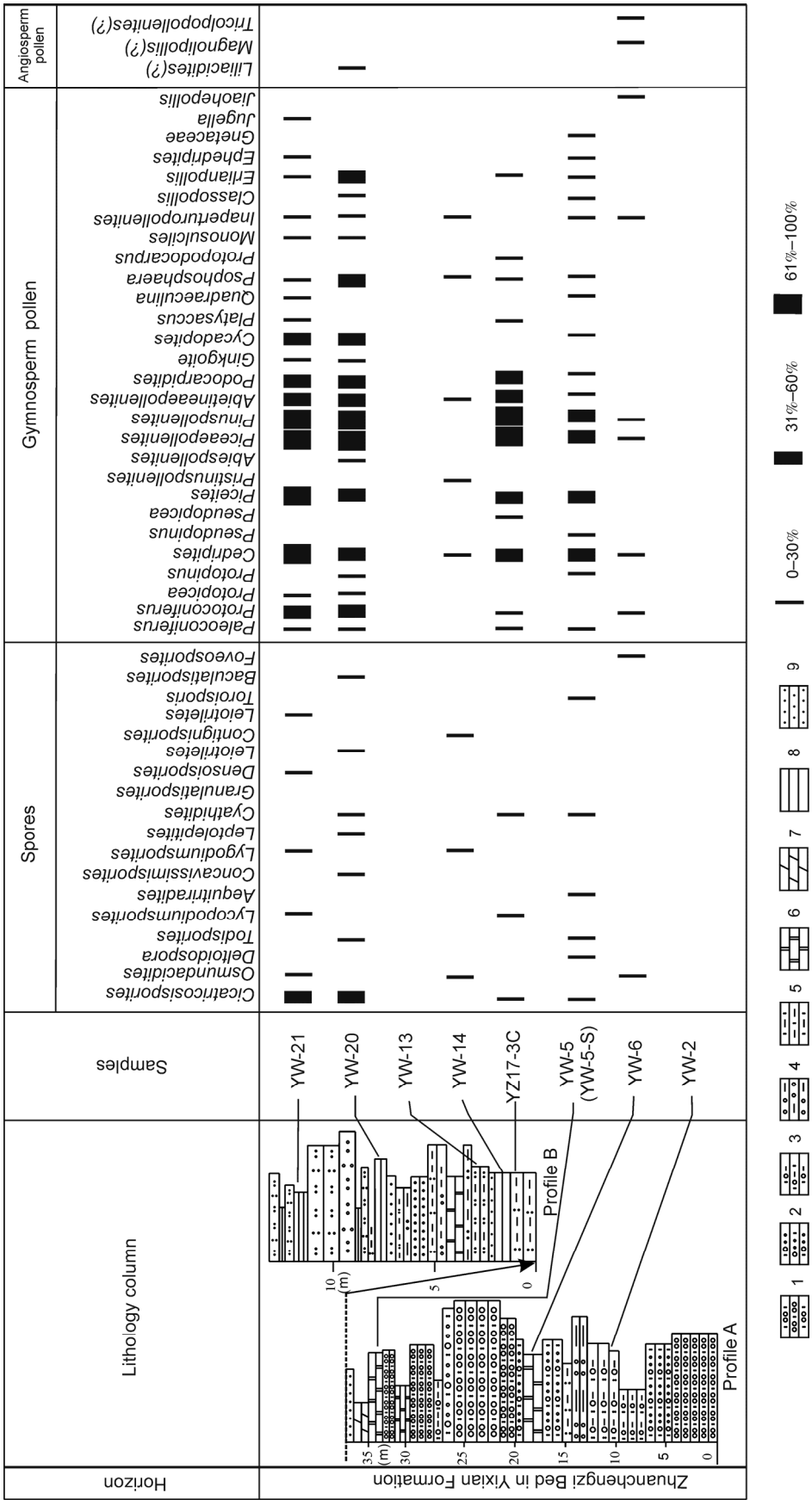

Figure 3 Spore and pollen assemblage distribution and relative abundance in Zhuanchengzi Bed. 1. tuffaceous sandstone; 2. tuffaceous glutenite; 3. tuffaceous gompholite; 4. pelitic siltstone; 5. tuffaceous shale; 6. dolostone; 7. marlstone; 8. shale; 9. sandstone.

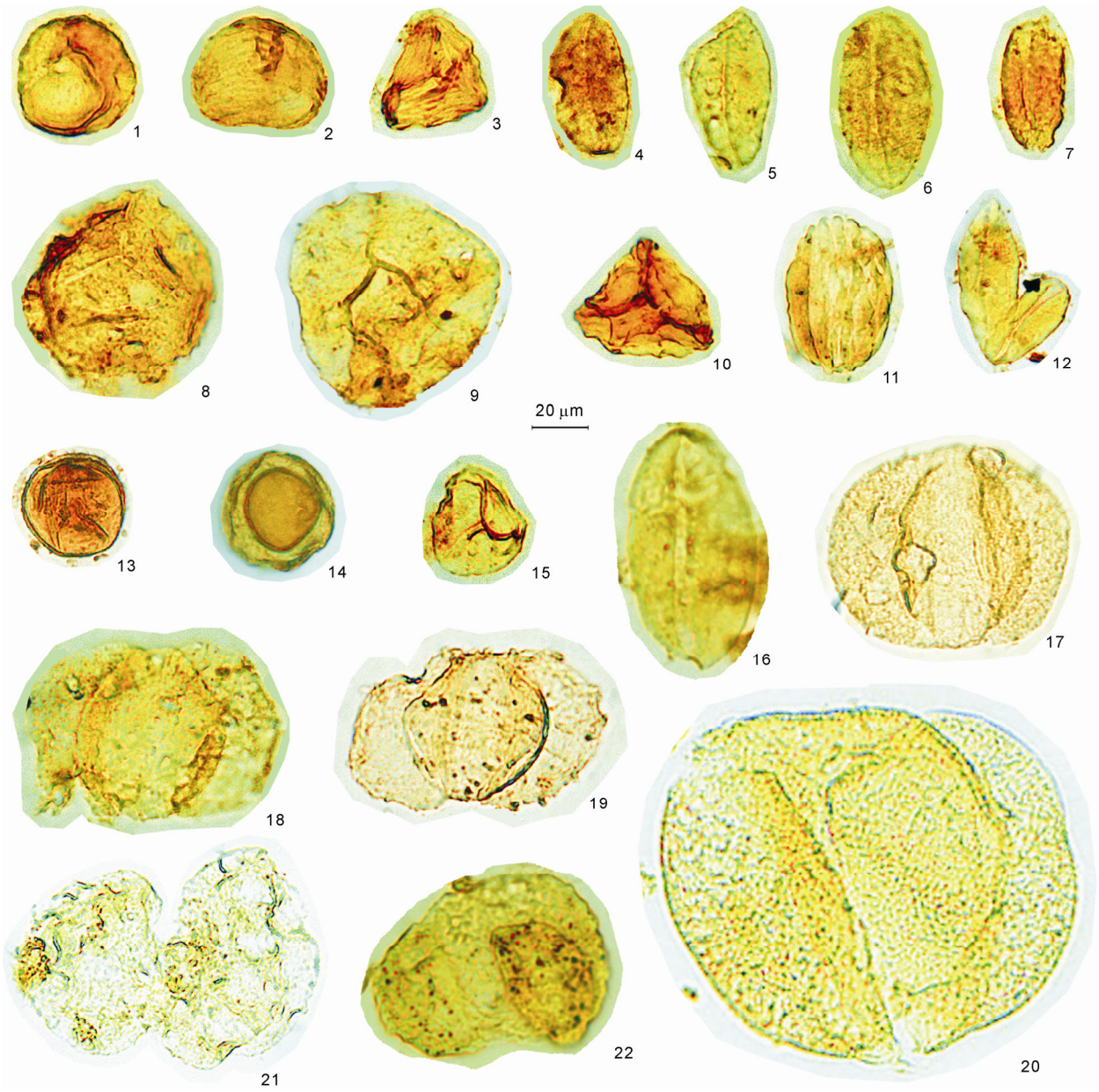

Figure 4 Spore and pollen fossils in Zhuanchengzi Bed (1). 1. *Punctatisporites minutes* Kosanke, YW-21; 2. *Cicatricosisporites annulatus* Archangelsky et Gamerro, YW-21; 3. *Cicatricosisporites australiensis* (Cookson) Potonié, YW-20; 4. *Cycadopites subgranulosus* (Couper) Bharadwaj et Singh, YW-21; 5. *Cycadopites* sp., YW-21; 6. *Cycadopites asjectus* (De Jersey) De Jersey, YW-21; 7. *Cycadopites acerrimus* (Leschik) Clarke, YW-20; 8. *Hymenophyllumsporites simplex* Pu et Wu, YW-21; 9. *Cyclogranisporites congestus* Leschik, YW-20; 10. *Cicatricosisporites australiensis* (Cookson) Potonié, YW-20; 11. *Ephedripites* sp., YW-21; 12. left: *Cycadopites typicus* (Mal.) Pocock, YW-20; right: *Cycadopites nitidus* (Balme) Pocock, YW-20; 13. *Punctatisporites* sp., YW-6; 14. *Perinopollenites limatus* Lu et Wang, YW-5-S; 15. *Undulatisporites pannuceus* (Brenner) Singh, YW-20; 16. *Cycadopites deterius* (Balme) Pocock, YW-21; 17. *Pseudopicea variabiliformis* (Mal.) Bolkhovitina, YW-20; 18. *Pinuspollenites divulgatus* (Bolkh.) Qu, YW-14; 19. *Podocarpidites multisimus* (Bolkh.) Pocock, YZ17-3C; 20. *Piceaepollenites* sp., YW-5-S; 21. *Platysaccus proximus*（Bolkh.）Song comb. nov., YW-21; 22. *Pinuspollenites divulgatus* (Bolkh.) Qu, YW-21.

strong dispersal ability of conifer pollen, especially Pinaceae pollen, its burial place can be far away from the parent plant. Therefore, Pinaceae pollen content should be slightly higher than the other types (usually more than 30%) in order to participate in the naming. If it is more than 70%, its palynological vegetation type should be named as the coniferous forest. The impacts of the distributions of the vegetation latitudes, longitude zonality, and vertical zonality on the sporopollen spectrum should also be taken into account.

The division of palynological climatic zone classified each genus from the sporopollen spectra into five categories: tropics, subtropics, temperate zone, eurythermic tropics-subtropics, and tropics-temperate zone (Table 3). The climatic zone types were divided based on data statistics, classification,

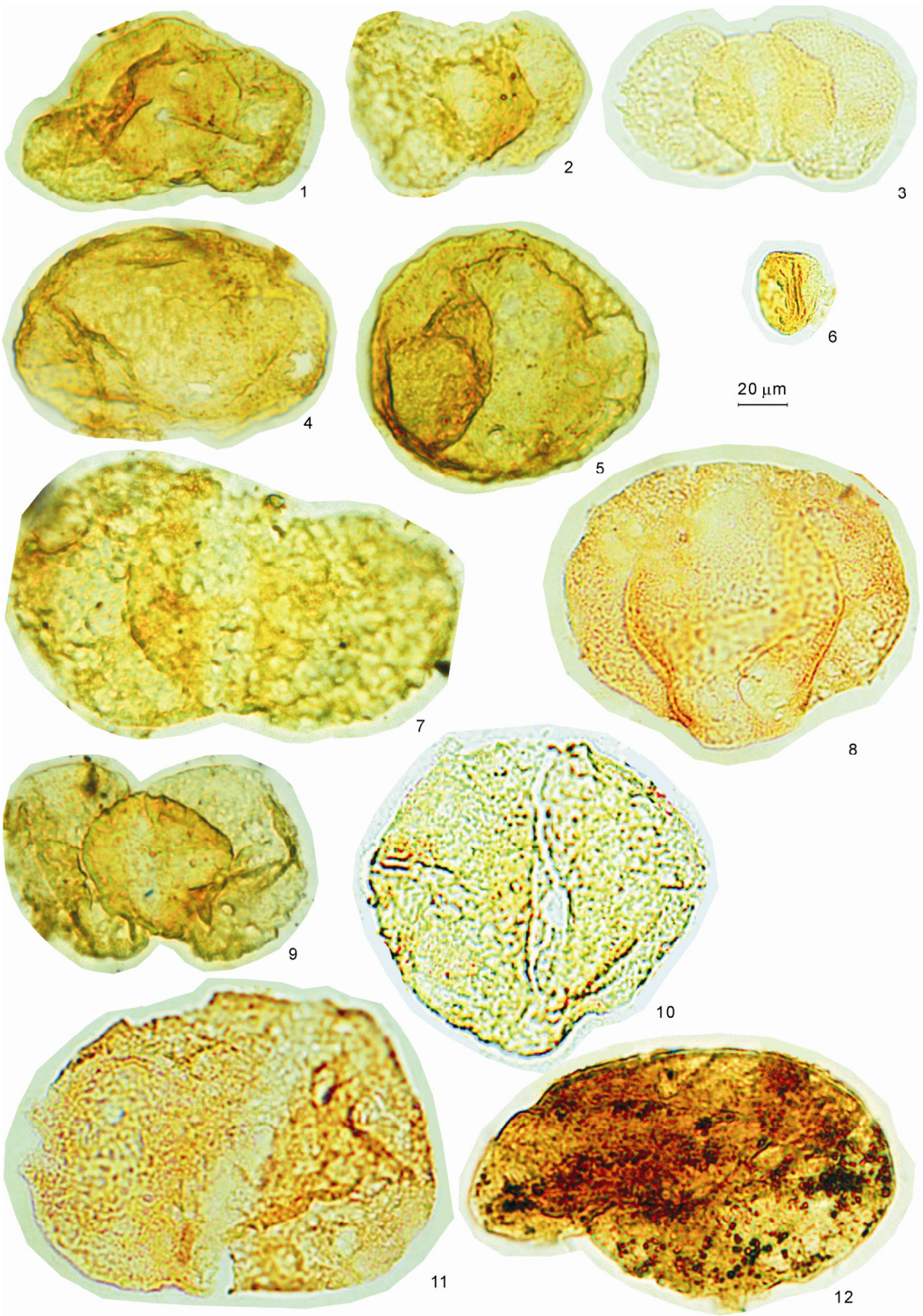

Figure 5 Spore and pollen fossils in Zhuanchengzi Bed (2). 1. *Pinuspollenites alatiopllenites* (Rouse) Liu, YW-21; 2. *Platysaccus cervicalis* (Pu et Wu) Song comb. nov., YW-21; 3. *Podocarpidites biformis* Rouse, YZ17-3C; 4. *Cedripites leptodermus* (Zauer) Krutzsch, YW-21; 5. *Cedripites globulisaccatus* Pu et Wu, YW-21; 6. ?*Tricolpopollenites* sp., YW-5-S; 7. *Podocarpidites tricoccus* (Mal.) Pu et Wu, YW-14; 8. *Piceites enodis* Bolkhovitina, YZ17-3C; 9. *Podocarpidites unicus* (Bolkh.) Pocock, YW-6; 10. *Protoconiferus funarius* (Naumova) Bolkhovitina, YW-21; 11. *Protopinus* sp., YW-5-S; 12. *Piceaepollenites singularae* (Bolkh.) Zhang, YW-14.

and analogies, along with the reference to the modern climatic zone types. Together, seven bands were delimited: tropical zone, south subtropical zone, middle subtropical zone, north subtropical zone, warm temperate zone, temperate zone, and cool temperate zone.

The division of palynological humidity type classified each genus from the sporopollen spectra into five categories: arid plants, semi-arid and semi-humidogene plants,

Table 2 Ecology of major pollen plant of the Yixian Formation in western Liaoning (vegetation zone type)[a)]

Coniferous forest	Deciduous broad-leaf forest	Evergreen broad-leaf forest	Shrub	Herb
Classopollis	*Ginkgo*	*Cyathidites*	*Cicatricosisporites*	*Leptolepidites*
Podocarpidites	*Monosulcites*	*Cycadopites*	*Concavissimisporites*	*Toroisporis*
Cedripites	*Tricolpites*	*Quercoidites*	*Lygodiumsporites*	*Leiotriletes*
Abietineaepollenites		*Clavatipollenites*	*Ephedripites*	*Deltoidospora*
Piceaepollenites		*Tricolpollenites*	*Triporopollenites*	*Osmundacidites*
Abiespollenites				*Todisporites*
Pinuspollenites				*Lycopodiumsporites*
Parcisporites				*Foveosporites*
Parvisaccites				*Densoisporites*
Palaeoconiferus				*Liliacidites*
Piceites				*Polyporites*
Protopodocarpus				
Protopinus				
Pseudopicea				
Inaperturopollenites				
Psophasphaera				
Erlianpollis				
Jiaohepollis				

a) Modified from Gao et al., 1999.

Table 3 Ecology of major pollen plant of the Yixian Formation in western Liaoning (climatic zone type)[a)]

Tropics	Tropics-subtropics	Subtropics	Tropical-temperate zone	Temperate zone
Cyathidites	*Toroisporis*	*Cedripites*	*Lycopodiumsporites*	*Piceaepollenites*
Leptolepidites	*Deltoidospora*	*Quercoidites*	*Foveosporites*	*Inaperturopollenites*
Cicatricosisporites	*Leiotriletes*	*Ginkgo*	*Baculatisporites*	*Ephedripites*
Concavissimisporites	*Classopollis*		*Osmundacidites*	*Jiaohepollis*
Lygodiumsporites	*Monosulcites*		*Todisporites*	*Piceites*
Cycadopites	*Tricolpites*		*Abietineaepollenites*	*Paleoconiferus*
Podocarpidites			*Pinuspollenites*	*Protopicea*
Clavatipollenites			*Parvisaccites*	*Protopinus*
			Psophosphaera	*Protoconiferus*
			Polyporites	*Pseudopinus*
				Triporopollenites

a) Modified from Gao et al., 1999.

humidogene plants, marsh plants, and aquatic plants. No aquatic plant types were found in western Liaoning, therefore it cannot be included in statistics (Table 4). Based on data statistics, classification, and analogies, five palynological humidity types were recognized: arid, semi-arid, semi-arid and semi-humidogene, semi-humidogene, and humidogene. For example, the corresponding arid (or humidogene) content must be greater than 50% of the drought (or wet weather).

Application of the concept of "Palynological Vegetation" was done according to the ecological characteristics of sporopollen spectrum and palynological parent plants. Vegetation type (Table 5), climatic zone type (Table 6), and humidity type (Table 7) were classified quantitatively for the Zhuanchengzi Bed of the Yixian Formation in Western Liaoning. We calculated the percentage of palynological vegetation types, climatic zone types, and humidity types in each of the samples, and the percentage curves were drawn. Finally, we produced the paleoclimatic evolution diagram of the Zhuanchengzi Bed in the Yixian Formation of western Liaoning (Figure 6).

Li and Liu (1999) studied the paleoclimate of the Yixian Formation in western Liaoning, and concluded that it is characterized by warm and humid conditions. Ding and Zhang (2004) found a similar result, and they concluded that the dominant palynological vegetation type is coniferous forest for the humid subtropical-temperate zone in the Yixian Formation (equivalent to the Zhuanchengzi Bed). Li (2010) reported a warm and humid climate for the Yixian Formation of Jinjiagou, western Liaoning. This study is consistent with the previous findings, while simultaneously obtaining more accurate paleoclimate evolution characteristics.

Table 4 Ecology of major pollen plants in the Yixian Formation of western Liaoning (humidity type)[a)]

Arid plants	Semi-arid and semi-humid plants	Humidogene plants	Marsh plants
Leptolepidites	*Lycopodiumsporites*	*Cyathidites*	*Baculatisporites*
Classopollis	*Foveosporites*	*Leiotriletes*	*Osmundacidites*
Ephedripites	*Cycadopites*	*Deltoidospora*	*Todisporites*
Tricolporopollenites	*Ginkgo*	*Toroisporis*	
Liliacidites	*Abiespollenites*	*Cicatricosisporites*	
Polyporites	*Abietineaepollenites*	*Concavissimisporites*	
	Cedripites	*Lygodiumsporites*	
	Parvisaccites	*Podocarpidites*	
	Pinuspollenites	*Parcisporites*	
	Inaperturopollenites	*Piceaepollenites*	
	Monosulcites	*Erlianpollis*	
	Psophosphaera	*Paleoconiferus*	
	Tricolpites	*Protoconiferus*	
	Quercoidites	*Piceites*	
		Protopinus	
		Pseudopinus	
		Pseudopicea	
		Clavatipollenites	

a) Modified from Gao et al., 1999.

Table 5 Pollen vegetation classification in the Zhuanchengzi Bed of Yixian Formation, western Liaoning

Horizon	Sample No.	Sporopollen contents reflecting palynological vegetation type (%)						Palynological vegetation type
		Coniferous forest	Deciduous broad-leaf forest	Evergreen broad-leaf forest	Shrub	Herb	Others	
Zhuanchengzi Bed in Yixian Fm.	YW-21	47.61	3.23	6.45	20.13	9.68	12.90	Coniferous forest, shrub
	YW-20	48.21	2.84	5.86	16.49	12.03	14.57	Coniferous forest, shrub and herb
	YW-14	48.75	2.03	4.56	11.68	15.72	17.26	Coniferous forest, shrub and herb
	YZ17-3C	48.92	1.77	3.39	8.32	18.24	19.36	Coniferous forest, herb
	YW-5-S	49.01	1.01	2.27	6.82	20.45	20.44	Coniferous forest, herb
	YW-6	50.89	1.98	1.58	5.21	22.57	17.77	Coniferous forest, herb

Table 6 Classification of pollen climatic zone in the Zhuanchengzi Bed of Yixian Formation, western Liaoning

Horizon	Sample No.	Sporopollen contents reflecting climatic zone type (%)						Climatic zone type	Evolution
		Tropics	Tropics-subtropics	Subtropics	Tropical-temperate zone	Temperate zone	Others		
Zhuanchengzi Bed in Yixian Fm.	YW-21	22.58	3.23	6.45	25.81	12.90	29.03	North subtropics	Warm→much warmer
	YW-20	20.35	5.49	6.77	26.83	10.67	29.89	North subtropics	
	YW-14	18.73	7.03	7.68	28.23	12.21	26.12	Warm temperate zone	
	YZ17-3C	17.05	12.42	8.12	29.96	8.73	23.72	Warm temperate zone	
	YW-5-S	15.56	11.11	8.89	31.11	6.67	26.66	Warm temperate zone	
	YW-6	14.92	9.67	8.34	32.87	6.80	27.40	Warm temperate zone	

Table 7 Classification of pollen humidity in the Zhuanchengzi Bed of Yixian Formation, western Liaoning

Horizon	Sample No.	Sporopollen contents reflecting humidity type (%)					Humidity type	Evolution
		Arid plants	Semi-arid and semi-humid plants	Humidogene plants	Marsh plants	Others		
Zhuanchengzi Bed in Yixian Fm.	YW-21	0	32.26	48.39	3.23	16.12	Moist	Semi-moist→moist
	YW-20	2.01	34.18	44.86	3.13	15.82	Moist	
	YW-14	5.27	35.85	40.91	3.04	14.93	Moist	
	YZ17-3C	7.82	37.28	35.14	2.91	16.85	Semi-moist	
	YW-5-S	9.09	38.64	31.82	2.27	18.18	Semi-moist	
	YW-6	9.51	39.91	29.11	2.02	19.45	Semi-moist	

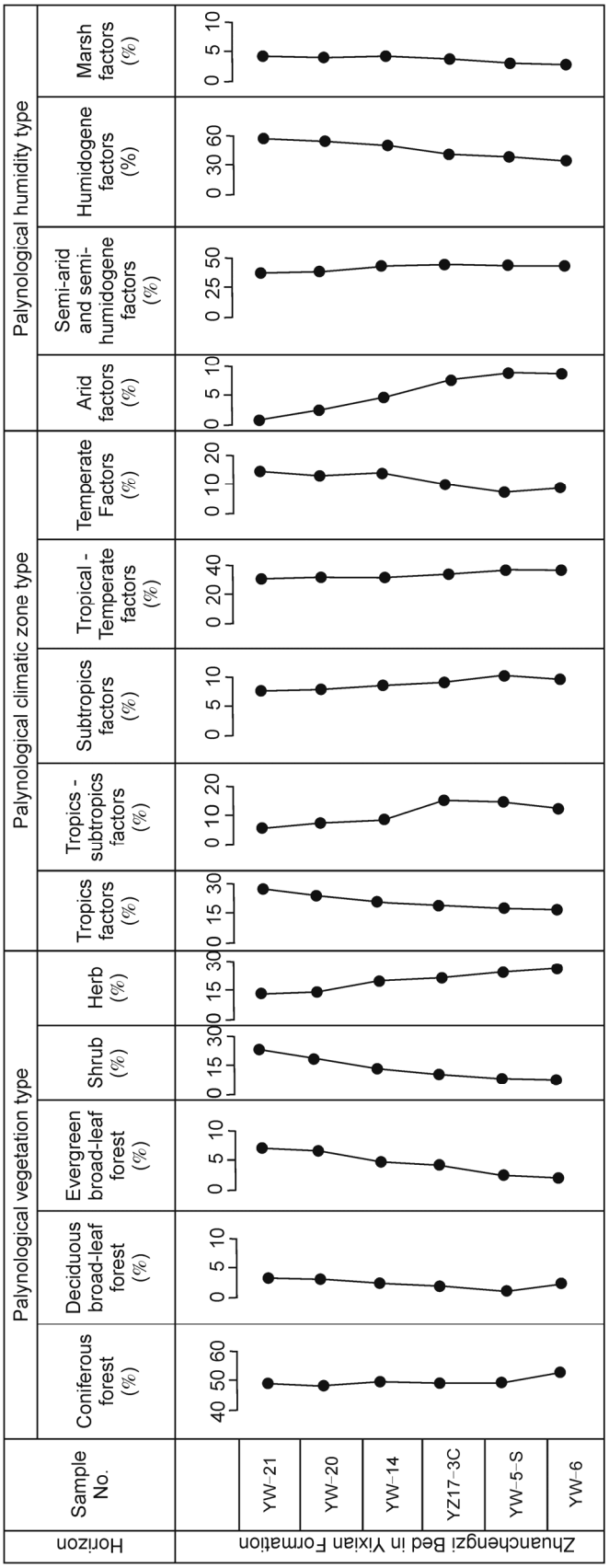

Figure 6 Paleovegetation and paleoclimate evolution in the Zhuanchengzi Bed of Yixian Formation, western Liaoning.

The results indicate that the overall paleoclimate was warm and humid and there was the presence of various palynological vegetation types, including coniferous forest, deciduous forest, evergreen broadleaf forest, herbs, and shrubs, during the deposition period of the Zhuanchengzi Bed in the Yixian Formation. Local paleoclimatic conditions evolved from warm to much warmer and from semi-humid to humid. The dominant palynological vegetation type was always coniferous forest. The coexistence of deciduous forest, evergreen broad-leaf forest, herbs, shrubs, and some arid plants indicates vertical zonation of vegetation and seasonal climate change. At the same time, there is laminated dolomite of a certain thickness in the middle of the Zhuanchengzi Bed. We generally considered the characteristics of a dry heat environment associated with intense evaporation (Xiang et al., 2009), which shows that there may be a transient or local dry heat environment in the background of the warm and humid conditions.

The study defines a boundary at the upper YZ17-3C sample, and divides the paleoclimatic evolution into two stages for the Zhuanchengzi Bed of the Yixian Formation.

(1) The first stage of evolution: semi-humid and warm temperate zone (below the boundary, i.e., the three samples following the upper YZ17-3C sample).

The higher abundance and diversity of sporomorph indicate a warm and humid paleoenvironment and prosperous plants. Because of its stronger ability to float and adapt to climate change, gymnosperms are dominant, especially pollen from bisaccate conifers. The conifers are characterized by the abundance of Pinaceae pollen, such as *Cedripites* and *Pinuspollenites*. The palynological vegetation type is dominated by coniferous forest, with the average content of 49.61%. Herb plants are secondary, with an average content of 20.42%. The climate is warm temperate. Tropical and temperate factors dominate, with the average content of 31.31%; at the same time, semi-arid and semi-humidogene as well as marsh types of sporomorph are dominant with average contents of 38.61% and 32.02%, respectively. This indicates an overall semi-moist and warm temperate climate.

(2) The second stage of evolution: humid north subtropical zone (above the boundary, i.e., the three samples above the upper YZ17-3C sample).

Sporomorph abundance and diversity is higher still. Gymnosperm pollen grains remain the dominant class. The landscape is still dominated by coniferous forest, but the average content decreases (48.19%). The herb plant content also decreases, with an average content of 12.48%. Shrub plants increase, with an average content of 16.10%. This indicates that the climate changes to a much warmer and moister condition. The climatic type is north subtropical, and tropical and temperate types are still dominant but with their content reduced to 26.96%. Meanwhile, tropical types increase to 20.55%. Semi-arid and semi-humidogene as well as marsh types of sporomorph still dominate, but the former content reduces to 34.10% while the latter increases to 44.72%. This indicates a change to much warmer and moister conditions and shows a moist north subtropical zone.

5 Discussion

5.1 Geological dating of palynomorph assemblage

There have been numerous previous reports about geological dating of the palynomorph assemblage in the Yixian Formation of western Liaoning. Some researchers believed it should be dated as the Berriasian stage of the Early Cretaceous (Pu and Wu, 1985; Yu, 1989; Li and Liu, 1999; Ding and Zhang, 2004), and other researchers believed it should be dated as the Tithonian stage of the Late Jurassic (Wang et al., 2000). Li and Batten (2007) believed that the geological date of the palynomorph assemblage in the Yixian Formation was not older than the Valanginian-Hauterivian or Barremian stages of the Early Cretaceous.

We here suggest that the palynomorph assemblage in the Zhuanchengzi Bed of the Yixian Formation may have been deposited in the late Valanginian or Hauterivian-Barremian stages of the Early Cretaceous.

The few pteridophyte spores provide evidence for the first level of approximation in determining the geological dating of palynomorph assemblage. A certain amount of *Cicatricosisporites* and even *C. australiensis* appear in the assemblage, the morphology of the dispersing spores can be compared with spore isolated *in situ* from the sporangium spores and germ isolated from the reproductive pinna of large fossilized *Ruffordia goepperti* (Dunker) Seward (Couper, 1958; Deng et al., 1997; Deng, 1998). Zheng et al. (2003) believed that *R. goepperti* possesses "unmistakable early Cretaceous elements." In addition, *Jugella* and *Ephedripites* are also characteristic of the Early Cretaceous elements. Therefore, the geological date of deposition for Zhuanchengzi Bed in the Yixian Formation must be the Early Cretaceous.

Furthermore, we now discuss the deposition occurred in the early or middle stages of the Early Cretaceous. The study identified possible angiosperm pollen grains, which is consistent with the report by Wang et al. (2000) of angiosperm pollen fossils in the Yixian Formation of Sihetun. Over the past several decades, paleontologists have discovered *Archaefructus liaoningensis*, *Archaefructus sinensis*, and *Hyrcantha decussate* in the Yixian Formation of western Liaoning (Dilcher et al., 2007; Sun et al., 2008). In light of the origin time of angiosperms, we are more inclined to date the deposition to the middle or late Early Cretaceous.

According to palynomorph stratigraphic correlation, we believe that the palynomorph of this study can be compared with that from the late Valanginian-Barremian in the Northern Siberia area of Russia (Pestchevitskaya, 2007). The comparison is direct and reliable since the two areas were all located in northeast of Laurasia, the micro-phytogeo-

graphical divisions are all in the north region of the Early and Middle Cretaceous (Svivastava, 1978, 1981, 1983), and the areas have similar palynological vegetation types. The main basis for dividing the palynology assemblage was species types of Schizaeaceae and Gleicheniaceae in the Northern Siberia region. Pteridophyte spores were mainly *Cicatricosisporites*, *Lygodiumsporites*, *Aequitriradites*, and *Foraminisporis*; *Taxodiaceae* content was the highest in gymnosperms pollen; and there was sporadic angiosperm pollen. It is worth noting that angiosperm pollen appeared within the late Valanginian stage to the Hauterivian stage in Northern Siberia area, and they are sporadically distributed until the Barremian stage.

Therefore, our comprehensive analysis suggests that the palynomorph assemblage in the Zhuanchengzi Bed of Yixian Formation was likely deposited in the late Valanginian or Hauterivian-Barremian.

5.2 The origin of angiosperm pollen

Two popular hypotheses on the origin of angiosperm pollen have been proposed. The first hypothesis, based on molecular systematic analysis, assumes that the angiosperms emerged during the Triassic or pre-Triassic period (Doyle and Donoghue, 1986; Wolfe et al., 1989; Brandl et al., 1992; Martin et al., 1989, 1993). The other hypothesis, based on fossil records, dated the origin of the group to be between the Late Jurassic (Sun et al., 1998) and the Early Cretaceous (Friis et al., 1999; Sun et al., 2002, 2011). It is most likely that the different methods of analysis involved have led to these two competing hypotheses (Doyle, 2011; Zavada, 2007; Clarke et al., 2011; Smith et al., 2010; Bell et al., 2010; Magallón, 2010).

The previous palynological studies on the origin and evolution of angiosperms were based mainly on palynological data from after the Barremian stage of the Early Cretaceous (Hughes, 1994; Crane et al., 1995; Feild et al., 2004; Heimhofer, 2010; Zhang et al., 2014). The earliest recognized angiosperm pollen appeared in the Valanginian-Hauterivian stage, and they became widespread after the Barremian stage (Hughes and McDougall, 1987; Brenner, 1996; Zhang, 1999; Wang, 2000).

A. liaoningensis was found in the Zhuanchengzi Bed of the Yixian Formation, Huangbanjigou, Beipiao, western Liaoning (Sun et al., 1998). It was identified as the fossilized seeds of an angiosperm, and it was dated to be the Late Jurassic. Wang et al. (2000) discovered the earliest angiosperm in a horizon containing bird fossils in the Sihetun area of Beipiao, and they summarized 8 genus and 3 categories, namely, nonporous ditch pollen types (as the representative of *Paraknemapollis* type and *Cyclolophopollis*). The original single distal pole ditch pollen types were identified (as the representative of *Magnolipollis*, *Liliacidites*, and *Clavatipollenites*). The original tricolpate pollen types were also identified (as the representative of *Prototricolpites*). These were dated to be the Tithonian stage of the Late Jurassic. Li and Batten (2007) believed that the emergence of angiosperm pollen should not be earlier than the Valanginian-Hauterivian or Barremian stages of the Early Cretaceous.

The geological layer in this study may be from the late Valanginian or Hauterivian-Barremian stages of the Early Cretaceous, and a very small amount of possible angiosperm pollen were found. These purported species are similar to *Liliacidites*, *Magnolipollis*, and *Tricolpopollenites* that Wang et al. (2000) previously reported. However, due to the serious effect of volcanic activities in the Yixian Formation of western Liaoning areas and the poor preservation of spores and pollen, we are unable to identify better angiosperm pollen fossils. Nevertheless, we believe that the angiosperm pollen we found is from late Valanginian or Hauterivian to Barremian stages in the Early Cretaceous. Our age speculation is consistent with the isotopic dating results. This may help resolve the inconsistency between biostratigraphic age and isotopic age in the Yixian Formation. It can also provide reference for the study of the Jurassic/Cretaceous boundary. Its significance is self-evident. Of course, more conclusive fossil evidence is needed to explore the origin of angiosperm pollen in western Liaoning and refine the chronostratigraphic correlation.

5.3 The evolution of paleoclimate

This study concludes that the paleoclimate then was warm and humid, which is consistent with the hot and humid environment in which the Jehol Biota lived at that time in western Liaoning area. Against the climate background in the Cretaceous, the temperature fluctuations in the Hauterivian-Aptian stages of the Early Cretaceous were particularly strong (Gerta, 2008). From the average temperature of 12–14°C in the Valanginian stage to 12–16°C in the Hauterivian stage and then to 16–24°C in Barremian-Aptian stage, the temperatures increased in volatility. Amiot et al. (2011) studied the oxygen isotope of reptile fossils such as dinosaurs in the Jehol biota of East Asia. Their results showed that it was a temperate climate in Barremian-early Albian of the Early Cretaceous in northeastern China, and the temperature was 10±4°C. These conclusions appear to be consistent with the dominant vegetation types of coniferous forest that we have shown. Therefore, the coexistence of various vegetation types and the 50% proportion of coniferous forest show that the dominant vegetation types of coniferous forest are indicative of the importance of vertical zonation in vegetation.

Vertical zonation of vegetation seems to suggest that the contrast of the surrounding topography may have been quite large during the deposition of the Yixian Formation in western Liaoning. Zhang et al. (2001a, 2001b) first proposed the idea of the existence of a plateau in eastern China, and other scholars have since discussed the possible exist-

ence of a plateau in eastern China from different perspectives. Therefore, inferredfrom the vertical zonation of vegetation types and the warm and humid paleoclimate, the geomorphological contrast may be large during deposition of the Yixian Formation in western Liaoning. However, more convincing evidence and additional inference synthesis through other approaches are needed in the future.

6 Conclusions

Through the above analysis, we come to the following conclusions.

(1) The palynomorph assemblage in the Zhuanchengzi Bed is *Protoconiferus-Cicatricosisporites*. The assemblage is dominated by gymnosperm pollen, especially pollen of bisaccate conifers. Pteridophyte spores were less abundant, and there were a few instances of possible angiosperm pollen.

(2) The palynomorph assemblage in the Zhuanchengzi Bed of the Yixian Formation may have been deposited in the late Valanginian or Hauterivian-Barremian periods of the Early Cretaceous.

(3) The overall paleoclimate during the period associated with the Zhuanchengzi Bed in the Yixian Formation was warm and humid, and palynological vegetation types were various, including coniferous forest, deciduous forest, evergreen broadleaf forest, herbs, and shrubs. Local paleoclimate evolved from warm to much warmer and from semi-humid to humid. The primary palynological vegetation type was always coniferous forest. The coexistence of deciduous forest, evergreen broad-leaf forest, herbs, shrubs, and some arid plants indicates vertical zonation of vegetation and seasonal climate changes.

(4) Inferred from the vertical vegetation types and the warm humid climate, the geomorphological contrast may have been large during deposition of the Yixian Formation in western Liaoning.

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