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Palynology of the Early Cretaceous Hanxia Section in the Jiuquan Basin, Northwest China: The discovery of diverse early angiosperm pollen and paleoclimatic significance

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ABSTRACT

The Lower Cretaceous deposits of the Jiuquan Basin (Northwestern China) located in central Asia are famous for the abundant and diverse fossil products with distinct characteristics of Jehol Biota. However, few early angiosperm remains have been published in their entirety. This study presents a palynomorph record from the recently reported fossil-bearing Zhonggou Formation of the Hanxia Section in the Jiuquan Basin. Here, we first discovered abundant and diverse angiosperm pollen with 16 taxa, which can be classified into four morphological types: tricolpate, polyaperturate, monosulcate and etrachotomocolpate apertures. The palynomorph assemblages contain a large number of biostratigraphically significant palynomorphs, such as numerically abundant tricolpate and rare polyaperturate angiosperm pollen grains, which indicate an Early Albian age for the Zhonggou Formation of the Hanxia Section. The overall palynomorph assemblage is dominated by the *Perinopollenites*, followed by the *Classopollis*; bisaccate pollen indicate Taxodiaceae-dominant vegetation types. As such, a relatively temperate and humid climatic condition is suggested for this area. Furthermore, two palynomorph assemblages can be distinguished in a stratigraphically upward order with an obviously increasing *Classopollis* content, indicating a gradual aridification trend during the Early Albian. This climatic change may affect the diversification of early angiosperms based on the correlation with the stratigraphic distribution of discovered angiosperm pollen.

1. Introduction

The diversification of angiosperms marks the profound change of the Mesozoic flora evolution. In particular, the radiation of the flora during the late Early Cretaceous represents one of the most radical changes in the evolution of Mesozoic terrestrial ecosystems, which include the change from ferns, conifers and cycads- to angiosperm-dominated flora within a time span of approximately 30 Ma (Lidgard and Crane, 1988; Crane et al., 1995; Hochuli et al., 2006). In this stage, an obvious vein density increase and phylliform complication was exhibited by the angiosperm mesofossil records (Archangelsky et al., 2009; Doyle, 2011; Feild et al., 2011). The early angiosperm pollen showed a sharp increase in morphology and abundance (Doyle and Robbins, 1977; Heimhofer et al., 2007; Heimhofer and Hochuli, 2010; Zhang et al., 2014). However, these fossil records are not comprehensively representative of the global fossil distribution. In particular, these flowering plant fossil records from the spacious inland of continents are relatively scarce.

The Jiuquan Basin is located in the northwest inland area of China, and contains a set of thick Lower Cretaceous deposits. This sedimentary sequence is famous for a variety of well-preserved fossils, such as birds, plants, insects, amphibians, mollusks, etc. (e.g. Hong, 1982; Hu and Xu, 2005; You et al., 2006; Deng and Lu, 2008). In recent years, the fossil-bearing top Zhonggou Formation of the Hanxia Section was repeatedly referenced for its numerous well-preserved fossils (Deng and Lu, 2008; Du et al., 2013; Dong et al., 2014; Zheng et al., 2015). This area was even regarded as the westernmost extension of Jehol Biota for the similar fossil assemblage and taphonomic characteristics (e.g. Chen, 1988; Wang, 1990; Zhou, 2006). However, it lacks the typical angiosperm remains (megafossil and microfossil) compared with the traditional Jehol Biota of western Liaoning, China. On the other hand, the Lower Cretaceous of Jiuquan Basin has substantial chronological uncertainties because of the lack of an effective fossil index or reliable absolute ages, although there are abundant fossil materials and volcanic lava layers (Li and Yang, 2004).

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In this study, we present a detailed palynological record including the early angiosperm pollen from the Zhonggou Formation of the Hanxia Section in the southwestern Jiuquan Basin. Based on our palynological data, we attempted to 1) provide a valuable biostratigraphic control for the Lower Cretaceous strata and 2) decipher the aspects of angiosperm diversification and paleoenvironments within this region.

2. Geological setting

The Jiuquan Basin is located at the convergence zone between the Qilian orogeny belt and the Altyn fault (Fig. 1); it is a small-sized petroliferous basin on the western end of the Hexi Corridor Basin group, north of the Qinghai–Tibet Plateau, with an area of 22,000 km^2 (Li et al., 2006; Pan et al., 2006; Chen et al., 2014). It is filled with Permian, Jurassic, Cretaceous and Cenozoic deposits. The Lower Cretaceous, as the main source of rock, is always a keystone strata of research. The thickness of which significantly varies from 1500 to 3000 m. There are three formations that are divided from the bottom to the top, the Chijinbao, Xiagou and Zhonggou formations. The Chijinbao and Xiagou formations have two coarse–fine–coarse-grained sedimentary cycles. The fine-grained sedimentary rocks are mainly composed of black oil shale, carbonaceous shale and gray mudstone. The Zhonggou Formation is characterized by the calcareous-clastic sedimentary rock with a grayish green color that distinctly differs from the underlying Chijinbao and Xiagou formations. From the middle, the reddish calcareous mudstone interlayers begin to emerge with a thickness of 20–30 cm for the single layers (Fig. 2). The Zhonggou Formation is well exposed at the Hanxia and Xinminbao sites. The presently published fossil materials were all collected from the Hanxia site (e.g. Du et al., 2013). In the western basin, there are also several layers of basaltic and andesitic lava interbedded within the lacustrine mudstone. The volcanic facies is more complicated, in which flood basalt facies, crater facies, and volcaniclastic facies all occur in this area.

So far, a large amount of diverse fossils were discovered from the Lower Cretaceous in the Jiuquan Basin. The fossil types include insects, ostracods, conchostracans, charophytes, bivalves, paleo-birds, megafossil plants, sporopollen, etc. (e.g. Hong, 1982; Hu and Xu, 2005; You et al., 2006; Deng and Lu, 2008). The characteristics of the fossil association can be correlated with the Jehol Biota. As such, it is also defined as the western extension of the Jehol Biota (e.g. Chen, 1988; Wang, 1990; Zhou, 2006). Therefore, the studied Hanxia section is one of the most productive fossil-bearing sites. In recent years, a large number of well-preserved fossils were published, such as dragonflies (*Hemeroscopus baissicus*, Zheng et al., 2015) and megafossil plants (*Pseudofrenelopsis*: Deng et al., 2005; *Brachyphyllum*: Du et al., 2013; *Equisetum*: Sun et al., 2013; *Athrotaxites yumenensis* sp.: Dong et al., 2014; and others, Deng and Lu, 2008; Dong et al., 2013). These fossil records provided important paleoclimatic and ecological information for the inland of East Asia during the Early Cretaceous.

Although rich in paleontology, the precise geological age and correlation of the Lower Cretaceous strata in the Jiuquan Basin remain unresolved, leading to various interpretations of its stratigraphic age. This stratum was first assigned to the Upper Jurassic. Until the 1970s to '80s, the age of the Early Cretaceous was proposed based on palynomorph and fish fossils (Hsü and Jiang, 1974; Ma, 1984; Jiang and Yang, 1986). However, studies on a more precise determination of the stratigraphic age are limited. Liu (2000) investigated palynological records from the Hanxia Section studied herein and established assemblages of *Cicatricosisporites*–*Schizaeoisporites*–*Classopollis*–*Jiaohepollis* for the Xiagou and Zhonggou formations, which were assigned to the

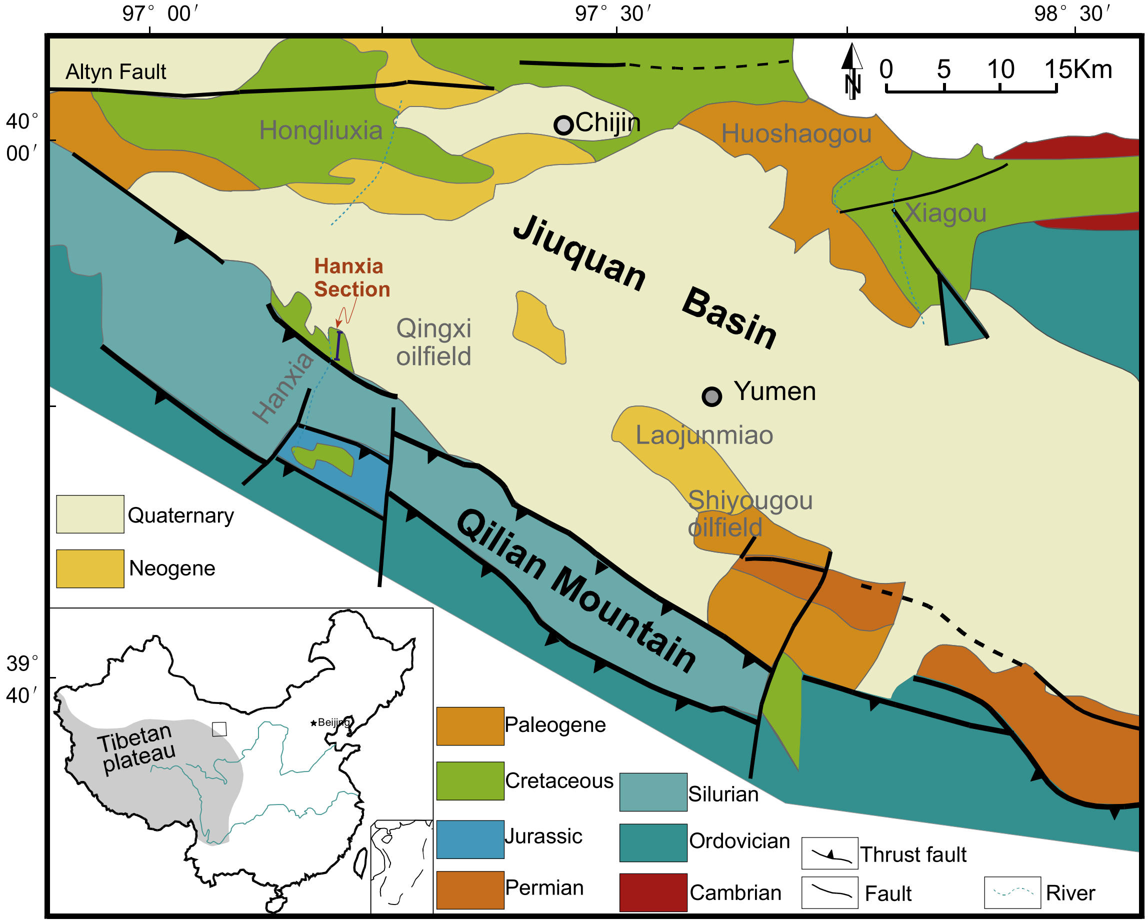

Fig. 1. Geological sketch map of the western Jiuquan Basin and the location of the studied section.

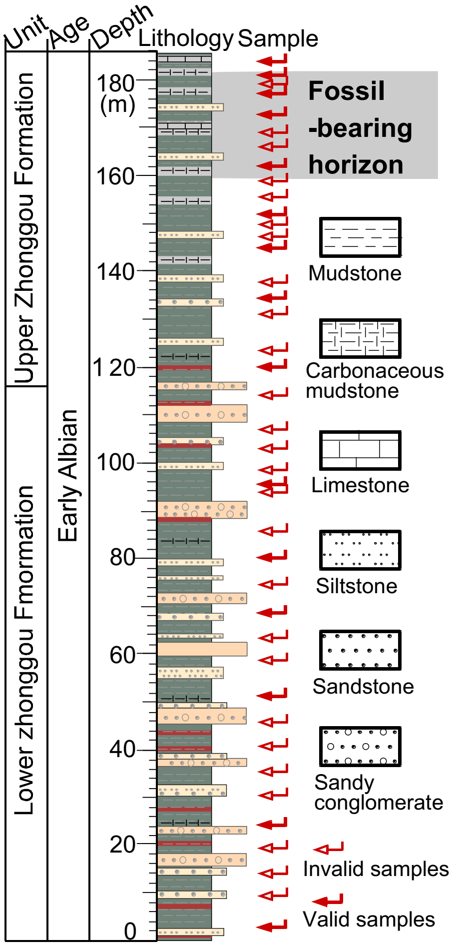

Fig. 2. Stratigraphy and sedimentary logs of the Zhonggou Formation in the Hanxia Section and the corresponding palynological samples.

Hauterivian–Barremian. Hu (2004) and Fu and Yuan (1998) reported diverse ostracod fossils within the Xiagou and Zhonggou formations from the Hongliuxia and Xinminbao sites. They correlated the Xiagou and Zhonggou formations to the Barremian. The lava layers within the Lower Cretaceous could have been important for age-control. The multiple discrepant radiometric age results (Yang et al., 2001; Li and Yang, 2004) and the fuzzy contact relationship with the sedimentary strata do not provide definite age-control for the Lower Cretaceous in the Jiuquan Basin.

3. Materials and methods

The material discussed herein was collected from the Zhonggou Formation exposed at the Hanxia section in the southwestern basin. The studied area is located in the west-north Gobi desert of China, which is an extremely hostile environment. The section was sampled alongside the northern Qilian Mountain where it is best exposed. The total thickness of the sampled strata was approximately 186 m. The sampled sequence can be divided into two parts, the Lower Zhonggou Formation and the Upper Zhonggou Formation. The Lower Zhonggou Formation is composed of gray–green shale, mudstone and purple to red mudstone and siltstone, and interbedded with coarse-grained sandstone and sandy conglomerate. A few thin gray calcareous mudstone layers also occurred. The fossil charcoals are rich in this sequence. The Upper Zhonggou Formation consists mainly of gray–green mudstone, calcareous siltstones and few mudstones, interbedded with fine-grained sandstones. Increasing carbonate composition also characterizes this part. The top horizon hosts a rich and diverse array of insects, fish, megafossil plants, etc. (approximately 160–182 m of the sampled section). A total of 41 samples were collected for palynological analysis from thin interbedded gray to greenish gray mudstone and shale.

For palynological preparation, sedimentary rock samples weighing between 30 and 50 g were processed using conventional acid treatment. The samples were treated with HCl and HF acid to remove carbonates and silicates, respectively. Separated palynomorphs from the residue were subsequently filtered through a 10 μm nylon sieve to remove the fine fraction. Finally, the palynomorph-productive residues were mounted on slides using glycerol for identification. All samples were studied using Zeiss AXO-40 microscope at the Laboratory of Petroleum Resources Research (Gansu province, China). Photomicrographs were taken using the digital camera installed in the microscope. Palynomorph determination was performed according to Song et al. (1999, 2000) and Gao et al. (1999). More than 300 grains in each sample (excluding the outlier, sample HX13) were determined to obtain statistically significant palynomorph abundance and diversity. All of the palynomorph slides are stored at the Key Laboratory of Petroleum Resources Research, Institute of Geology and Geophysics, Chinese Academy of Sciences.

4. Results

The results show that just 25 samples were palynologically productive. The HX13 sample was relatively poorly palynomorph-bearing, in which just 65 grains of spores and pollen were counted. There are 31 spore species and 60 pollen taxa, including 16 angiosperm pollen taxa. All palynomorphs are relatively well-preserved despite being slightly damaged. The color of the thin-walled palynomorphs ranged from light yellowish to orange, indicating a low level of thermal maturation. The representative palynomorphs are illustrated in Plates I and II, and their relative abundance and distribution within the sections are shown in Fig. 3A and B, respectively. The palynological assemblage is dominated by the gymnosperm pollen, followed by the fern spores. The angiosperm pollen contributed only minor amounts, but with morphologically diverse pollen taxa. These diverse angiosperm pollen were first discovered from this area in this study. Based on the identified distribution and abundance of spore-pollen in the stratigraphic succession, two palynomorph assemblages have been recognized. Their distribution and abundance characteristics are described below in ascending order.

4.1. Palynomorph assemblage I (PA I)

Palynomorph assemblage I (PA I) spans from the base to 135 m of the Hanxia section, roughly corresponding to the coarse clastic Lower Zhonggou Formation. It is characterized by a low content of *Classopollis* (average 9.5%) and a relatively high content of diverse spores (average 14.6%). The gymnosperm pollen are dominated by the pollen grains of taxodiacean affinity (including *Concentrisporites* and *Perinopollenites*) (average 47%). The bisaccate conifer pollen (including predominantly *Paleoconiferus*, *Piceites*, *Pinuspollenites*, *Podocarpidites*, *Protoconiferous*, *Protopinus*, and *Pseudopinus*) show a significant variation in abundance ranging from 2% to 37% (average 15%). *Ephedripites* are the common types, with an average of 4.2%, including three structural taxa, *Ephedripites* (Ephedripites) sp., *Ephedripites* (Spiralipites) sp., *Ephedripites* (Ephedripites) *sphaericus* and *Ephedripites* (Ephedripites) *mingshuiensis*. *Cycadopites* pollen are also common with an average of 3.3%. The Araucariaceae pollen including *Araucariacites australis* and *Callialasporites dampieri* are rare in the assemblage. All other pollen types such as *Cerebropollenites*, *Jiaohepollis* and *Chasmatosporites* occur at very low numbers.

The fern spores are abundant, though numerically subordinate. The *Cyathidites* and *Deltoidospora* are the dominant types, which account for an average of 6.4% of the total. The subordinated taxa of spores are *Cicatricosisporites* (average 1.4%), with diverse species shown in Fig. 3A and B. Other spore types such as *Densoisporites velatus*, *Foveotriletes subtriangularis*, *Hsuisporites* sp. and *Osmundacidites alpines* are characterized by a very low abundance.

The angiosperm pollen have a low abundance but have a relatively high diversity. All taxa levels are below 3% of the total palynomorph. Most pollen type content was below 1% and was not obviously statistically significant. In this assemblage, the angiosperm pollen are mainly composed of tricolpate types, including *Tricolpites amplifissus*, *Tricolpites* sp. 1, *Retitricolpites* sp., *Retitricolpites* sp. 1, cf. "*Retitricolpites* sp.", *Rousea* sp., cf. and "*Rousea* sp.". The polyaperturate forms were also discovered in this assemblage, although with low content. There was just one grain of *Asteropollis asteroids* discovered from the HX18 samples.

4.2. Palynomorph assemblage II (PA II)

This assemblage corresponds stratigraphically to the part of the calcareous mudstone of the Upper Zhonggou Formation (between 135 m and 186 m, Fig. 2). It is characterized by increasing amounts of *Classopollis* (from 0.8% to 29%, average 14.6%) and the low spore content. The gymnosperm pollen are still dominant, as evidenced by numerous *Perinopollenites* (54.3%) of taxodiacean affinity, with an obvious decreasing trend at the top of sampled sequence. The bisaccate conifer pollen presents an obvious increasing trend from 2.8% to 32%, with an average of 14.8%. The *Ephedripites* content was not largely changed compared to the PF I, but a new species appeared, *Ephedripites* (Ephedripites) *mingshuiensis*, consisting of just two grains from the HX37 samples at 175 m of the Hanxia section. *Cycadopites* and *Jugella* are the common types. The other types such as *Callialasporites*, *Cerebropollenites*, *Chasmatosporites* and *Jiaohepollis* are rare.

The abundance and diversification of fern spores are obviously low compared to the PF I. The *Cyathidites* (average 0.2%) and *Deltoidospora* (average 2.6%) are relatively rare in the samples. The *Cicatricosisporites* content (average 0.4%) was also less than the PF I. The other rare types are *O. alpines*, *Lygodiumsporites japoniciformis*, *Leptolepidites* sp., *O. alpines*, etc.

The angiosperm pollen group in this assemblage is characterized by the abundance and diversification of tri- or tetrachotomocolpate aperture *Asteropollis* and columellate-tectate *Clavatipollenites*. The tricolpate pollen types were moderately less than PF I, including *Tricolpites* sp., *Retitricolpites* sp., *Retitricolpites* sp. 2 and cf. "*Retitricolpites* sp.". Two *Poloyporites* types were also discovered in samples HX 40 and 41, but the content was very low.

5. Discussion

5.1. The characteristics of early angiosperm pollen

This diverse early angiosperm pollen group from the Jiuquan basin is the first discovery of its kind. The previous palynological studies of the Lower Cretaceous of this area only reported one particular angiosperm pollen type (*Tricolpites gansuensis* sp. nov.) (Jiang and Yang, 1986). Another reported species (*Magnoliaepollenties gansuensis* sp. nov.) might not belong to the early angiosperm pollen based on its shape in the fossil plate and the taxa description (Jiang and Yang, 1986). These fossil records were not given the explicit fossil-bearing horizon or sites in the studies. After that, Liu (2000) specifically performed a palynology study for Hanxia Section; unfortunately, angiosperm pollen was not discovered.

Morphological diversification characterized the studied angiosperm pollen group of the Jiuquan Basin and can be divided into four types, tri- or tetrachotomocolpate aperture, columellate-tectate, tricolpate and polyaperturate. However, the diversity and abundance are low compared to angiosperm pollen assemblies from coastal regions of the world (Doyle and Robbins, 1977; Gao et al., 1999; Heimhofer et al, 2007; Zhou et al., 2009; Heimhofer and Hochuli, 2010). The monocot and magnoliid pollen are especially scarce, such as *Pennipollis* and *Retimonocolpites*. This similar phenomenon also occurred at the Yingen–Ejinaqi and Erlian Basins at mid-western Inner Mongolia, in central Eurasia (Hua, 1991; Zhang et al., 2014). The environmental difference among the different regions may be the main cause of this globally disproportionate distribution of early angiosperm diversification.

On the other hand, the distribution of these pollen types along the stratigraphic sequence showed great differentiation (Fig. 4). The monocots and tetrachotomocolpate pollen (*Clavatipollenites* and *Asteropollis*) mainly occurred at the top horizon of the section, from approximately 152 m in the section. In particular, samples 40 and 41 are mostly rich in these pollen types. The polyaperturate pollen was also distributed in the top horizon, similar to the monocots and tetrachotomocolpate types. On the contrary, the tricolpate pollen was missing at the top part of the section, and almost continuously and abundantly occurred in the lower-middle parts. In view of the evolutionary history of angiosperm pollen, the monocots and tetrachotomocolpate types originated from the monocotyledon plants, which occurred earlier than the tricolpate and polyaperturate pollen produced by eudicotyledon angiosperm (Heimhofer et al., 2007; Heimhofer and Hochuli, 2010). As such the distribution differentiation of these angiosperm pollen on the sedimentary sequence is likely not caused by evolution. The environmental conditions may have an important role in the early angiosperm diversification in this study.

5.2. The age of Zhonggou formation based on palynostratigraphy

So far, the stratigraphic age of the lower Cretaceous in the Jiuquan Basin remains unclear, due to multiple conflicting biostratigraphic frames based on sporopollen (Liu, 2000) and ostracod (Fu and Yuan, 1998; Hu and Xu, 2005) as well as the various age results for volcanic lava (Yang et al., 2001; Li and Yang, 2004; Li et al., 2013). Many newly discovered palynomorphs in this study, especially angiosperm pollen from the Zhonggou Formation, may provide a more reliable biostratigraphic frame. The palynomorph assemblage shows a typical aspect of Early Cretaceous palynofloras. *Cicatricosisporites*, *Ephedripites*, *Jiaohepollis* and *Jugella* are relatively typical taxa groups from the Lower Cretaceous (e.g. Gao et al., 1999; Li and Liu, 1994; Herngreen et al., 1996).

Plate I. Representative taxa of the palynological assemblages recovered from the Hanxia Section. The scale bar is 20 μm.
1, *Undulatisporites undulapolus*, HX10 (1), 53 m; 2, *Deltoidospora* sp., HX13 (1), 70 m; 3, *Undulatisporites undulapolus*, HX23 (1), 121 m; 4, *Punctatisporites minutes*, HX10 (1), 53 m; 5, *Cyathidites* sp., HX15 (1), 82 m; 6, *Densoisporites* velatus, HX15 (1), 82 m; 7, *Cicatricosisporites mediotriatus*, HX26 (1), 135 m; 8, *Cicatricosisporites minor*, HX38 (2), 180 m; 9, C. *Cicatricosisporites pseudotripartitus*, HX34 (1), 164 m; 10, *Converrucosisporites* sp., HX10 (1), 53 m; 11, *Cerebropollenites carlylensis*, HX34 (1), 164 m; 12, *Classopollis annulatus*, HX38 (1), 180 m; 13, *Jiaohepollis flexuosus*, HX41 (1), 186 m; 14, *Cycadopites typicus*, HX5 (1), 25 m; 15, *Cycadopites* sp., HX15 (1), 82 m; 16, *Ephedripites* (Ephedripites) *mingshuiensis*, HX37 (1), 175 m; 17, *Ephedripites* (Spiralipites) sp., HX26 (2), 135 m; 18, *Ephedripites* (Ephedripites) sp., HX18 (1), 97 m; 19, *Jugella* sp., HX37 (1), 175 m; 20, *Concentrisporites fragilis*, HX38 (1), 180 m; 21, *Perinopollenites elatoides*, HX18 (1), 97 m; 22, *Ephedripites* (Ephedripites) *sphaericus*, HX26 (1), 135 m; 23, *Perinopollenites* sp., HX5 (1), 25 m; 24, *Exesipollenites tumulus*, HX26 (1), 135 m; 25, *Leptolepidites* sp., HX23 (1), 121 m; 26, *Chasmatosporites major*, HX18 (1), 97 m.

Plate II. Taxa of the angiosperm pollen recovered from the Hanxia Section. For each illustration, section depth and sample number are given. (see on page 6)
1, *Retitricolpites* sp. HX23 (2), 121 m; 2, *Retitricolpites* sp., HX31 (2), 153 m; 3, cf. "*Retitricolpites* sp.", HX26 (2), 135 m; 4, cf. "*Retitricolpites* sp.", HX26 (2), 135 m; 5, cf. "*Retitricolpites* sp.", HX23 (2), 121 m; 6. *Retitricolpites* sp. 1, HX23 (2), 121 m; 7, *Retitricolpites* sp. 2, HX31 (1), 153 m; 8, *Tricolpites* sp., HX31 (1), 153 m; 9, *Retitricolpites* sp. 3, HX5 (1), 25 m; 10, cf. "*Retitricolpites* sp.", HX5 (1), 25 m; 11–13, *Retitricolpites* sp. 4, HX5 (1), 25 m; 14, 15, *Retitricolpites* sp. 4, HX5 (1), 25 m; 16, 17, *Retitricolpites* sp. 4, HX5 (1), 25 m; 18, *Retitricolpites* sp. 2, HX37 (2), 175 m; 19, 20, *Retitricolpites* sp. 4, HX5 (1), 25 m; 21, cf. "*Rousea* sp.", HX31 (1), 153 m; 22, 23, *Polyporites* sp., HX23 (2), 121 m; 24, *Polyporites* sp. 1, HX41 (2), 186 m; 25, *Polyporites* sp. 1, HX23 (2), 121 m; 26, 27, *Asteropollis* sp., HX40 (1), 183 m; 28, *Clavatipollenites* sp., HX40 (1), 183 m; 29, *Clavatipollenites hughesii*, HX40 (2), 183 m; 30, *Clavatipollenites* sp. HX41 (2), 186 m; 31, 32, *Clavatipollenites* cf. *hughesii*, HX41 (2), 186 m.

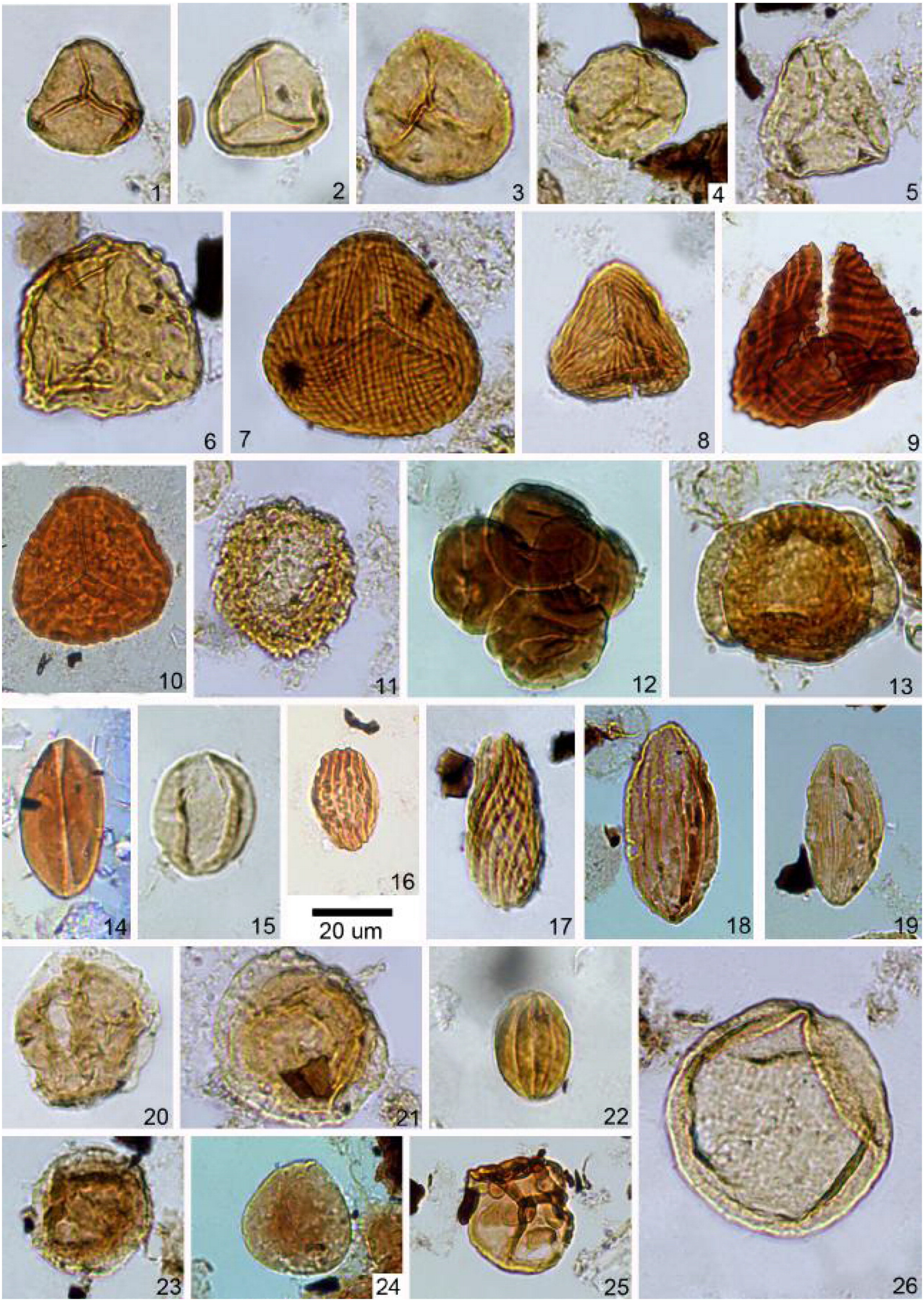

Plate I

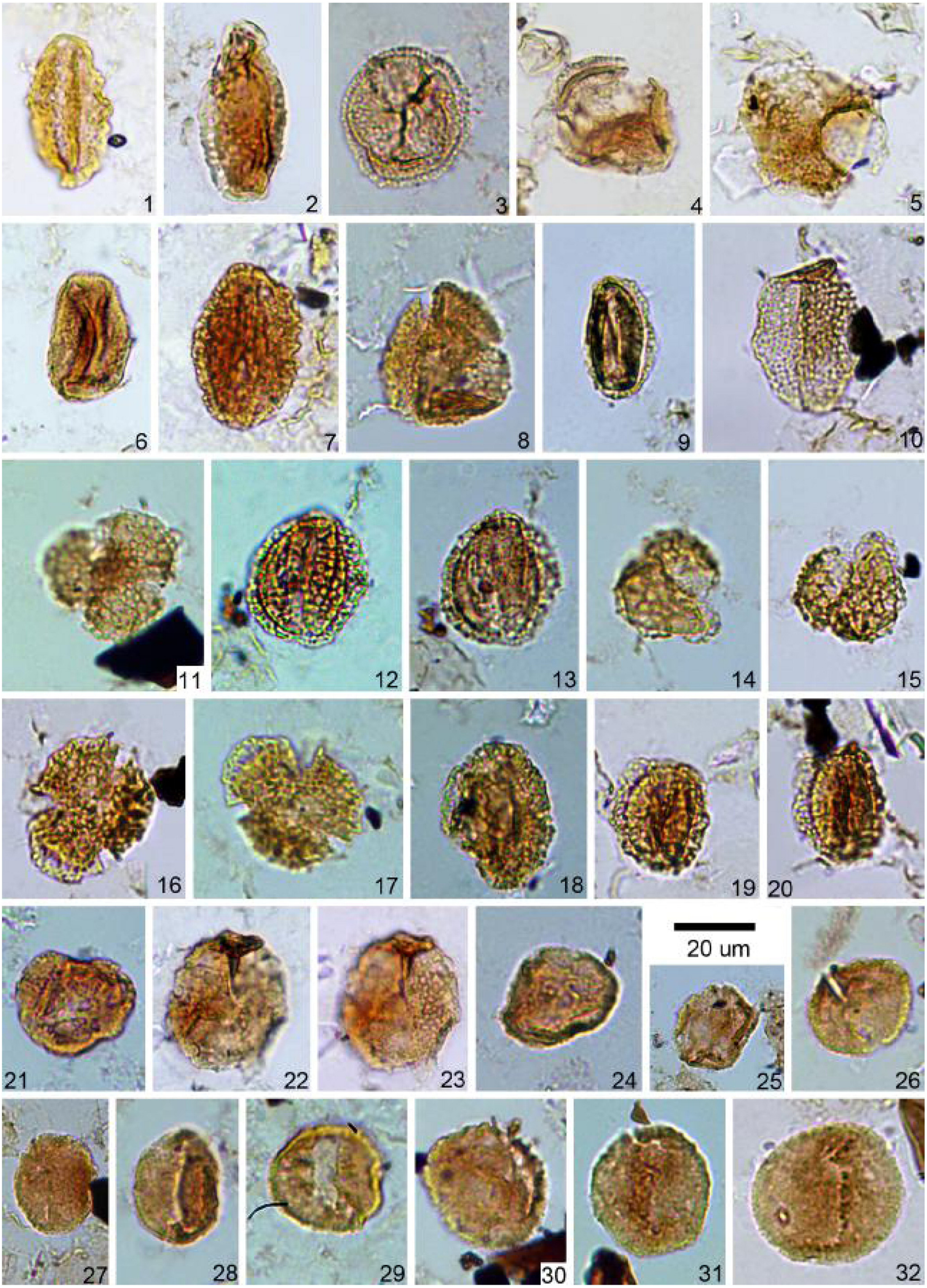

Plate II (*caption on page 4*).

Furthermore, the morphologically diversified *Cicatricosisporites* and *Ephedripites* are widely distributed in the mid-late Early Cretaceous. Furthermore, the *Cicatricosisporites* genus again becomes less abundant and diverse since the early Late Cretaceous. The *Jugella* and *Ephedripites* occasionally occur in the Early Cretaceous, and then become more common and morphologically diversified from the Barremian (Hochuli, 1981; Schrank, 1992; Herngreen et al., 1996; Gao et al., 1999). These palynomorphs have age and diagnostic significance and are all diversified in the upper Zhonggou Formation. In particular, very low content of *Ephedripites* (Ephedripites) *mingshuiensis* was discovered from the upper sampled section. This type generally occurred in the Late Cretaceous deposits, such as the Mingshui Formation of Songliao Basin (Gao et al., 1999) and the Taizhou Formation of Jiangsu Province, China (Zhou et al., 2009). The abovementioned palynomorphs are more likely to indicate a sedimentary sequence of the late Early Cretaceous or a younger age for the studied Upper Zhonggou Formation.

The early angiosperm pollen are usually used as age-diagnostic fossils for terrestrial deposits, due to their rapid radial evolution (e.g. Li et al., 2011). The various early angiosperm pollen types from the Jiuquan Basin provide a good opportunity for the biostratigraphic control of the Lower Cretaceous. The *Clavatipollenites* that occurred in the upper sampled section usually have a wide evolutionary range from the Early Cretaceous to the earliest Late Cretaceous. The *Asteropollis* have a relative narrow time span from approximately the latest Barremian to the Cenomanian in China (e.g. Zhang et al., 2014). The tricolpate pollen occurred later, generally from the early Albian, excluding the equatorial region with a slightly earlier time than other areas (e.g. Heimhofer and Hochuli, 2010). The age of the *Poloyporites* genus also occurred in the latest Early Cretaceous slightly later than the emergence time of tricolpate pollen in China (Hua, 1991; Zhang, 1999). Based on the evolutionary time-span of the above pollen taxa, the age of the upper Zhonggou Formation is not likely to be earlier than the Albian. However, it is not as likely as the Late Cretaceous because of the lack of some typical age-diagnostic pollen. The abundance and diversity of angiosperm pollen do not reach the level of the Late Cretaceous, even the late Albian (Gao et al., 1999; Li et al., 2011). This discovered angiosperm pollen assemblage also lacks tricolporate pollen, which usually emerged from the late Albian. We therefore conclude that the sampled Zhonggou Formation is early Albian in age based on these age-diagnostic palynomorphs.

The volcanic lavas in the Jiuquan Basin are well developed in the Lower Cretaceous, however, the contact relationship between them remains unclear (Li and Yang, 2004; Wang et al., 2004). So far, the ages of these lava layers greatly differ. The two lava layers exposed at this studied Hanxia section were respectively dated at 123.8 ± 2.6 Ma and 115.0 ± 4.5 Ma using the single zircon U–Pb isotope method (Li et al., 2013). Li and Yang (2004) reported many K–Ar ages of the volcanic lavas for different bearing sites in the Basin: 106.6 ± 2.2, 112.0 ± 0.6 Ma and 82.05 ± 0.8, 82.05 ± 2.87 Ma for the Hongliuxia area, 99.2 ± 1.2, 105.3 ± 1.3 Ma for the Beidayao area, and 112.8 ± 3.4, 118.8 ± 3.6 Ma for the Changma area. Further analysis can be summarized as these various volcanic lavas bearing mainly the Aptian time-span (110–125 Ma). This age is obviously earlier than the Zhonggou Formation which indicates that these volcanic lavas are underlying sediments for the Zhonggou Formation, inconformable contact with the Lower Cretaceous sedimentary rock in the Jiuquan Basin.

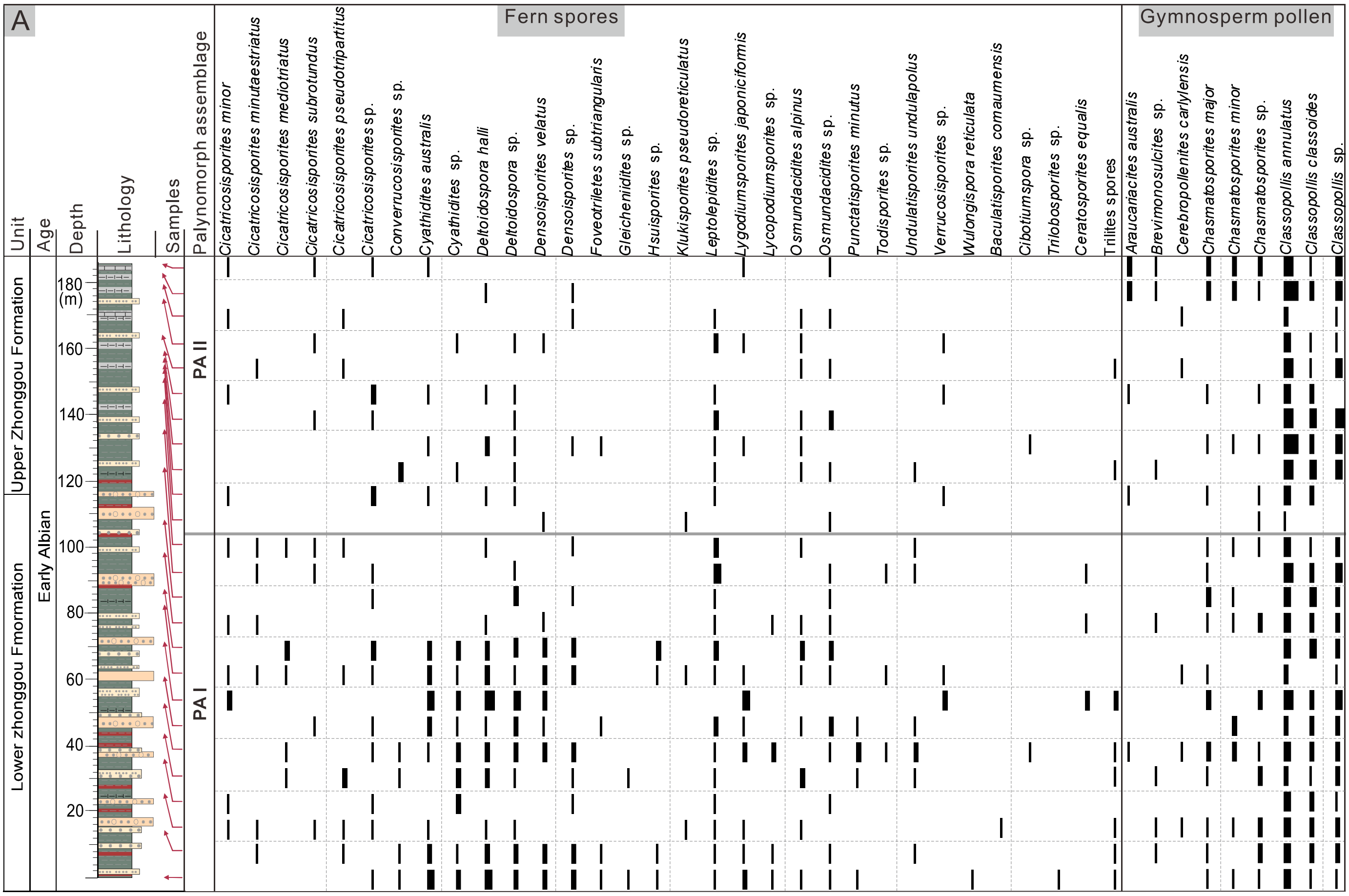

Fig. 3. A and B. Quantitative stratigraphic distribution of spores and pollen in the present study.

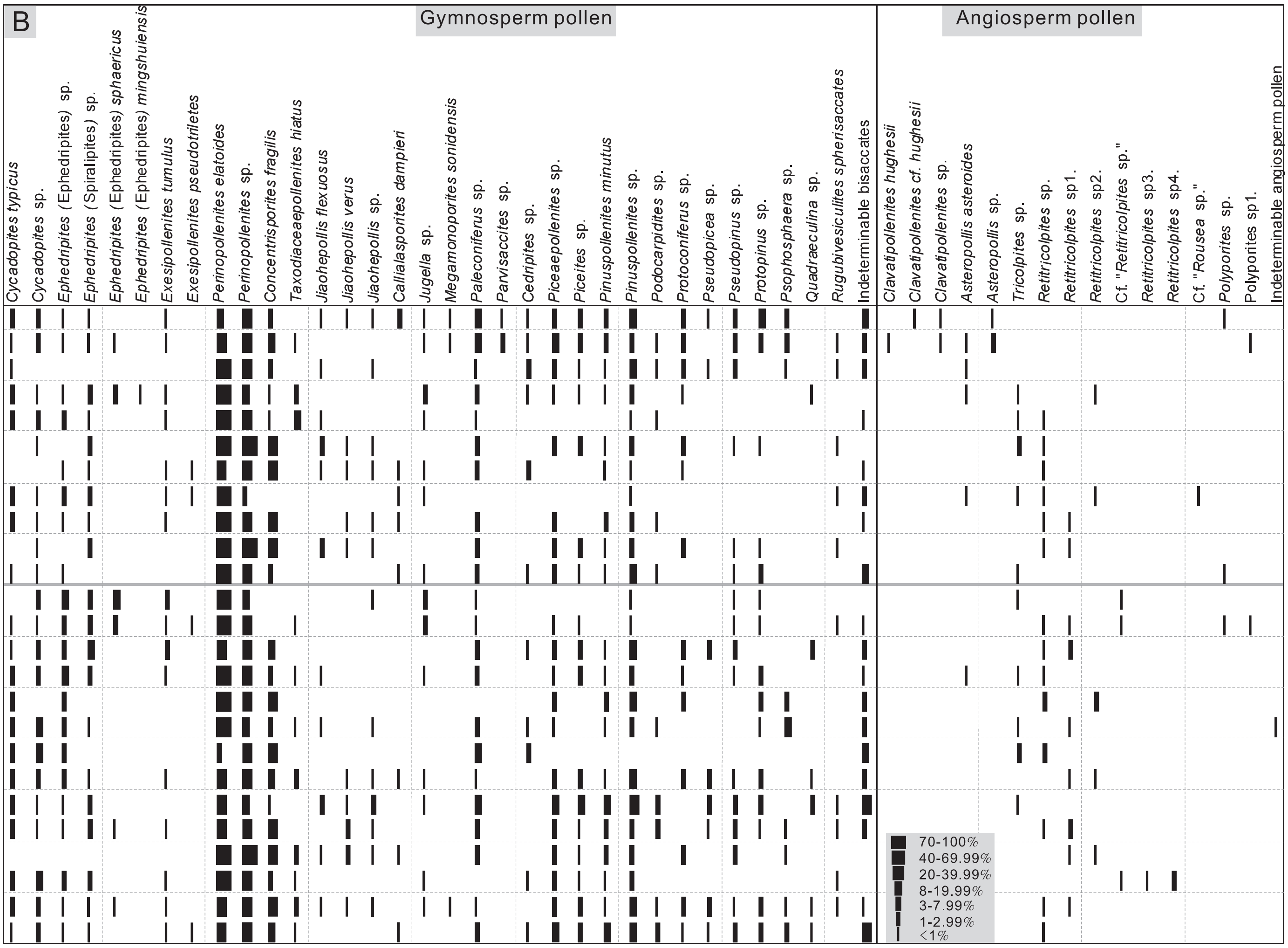

Fig. 3 (*continued*).

5.3. Paleovegetation and paleoenvironment

The total palynological assemblage of the upper Zhonggou Formation reflects a relatively high diversity of the corresponding flora. The dominant *Perinopollenites* pollen are estimated to have been produced by the Taxodiacean conifers, a common fossil plant type in the studied section (Deng and Lu, 2008; Dong et al., 2014). These parent plants (such as *Athrotaxites* and *Elatides*) mainly grow in high latitude regions in cold and humid conditions (Miller and LaPasha, 1983; Chen and Deng, 1990; Wan, 1996; Sun et al., 2001; Volynets, 2009). The common *Classopollis* elements produced from drought-resistant and thermophilous Cheirolepidiacean conifers show leaf and wood structures indicative of adaptation to seasonally arid conditions (e.g. Du et al., 2013, 2014). These megafossil plant types are also common in the studied section (Du et al., 2013) corresponding to the high *Classopollis* content horizon. The Bisaccate pollen with a large variation in content are produced by the Podocarpaceae and Pinaceae, which are indicative of relatively dry upland or boreal realm vegetation with a relatively cold climate (Vakhrameyev, 1982; Abbink et al., 2001). Spore-producing pteridophytes with characteristics of relatively moist and thermophilic vegetation prefer to live along riversides and/or in coastal lowlands (e.g. Abbink et al., 2001). The ephedraceae pollen at a relatively low content are usually considered as indicators of warm semi-arid to arid environments and extreme temperature conditions based on the modern ephedraceae plant adaptability (Yi et al., 1993; Yang, 2002; Herzschuh et al., 2004). In general, all of angiosperm pollen are of uncertain botanical lineage or lack any comparable modern taxa. Here, the angiosperm flora still did not contain plants as reflected by the very minor contribution of pollen content. Thus, palynological assemblage from the upper Zhonggou Formation inferred vegetation comprising the Taxodiacean, Cheirolepidiacean and Podocarpaceae/Pinaceae with subordinate pteridophytes, ephedraceae, angiosperm flora and others. This characteristic vegetation indicated a relatively temperate and semi-humid climate, with frequent seasonal dryness. This climate likely equated to the adjacent Gongpoquan Basin in the northwest, as they have similar vegetation types (Tang et al., 2001). However, their climatic conditions are wetter and colder than the eastern adjacent Hekou and Liupanshan Basins which have high xerophytic and thermophilous Cheirolepidiaceae-producing *Classopollis* content (>50%) (Yu et al., 1982; Li and Du, 2006; Zhang et al., 2012). This may be the result of the effects from western Tethys based on the strength of westerly circulation at midlatitudes.

The vegetation compositions were obviously changed from PF I to PF II in ascending stratigraphic order. Generally, the vegetation of the sampled section is characterized by an increasing trend of drought-resistant Cheirolepidiacean flora reflected by the *Classopollis* content from base to top, which indicates a gradually intensified aridification trend. In particular, the Cheirolepidiacean flora flourished the most in samples HX40 and 41 at the top horizon of the section. It is interesting to note that the angiosperm pollen are almost totally composed of monocots and tetrachotomocolpate types (*Clavatipollenites*, *Asteropollis*), which were barren in PF I of the lower stratigraphic horizon. In contrast,

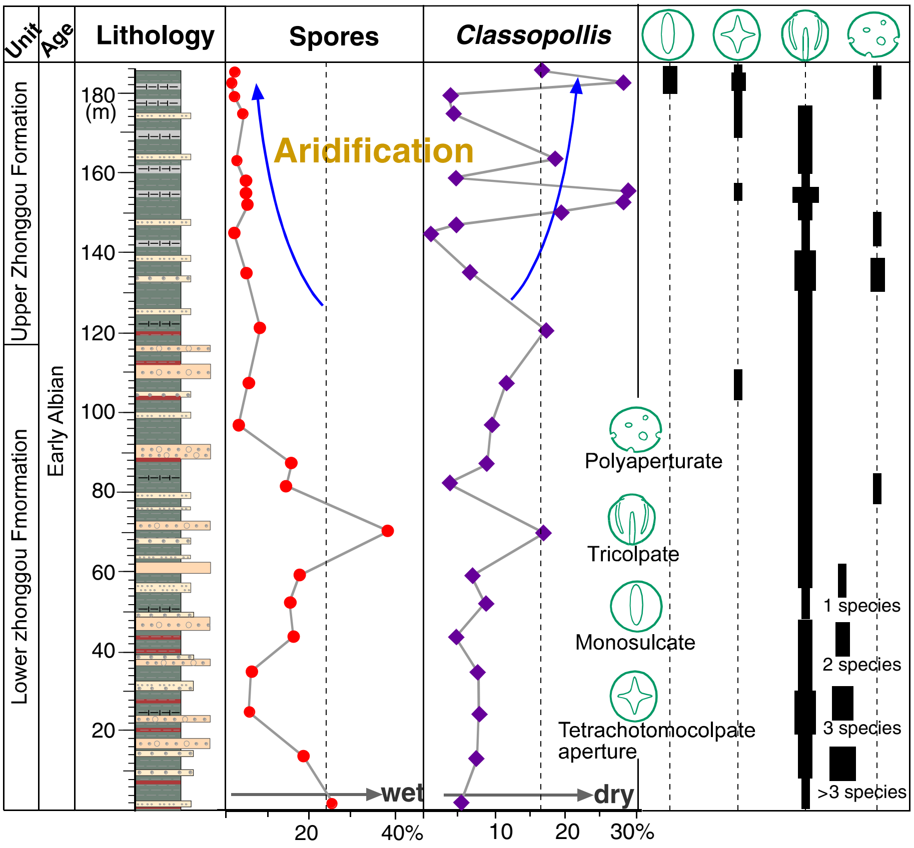

Fig. 4. The correlation between climate-indicating palynomorph (spores and *Classopollis*) percentages and the distributions of angiosperm pollen of the Zhonggou Formation during the Albian.

eudicotyledon pollen (tricolpate) are abundant in the lower to middle horizon corresponding to a relatively humid climate. We speculate that the parent plant of tricolpatepollen most likely grew in a wet environment. The tricolpate pollen of low-latitude generally occurred earlier than the high latitude region (Archangelsky et al., 2009; Heimhofer and Hochuli, 2010). The moist and shady disturbed habitats along the paleoequator more likely facilitated the earlier development of this angiosperm type. On the contrary, *Asteropollis* as the representative tetrachotomocolpate pollen, is prosperous in the middle and high latitudes of the earth (Zhang et al., 2014). Considering the global distribution of these pollen types, we have more reason to speculate that the relatively dry condition is beneficial to the growth of monocotyledon pollen. The distribution range of polyaperturate pollen is similar to the *Asteropollis* types, which implies that dry conditions are suitable for parent plants of these pollen types, while the tricolpate pollen with eudicotyledon affinities were more likely to grow in humid environments.

6. Conclusion

1) The palynological study of the Hanxia Section outcrops with fossil-bearing deposits revealed diverse palynoflora assemblages. It is noteworthy that a very diverse angiosperm pollen group (16 taxa) was recognized. The abundant and diverse tricolpate and rare polyaperturate angiosperm pollen are the first to be discovered in this area. The palynomorph composition is dominated by the *Perinopollenites* types as a whole. Furthermore, two palynological assemblages can be distinguished in the sedimentary rocks of the sampled section based on the abundance of palynomorph taxa.
2) The two palynomorph assemblages contain abundant biostratigraphically significant palynomorph genera, especially angiosperm pollen, which suggests overall, the age of the early Albian for the Upper Zhonggou Formation of the sampled section. Our study showed that this age is much younger than previously thought based on biostratigraphy. It is also younger than most volcanic age data indicate because these volcanic lavas have underlying sedimentary rock.
3) A reconstruction of the vegetation shows Taxodiaceae-dominated forests with subordinate Cheirolepidiaceae, Pinaceae and few pteridophyte plants, indicating a relatively temperate and humid climatic condition. The vegetation change from the bottom to the top of the sampled section also suggests a gradual aridification trend during the early Albian. These climatic conditions may affect the diversification of early angiosperms.

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