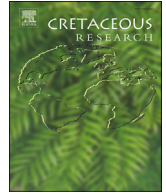




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Short communication

Discovery of water fern megaspore *Ghoshispora* and new dating for the Upper Cretaceous Yong'ancun Formation in Jiayin, NE ChinaFei Liang^{a, b}, Xiao Tan^{a, b}, Yujin Zhang^c, Yuhui Feng^{a, b, **, *}, Eugenia Bugdaeva^d,
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ARTICLE INFO

Article history:

Received 12 April 2023

Received in revised form

24 July 2023

Accepted in revised form 6 August 2023

Available online 10 August 2023

Keywords:

Upper Cretaceous

Yong'ancun Formation

Zircon dating

Ghoshispora

Santonian

ABSTRACT

The Upper Cretaceous Yong'ancun Formation of the Jiayin area, outcropping along the Heilongjiang (Amur) River in China and yielding fossil plants and dinosaurs, has been considered Santonian in age mainly based on palynostratigraphic studies. Until now, there is no document on isotopic dating and guide fossils from this formation, limiting stratigraphic correlation with its equivalents from adjacent basins. This study reports a new age (84.64 ± 0.65 Ma, late Santonian) for the Yong'ancun Formation based on zircon LA-ICP-MS U–Pb dating for the first time from a rhyolitic tuff in the top of the unit. *Ghoshispora*, a fossil genus of megaspore of water fern is also reported for the first time, co-occurring with other valuable guide fossils such as *G. zhaoi* and *G. triangulata*. Based on the presence of *Ghoshispora* and plant megafossils, the flora of the Yong'ancun Formation is now interpreted to reflect a moist and warm climate, implying that the temperature dropped from high (mid-Cretaceous thermal maximum, KTM) to moderate warm and wetter conditions, at least in the Heilongjiang (Amur) inland region, close to the paleo-Pacific Ocean. The new discovery and dating evidence could provide valuable data for the correlation with the Yaojia Formation of the Songliao Basin, China.

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1. Introduction

The Late Cretaceous is a critical time interval, witnessing the turnover from warm to cooler climates (Linnert et al., 2014; Jones et al., 2022). Fossil plants are key indicators for climate change. The Upper Cretaceous non-marine strata are widely distributed in Northeast China, particularly in the Songliao Basin and Jiayin area (Chen et al., 2003; Sha, 2007; Wan et al., 2007; Sun et al., 2011), providing important data to study of the climate transition in this interval. In recent years, integrated bio-, chemo-, and magnetostratigraphic studies, and radiometric dating have been undertaken for the Upper Cretaceous cores in the Songliao Basin

(Chamberlain et al., 2013; Deng et al., 2013; Wan et al., 2013; Wang et al., 2013; Xi et al., 2019). The results provide a standard for stratigraphic correlation and divisions of the Upper Cretaceous in China, particularly for the eastern part of NE China. The Upper Cretaceous strata of the Jiayin area are well exposed along the Heilongjiang (Amur) River, the border of China and Russia. These strata have been considered as the marginal deposits of the Zeya-Bureya Basin, Russia (IBP et al., 2001). The Yong'ancun Formation in Jiayin yields many important fossils such as dinosaur track *Jiayinosauropis*, aquatic angiosperm *Nelumbo jiayinensis*, angiosperm *Dalembia*, and abundant spores and pollen (BGMRH, 1993; Dong et al., 2003; Markevich et al., 2005; Sun et al., 2007, 2011, 2020; Liang et al., 2018). This formation has been correlated to the Middle Kundur Formation of the Zeya-Bureya Basin, Russia and the Yaojia Formation of the Songliao Basin, both of which are considered Santonian in age (Markevich et al., 2005; Sun et al., 2011; Liang et al., 2015). Accurate dating has been lacking and guide fossils are missing, and there is no report on volcanic tuffs from the Yong'ancun Formation. In 2021, the authors have found rhyolitic tuff

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layers at the top of the Yong'ancun Formation and have collected zircons for radiometric dating. We have also carried out palynological studies, newly recording thirteen species in eight genera, including the megaspore of water fern *Ghoshispora*, a valuable stratigraphic marker from the Yong'ancun Formation. These palynomorphs cooccur with other megafossils, including abundant aquatic angiosperms *Nelumbo*, *Cobbania*, *Quereuxia*, warm temperate *Ginkgo* and conifers, all of which indicate a moist and warm climate. The results of these observation imply that the temperature changed from high during the Cretaceous Thermal Maximum (KTM) to moderate warm and wetter conditions, at least in the inland areas of the Heilongjiang (Amur) River region which was located nearby the paleo-Pacific Ocean during the Santonian (middle Late Cretaceous). The new record of water fern megaspore helps clarify the relationships among the Jiayin area, Songliao and Zeya-Bureya basins during the Santonian.

2. Material and methods

All radiometric dating and palynomorph samples were all collected from the Upper Cretaceous in the Yong'ancun Formation at the East Hill of the Yong'ancun village, Jiayin County of Heilongjiang Province in Northeast China. The Jiayin County is located in the southeastern margin of the Zeya-Bureya Basin of Russia, and more than 500 km to the northeast of the Songliao Basin (Fig. 1A). The rhyolitic tuff samples for dating and five samples of spores and pollen were all collected from the upper part of the Yong'ancun

Formation which is composed mainly of alternating yellow-brown, cross-bedded sandstones, greyish-brown siltstones and mudstones (Fig. 1B). The rhyolitic tuff is composed of embayed quartz, angular feldspar and some biotite fragments (ca. 12%) and volcanic ash (ca. 88%) with a tuffaceous texture and some feldspar grains having been altered to chlorite (Fig. 2).

2.1. Palynological analysis

Each palynological sample was crushed and macerated using 30% HCl reagent for more than 6 h, and then rinsed with distilled water for more than three times. Afterwards, each sample was treated with 40% HF for more than 48 h and washed with distilled water, macerated with 5% KOH, followed by washing with distilled water. Finally, prepared samples were mounted on microscope slides, observed and photographed using a Leica DM3000 light microscope. All prepared slides are housed in the College of Paleontology of Shenyang Normal University, in Shenyang, China.

2.2. U–Pb dating

The tuff textures (Fig. 2) were analyzed in single and crossed polarized light with a polarizing microscope (Olympus BX53). Zircon particles were separated using heavy liquid (bromoforn) and magnetic techniques at the Langfang Yuneng Mineral Technology Service of Hebei Province, China. The preferred zircon crystals were mounted in epoxy resin and further polished to

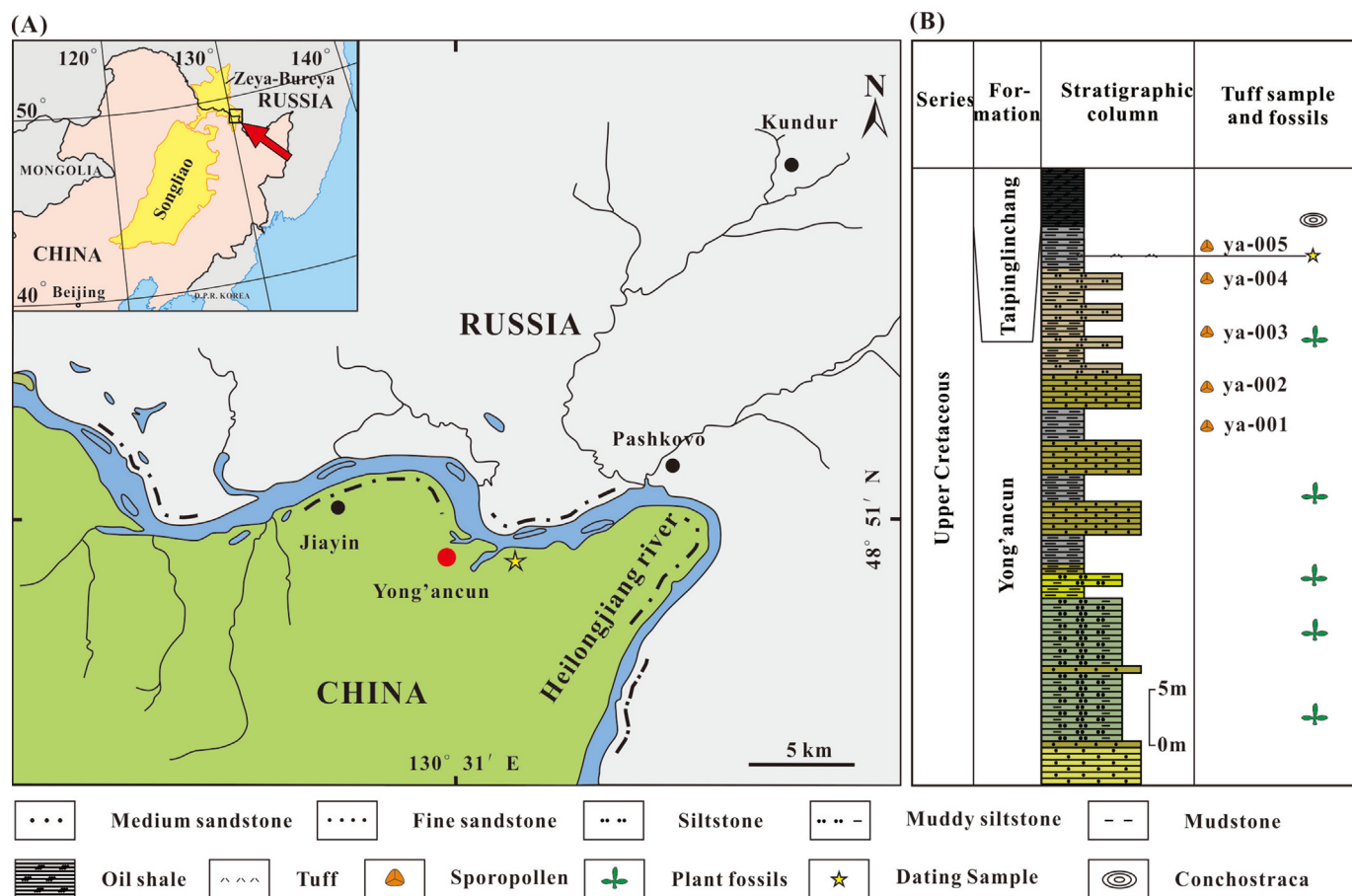


Fig. 1. Fossil site and stratigraphic column of the Yong'ancun Formation. (A) Locations of the Yong'ancun Formation. The red arrow shows the geographic position of Jiayin County; (B) The composite stratigraphic column showing the upper Yong'ancun Formation and its overlying Taipinglinchang Formation, next to the occurrence of the rhyolitic tuff samples, and fossils.

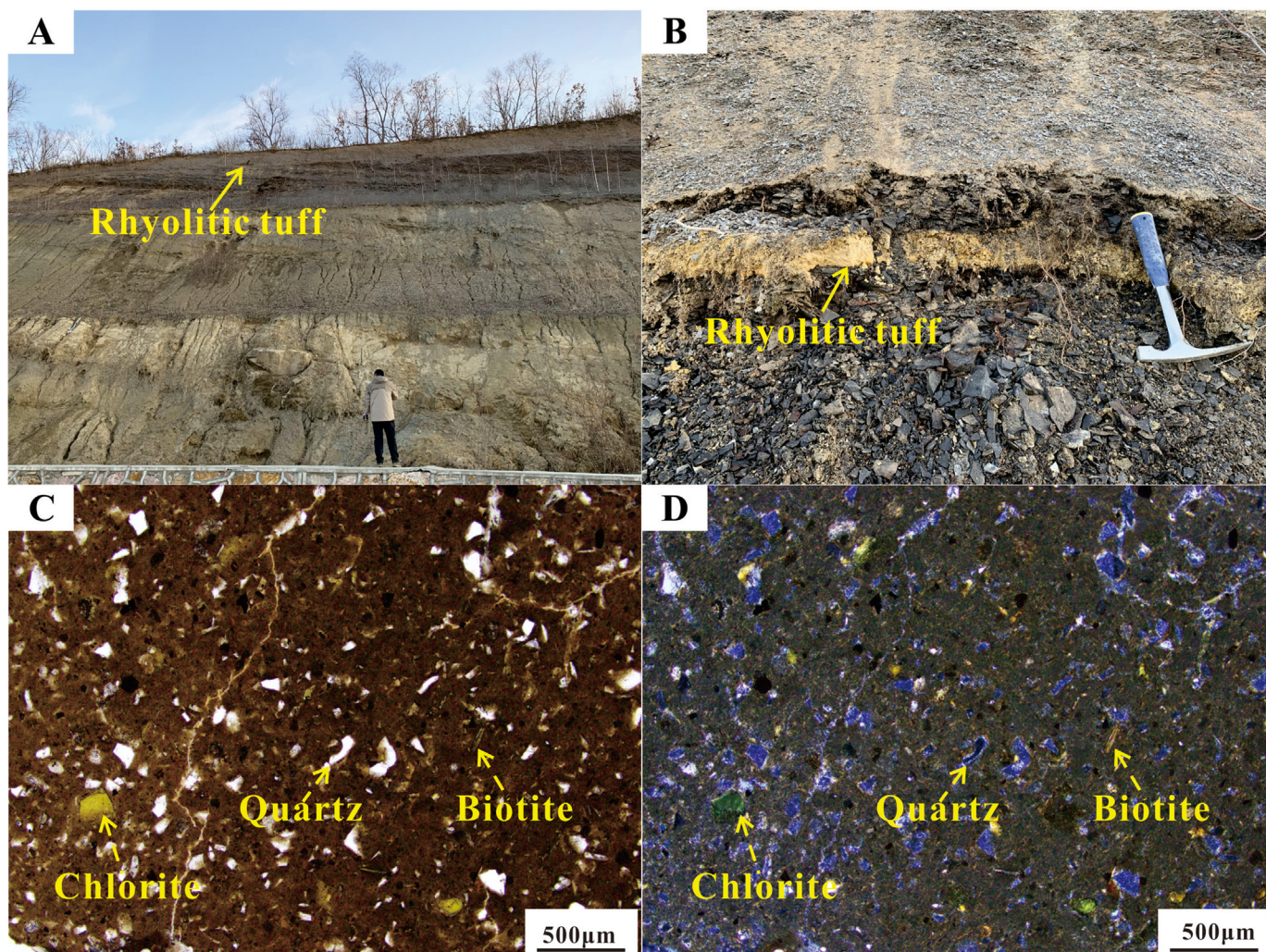


Fig. 2. The rhyolitic tuff sample for U–Pb dating. (A), (B) The tuff outcrop; (C), (D). Zircon U–Pb dating sample with tuff textures in single and crossed polarized light.

expose the internal structure. Transmitted light, reflected light and Cathodoluminescence (CL) were used to examine each zircon crystal for microfractures, internal inclusions, oscillatory zoning, etc., to ensure the location of analysis spots. U–Pb zircon dating using LA-ICP-MS was performed at Tianjin Center of China Geological Survey, China. The instrument configuration consisted of a quadruple ICP-MS (Agilent 7900) coupled with a 193-nm excimer LA system (RESOLUTION-LR). The laser beam had a diameter of 29 μm , an energy density of 3 J cm^{-2} and a repetition rate of 7 Hz. Each set of eight samples was analyzed twice for zircon standard 91500, once for zircon standard Plesovice, and once for glass standard NIST 610 (Jackson et al., 2004; Hou et al., 2009; Geng et al., 2011). Isotopic ratios of zircons were processed with ICPMSDataCal 10.9, and the concordia diagram and weighted average ages of zircons were calculated by using Isoplot software (Ludwig, 2003; Liu et al., 2008).

3. Results

3.1. Zircon U–Pb dating

Representative zircon CL images, selected LA spot locations and spot ages are shown in Fig. 3A, and the concordia plots and weighted mean ages are shown in Fig. 3B–C. Detailed data on the U

and Th contents, isotopic ratios, and age of each zircon grain are shown in Table 1. A total of 25 spots from 25 zircons were analyzed for dating, with 17 grains showing <5% discordance. These 17 zircons are mainly sub-euhedral to euhedral in shape, with length of 100–300 μm and aspect ratio of 1–5, and exhibit distinct oscillatory zoning in CL images with Th/U ratios of 0.44–0.75, indicating their magmatic origin (Koschek et al., 1993). The dating data of these zircons all fall on the concordia curve and yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 84.64 ± 0.65 Ma ($n = 17$, MSWD = 0.74). This dating result is considered to be the age of the volcano eruption from which the rhyolitic tuff was produced.

3.2. Stratigraphic distribution of palynomorphs

The palynoflora of the Yong'ancun Formation is dominated by gymnosperm pollen, followed by fern spores, and angiosperm pollen. Thirteen species in eight genera are newly recognized from the studied samples (Fig. 4A–P). In addition to *Densoisporites velatus* (Fig. 4F), *Cicatricosisporites multicostatus*, *C. dorogensis* (Fig. 4G–H), *Classopollis classoides* (Fig. 4K), and *Mancicorpus triangulus* (Fig. 4L–M), the following genera, *Ghoshispora* (Fig. 4A–E), *Appendicisporites* (Fig. 4I–J), *Gnetaceaepollenites* (Fig. 4N–O) and *Tripoporollenites* (Fig. 4P) are reported for the first time from the Yong'ancun Formation. The representative elements such as *Cyathidites*,

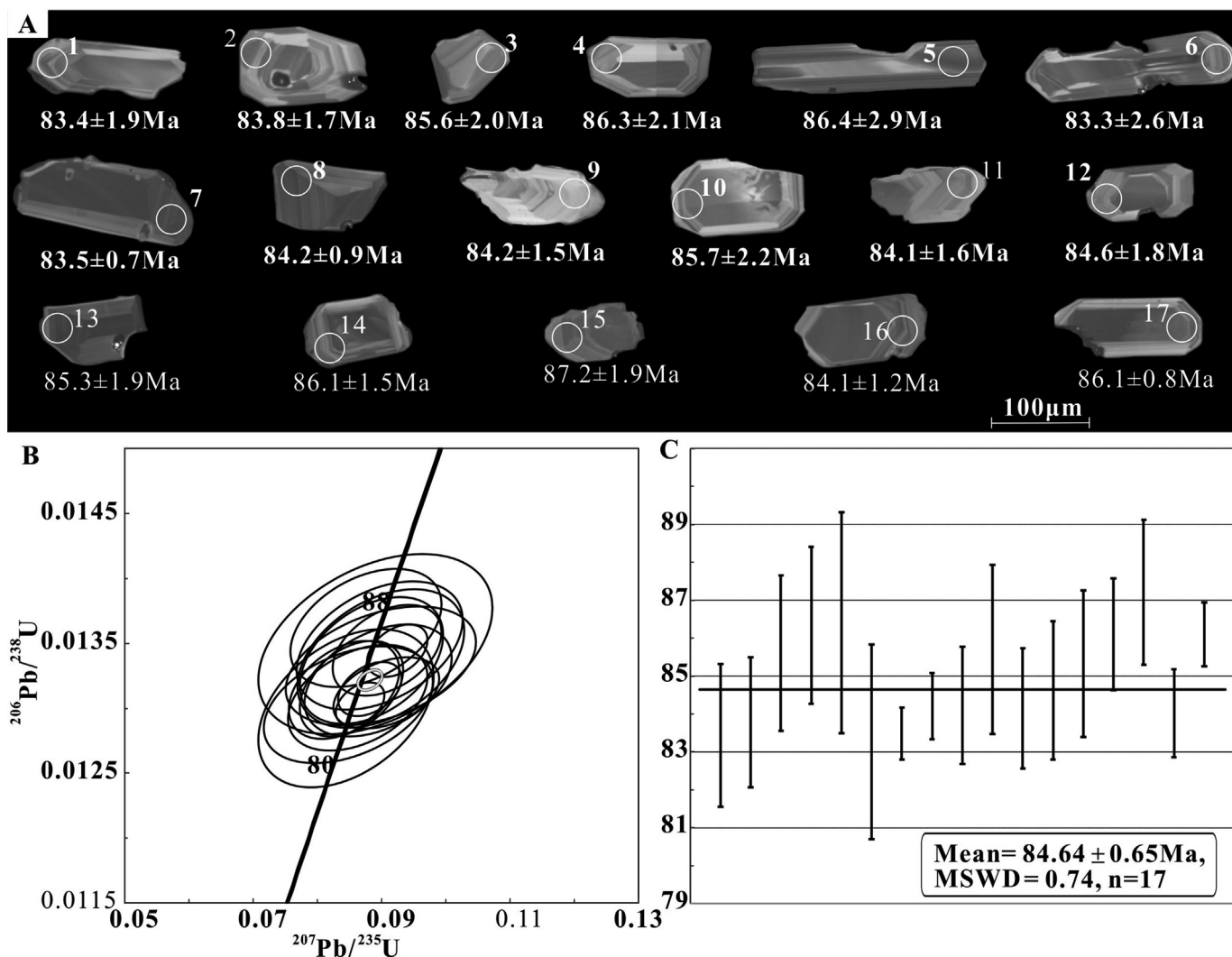


Fig. 3. Illustration of U–Pb dating analysis and results. (A) CL images; (B) Concordia plots of the rhyolitic tuff; (C) The weighted mean ages of the rhyolitic tuff.

Dictyotriletes, *Pinuspollenites*, *Podocarpidites*, *Ginkgocycadophytus* and *Psophosphaera* also occur, similar with the *Dictyotriletes-Cyathidites-Pinuspollenites* sub-assembly (Liang et al., 2015).

The Yong'ancun and Taipinglinchang formations can be correlated to the Middle and Upper Kundur formations respectively (Fig. 5; Golovneva et al., 2020; Sun et al., 2020). The newly found *Ghoshispora* and *Appendicisporites* represent guide fossils for biostratigraphic correlations between the Songliao Basin and Jiayin area. We selected typical species of palynomorphs with common ranges in these two locations (Fig. 5). The distribution of *Ghoshispora* (formerly named *Balmeisporites*) indicates that the upper part of the Yong'ancun Formation is equivalent to the Yaojia Formation. The presence of *Appendicisporites tricornitatus*, *A. macrorhynchus*, *Cicatricosporites dorogensis*, *Classopollis classoides*, *Mancicorpus triangulus* and *Densoisporites velatus*, indicates that the assemblage of the upper part Yong'ancun Formation is correlatable to the *Cyathidites-Schizaeoisporites* assemblage zone of the Member 1 and *Schizaeoisporites-Cyathidites-Proteacidites* assemblage zone of the Members 2 and 3 of the Yaojia Formation (Gao et al., 1999; Li et al., 2011; Zhao et al., 2014; Batten et al., 2016), virtually, the compositions of the latter two palynological assemblage zones are quite similar. However, the range of *Ghoshispora multifida*, *Cicatricosporites dorogensis*, *Classopollis*

classoides and *Mancicorpus triangulus* includes in the Members 2 and 3 of the Yaojia Formation and extends to the Nenjiang Formation (Fig. 5). While the zircons dating suggest that the upper part of the Yong'ancun Formation is equivalent to the Members 2 and 3 of the Yaojia Formation. To sum up, on the basis of the guide fossils and the zircons dating, the upper part of the Yong'ancun Formation is correlatable to the Members 2 and 3 of the Yaojia Formation.

4. Discussion

4.1. Age of the upper part of Yong'ancun Formation

The Late Cretaceous palynoflora of the Yong'ancun Formation was first studied in detail by Markevich et al. (2005) and recognized *Kuprianipollis santaloides-Duplosporis borealis* assemblage (Assemblage I). Later, some of the present authors supplemented the palynoflora of this formation (Liang et al., 2015). All the palynological studies suggested the age of the Yong'ancun Formation as Santonian (Sun et al., 2011, 2020). On the other hand, for the conchostracan guide fossil, *Halyssetheria yui* (Chang), indicating the lowest Campanian for the Nenjiang Formation of the Songliao Basin, was found from the basal beds of the Taipinglinchang Formation in the East Hill

Table 1
Zircon U–Pb dating results of Y-1 sample.

Spots No.	Content ($\times 10^{-6}$)		Th/U	Isotope ratios				Age (Ma)				Concordance						
	Th	U		$^{207}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{206}\text{Pb}/^{238}\text{U}$	$^{208}\text{Pb}/^{232}\text{Th}$	$^{207}\text{Pb}/^{206}\text{Pb}$	$^{207}\text{Pb}/^{235}\text{U}$	$^{206}\text{Pb}/^{238}\text{U}$	1 σ	1 σ						
Y-1-1	79	158	0.50	0.0490	0.0058	0.0848	0.0087	0.0130	0.0003	0.0043	0.0003	150.1	255.5	82.6	8.1	83.4	1.9	99%
Y-1-2	99	146	0.68	0.0483	0.0045	0.0863	0.0071	0.0131	0.0003	0.0048	0.0002	122.3	194.4	84.1	6.7	83.8	1.7	99%
Y-1-3	67	119	0.56	0.0485	0.0047	0.0885	0.0073	0.0134	0.0003	0.0051	0.0002	124.2	214.8	86.1	6.9	85.6	2.0	99%
Y-1-4	132	201	0.66	0.0510	0.0057	0.0897	0.0085	0.0135	0.0003	0.0043	0.0002	239.0	240.7	87.2	7.9	86.3	2.1	99%
Y-1-5	175	210	0.84	0.0485	0.0075	0.0890	0.0120	0.0135	0.0005	0.0049	0.0003	124.2	329.6	86.6	11.2	86.4	2.9	99%
Y-1-6	185	257	0.72	0.0475	0.0051	0.0844	0.0090	0.0130	0.0004	0.0045	0.0002	72.3	250.0	82.3	8.4	83.3	2.6	98%
Y-1-7	323	726	0.45	0.0484	0.0014	0.0866	0.0025	0.0130	0.0001	0.0042	0.0001	116.8	63.9	84.4	2.3	83.5	0.7	98%
Y-1-8	193	438	0.44	0.0488	0.0018	0.0882	0.0033	0.0131	0.0001	0.0042	0.0001	200.1	88.9	85.8	3.0	84.2	0.9	98%
Y-1-9	38	77	0.49	0.0485	0.0040	0.0853	0.0053	0.0132	0.0002	0.0044	0.0002	185.2	251.8	87.4	5.0	84.2	1.5	98%
Y-1-10	93	124	0.75	0.0499	0.0059	0.0899	0.0086	0.0134	0.0004	0.0044	0.0002	190.8	181.5	82.0	8.0	85.7	2.2	98%
Y-1-11	46	92	0.50	0.0502	0.0042	0.0841	0.0057	0.0131	0.0002	0.0041	0.0002	205.6	246.3	87.0	5.3	84.2	1.6	97%
Y-1-12	83	136	0.62	0.0519	0.0055	0.0894	0.0076	0.0132	0.0003	0.0048	0.0002	279.7	229.6	87.3	7.0	84.6	1.8	97%
Y-1-13	585	1051	0.56	0.0482	0.0050	0.0898	0.0098	0.0133	0.0003	0.0046	0.0002	109.4	41.7	88.3	9.1	85.3	1.9	97%
Y-1-14	342	664	0.52	0.0494	0.0033	0.0909	0.0056	0.0134	0.0002	0.0046	0.0002	164.9	200.0	85.3	5.2	86.1	1.5	97%
Y-1-15	200	413	0.48	0.0464	0.0041	0.0876	0.0078	0.0136	0.0003	0.0050	0.0002	20.5	155.5	88.2	7.3	87.2	1.9	97%
Y-1-16	137	248	0.55	0.0509	0.0034	0.0908	0.0054	0.0131	0.0002	0.0045	0.0002	235.3	108.3	89.8	5.1	84.0	1.2	95%
Y-1-17	231	505	0.46	0.0500	0.0016	0.0924	0.0031	0.0134	0.0001	0.0048	0.0001	194.5	108.3	89.8	2.9	86.1	0.8	95%

section at the Yong'ancun village, just overlying the top of the Yong'ancun Formation (Li et al., 2004). This provides supplementary evidence for the Santonian age for the Yong'ancun Formation (Sun et al., 2011). All the age determinations have been based on paleontological studies, lacking radiometric dating. The Yong'ancun Formation has been considered to be equivalent to the Yaojia Formation (Sun et al., 2011, 2020; Liang et al., 2015), as the latter was dated as 84.2–86.5 Ma in age (Wan et al., 2013; Wang et al., 2013; Xi et al., 2019). In this study, the authors first report the zircon LA-ICP-MS U–Pb dating from the rhyolitic tuff in the upper part of the Yong'ancun Formation as 84.64 ± 0.65 Ma age.

The new dating of the Yong'ancun Formation is late Santonian, and indicates that the upper part of the formation is equivalent to the Members 2 and 3 of the Yaojia Formation, which ranges from 84.5 to 85.8 Ma (Wan et al., 2013). *Ghoshispora zhaoi*, *G. triangulata*, *G. minutaestriatus*, *Appendicisporites tricornitatus*, *Cicatricosisporites dorogensis*, etc., are recorded in both formations (ISRDDOF, 1976; Zhao et al., 2014; Batten et al., 2016) (Fig. 5). The genus *Ghoshispora*, an extinct heterosporous water fern megaspore, is a valuable stratigraphical marker and a good paleoenvironmental indicator with a wide geographical distribution from middle to high latitudes of the Northern Hemisphere, and its stratigraphic range is commonly considered the Albian to Danian (Cookson & Dettmann, 1958; Srivastava, 1967, 1978; Bergad, 1973; Dettmann, 1995; Wan et al., 2004; Kutluk et al., 2011; Batten et al., 2011, 2016). Most of species of this genus ranged from the Campanian to the Maastrichtian (Kutluk et al., 2011; Batten et al., 2011, 2016), although many species could extend into the Santonian, even in older deposits, as recorded in the Songliao Basin (ISRDDOF, 1976; Gao et al., 1999; Batten et al., 2011, 2016; Zhao et al., 2014).

4.2. Implications for environmental and climatic changes in Santonian

The Cenomanian-Santonian interval (ca. 100 to 83 Ma) has been considered as the mid-Cretaceous thermal maximum (KTM), among Earth's warmest sustained intervals of the Phanerozoic (Huber et al., 2018; Jones et al., 2022). This interval is characterized by major paleoceanographic changes, such as an oceanic anoxic event, which triggered environmental changes and had profound impacts on the greenhouse world of the Cretaceous (Jenkyns, 1980; Huber et al., 2018; Jones et al., 2022). A distinct cooling trend occurred during the Late Cretaceous and both the ocean and land temperatures dropped considerably (Huber et al., 2002, 2018; Wan et al., 2011; Wang et al., 2014). In the Jiayin area, the cuticle analyses based on *Ginkgo* showed the paleo-CO₂ descending trends, as the temperature gradually decreased with some fluctuations during Santonian to Campanian (Quan et al., 2009; Wan et al., 2011). The megaspores of *Ghoshispora* and pollen of *Mancicorpus* are usually associated with relatively warmer, moist sub-tropic climate (Gao et al., 1999; Zhao et al., 2014). Together with other palynomorphs and associated macrofossils, the plants of the Yong'ancun flora indicate a warm temperate and humid climate, and an environment with abundant water (Sun et al., 2007, 2020; Markevich et al., 2011; Liang et al., 2015, 2018, 2021).

The Yong'ancun Formation is dominated by a fluvial-lacustrine depositional system (Sun et al., 2007, 2020). Abundant aquatic angiosperm fossils *Quereuxia*, *Cobbania* and *Nelumbo* indicate fresh water conditions, such as marsh or lake shorelines or riverbanks (Sun et al., 2007; Quan and Sun, 2008; Liang et al., 2018, 2021). The newly found megaspore *Ghoshispora* is a water-fern commonly dwelling in a brackish or fresh water environment (Batten et al., 2011, 2016). The presence of conchostracans (Sun et al., 2020), dinosaurs (Dong et al., 2003) and aquatic angiosperms also indicates a fresh water environment.

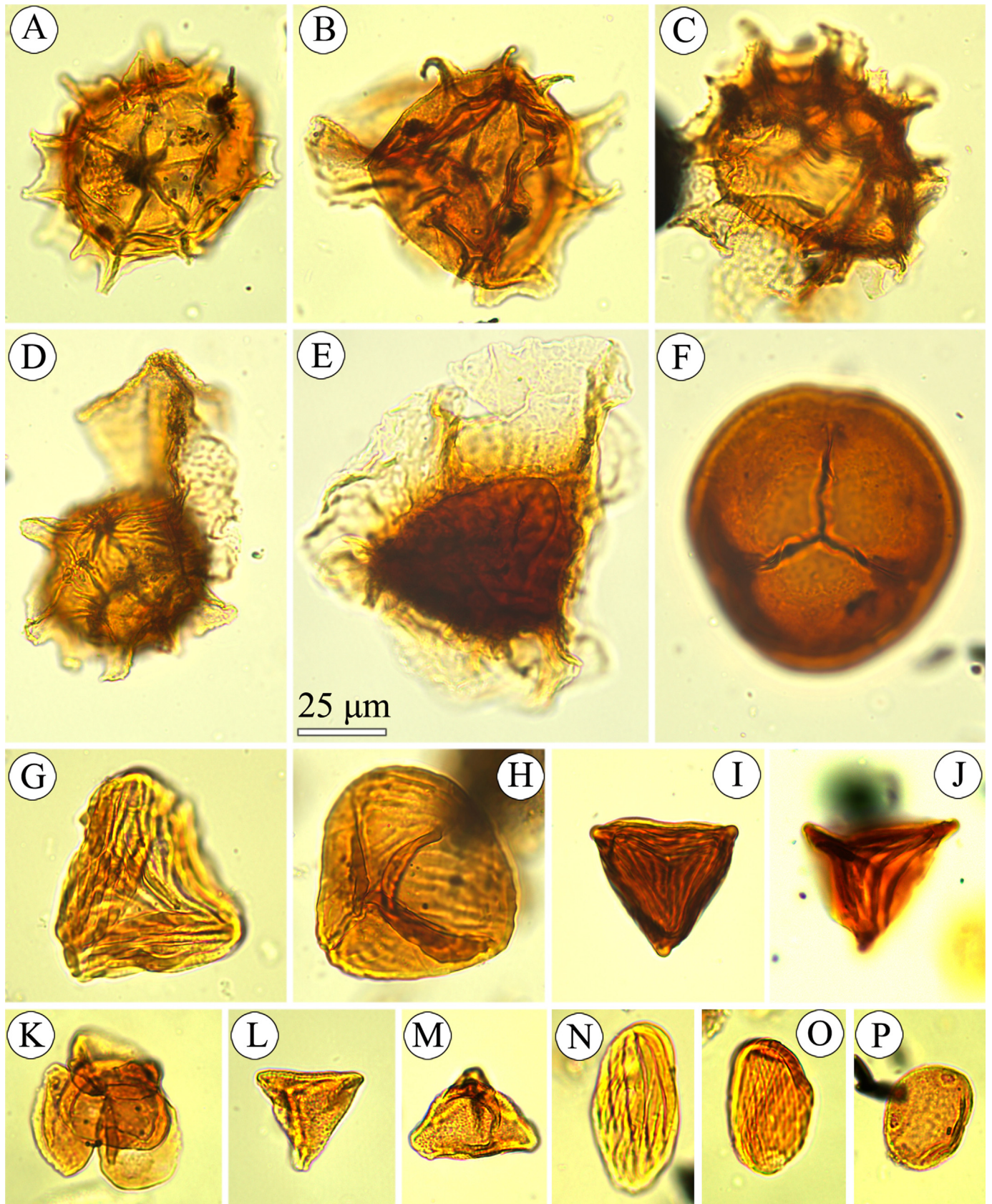


Fig. 4. Fossil spores and pollen from the top of the Yong'ancun Formation. A–C. *Ghoshispora multifida* (Zhao) Kutluk, No. ya-002, ya-004, ya-003; D. *G. zhai* (Zhao) Batten, No. ya-001; E. *G. triangulata* (Zhao) Kutluk, No. ya-001; F. *Densoisporites velatus* Weyland et Krieger, No. ya-001; G. *Cicatricosisporites multicostatus* Poc., No. ya-003; H. *Cicatricosisporites dorogensis* Pot. et Gell., No. ya-004; I. *Appendicisporites tricornitatus* Weyland et Greifeld, No. ya-001; J. *Appendicisporites macrorhysus* (Bolch.) Poc., No. ya-001; K. *Classopollis classoides* (Pflug) Pocock et Jansonius, No. ya-003; L–M. *Mancicorpus triangulus* Yu, Guo et Mao, No. ya-005, No. ya-002; N. *Gnetaceapollenites evidens* (Bolch.) Chlon., No. ya-005; O. *Gnetaceapollenites ovatus* (Pierce) Verb., No. ya-005; P. *Triporopollenites rugatus* Newman, No. ya-005.

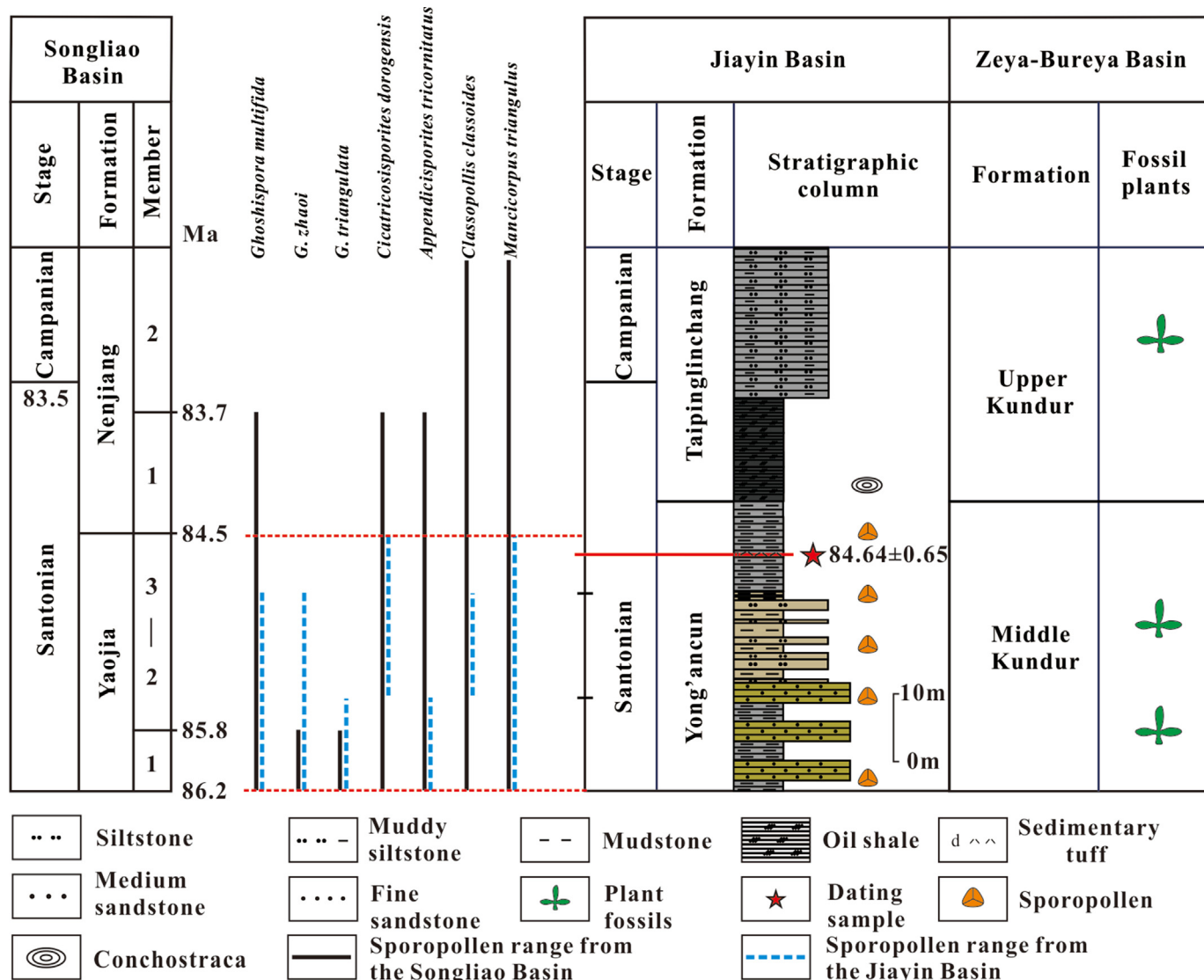


Fig. 5. The ranges of spores and pollen taxa of Jiayin area and the Songliao Basin (Sk1) in China, and their correlation with the Zeya-Bureya Basin in Russia. The time scale after Wan et al. (2013); the geological distributions of spores and pollen in the Songliao Basin (Sk1) after Gao et al. (1999) and Batten et al. (2016); the Upper Cretaceous strata correlations of the Jiayin and Zeya-Bureya basins after Sun et al. (2020) and Golovneva et al. (2020).

5. Conclusions

- (1) The new LA-ICP-MS zircon U–Pb dating (84.64 ± 0.65 Ma) from the rhyolitic tuff in the upper part of Yong'ancun Formation in the Jiayin area indicates a late Santonian age. Integrated biostratigraphy suggests that the Yong'ancun Formation is equivalent to the Yaojia Formation of the Songliao Basin, which is middle to late Santonian in age.
- (2) The newly found water fern megaspore *Ghoshispora*, a valuable stratigraphic and palaeoenvironmental fossil, next to associated megafossils, indicates that the Yong'ancun flora lived in a moist, warm climate, fresh water environments. The temperature changed from high (KTM) to moderate warm and wetter conditions, at least in the inland Heilongjiang (Amur) region, nearby the paleo-Pacific Ocean, during the Santonian.

Data availability

Data will be made available on request.

Acknowledgments

The authors acknowledge the support of the National Natural Science Foundation of China (Grant Nos. 42172017, 41902009, 42172024), and of the State Key Laboratory of Palaeobiology and Stratigraphy (Nanjing Institute of Geology and Palaeontology, CAS, Grant No. 183117). Thanks are also extended to our Chinese colleagues W.H. Wu, T. Yang and Y.G. Yang for their help in the field in Jiayin for fossil collecting, and to the editor and to anonymous reviewers for their kind comments for the manuscript.

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