

Recent advance in study of K-Pg boundary in Jiayin of Heilongjiang, China and its adjacent area

SUN Ge^{1,2,3}, SUN Chunlin^{3,4}, SUN Yuewu^{3,4}, ZHANG Shuqin^{3,4}, WU Wenhao^{3,4},
YANG Tao^{1,2}, LIANG Fei^{1,2}, FENG Yuhui^{1,2}, Markevich V⁵, Ashraf A R⁶,
Bugdaeva E.⁵, Tekleva M.⁷ and Suzuki S.⁸

1. College of Paleontology, Shenyang Normal University, Shenyang 110034, China;
2. Key-Lab of Evolution of Past Life in NE Asia, MNRC, Shenyang 110034, China;
3. International Center of Geoscience Research and Education in NE Asia, Jilin University, Changchun 130026, China;
4. Research Center of Paleontology & Stratigraphy, Jilin University, Changchun 130026, China;
5. Federal Scientific Center of the East Asia Terrestrial Biodiversity, FEB RAS, Vladivostok 690022, Russia;
6. Institute of Geology and Paleontology, University of Bonn, Bonn D-5300, Germany;
7. Paleontological Institute, RAS, Moscow 117647, Russia;
8. Okayama University, Okayama 700-8530, Japan

Abstract: The non-marine Cretaceous-Paleogene boundary (KPgB) in Jiayin of Heilongjiang was first defined and reported in China by the authors' research team in 2011. Thereafter the continuous research on the KPgB and its related Late Cretaceous biota in Jiayin has been made by the authors in 2012-2020. The achievements of the research are mainly reflected as follows: (1) a new drilling borehole with 60 m in depth carried out in the Xiaoheyan of Jiayin in 2016, supplemented new palynological evidence for the KPgB definition in 2011; (2) some radiometric dating newly made on the strata related to the KPgB in Jiayin and its neighboring Russian area, provided the supplemental evidence for the KPgB definition in Jiayin; (3) many new fossils found by the authors, represented by the angiosperms *Dalembia* and *Nelumbo*, refresh understanding the Late Cretaceous environment of Jiayin; and (4) the TEM method is applied in the study of pollen exine ultrastructure of *Pseudoin-tegricorpus*, *Wodehouseia*, and *Aquilapollenites*, promoting the late Maastrichtian ecological study in Jiayin, related to the KPgB.

Keywords: K-Pg boundary; new; achievement; Jiayin; China

Introduction

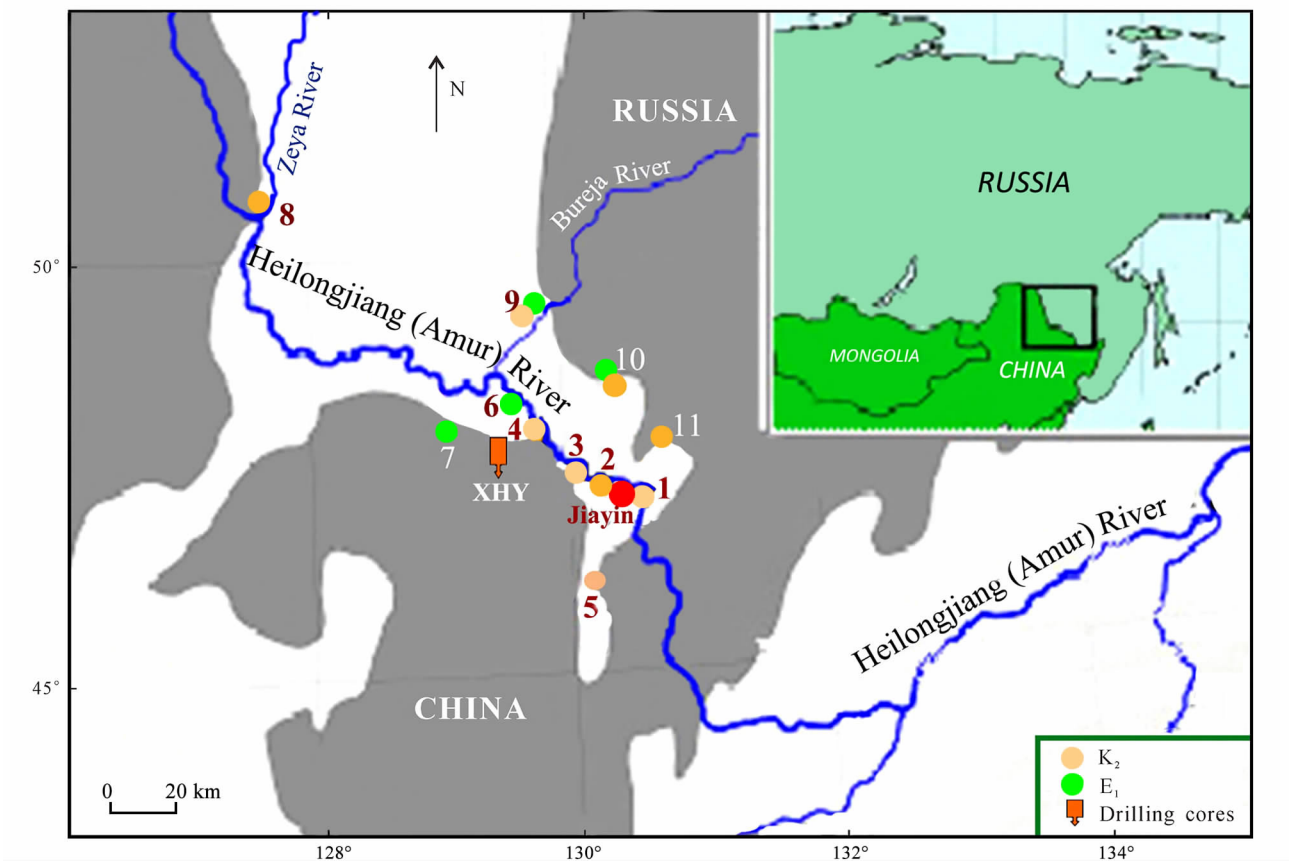
During 2002-2011, under the financial supports for the projects of NSFC- 3022130698 and 40842002, and Dept. Land & Resources of Heilongjiang Prov-

ince, China, the international research team joined by the authors, had studied in depth the Late Cretaceous-Paleocene biotas and the non-marine K-Pg boundary (KPgB) in Jiayin of Heilongjiang, China and its adjacent areas of Russia, and made the first determina-

tion of the KPgB in village Xiaoheyuan (XHY) nearby the Heilongjiang (Amur) River in Jiayin County of Heilongjiang Province, China (49°14'53"N, 129°35'14" E in central coordinate), and formally reported the KPgB definition in the International Symposium on Geology and Paleontology in Yichun, China on August 20–24, 2011 (Sun *et al.*, 2011) (Fig. 1).

The Upper Cretaceous-Paleocene strata are very widely developed in Jiayin along the Heilongjiang (Amur) River, composed of (in ascending order) the Upper Cretaceous Yong'ancun Formation (Santonian, yielding dinosaurs), Taipinglingchang Fm (Campa-

nian), Yuliangzi Fm (lower-middle Maastrichtian, with main dinosaur-bearing beds) and Furao Fm (upper Maastrichtian); and the Paleocene Wuyun Fm consisting of the Baishantou Member and Coal-bearing Member (Sun *et al.*, 2002, 2005, 2011). Since the KPgB strata are covered by the Quaternary deposits in this area, the authors' research team made three drilling boreholes (XHY-2005, 2006, 2008) nearby the Xiaoheyuan of Wuyun, and collected more than a thousand samples from the boreholes for the KPgB study during 2005-2008, and successfully defined the KPgB in 2011 (Sun *et al.*, 2011).



1. Yong'ancun; 2. Taipinglingchang; 3. Longgushan; 4. Wuyun; 5. Wulaga; 6. Baishantou; 7. Jiayin coalmine; 8. Blagoveshensk; 9. Belaya Gora; 10. Akhara-Boguchan; 11. Kundur

Fig. 1 Sketch map showing the KPgB in Jiayin of Heilongjiang and related research sites in Jiayin and its adjacent areas

There are seven palynological assemblage zones in the Jiayin and its adjacent Zeya-Bureya Basin of Russia, made by Markevich *et al.* for many years (IBP *et al.*, 2001; Markevich *et al.*, 2006, 2011). The key-evidence to document the KPgB in the Xiao-

heyuan of Jiayin was found in the interval between the palynological assemblage zones V (upper Maastrichtian) and VI (Danian) in all the boreholes XHY-2005, 2006 and 2008, correspondingly the upper Maastrichtian Furao Formation and the lower Danian

Baishantou Member of Wuyun Formation in the drilling site (Sun *et al.*, 2011; Markevich *et al.*, 2011) (Fig. 2).

The Assemblage Zone V (*Aquilapollenites stelckii*-*Pseudointegricarpus clarireticulatus* Ass.) below the KPgB, is represented by *Aquilapollenites conatus*, *A. stelckii*, *A. reticulatus*, *A. striatus*, *Integricarpus bellum*, *Pseudointegricarpus clarireticulatus*, *marsypiletes cretacea*, *Tricolpites variexinus*, *Triprojectus amoenus*, *Orbiculapollis lucidus*, *Wodehouseia aspera*,

and *Quercoidites minor*, etc. characteristic for the late Maastrichtian age (Markevich *et al.*, 2006, 2011). The Assemblage Zone VI (*Triatriopollenites confusus*-*Aquilapollenites spinulosus* Ass.) above the KPgB, is represented by *Triatriopollenites plicoides*, *T. confusus*, *Momipites tenuipolus*, *Rhoipites pissinus*, *Anacolosidites subtrudens*, *Aquilapollenites spinulosus*, etc. characteristic for the early Danian age. Moreover, at the base of the Danian deposits of the borehole XHY-2005, the “fern spike” is well expressed above the KPgB,



Fig. 2 Sketch map showing the stratigraphic column of K – Pg boundary in Xiaoheyuan of Jiayin, evidenced palynologically (A, after Sun *et al.*, 2011), and the celebration for the KPgB definition in Jiayin held in the borehole site of Xiaoheyuan on Aug. 24, 2011 (B, C)

which is similar to the case in the section of the Belaya Gora of the Zeya-Bureya Basin, Russia (Markevich *et al.*, 2011) (Fig. 2).

On the other hand, all the related isotopic, paleomagnetic and geochemical studies of the boreholes XHY-2005, 2006 and 2008, supported the definition of the KPgB in the Xiaoheyuan of Jiayin evidenced with the palynological fossils. The U-Pb zircon dating from the rhyolite tuff in the lower Baishantou Member in Baishantou nearby the Xiaoheyuan (XHY) 64.1 ± 0.7 Ma age (Suzuki *et al.*, 2011), evidenced the Baishantou Member above the KPgB, as the early Paleocene (Danian) age. The paleomagnetic measurement on the drilling cores XHY-2006 and 2008, showed that the reversed interval C29r is probably within 22.0–22.35 m in the core of XHY-2006, and the reversed interval C29r probably within 23.22–23.32 m in XHY-2008, which supported the KPgB definitions by the palynological analysis (i. e. the KPgB as in 22.0–22.05 m in XHY-2006, and 23.05–23.25 m in XHY-2008) (Sun *et al.*, 2011). The geochemical analyses showed no any significant anomaly of Iridium (Ir) in the KPgB strata in the borehole XHY-2005, 2006 and 2008 in Xiaoheyuan, Jiayin (Sun *et al.*, 2011).

1 New drilling for study of the KPgB in Xiaoheyuan of Jiayin

With the new projects 2015FY310100 and DD20160120-04, supported by Ministry of Science and Technology, China (MOST) and China Geological Survey (CGS), respectively, the authors made a new drilling in the Xiaoheyuan of Jiayin in 2016, for further study of the KPgB. The new borehole (XHY-2016) is located nearby the stratotype borehole XHY-2006, and 60 m in depth, in which the authors collected 393 samples from the Upper Cretaceous-Paleocene for the KPgB study. There are 55 samples from the strata of 19.00–24.06 m in the new borehole, in which the spore-pollen assemblage from 19.00–22.88 m (with 29 samples analyzed) showing the Danian age, while those from 22.98–24.60 m (with 26

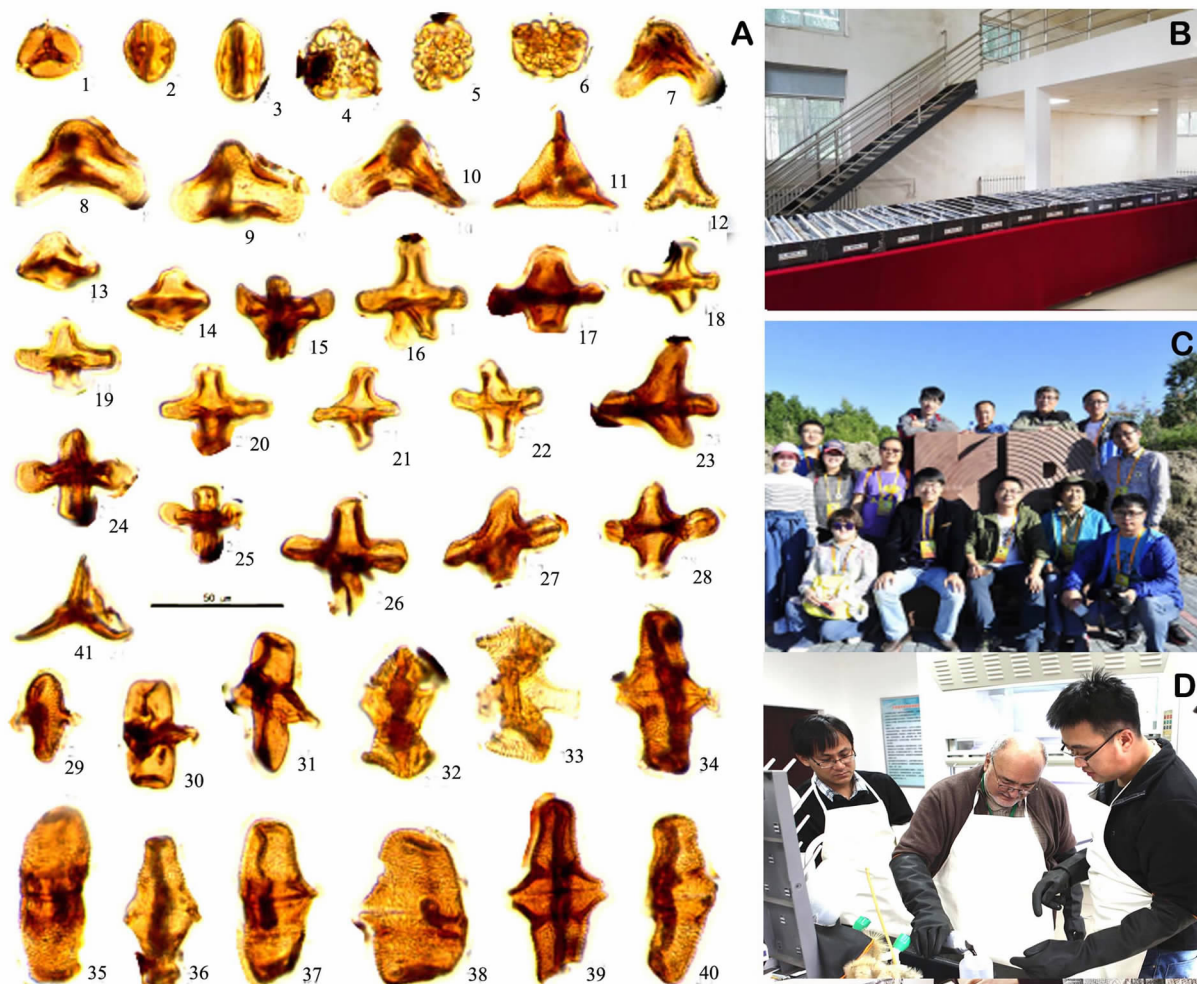
samples analyzed) showing the late Maastrichtian age. The KPgB definition in this borehole (XHY-2016) would be considered in the interval about 22.88–22.98 m in the new borehole, which is quite close to the definition of the KPgB in the Xiaoheyuan by the authors' research team in 2011 (Sun *et al.*, 2011).

The Maastrichtian palynological assemblage in the new borehole XHY-2016, shows the characters of the Assemblage V, proposed by Markevich *et al.* (2006, 2011). In the strata of 22.98–24.60 m, the spore-pollen spectra seem to be composed of three sub-assemblages (in descending order): the Sub-Assemblage III (*Pseudointegricorpus clarireticulatus* *Aquilapollenites striatus* subass., in 22.98–23.60 m); the Sub-Assemblage II (*Aquilapollenites conatus* *Marsypiletes cretacea* subass., in 23.60–23.72 m); and the Sub-Assemblage I (*Aquilapollenites stelckii* *Wodehouseia spinata* subass., in 23.72–24.06 m). All the sub-assemblages show the Maastrichtian age, especially by the important Maastrichtian taxa *Pseudointegricorpus clarireticulatus*, *Aquilapollenites stelckii*, *Marsypiletes cretacea*, and *Integricorpus bellum* (Fig. 3). The study provides new supplement for the previous determination of the KPgB in Jiayin (Sun *et al.*, 2011; Markevich *et al.*, 2006, 2011).

2 New radiometric dating concerned the KPgB in Jiayin

In 2011 two of the authors (Suzuki & Sun) with Knitte obtained the LA-ICP-MS zircons dating age 64.1 ± 0.7 Ma from the rhyolitic tuff of the Baishantou Member of the Wuyun Formation above the KPgB in Baishantou nearby the Xiaoheyuan of Jiayin (Suzuki *et al.*, 2011), which provided important evidence to document the correctness of the KPgB definition in the Xiaoheyuan (Sun *et al.*, 2014) (Fig. 4D).

In 2013, Knitte with two of the authors (Suzuki & Sun) was making the LA-ICP-MS dating of single igneous zircon from the tuff bed in the uppermost part of the Middle Tsagayan Sub-Formation in Belaya Gora (Ploskaya Mt.) of Zeya-Bureya basin, Russia near the Baishantou of Wuyun, China about 30 km to north,



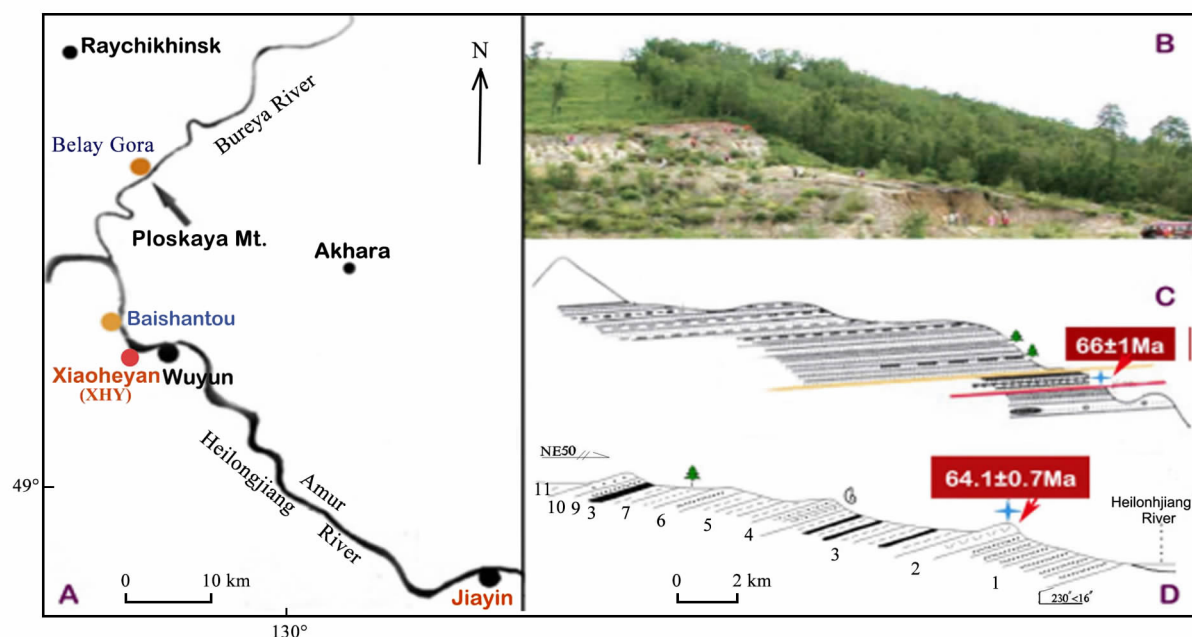
A. Some pollen newly found from the Maastrichtian beds 24.02–24.06 m in borehole XHY-2016; 1–3 *Nothopollenites* sp. ; 4–6 *Marsipiletes cretacea* ; 7–10 *Mancicorpus polaris* ; 11, 24, 25 *Aquilapollenites funkhouseri* ; 12, 32, 33 *A. conatus* ; 13, 14 *Pentapollenites normalis* ; 15 *Aquilapollenites rigidus* ; 16, 18–22 *A. stelckii* ; 17. *A. amplus* ; 23 *A. crassatus* ; 26–28 *A. subtilis* ; 29 *A. reticulatus* ; 30, 31 *Integricorpus* sp. ; 34–40 *Pseudointegricorpus clarireticulatus* ; 41 *Translucentipollis plicatilis* ; B. The core specimens from the borehole XHY-2016 housed in the PMOL; C. The drilling site of Xiaoheyuan; D. Palynological analyses for study of the XHY-2016, in Shenyang, directed by Prof. Ashraf (middle).

Fig. 3 Some Maastrichtian pollen from the new borehole XHY-2016 in Xiaoheyuan, Jiayin

and obtained 66 ± 1 Ma U-Pb average (Knitte *et al.*, 2013), which also provided the indirect evidence for the definition of the KPGB in Jiayin, because the Middle Tsagayan Sub-Formation in Belaya Gora is basically correlated with the Furao Formation in Jiayin aged the late Maastrichtian. In addition, the authors considered that the previous KPGB in the Belaya Gora section defined in Russia (BPI *et al.*, 2001) might be slightly revised (Sun *et al.*, 2014) (Fig. 4C).

Besides, very recently, one of the authors (Feng*) has made a new radiometric dating from the rhyolitic tuff of bed 98.8 m in the borehole XHY-2005, and obtained the zircon LA-ICP-MS dating age of 67.16 ± 0.6 Ma (Feng *et al.*, 2021, M*), which is a well isotopic evidence for supplementing the age of the strata below the KPGB in the borehole section of Xiaoheyuan of Jiayin.

* Feng Y H. 2021. A new zircon LA – ICP – MS dating age of 67.16 ± 0.6 Ma from a rhyolitic tuff in the borehole XHY – 2005, below the Cretaceous–Paleocene boundary in Xiaoheyuan of Jiayin, Heilongjiang, China (in preparation).



A. Geographic map of Jiayin and its neighboring area in Russia (after Knitte *et al.*, 2013 with some revision); B, C. Illustrations of the KPgB section in Belaya Gora of Russia (after BPI *et al.*, 2001; Sun *et al.*, 2014), the orange color line is the previous KPgB, while the red color line is by the authors' idea. D. Paleocene section in Baishantou of Jiayin (after Sun *et al.*, 2011, 2014).

Fig. 4 New radiometric dating in Belaya Gora of Russia and in Baishantou of China showing age of strata overlying KPgB in Jiayin and its neighboring area

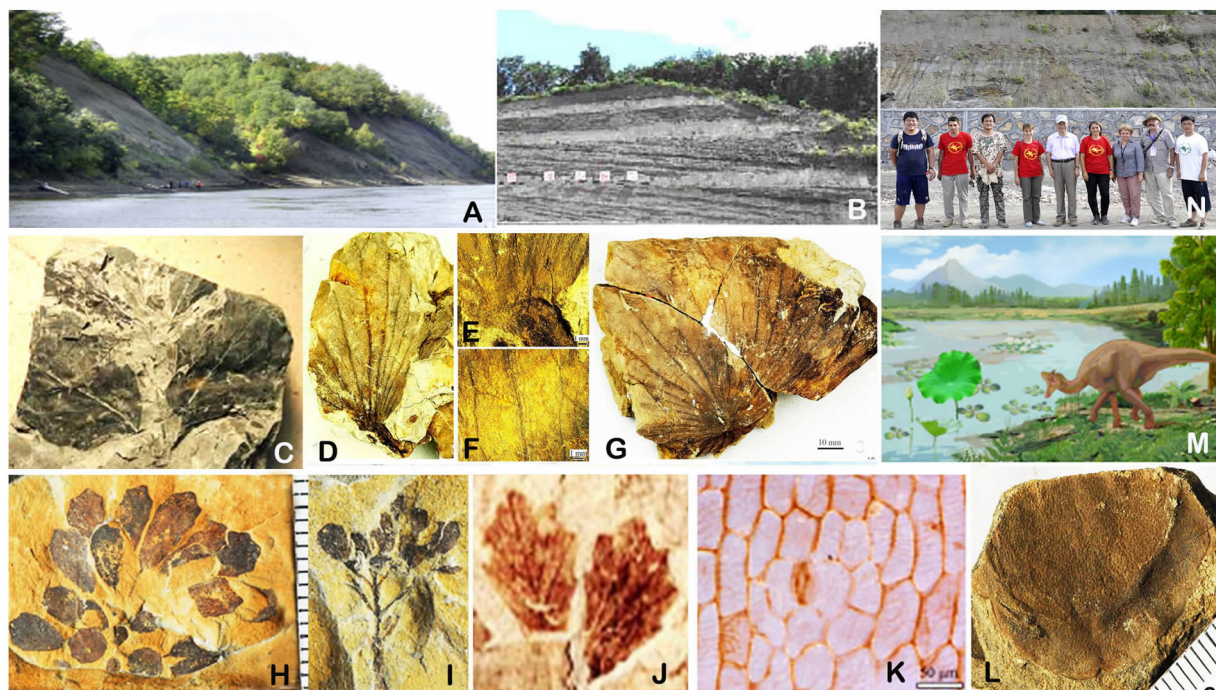
3 New plant fossils discovered from Upper Cretaceous in Jiayin

During 2014–2020, the authors have found a lot of new fossils from the Upper Cretaceous Yong'ancun Formation (Santonian), represented by the angiosperm taxa *Dalembia* with new species *D. jiayinensis* Sun et Golovneva (Sun *et al.*, 2016), and the aquatic angiosperm *Nelumbo* with new species *N. jiayinensis* Liang *et al.* (2018). Besides, the authors have also found a lot of new fossils of aquatic angiosperms such as *Quereuxia* and *Cobbania* (Sun *et al.*, 2014, 2020; Liang & Sun, 2015).

The new species of *Dalembia* is reported from the Yong'ancun Formation exposed along the Heilongjiang (Amur) River in Jiayin, for the first time. The leaves of *Dalembia* are compound, odd-pinnate, consisting of five leaflets which are pinnately-lobed, elliptic-rhomboid or ovate in outline, with a blunt or rounded apex. Lobes are short, simple, decreasing upwards, with

wide and rounded sinuses. Apices of the lobes are usually rounded. Venation pinnate or palmately-pinnate, craspedodromous or semi-craspedodromous. The species *D. jiayinensis* extends both the geographical and stratigraphic ranges of the genus *Dalembia*. This is the first record of *Dalembia* in China and the most southern and youngest (the Santonian) occurrence of this genus (Sun *et al.*, 2016) (Fig. 5C).

The aquatic angiosperm *Nelumbo* with its new species (*N. jiayinensis*) was newly found from the Yong'ancun Formation of Jiayin. The new taxon is the first report on fossil *Nelumbo* from the Upper Cretaceous in China. The leaves of *N. jiayinensis* are simple with entire margins, about orbicular in shape, with a peltate and symmetric lamina. The venation is actinodromous with 20–25 primary veins, the secondary and tertiary veins are poorly developed and interweave into meshes. The areoles are irregularly polygonal in shape and well developed. Combined with data derived from associated fossil bivalves and dinosaur track,



A, B. Upper Cretaceous Yong'ancun Formation in East Hill of Yong'ancun, Jiayin, yielding the new angiosperm fossils shown in C-L; C. *Dalembia jiyinensis* Sun et Golovneva (2016); D-G. *Nelumbo jiyinensis* Liang *et al.* (2018); H-K. *Quereuxia angulata*, K showing the leaf upper cuticle characters; L. *Cobbania corrugata*; M. Reconstruction of Jiayin area in Late Cretaceous; N. Colleagues of the authors' research team in field working in Yong'ancun, 2015 (2-7th from right: Drs. Yu. Bolotsky, T. Kodrul, L. Golovneva, G. Sun, N. Nosova, and T. Yang).

Fig. 5 New angiosperm fossils found in Upper Cretaceous of Jiayin in 2015-2020

the angiosperm *Nelumbo* seems to indicate a fluvio-lacustrine environment under a warm but seasonal temperate (Liang *et al.*, 2018).

Besides, some new material of dinosaurs were found from the lower Maastrichtian Yuliangzi Formation in Longgushan of Jiayin, also (Sun *et al.*, 2015), which enriched evidences for understanding the paleoecological condition in Jiayin and its adjacent areas during the late Late Cretaceous time.

4 TEM method applied in study of pollen ultrastructure from the KPgB strata in Jiayin

The transmission electron microscopy (TEM) method is an efficient method for study of the pollen ultrastructure. During 2012–2020 some of the authors (Tekleva *et al.*) studied the exine ultrastructure of pollen *Pseudointegricorpus*, *Wodehouseia* and *Aquilapollenites*, from the upper Maastrichtian Furao Formation in the stratotype boreholes of Xiaoheyan, Jia-

yin, which greatly promoted the taxonomic and paleoecological study in Jiayin during the Late Cretaceous (Tekleva *et al.*, 2012, 2015, 2019, 2020).

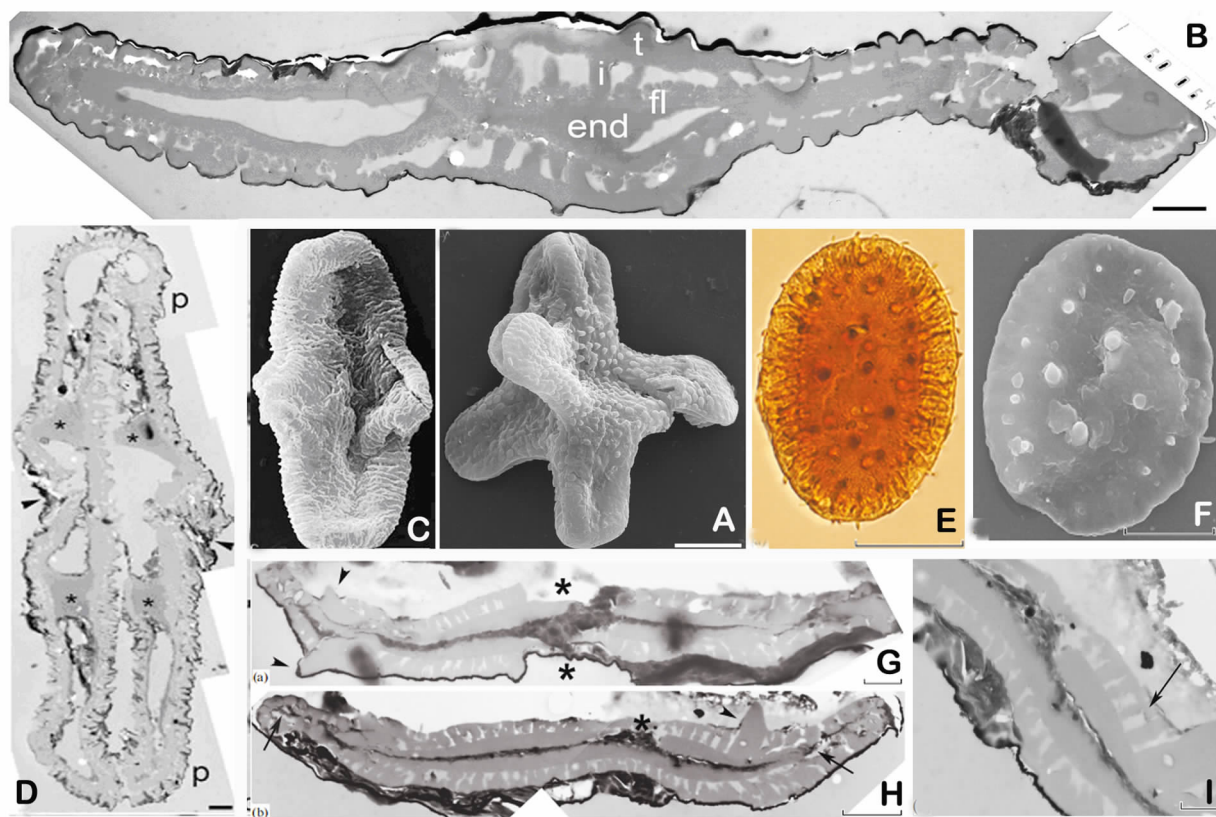
From the TEM study of the dispersed pollen *Wodehouseia spinata* Stanley, the result showed that the plants produced such pollen were probably of a wetland or aquatic habit, with adaptation to a sudden changing of a water regime during the vegetation season. The pattern of the exine sculpturing and sporoderm ultrastructure suggests that insects contributed to the pollination (Tekleva *et al.*, 2019) (Fig. 6, E-I).

The TEM study of the pollen *Pseudointegricorpus clarireticulatum* (Samoil.) Takahashi showed that the pollen size, pole outlines and the shape of equatorial projections within the species. The exine is striate-reticulate, semitectate and columellate. The complex structures have harmomegathic function and include equatorial projections, endexinous thickenings, difference in the thickness of the infratectum, foot layer, endexine, and equatorial furrows. Exine layers taper

towards colpi regions while they break abruptly in furrow regions. The furrows could have helped to shed the exine quickly and enabled pollen germination (Tekleva *et al.*, 2015) (Fig. 6, C, D).

Three species, *Aquilapollenites quadricretaceus*, *A. stelckii*, and *A. amicus*, from the upper Maastrichtian of Xiaohayan studied by TEM method, showed rare specimens of the first two species with reduced polar and/or

equatorial projections and that they were more similar to each other in exine ultrastructure than those to *A. amicus*, which has thicker foot layer and thin infratectum. A comparison with living Lythraceae pollen revealed characters similar triprojectate pollen, probably resulting from convergent evolution. The possible adaptation of some Triprojectacites species to a wetland environment was suggested (Tekleva *et al.*, 2020) (Fig. 6, A, B).



A, B. *Aquilapollenites quadricretaceus*, A. pollen grains with usual polar and equatorial projections. bar = 10 μm ; B. TEM transverse section of whole pollen grain. bar = 1 μm . (t-tectum, i-infratectum, fl-foot layer, end-endexine) (after Tekleva *et al.*, 2020, plate II, 1; plate VII, 1); C, D. *Pseudointegricarpus clarireticulatum*, D. TEM longitudinal sections through the whole pollen grain, endexinous thickening and equatorial furrows are cut; bar = 2 μm . Arrowheads point to regions of equatorial furrow, p-polar projection (after Tekleva *et al.*, 2015, Fig. 4c, Fig. 6b); E-I. *Wodehouseia spinata*, E. photo of LM, F. photo of SEM, G-I. photos of TEM, G the section through both pores showing differently thick endexine, columellate infratectum and medium-sized echini (arrowheads); H showing endexine of various thickness, columellate infractum, cavities in exine near the flange (arrow) and a large echinum (arrowheads); G-bar = 1 μm , H-bar = 2 μm ; I. the section through a pore with no exine layers; endexine of various thickness, infractal columellate, in branched (arrow) and large echinum are visible; bar = 1 μm (after Tekleva *et al.*, 2019, Fig. 1a; Fig. 2a; Fig. 4a, b; Fig. 5a).

Fig. 6 TEM method applied in study of pollen exine ultrastructure in Jiayin

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Late Cretaceous biota and the KPgB in Jiayin, China; especially to Dr. Golovneva L. and Dr. Knitte H. for their contributions to the fossil plant taxonomy and the radiometric study for the Late Cretaceous biota and the

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