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Jurassic-Cretaceous Non-Marine Stratigraphy and Entomofaunas in Northern China

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1.1 Introduction

Northern China is an administrative and geographical region referring to the area located north of the Yellow River. Since the Late Triassic, the continental area of northern China was formed, and during the Jurassic and Cretaceous, almost all of northern China had become part of the Asian continent except for the southern Tibet, west of the Tarim basin of northwest China and Heilongjiang of northeast China. Thus, the Jurassic to Cretaceous strata of northern China are dominated by terrestrial sediments, volcanic rocks and volcanic sedimentary formations and coal-bearing beds. A great deal of fossils have been found and documented in numerous localities and horizons. The Jurassic and Cretaceous insects have been reported from several localities in Xinjiang, Gansu, Shaanxi, Inner Mongolia, Hebei, Beijing, Liaoning, Jilin and Shandong. Among them, the studies of the Jurassic and Cretaceous insect fossils from the Yumen-Jiuquan Basin, Gansu; Yanliao Area (Beijing-northern Hebei-western Liaoning-southeastern Inner Mongolia) and Laiyang Basin of Shandong have been more extensive, in-depth and detailed than the sporadic reports from other localities.

Using the non-marine insect-bearing stratigraphic occurrences, together with radiometric ages and accompanying fossils, the Jurassic and Cretaceous non-marine strata of northern China can be divided and correlated as shown in Table 1.1.

1.2 Non-marine Jurassic and Cretaceous Insect Fossil-Bearing Lithostratigraphic Division and Correlation in Northern China

Non-marine Jurassic and Cretaceous deposits are widely distributed in several basins in northern China, including variegated beds, red beds, coal-bearing horizons,

evaporates and volcanics. These deposits, often of great thickness, contain a rich fossil biota and significant oil, coal and non-metallic mineral resources.

A relatively complete non-marine Jurassic and Cretaceous stratigraphic sequence and a stratigraphic correlation have been established in northern China (Table 1.1). There are two main representative stratigraphic sequences containing insect fossils; one occurs in the Yumen-Jiuquan Basin, Gansu, and the other in the Yanliao Area of Beijing-northern Hebei-western Liaoning-eastern Inner Mongolia. These deposits contain a diverse and abundant continental biota, including insects, conchostracans, ostracods, bivalves, gastropods, fish, dinosaurs, birds, reptiles, amphibians, mammals and plants. During the past decades, a number of studies have been published on the non-marine Jurassic and Cretaceous strata of this region [2–4]. Recent radiometric dating results have complemented biostratigraphic studies [5, 6]. During the last 10 years, we have undertaken a reassessment of the Jurassic and Cretaceous biostratigraphy of northern China, and have improved the assemblage sequence and zonation for insects and many accompanying fossil groups (Tables 1.2 and 1.3).

In northern China, Jurassic and Cretaceous non-marine insect fossil-bearing rocks can be recognized as two different depositional types: (i) large and stable inland depositional basins without volcanic material which is distributed in northwest China, represented by the Yumen-Jiuquan Basin and (ii) intermountain basins with abundant volcanic intercalations of lavas and tuffs separated and controlled by faults which are distributed in Northeastern China represented by the Beijing-northern Hebei-western Liaoning-southeastern Inner Mongolia basins (Yanliao Area).

1.2.1 Yumen-Jiuquan Basin in Gansu Province

During the mid-Mesozoic, the Yumen-Jiuquan Basin was a representative of large and stable inland depositional

Table 1.1 Jurassic-Cretaceous non-marine lithostratigraphic division and correlation at selected insect-bearing localities in the northern China. Geological time scale is based on The ICS International Chronostratigraphic Chart (version 2013) [1].

System	Series	Stage	Time* in Ma	Jiuquan, Gansu	Beijing	North Hebei	West Liaoning	Yanji, Jilin	Laiyang, Shandong
Cretaceous	Upper	Maastrichtian	66						Wangshi Group
		Campanian	72.1						
			83.6						
			86.3						
			89.8						
			93.9						
	Cenomanian	100.5		Sunjiawan Fm (Xiazhuang Fm)	Sunjiawan Fm (Tujinzhai Fm)	Sunjiawan Fm	Longjing Fm		
	Lower	Albian		Zhonggou Fm	Lushangfen Fm	Qinshila Fm	Fuxin Fm	Dalazi Fm Quanshuicun Fm	Dasheng Group
				Xiaogou Fm	Tuoli Fm	Jiufotang Fm	Jiufotang Fm	Changcai Fm	Qinshan Fm
				Chijingpu Fm	Dahuichang Fm	Yixian Fm	Yixian Fm	Tuntianying Fm	Laiyang Fm
			Chijingqiao Fm	Donglanggou Fm	Dabeigou Fm	Dabeigou Fm			
Jurassic	Upper	Hauterivian	129.4		Zhangjiakou Fm	Zhangjiakou Fm	Zhangjiakou Fm		
		Valanginian	132.9						
			139.8						
		Berriasian	145.0						
	Upper	Tithonian		Boluo Fm	Tuchengzi Fm (Houcheng Fm)	Tuchengzi Fm (Houcheng Fm)	Tuchengzi Fm		
		Kimmeridgian	152.1						
		Oxfordian	157.3		Tiaojishan Fm	Tiaojishan Fm	Tiaojishan Fm (Lanqi Fm)		
			163.5	Xinhe Fm	Jiulongshan Fm	Jiulongshan Fm	Jiulongshan Fm (Haifanggou Fm)		Santai Fm
	Middle	Callovian	166.1						
		Bathonian	168.3						
Bajocian		170.3							
Aalenian		174.1		Longmen Fm				Fangzi Fm	
Lower	Toarcian	182.7	Zhongjiangou Fm	Yaopo Fm	Mentougou Fm (Xiahuayuan Fm)	Beipiao Fm		Wennan Fm	
	Pliensbachian								
	Sinemurian	190.8	Dashankou Fm	Xinglonggou Fm	Xinglonggou Fm	Xinglonggou Fm			
	Hettangian	199.3							
		201.3							

Conformity

Disconformity

Unconformity

Hiatus

basins without volcanoclastic deposits in northwestern China. The Jurassic and Cretaceous non-marine rocks in the Yumen-Jiuquan basin comprise, in ascending order: the Dashankou, Zhongjiangou, Xinhe, Boluo, Chijinqiao, Chijingpu, Xiagou and Zhonggou Formations (Table 1.1).

The Dashankou Formation (maximum thickness, 510 m) consists of a basal gray-green conglomerate and sandstones intercalated with purple-red siltstones and mudstones. It unconformably overlies the Upper Triassic Nanyinger Formation.

The Zhongjiangou Formation (maximum thickness, 174 m) rests conformably on the Dashankou Formation and mainly comprises basal gray conglomerate, middle gray-green sandstones, mudstones and intercalated coals.

The Xinhe Formation (maximum thickness, 600 m) conformably overlies the Zhongjiangou Formation and is mainly composed of yellowish-green and dark gray sandstones intercalated siltstones and mudstones.

The Boluo Formation (maximum thickness, 700 m) conformably overlies the Xinhe Formation and includes purplish-red siltstones, sandstones and conglomerate.

The Chijinqiao Formation (maximum thickness, 200 m) unconformably overlies the Upper Jurassic Boluo Formation or other older strata. It is divided into a lower purplish-red conglomerate and sandstones and upper dark gray and gray-green siltstones, thin-bedded shales and mudstones. It yields abundant Jehol Fauna fossils [7].

The Chijinpu Formation (maximum thickness, 400 m), conformably overlying on the Chijinqiao Formation, is dominated by yellowish-green thick-bedded to massive sandstone and conglomerate beds in the lower part, and gray-black mudstone, sandstone, siltstone intercalated with shale and thin coal beds in the upper part. It contains abundant fossils of the conchostracan *Neodiestheria* sp. and bivalves *Sphaerium jeholensis*, *S. anderssoni*, *S. subphanum* and abundant Jehol Entomofauna fossils listed in Table 1.2 [7].

The Xiagou Formation (maximum thickness, 580 m) conformably overlies the Chijinpu Formation and consists of gray-green to purple-red siltstones, interbedded with thinly-bedded mudstone and shales, with abundant insect fossils.

The Zhonggou Formation (maximum thickness, 398 m), conformably overlying on the Xiagou Formation, is unconformably overlain by the Neogene Kuquan Formation and characterized by purple-red siltstones and siltstones.

1.2.2 Intermountain Volcanic Basins in Beijing-Northern Hebei-Western Liaoning-Southeastern Inner Mongolia

Volcanic activities in Northeastern China caused by tectonic movements have been intense throughout the mid Mesozoic period. The Jurassic-Cretaceous strata distributed in the Yanliao Area of Beijing-northern Hebei-western Liaoning-southeastern Inner Mongolia are representative of intermountain basins with abundant volcanic intercalations of lavas and tuffs separated and controlled by faults. Both the renowned Yanliao Biota and Jehol Biota have been found and named in this area originally. The Mesozoic non-marine rocks of Northeastern China have been studied since the 1920s [8], and hundreds of academic papers, including extensive monographs with a stratigraphic context, have been published [1–23].

The Jurassic and Cretaceous non-marine rocks in the Yanliao Area can be divided into 10 typical Formations, in ascending order: Xinglonggou, Mentougou, Jiulongshan, Tiaojishan, Tuchengzi, Zhangjiakou, Dabeigou, Yixian, Jiufotang, Fuxin and Sunjiawan Formations (Table 1.1).

The Xinglonggou Formation (maximum thickness, 905 m), unconformably overlies the Upper Triassic Kuntouboluo Formation, is mainly composed of basalts, andesites and tuffaceous conglomerate and is widely distributed in the Yanliao Area.

The Mentougou Formation (maximum thickness, 1330 m) rests disconformably on the Xinglonggou Formation and is characterized by coal-bearing beds, mainly consisting of lacustrine siltstones, mudstones, shales and sandstones, and rich in tuffaceous materials. These coal-bearing rocks have been called as Beipiao Formation in Liaoning Province or Xiahuayuan Formation in Hebei Province. In Beijing the Mentougou Formation can be divided into Upper Longmen Formation and Lower Yaopo Formation.

The Jiulongshan Formation (maximum thickness, 680 m) unconformably overlies the Mentougou Formation. It consists of varicolored fine-grained sandstones, fine conglomerates, siltstones, mudstones and shales, rich in fossils. To date, about 837 insect species in 476 genera, 166 families and 22 orders have been reported [2, 3, 24, 25]. The main contents of Yanliao Biota have been collected from this Formation. In Liaoning Province, the Jiulongshan Formation is also called the Haifanggou Formation. The fossil beds of Jiulongshan Formation in the Daohugou Village, Inner Mongolia, have been informally called the “Daohugou Formation”, but this usage has received little acceptance because

it is a junior synonym of the Jiulongshan Formation [5, 26–28]. There is a short hiatus between the Mentougou Formation and the Jiulongshan Formation in the Yanliao Area.

The Tiaojishan Formation (maximum thickness, 3500 m) rests disconformably or unconformably on the Jiulongshan Formation. It is dominated by thick-bedded to massive volcanic rocks, mainly basalts, andesites, trachyandesite and rhyolite. In Liaoning Province the Tiaojishan Formation is also called the Lanqi Formation.

The Tuchengzi Formation (maximum thickness, 2600 m), unconformably overlying the Tiaojishan Formation, is a suite of fluvial red and variegated coarse-grained, clastic sedimentary rocks and tuffaceous materials, mainly conglomerate, tuffs, coarse-grained sandstones, pebbly sandstones, alternating with mudstones and siltstones. In Hebei Province and Beijing, the Tuchengzi Formation is also called the Houcheng Formation.

The Zhangjiakou Formation (maximum thickness, 1640 m) unconformably overlies the Tuchengzi Formation. It is dominated by medium-acidic volcanic rocks including purplish-red andesites, rhyolite, acidic volcanic breccia and tuffs, occasionally with several sedimentary intercalations. It may be absent in western Liaoning.

The Dabeigou Formation (maximum thickness, 344 m) is composed of fluvial gray sandy conglomerates, coarse-, medium- and fine-grained sandstones, siltstones, mudstones, intercalating tuffaceous materials, unconformably overlying the Zhangjiakou Formation. It is also absent in western Liaoning. The foregoing data indicate that there may be a long hiatus between Lower Tuchengzi Formation and Upper Yixian Formation in western Liaoning [2, 3, 29]. In Beijing, the Dabeigou Formation is also called the Donglanggou Formation.

The Yixian Formation (maximum thickness, 2442 m) rests unconformably on the Tuchengzi Formation in western Liaoning, but conformably overlies the Dabeigou Formation in northern Hebei. It consists mainly of volcanic rocks with several fossil-bearing lacustrine sedimentary intercalations, mainly a basal tuffaceous conglomerate, gray to black and purplish-red andesites, basalts, grayish-green or grayish-yellow tuffs, tuffaceous sandstones, grits, sandy shales, mudstones, tuffaceous silty mudstones and siltstones and sandstones. It is rich in the well-known Jehol Biota such as insects, ostracods, conchostracan, bivalves, fish, reptiles, feathered dinosaurs, early birds, mammals and early angiosperms. To date, about 862 insect species in 573 genera, 204 families and 19 orders have been reported [2–4, 6, 29–34]. In Beijing, the Yixian Formation is also called Dahuichang Formation.

The Jiufotang Formation (maximum thickness, 2118 m) conformably or disconformably overlies the Yixian Formation. It is characterized by lacustrine medium gray to black, grayish-green or yellowish-gray shaley tuffaceous siltstones and shales, silty limestones, grained sandstones, thin-bedded tuffs, grained tuffaceous sandstones, tuffaceous grits and coarse-grained gravelly sandstones. Coal beds and oil shales sometimes occur in the upper part of the Formation. The Jiufotang Formation grades laterally toward southwest into clastic facies, with more coarse sedimentary rocks, which are called the Tuoli Formation in Beijing.

The Fuxin Formation (maximum thickness, 1550 m), conformably overlying the Jiufotang Formation, consists of coal-bearing siliciclastic rocks, with numerous cycles of gray and white sandstones with pebbles, grained sandstones, siltstones, mudstones, carbonaceous argillites and coal seams in the lower part and greenish-gray, yellowish-gray sandy conglomerates, coarse or fine-grained sandstones, siltstones, mudstones, thin-bedded coal beds and coal lenses in the upper part [9, 23, 35]. The Fuxin Formation is also called the Lushangfen Formation in Beijing and the Qinshila Formation in northern Hebei.

The Sunjiawan Formation (maximum thickness, 660 m), conformably or disconformably overlying the Fuxin Formation and overlain by Neogene rocks, is a suite of fluvial and flood accumulation facies, mainly with varicolored conglomerates and many intercalations of thin-bedded sandstones, siltstones and mudstones. This Formation is also called the Xiazhuang Formation in Beijing and the Tujinzhi Formation in northern Hebei.

Most of the Upper Cretaceous in the Yanliao Area is missing.

Non-marine Jurassic and Cretaceous rocks in the Jilin and Shandong are little different from those of the Yanliao Area. However, their stratigraphic sequence is incomplete; only the Laiyang Formation in Shandong has abundant insect fossils belonging to the Jehol Entomofauna.

1.3 Non-marine Jurassic and Cretaceous Entomofaunas in Northern China

Fossil insects are commonly abundant and widely distributed in the mid Mesozoic non-marine sediments that accumulated in freshwater fluvial or lacustrine environments. Over the past two decades, a large number of well-preserved insect fossils from the Jurassic and Cretaceous in northern China have been reported.

These fossil insects and their assemblage are a valuable group for providing zonation of non-marine rocks and assisting in their correlation. As a result, they can be useful for biostratigraphy subdivision and correlation of non-marine successions [2, 3, 36].

Insect fossils from the Jurassic and Cretaceous in northern China have been studied by palaeoentomologists since 1923 [8]. To date, three entomofaunas are known from the Jurassic and Cretaceous in northern China according to their stratigraphic and biogeographic occurrences. They are the Middle Jurassic Yanliao Entomofauna (Bathonian to Callovian in age), the Early Cretaceous Jehol Entomofauna (Hauterivian to Aptian in age), and late Early Cretaceous Fuxin Entomofauna (Albian in age) [2, 36] (Table 1.2).

1.3.1 Yanliao Entomofauna

The Yanliao Entomofauna is an important component of the Yanliao Biota in the Middle Jurassic, which has become well-known in recent years because of the discovery of the best-preserved crown salamanders, the earliest known feathered dinosaurs, the earliest known gliding and aquatic mammaliaforms, the earliest known eutherian mammals and early angiosperms, etc. [2, 3, 5].

In 1983, abundant fossil insects collected from Haifanggou Formation have been named as Yanliao Entomofauna by Hong [24]. In 1995, the Yanliao Entomofauna has been extended into Yanliao Fauna by Ren *et al.* [2, 36], because a wide range of additional non-marine taxa including conchostracans, bivalves, fish, reptiles, and mammaliaforms coexisted with the insects. With abundant fossil plants found from the Jiulongshan Formation, the term “Yanliao Biota” has been used by multiple authors, but with different definitions [5, 34, 36]. The Yanliao Biota has also been referred to as the “Daohugou Biota”, after many fossils found and documented from the Daohugou locality (Figure 1.1) in southeastern Inner Mongolia since 2002 [5, 26, 37, 38]. However, the term “Yanliao Biota” is gaining recognition among researchers since so-called “Daohugou Biota” is a junior synonym of the Yanliao Biota. Herein the Yanliao Entomofauna is preferred to include all insect fossils from the Middle Jurassic Haifanggou/Jiulongshan Formation and the Upper Jurassic Lanqi/Tiaojishan Formation because these Formations share strong similarities in terms of fossil content. A comprehensive review of the Yanliao Biota, building on previous reviews written from various perspectives, has been provided by Xu *et al.* [5, 25, 34, 36].

Hitherto, about 837 insect species in 476 genera, 166 families and 22 orders have been reported from the Yanliao Entomofauna [2, 3, 24, 25, 36, 39]. The most common



Figure 1.1 Fossil excavation site at the Daohugou locality. Source: Photo by Dr. Chungkun Shih.

taxa of the Yanliao insect fossil assemblages are listed in Table 1.2 and presented in Chapters 5–27.

Among abundant Yanliao herbivorous insects, the pollinating scorpionflies, including Mesopsychidae (e.g. *Lichnomesopsyche gloriae* Ren, Labandeira & Shih, 2010), Aneuretopsychidae (e.g. *Jeholopsyche liaoningensis* Ren, Shih & Labandeira, 2011) and Pseudopolycentropodidae (e.g. *Pseudopolycentropus janeannae* Ren, Shih & Labandeira, 2010) [40–43], have made significant contribution to the evolutionary development of pollination. These taxa had elongate, siphonate (tubular) proboscides and fed on ovular secretions of extinct gymnosperms, and likely engaged in pollination mutualisms with gymnosperms during the mid-Mesozoic, at least 70 million years before the similar and independent coevolution of nectar-feeding flies, moths, and beetles on angiosperms [43]; see also Chapters 24.3 and 28.2.

Amazingly, the herbivore katydid *Archaboilus musicus* Gu, Engel & Ren, 2012, with exceptionally well-preserved stridulatory structures in the forewings produced a low-frequency song to attract potential mates and constituted a normal part of the auditory background in the Yanliao Fauna ecosystem [44]; see also Chapter 30.2.

Yanliao Entomofauna is also characterized by some ectoparasitic insects. Some stem fleas of *Pseudopulex jurassicus* Gao, Shih & Ren, 2012, *P. wangi* Huang, Engel, Cai & Nel, 2013, *Hadropsylla sinica* Huang, Engel, Cai & Nel, 2013, etc., with long serrated stylets might have lived on and sucked blood of relatively large hosts, such as contemporaneous feathered dinosaurs or pterosaurs or medium-sized mammals. [28, 45–48]; see also Chapter 28.4.

Lacewings of *Bellinympha filicifolia* Wang, Ren, Liu & Engel, 2010 and *B. dancei* Wang Y., Ren, Shih & Engel, 2010 mimicked pinnate cycadophyte leaves [49] (see also Chapter 29.2.1), together with hangingfly *Juracimbrophlebia ginkgofolia* Wang Y., Labandeira,

Table 1.2 Biostratigraphic sequence of entomofaunas in Northern China during the Jurassic and Cretaceous.

System	Stage	Formation	Fauna	Ephemeroptera	Odonata	Plecoptera	Blattaria	Notoptera	Coleopteroidea	Phasmatodea	Orthoptera	Dermaptera	Homoptera
Cretaceous	Maastrichtian												
	Campanian												
	Santonian												
	Coniacian												
	Turonian												
	Cenomanian	Sunjiawan (Xiazhuang)	Fuxin Entomofauna										
	Albian	Fuxin (Lushangfen)											
	Aptian	Jiufotang	Jehol Entomofauna										
	Barremian	Yixian											
	Haaterivian	Dabeigou											
	Valanginian												
	Berriasian	Zhongjiakou											
Jurassic	Tithonian	Tuchengzi											
	Kimmeridgian												
	Oxfordian	Tiaojishan	Yanliao Entomofauna										
	Callonian	Jiulongshan											
	Bathonian	(Haifangou)											
	Bajocian												
	Aalenian	Mentougou (Beipiao)											
	Toarcian	(Xiahuyuan)											
	Plensbachian												
	Sinemurian	Xinglonggou (Nandaling)											
	Hettangian												

(Continued)

Table 1.2 (Continued)

[illegible]



Figure 1.2 A delegation of the Insect Fossil Conference visited the Daohugou Fossil Museum under construction in August, 2010. Source: Photo by Dr. Chungkun Shih.

Shih & Ren, 2012 mimicked a type of ginkgo leaf display several unusual mutualistic relationship and paleoecological features between insects and plants [50] (see also Chapter 29.2.2).

The majority of the fossils recovered from the Yanliao Entomofauna in Daohugou are complete, well-preserved and articulated with many fine-scale structures, including mouthparts, antennae and setae of insects. Some of the fossils of insects, plants and other animals are displayed in the Daohugou Fossil Museum (Figures 1.2 and 1.3) and the Ningcheng National Geological Park Museum (Figure 1.4). Many Yanliao insect fossils are even preserved in ways that provide behavioral information. For example, a male–female pair of the froghoppers *Anthoscytina perpetua* Li, Shih & Ren, 2013 preserved in a mating position is the earliest documented fossil record of copulating insects [51]; see also Chapter 30.4. Possible mechanisms of exceptional fossil preservation for the Yanliao Entomofauna could be the apparently sudden deaths and rapid burial caused by recurrent volcano eruptions and poisonous gases.

Studies of many insect fossils from the Yanliao Entomofauna indicated that the paleoenvironment and climate in the Daohugou paleolakes or swamp areas might have been a near-shore shallow lacustrine and wetland basin with a warm, humid climate, diverse and abundant vegetation, and highly aquiferous soil [3, 25, 52, 53]. Simultaneously, some high mountain insects, such as snakeflies *Mesoraphidia daohugouensis* Lyu, Ren & Liu, 2015 and *Ororaphidia bifurcata* Lyu, Ren & Liu, 2017 [54, 55], hairy-bodied tettigarctid *Hirtaprosbole erromera* Liu, Li, Yao & Ren, 2016 [56], support that there were high mountains above 800 m in paleoaltitude in the Daohugou area.

1.3.2 Jehol Entomofauna in the Yanliao Area

The Mesozoic fossils and strata in western Liaoning, northern Hebei and southeastern Inner Mongolia (Yanliao Area) have been studied for nearly 90 years. The first systematic palaeontological and stratigraphic studies on the Yanliao Area fossils were conducted by Grabau in 1923 [8]. During 1920–1940, the Yanliao Area was once called “Jehol” Province. The fossils from the Linyuan County, Liaoning Province was named “Jehol” by Grabau in 1923. In 1928, Grabau gave the name Jehol Fauna to the fossil community from the Jehol Series (= Yixian and Jiufotang Formations). In 1962, the Chinese paleontologist Gu Zhiwei first proposed the terms of “Jehol Group” and “Jehol Biota,” representing an Early Cretaceous terrestrial ecosystem that is mainly distributed in Northeastern China [57]. The term “Jehol Biota” has been extensively used and is well-known today. The diversity of the Jehol Fauna has been summarized by some authors in a different period [2–4, 6, 17, 31–33, 58] (Table 1.3).

In 1995, insect fossils from the Yixian and Jiufotang Formations have been referred as Jehol Entomofauna by Ren [2, 3, 36]. The Early Cretaceous Jehol Entomofauna bears a close taphonomic resemblance to the Middle



Figure 1.3 The Daohugou Fossil Museum. Source: Photo by Dr. Chungkun Shih.

Figure 1.4 The Ningcheng National Geological Park Museum. Source: Photo by Dr. Chungkun Shih.

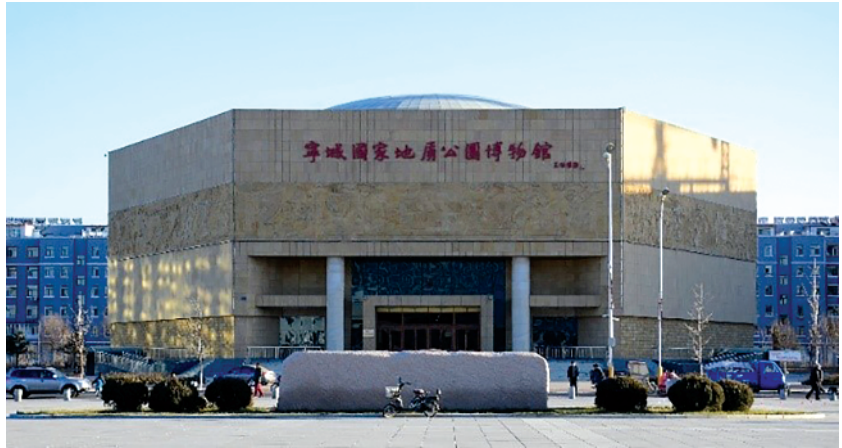


Figure 1.5 A delegation of the Insect Fossil Conference visited the Shihetun Fossil site in August, 2010. Source: Photo by Dr. Chungkun Shih.

Jurassic Yanliao Entomofauna [32]. The majority of the insect fossils recovered from the Yixian Formation are complete and articulated, with many fine-scale structures and details preserved.

Up to now, fossil insects, with their remarkable diversity, exceptional preservation and implications for evolution of many insect lineages, represent some of the most important discoveries among the Jehol Fauna, e.g. the Shihetun fossil site (Figure 1.5). To date, about 862 insect species in 573 genera, 204 families and 19 orders in the Jehol Fauna have been published [2–4, 6, 29–34, 39, 58] (Chapters 5–27). There are three distinct insect assemblages, approximately corresponding to the early, middle and late stages of the Jehol Entomofauna in Table 1.2 [32].

A hypothetical structure of ecosystem and their environmental settings of the Jehol Entomofauna have been preliminarily reconstructed. The insect assemblages in the Yixian Formation could be divided into four communities based on habitats, or five groups based on feeding habits. Of the four communities, the highest

species diversity occurred in the forest community, followed by the aquatic, soil, and alpine communities. Of the five feeding groups, the highest species diversity appeared in the phytophagous group, followed by the carnivorous, parasitic, saprophagous, and heterophagous groups [3, 32, 58, 59].

Overall, the insect community in the Yixian Formation lacustrine ecosystem was relatively stable. The climate of this region was warm and humid, while there was seasonal arid and semi-arid climate in microenvironment. There were plenty of calm deep-water lakes, while other water bodies existed around the lakes, such as swamps and shallow water environment. The soil on the land was nutritious and moist enough for a variety of plants, insects and other animals to survive. There were mountains with alpine lakes and streams at least 800 m high in paleoaltitude [58].

More importantly, the insects played a key role in the entire Jehol ecosystem as they constituted prey for nearly all major groups of vertebrates: fishes, amphibians, choristoderans, turtles, lizards, birds, and pterosaurs. They might also have provided food for some dinosaurs and mammals [6, 58]. Some of the Jehol specimens of insects, plants and other animals are treasured in the Shihetun Fossil Museum (Figure 1.6) and the Chaoyang Paleontological Fossil Museum (Figure 1.7).

In addition, insects in the Yixian Formation also provide some important evidence for the co-evolution between insects and plants and animals. A large number of pollinating insect fossils, such as brachyceran flies of *Protonemestrius jurassicus* Ren, 1998, scorpionflies of *Vitimopsyche kozlovi* Ren, Labandeira & Shih, 2010, kalligrammatid lacewing *Sophogramma papilionacea* Ren & Guo, 1996, and flower bug *Vetanthocoris decorus*, Yao, Cai & Ren, 2006, etc., indicate that pollinating insects might have played an important role in the origin and early evolution of the angiosperms [43, 60–62] (see also Chapter 28.2). The discovery of the largest definitive



Figure 1.6 A delegation of the Insect Fossil Conference visited the Shihetun Fossil Museum in August, 2010. Source: Photo by Dr. Chungkun Shih.



Figure 1.7 The Chaoyang Paleontological Fossil Museum. Source: Photo by Dr. Chungkun Shih.

fleas of *Pseudopulex magnus* Gao, Shih & Ren, 2012 [45], *Saurophthirus exquisitus* Gao, Shih & Ren, 2013 [45] and *Tyrannopsylla beipiaoensis* Huang, Engel, Cai & Nel, 2013 [48] and blood-feeding true bugs of *Torirostratus pilosus* Yao, Shih & Engel, 2014 and *Flexicorpus acutirostratus* Yao, Cai & Engel, 2014 [61] from the Jehol Entomofauna highlight the diversity of Early Cretaceous ectoparasitic insects (Chapters 28.4 and 28.5).

1.3.3 Fuxin Entomofauna

Fossils from the Fuxin Formation, conformably overlying the Jiufotang Formation which overlies the Yixian Formation, have been given various names in different taxa by multiple authors. In 1981, plant fossils, found in the Sahai Formation and the Fuxin Formation of western Liaoning and other equivalent strata, were referred to as Fuxin Flora by Feng Chen [12, 13], which were characterized by the dominance of the Filicopsida, Ginkgopsida and Coniferopsida, with abundant Cycadopsida and Equisetales.

In 1981, fossil insects from the Lushangfen Formation in west hills, Beijing (equivalent to Fuxin Formation in western Liaoning) were named as Lushangfen Entomofauna by Hong [63]; later this was abandoned by Hong in 1993 [64]. In 1987, all animal and plant fossils from the Fuxin Formation in western Liaoning were called Fuxin Biota by Wuli Wang [14]. The most common elements of the Jehol Fauna fossil assemblages have never been found in the Fuxin Biota, including insects: *Ephemenopsis trisetalis*, *Coptoclava longipoda*, *Chironomaptera gregaria*, *Clyptostemma xyphidie*, *Sinaeschuidia heishankouensis* (Table 1.2); conchostacans: *Eosestheria-Diestheria-Liaoningestheria*; fish: *Lycoptera*, *Peipiaosteus* and dinosaur: *Psittacosaurus* (Table 1.3).

Considering the different contents of insect fossils from those in Jehol Entomofauna, the insect fossil assemblages from Lushangfen Formation have been termed the Fuxin Entomofauna by Ren [2, 36]. This Entomofauna contains about 20 reported fossil species. Although the number of species and fossil quantity are obviously less than those of the Jehol Entomofauna in the strata below, the Fuxin insect fossils are characterized by many fossil termites *Jitermes*, *Yanjingtermes* and *Yongdingia*; Odonata *Hemeroscopus* and Coleoptera *Cionocoleus* and *Monticupes*, *Diluticupes*.

1.4 Geological Ages of Non-marine Jurassic and Cretaceous Strata and Entomofaunas in Northern China

The Jurassic and Cretaceous was a period of violent tectonic movements, great paleogeographic, paleoclimatic and biotic changes, and the formation of vast quantities of endogenic and sedimentary (particularly coal and oil) deposits of economic value. The global Mesozoic has included both marine and non-marine strata and fossils. The standard global chronostratigraphic scale for the Mesozoic is based primarily on marine fossils; ammonoids and microfossils (foraminiferans and calcareous nannoplankton) integrated with a well-established global polarity timescale and a relative abundance of radioisotopic ages. Unfortunately, the practical isotopic data for the ages of the boundaries between stages and systems from Upper Jurassic to Lower Cretaceous in the International Stratigraphical Chart are deficient. These ages are defined through the averaging and interpolating method with the assumption that an ammonite subzone would last one million years and all the subzones have equal evolutionary rates [65, 66]. Consequently, there were different opinions on the “international chronostratigraphic framework chart

for Jurassic/Cretaceous boundary” among geologists and the International Commission on Stratigraphy based on marine rocks and radiometric ages [1, 21–23].

Historically, different authors once placed the J/K boundary at 130, 135, 137, 142 or 145.5 Mya in the International Stratigraphic Charts [21, 65]. Until now, there is no reliable evidence to support whether to place the J/K boundary at 140 Mya, 142 Mya, 145.5 Mya, or at 135 Mya. This makes non-marine Jurassic and Cretaceous strata correlations challenging and very difficult to establish a non-marine Cretaceous stratigraphic framework chart in the global timescale [67–70]. To date, the position of the global Jurassic/Cretaceous boundary stratotype has not yet been formalized. A consensus on the age and correlation of the coal-, oil- and fossil bearing Jurassic-Cretaceous no-marine strata in northern China has not been achieved.

In this context, based on an updated time scale of The ICS (International Commission on Stratigraphy) International Chronostratigraphic Chart (version 2016) [1] and synthesized from the previous results, we correlate the non-marine Jurassic and Cretaceous rocks in northern China by the stratigraphic occurrences of insects, together with various radiometric ages of the intervening tuffs, tuffaceous rocks and lavas, other accompanying bivalves and dinoflagellate assemblage sequences found in the eastern Heilongjiang basins marine and non-marine interbeds [17–23].

In northern China, the ages of the Jiulongshan/Tiaojishan Formation bearing Yanliao Fauna and Yixian/Jiufotang Formations bearing Jehol Entomofauna are the focus of attention because major insect fossils are from these Formations.

The Jiulongshan/Haifanggou Formation has been widely accepted as the Middle Jurassic in age based on paleontological data [2, 3, 15, 24, 71]. In 2002, the strata section containing Yanliao biota at the Daohugou Village, Ningchen County, Inner Mongolia was measured, recognized and attributed to the Jiulongshan Formation and belonging to the Late Aalenian or Early Bajocian in age for the first time by Ren’s Team [37]. In the past decade, a new batch of isotopic radiometric data have

supported this age assessment and further indicated that the Jiulongshan is partially Bathonian but mainly Callovian [5]. For example, a $^{40}\text{Ar}/^{39}\text{Ar}$ age of 166.7 ± 1.0 Mya around the middle of the Haifanggou Formation and two recent $^{40}\text{Ar}/^{39}\text{Ar}$ dates of 159.5 ± 0.6 Mya for the Lanqi Formation were obtained in Beipiao, western Liaoning Province [72, 73]. At the Daohugou Locality a serial of $^{206}\text{Pb}/^{238}\text{U}$ SHRIMP ages (162 ± 2 Mya, 152 ± 2.3 Mya, 166 ± 1.5 Mya, 165 ± 2.4 Mya, 164 ± 1.2 Mya and 165 ± 1.2 Mya) and $^{40}\text{Ar}/^{39}\text{Ar}$ (159.8 ± 0.8 Mya, 164 ± 2.5 Mya) ages was obtained based on samples collected from the fossil-bearing layers respectively by different authors suggesting that the Daohugou beds are mostly Callovian [74–77].

The arguments over the age-range of the Jehol Group/Biota have arisen since 1920s. The age of the Yixian Formation, which yields the Jehol Biota, has been considered as late Tithonian, Early Cretaceous or spanning the Jurassic-Cretaceous boundary [2, 3, 6, 9–11, 15–21]. The point of view concerning Early Cretaceous age has been proven by new paleontological data and isotopic datings [22, 23].

A lot of age data using $^{40}\text{Ar}/^{39}\text{Ar}$ or U/Pb methods from tuff or lava flows of the lower Yixian Formation near Sihetun Village of Beipiao City, Liaoning, China have been obtained by many teams [78–82] ranging from the Barremian to the Aptian (from 130 to 120 Mya, interval about 10 Mya). Hence, the age data from the Yixian Formation may range from Hauterivian to Middle Aptian, but are mainly from around the Barremian-Aptian transition, and the age of the Jiufotang Formation is Middle Aptian.

Some SHRIMP U-Pb zircon age of 133.9 ± 2.5 Mya, 130.1 ± 2.5 from Dabeigou Formation in Luanping basin of northern Hebei and 135.8 ± 3.1 Mya, 136.3 ± 3.4 Mya, 135.4 ± 1.6 Mya from Zhangjiagou Formation have been obtained [83, 84]. This result not only supports a Hauterivian/Barremian-Early Albian age for the Jehol Biota, but also indicates that the non-marine Jurassic/Cretaceous boundary in the Yanliao Area is below the Yixian Formation, probably within the Tuchengzi Formation (Table 1.1).

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