Vertebrate assemblages of the Jehol Biota in western Liaoning, China

by

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Abstract

The Jehol Biota of western Liaoning Province is represented by four vertebrate complexes: the lower Yixian Fm. *Confuciusornis-Sinosauropteryx-Zhangheotherium* Complex; the middle Yixian Fm. *Monjurosuchus-Hyphalosaurus-Liaoxiornis* Complex; the upper Yixian Fm. *Lycoptera muroii-Manchurochelys manchouensis* Complex, and the Jiufotang Fm. *Cathayornis-Chaoyangia-Psittacosaurus* Complex. These assemblages are all determined to be Early Cretaceous in age and are correlated to the Mesozoic Geologic Time Scale of Gradstein et al. on the basis of ⁴⁰Ar/³⁹Ar dates from extrusive basalts and tuffs interbedded with the fossiliferous units. Age assignments for the vertebrate fossils are recognized as middle Barremian, late Barremian, and Aptian stages. The stratigraphic range represented by the Yixian and Jiufotang formations spans the late Valanginian through Barremian and Aptian stages.

Introduction*

Ever since the distinguished geologist A. W. Grabau erected the nomenclature of the Jehol System (Grabau, 1923) and Jehol Biota (Grabau, 1928) in the 1920’s, the sedimentary units comprising the Jehol Group and the fauna contained therein have constituted a focal point for Chinese and international geologists and paleontologists. The Jehol Biota is produced principally from the Yixian and Jiufotang formations in western Liaoning Province, in addition to stratigraphically equivalent sediments, and represents a prolific assemblage of plants and animals characteristic of the expansive region of northeast Asia (Chen, 1988; Wang, 1990; Hong, 1993).

In the 1940’s Japanese workers recovered reptilian specimens from the Yixian and Jiufotang formations at Jingangshan, in the Yixian Basin and the Fuxin, Pingquan, and Lingyuan basins (Endo, 1940; Endo and Shikama, 1942).

Since the 1970’s, paleontologists have described specimens excavated from the Jiufotang Fm. at the localities of Meigeyingzi and Boluochi in the Beipiao and Chaoyang basins including a psittacosaur dinosaur (Sereno et al., 1998; Zhou et al., 1991; Hou et al., 1993; Zhou, 1995, Hou, 1997). Most recently, a large quantity of exquisite archaic bird specimens typified by *Confuciusornis* (Hou, 1997; Hou et al., 1995; Hou, 1996; Hou et al., 1999) have been excavated from the lower Yixian Fm. at the localities of Jianshangou and Sihetun in the Jinlingsi and Yangshan basins (Wang et al., 1998), in addition to small “feathered” theropod dinosaurs (Chen et al., 1997, Ji et al., 1998), psittacosaur ceratopsians (Xu et al., 1998), pterosaurs (Ji and Ji, 1997; Ji and Ji, 1998), lizards (Ji, 1998; Ren et al., 1995), turtles (Ren et al., 1995), amphibians (Ji and Ji, 1998; Wang and Gao, 1999), and a mammal (Hu et al., 1997). In addition, at Dawangzhangzi, Lingyuan Co. the first discoveries of a long-necked aquatic reptile (Gao et al., 1999) and a small delicate bird (Hou and Chen, 1999) were documented. These vertebrates constitute the most significant members of the Jehol Biota.

Vertebrate complexes

The Jehol Biota may be generally recognized as four complexes:

**Lower Yixian Fm. ** *Confuciusornis-Sinosauropteryx-Zhangheotherium* complex: This complex is represented by an assemblage excavated at Sihetun, Beipiao Municipality. Specimens are produced from lacustrine shales of Member 3 in the Yixian Fm. at Sihetun, Shangyuanchiang, Yangshan and Jinlingsi basins and in the surrounding regions (Wang et

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These localities are generally correlated to the interbedded sediments of the Yixian Fm. at Jianshangou (Chen et al., 1980). Documented fossil localities include Sihetun, Jianshangou, Zhangjiagou, Huangbanjigou, Tuanshangou, Libalanggou, Heitizigou, Wudaigou, Miaogou, Dabangou, Dabeigou, Qingshiliang, and Jiancaogou. These localities trend north northeast spanning an approximately 12-14 km latitudinal range and approximately 4-5 km longitude range. The two principle vertebrate producing horizons occur in the lower section of the sediments at Sihetun and the upper section at Huangbanjigou (Wang et al., 1998, 1999). During the 1997-98 field seasons, the Institute of Vertebrate Paleontology and Paleoanthropology (IVPP) undertook extensive excavations in the lower sediments at Nangou, Sihetun, and Zhangjiagou while concurrent detailed geologic field work was undertaken at Sihetun and Jianshangou. Three sites encompassing 600 square meters at Sihetun and Zhangjiagou produced several dozen significant vertebrate bearing stratigraphic levels which produced several hundred specimens of fish, reptiles (turtles, pterosaurs, theropods, sauropods, ceratopsians), and birds, in addition to copious specimens of invertebrates and gymnosperm plant macrofossils. At Sihetun and its neighboring vicinities the stratigraphic sequence of the lower Yixian Fm. is well documented, as are vertebrate bearing fossil units and their taphonomic conditions (Wang et al., 1998, 1999). The vertebrate faunal complex may now be recognized in its entirety with the following taxa:

**Pisces:**
- *Lycoptera sinensis* Woodward
- *L. davidi* (Sauvage)
- *L. sp.*
- *Sinamia* sp.

**Amphibia:**
- *Liaobatrachus grabaui* Ji and Ji

**Chelonia:**
- *Manchurochelys liaoxiensis* Ji
- *M. sp.*

**Lacertilia:**
- *Dalinghesaurus longiditus* Ji

**Pterosauria:**
- *Eosipterus yangi* Ji and Ji
- *Dendrorhynchus curvidentatus*, Ji and Ji
- Pterodactyloidea gen. et sp. nov.

**Sauropoda:**
- Gen. et sp. indet.

**Theropoda:**
- *Sinosauropteryx prima* Ji and Ji
- *Protarchaeopteryx robusta* Ji and Ji
- *Caudipteryx zoui* Ji et al.
- Dromaeosauridae gen. et sp. nov.
- Therizinosauridae gen. et sp. nov.

**Ceratopsia:**
- *Psittacosaurus* sp.

**Aves:**
- *Confuciusornis sanctus* Hou et al.
- *C. sunae* Hou
- *C. chuonzhou* Hou
- *C. sp.*
- *Liaoningornis longidigitus* Hou
- *Eoenantiornithes buhleri* Hou et al.
Mammalia:

*Zhangheotherium quinquecuspidens* Hu et al.

The taxonomic diversity of this fauna is high, with specimens dominated by the primitive sauririne bird *Confuciusornis* (Hou et al., 1995), occasional occurrences of more derived ornithirine birds including *Liaoningornis* (Hou, 1996), and the earliest record of an enantiornithine bird *Eoenantiornithes* (Hou et al., 1999). Also documented is a developmental phase unprecedented in paleontology of small “feathered” theropods including *Sinosauropteryx* (Chen et al., 1977), *Protarchaeopteryx* (Ji and Ji, 1997), and *Caudipteryx* (Ji et al., 1998). Additional specimens representing the Dromaeosauridae and Therizinosauridae are present, as are relatively numerous specimens of psittacosaour ornithischians (Xu and Wang, 1998). Pterosaurs are dominated by the derived short-tailed Pterodactyloidea (Wang et al., 1998; Ji and Ji, 1997; Wang et al., 1999) and the long-tailed Ramphorhyncoidea also occur (Ji and Ji, 1998).

This complex preserves plesiomorphic characters while concurrently expressing derived characters. The high taxonomic diversity reflects a rapid period of radiation and a complex synthetic nature of the fauna.

The fossil vertebrates at Sihetun are principally produced from the lower stratigraphic section represented by an approximately 12 m thick unit of gray-black tuffaceous lacustrine shales interbedded with tuffs, more specifically from the lower 7 m (cross-section units 18-37), with specimens being noticeably prolific in units 25-29. The majority of the fauna is preserved in the same units producing a large quantity of *Confuciusornis* specimens which is a mere 5 mm thick tuffaceous shale (Wang et al., 1998; 1999). This represents both a phase of rapid radiation and evolution, in addition to a mass mortality event.

**Middle Yixian Fm. Monjurosuchus-Hyphalosaurus-Liaoxiornis Complex:**

This is produced from the interbedded sediments of the Yixian Fm. from the Daxinfangzi Unit in the Pingquan and Lingyuan basins (Chen et al., 1980) in addition to equivalent sediments bearing this complex. Localities include Daxinfangzi, Songzhangzi, Ershilipu, Dawangzhangzi, Fanzhangzi, and Shanzui in Yiyuan Co. Taxa within this complex include the following:

**Pisces**

*Peipiaosteus pani* Liu and Zhou
*Protopsephurus liui* Lu,
*Lycoptera davidi* (Sauvage)

**Sphenacodontidae**

*Monjurosuchus splendens* Endo

**Diapsida - family insertae sedis**

*Hyphalosaurus lingyuanensis*, Gao, Tang, and Wang

**Lacertidae**

*Yabeinosaurus tenuis* Endo and Shikama

Sauropoda indet.
Theropoda indet.

**Aves**

*Liaoxiornis delicatus* Hou and Chen

The notable characteristics of this complex include the extreme abundance of fish. In addition to the genera *Lycoptera* and *Peipiaosteus* (Lu, 1994) there is the first occurrence of *Protopsephurus* (Jin et al., 1995). Fresh water lacustrine reptiles are prolific with a relatively large quantity of *Monjurosuchus* (Endo, 1940) and the first documentation of the long necked aquatic reptile *Hyphalosaurus lingyuanensis* (Gao et al., 1999). Although avian quantity and diversity has decreased, there is an extremely tiny and delicate bird represented with a mosaic of primitive and
derived characters described as *Liaoxiornis delicatus* (Hou and Chen, 1999). This complex is extremely characteristic in its expression of primitive and derived taxa.

**The Upper Yixian Fm. Lycoptera muroii-Manchurochelys manchouensis Complex:** This is produced from the interbedded vertebrate bearing sediments of the Yixian Fm. at Jingangshi in the Fuxin and Yixian basins (Chen et al., 1980; Wang, et al., 1989). The predominant fossil locality is at Zaocishan, Yixian Co. Taxa include:

Pisces:
- *Lycoptera muroii* (Takai)

Chelonia:
- *Manchurochelys manchouensis* Endo and Shikama

Lacertilia:
- *Yabeinosaurus tenuis* Endo and Shikama

This complex is relatively simple in character with only the single fish *Lycoptera muroii* (Lu, 1994). *Yabeinosaurus* and *Manchurochelys* are relatively abundant (Endo, 1942).

**The Jiufotang Fm. Cathayornis-Chaoyangia-Psittacosaurus Complex:** This is produced from the vertebrate bearing sediments at Meigeyingzi and Boluochi in the Beipiao and Chaoyang basins. Taxa include:

Pisces:
- *Peipiaosteus pani* Liu and Zhou
- *Protopsephurus liui* Lu
- *Sinamia zdanskyi* Stensio
- *Lycoptera davidi* (Sauvage)
- *Jinanichthys longicephalus* (Liu et al.)
- *Longdeichthys luojiaxiaensis* Su
- *Huashia* sp.

Sauropoda indet.

Ceratopsia:
- *Psittacosaurus meileyingensis* Sereno et al.
- *P. mongoliensis* Osborn

Aves:
- *Sinornis santensis* Sereno and Rao
- *Boluochia zhengi* Zhou
- *Cathayornis yandica* Zhou, Jin, and Zhang
- *C. caudatus* Hou
- *Longchengornis sanyanensis* Hou
- *Cuspirostrornis houi* Hou
- *Largirostrornis sexdentornis* Hou
- *Chaoyangia beishanensis* Hou and Zhang
- *Songlingornis linghensis* Hou

Notable characteristics of this complex include the sharp decline of the fish genus *Lycoptera* which was so prolific in the Yixian Fm. and the continued abundance of *Peipiaosteus* and *Protopsephurus*, in addition to a large quantity of *Sinamia, Jinanichthys,* and *Longdeichthys* (Lu, 1994). Psittacosaurid ceratopsians are also abundant with the two species *P. mongoliensis* and *P. meileyingensis* (Sereno et al., 1988). Avian diversity is extremely high with a large quantity of remnant Sauriurae as represented by *Cathayornis* (Zhou et al., 1992; Hou, 1997) in addition to the derived Ornithurae such as *Chaoyangia* (Hou et al., 1993).
Discussion of chronology and correlation of vertebrate bearing units

There is definite controversy regarding the Jehol Biota and its age assignment. Geologists and paleontologists have applied different chronological methods and perspectives in their interpretations, resulting in three principle conclusions: some believe the age to be Late Jurassic (Chen, 1988; Wang, 1990; Hou et al., 1995; Chen et al., 1980; Wang, 1998; Wang et al., 1985, 1989; Gu, 1962, 1983; Liu and Zhou, 1965; Liu et al., 1963, 1986, 1987; Li et al., 1982; Sun et al., 1998), others regard the age as Late Jurassic to Early Cretaceous (Chen et al., 1997; Ji et al., 1998; Ren et al., 1995, 1997; Jin, 1996), and still others as solely Early Cretaceous (Grabau, 1923, 1928; Xu and Wang, 1998; Hao et al. 1986, 1982; Wang and Diao, 1984; Dong, 1980, 1993; Yabumoto, 1994; Li et al., 1993; Gu, 1995; Smith et al., 1995; Chen and Chen, 1997; Swisher et al., 1998). This text will address an age interpretation through the perspective of the vertebrate complexes. Previous literature recognizes the Lycoptera Ichthyofauna (Jin, 1996), the Psittacosaurus Herpetofauna (Wang and Diao, 1984; Swisher et al., 1998; Dong, 1980), and the two distinct Confuciusornis and Cathayornis avifaunas.

Lycoptera Ichthyofauna: This fauna is produced from the lower lacustrine sediments of the Jehol Group in North China, typically represented by the genera Peipiaosteus, Sinamia, and Lycoptera (Jin, 1996). P. pani is extremely morphologically close to Stichopterus from Russia and Mongolia. Also within this fauna is Protosphephurus liui which most closely resembles Paleosphephurus from the Late Cretaceous of Montana, North America, but the latter is more derived. Jinanichthys longicephalus is extremely close to Kuyangichthys from the Early Cretaceous Guyang Fm., at Guyang, Inner Mongolia. Londeichthys luojiaxiaensis is closest to Leptolepides sprattiformis from the Kimmeridgian-Tithonian stages of Germany and France.

A comprehensive perspective of the Lycoptera Ichthyofauna indicates a general complexion that resembles the Late Jurassic-Early Cretaceous Purbeckian-Wealden stages of western Europe. In recent years an Early Cretaceous fish fauna has been discovered in the northern part of Kyushu, western Japan, from the Wakino Subgroup (Kwanmon Group) (Dong, 1992) which provides further evidence for determining the age of Chinese ichthyofaunas. The Japanese fauna is basically consistent with those from the Guantou Fm. and other related lithologies in the southeast coastal regions of China. The principal taxa of the coastal faunas have each been identified as resembling the North China Lycoptera Ichthyofauna (Jin, 1996). The Xiye Subgroup is recognized as Hauterivian-early Aptian based upon interbedded marine units (Dong, 1995). Thus the Jehol Ichthyofauna can be assigned to the Early Cretaceous with relative certainty.

Psittacosaurus Herpetofauna: The reptiles within the four vertebrate complexes produced from the western Liaoning Basins may be unified into a single Psittacosaurus Fauna. Biogeographically, this fauna is represented in the extensive region of northeast Asia within sediments equivalent to the Jehol Group (Dong, 1980, 1993; Kimura et al., 1991; Sereno, 1990; Weishampel, 1990, Matsukawa, 1994). More recently, the fauna has also been documented in the Early Cretaceous of Thailand (Buffetaut and Suteethorn, 1992). Additional taxa representing the Jehol Biota have also migrated to neighboring regions (Chen, 1998, Buffetaut and Suteethorn, 1992).

The following reptilian taxa are recorded from the Psittacosaurus Fauna of western Liaoning: Manchurochelys manchouensis, M. liaoxiensis, M. sp., Monjurosuchus splendens, Yabeinosaurus tenus, Hyphalosaurus lingyuansensis, Dalinhosaurus longidigitus, Eosipterus yangi, Dendrorhynchoides curvidentatus, Pterodactyloidea gen. et sp. nov., Sauropoda indet. Sinosauropteryx prima, Protarchaeopteryx robusta, Caudipteryx zoui, Dromaeosauridae gen et sp. nov. Therizinosauridae gen et sp. nov., Theropoda indet. Psittacosaurus mongoliensis, P. meileyingensis, and P. sp.
There is a relatively close phylogenetic relationship between the turtles *Manchurochelys* from the Yixian Fm. of western Liaoning, *Dracochelelys* from the Shengjinkou Fm., Tugulu Group, in the Xinjiang Autonomous Region, and *Sinemys* from the Luohandong Fm., Zhidan Group, in Inner Mongolia (Gaffney, 1992).

*Yabeinosaurus* is a member of the Ardeosauridae, a family commonly found in the Upper Jurassic of Europe.

Two most recently described genera from the Xixian Fm. of Beipiao, *Dalinghosaurus* (Ji, 1998) and *Hyphalosaurus* (Gao et al., 1999), both maintain an extremely long caudal series and the latter also maintains a long cervical series with 19 vertebrae, but their phylogenetic status is still under study.

The pterosaurs are dominated by the Pterodactyloidea, such as *Eosipterus* produced from the lower Yixian Fm. at Sihetun (Ji and Ji, 1997) which most closely resembles *Huanhopterus* (Dong, 1982), a member of the Ctenochasmatidae from the Huachihuanhe Fm., Zhidan Group, Ordos Basin. *Eosipterus* and other recently recovered specimens compare well with the European Late Jurassic *Pterodactylus*, *Ctenochasma*, *Gnathosaurus*, and *Ornithodesmus* which generally retain a mosaic of plesiomorphic Late Jurassic characters in addition to derived Cretaceous characters. The newly described *Dendrorhynchus* (Ji and Ji, 1998) maintains a relatively long tail in addition to other plesiomorphic characters attributed to Late Jurassic pterosaurs.

The lower Xixian Fm. vertebrate complex displays both primitive and derived characteristics, and thus the entire faunal complex indicates it would be more appropriately assigned to the Early Cretaceous.

The prolific occurrence of psittacosaurid ornithischian and theropod dinosaurs is characteristic of the fauna. To date there are nine species of Psittacosauridae recorded from the Jehol Group of North China, a large quantity of which are produced from the lacustrine sediments in the lower Yixian Fm. at Sihetun (Wang et al., 1998, 1999; Xu and Wang, 1998) which represents the oldest record for the family. *P. mongoliensis* represents a higher stratigraphic position in the Jiufotang Fm. of China and the Aptian-Albian of Mongolia.

At least three genera and species of theropods are present in the Yixian Fm. (Chen et al., 1997; Ji et al., 1998) two of which are currently under study and assigned to the Dromaeosauridae and Therizinosauroidea. These small theropods are all “feathered,” appear to be evolving toward an avian morphology, and are phylogenetically more primitive than *Archaeopteryx* from the early Tithonian, Late Jurassic, of Germany (Ji et al., 1998). *Sinosauropteryx* is assigned to the Compsognathidae (Chen et al., 1997), a family which was previously only documented in the Late Jurassic Solnhofen Limestone of Germany. Further analysis is required to determine the accurate taxonomic assignment of *Protarchaeopteryx* and *Caudipteryx*. Other dromeosaurs are principally known from the middle to Late Cretaceous of Asia and North America (Weishampel, 1990; Jerzykiewicz and Russell, 1991; Ostrom, 1990; Barsbold and Maryanska, 1990), including *Phaedrolosaurus* and *Tugulusaurus* from the Early Cretaceous Tugulu Group of Xinjiang (Barsbold and Maryanska, 1990), *Velociraptor* (Osborn, 1924), *Adasaurus* (Barsbold, 1983) from the Late Cretaceous Campanian-Maastrichtian of Mongolia, and *Dromaeosaurus* (Matthew, 1922) and *Deinonychus* (Ostrom, 1969) from the Aptian-Albian of North America. The Therizinosauroidea is only documented from the Cretaceous of Central Asia with the majority of specimens being produced from the Late Cretaceous (Jerzykiewicz and Russell, 1991; Barsbold and Maryanska, 1990; Dong, 1979; Dong and You, 1997; Clark et al., 1994), including *Nanshiungosaurus* (Dong, 1979, Dong and You, 1997) from the Early Cretaceous Xinminbao Fm. of Mazongshan, Gansu, and *Alxasaurus* (Russell and Dong, 1993) from the Alashan Desert of Inner Mongolia. Late Cretaceous Cenomanian-Turonian segnosaurs are represented by
The *Confuciusornis* and *Cathayornis* avifaunas: Two distinct avian faunas are produced from the Yixian Fm. and Jiufotang Fm. respectively. The *Confuciusornis* Fauna contains four genera and six species represented by the Sauriurae *Confuciusornis sanctus*, *C. chuonzhous*, *C. sunae*, *C. sp.*, and *Liaoningornis delicatus*, in addition to the Ornithurae *Liaoningornis longidigitus*, and the enantiornithine *Eoenantiornithes buhleri*. The fauna is produced from the Yixian Fm. at Heitizigou and Sihetun, Beipiao Municipality, and Lingyuan Co.

The global paleontological record of archaic birds is extremely restricted, and as such the only remotely close comparison of *Confuciusornis* that can be made is to *Archaeopteryx* from the Late Jurassic Tithonian Stage of Germany. There are numerous characters shared between *Archaeopteryx* and *Confuciusornis* (Hou, 1995; Hou et al., 1995a, 1995b; Martin et al. 1998), although *Confuciusornis* also maintains apomorphic characters quite distinct from *Archaeopteryx*, including the loss of maxillary and mandibular dentition, the presence of a cutaneous beak, a relatively well developed sternum, proximal humerus with a pneumatic fenestra, and an extremely reduced tail with fused caudals (Hou, 1995). To date, *Liaoningornis* represents the oldest record of the Ornithurae, with characters more primitive than *Chaoyangia* from the Jiufotang Fm., western Liaoning, and *Ambiorix* from the Early Cretaceous of Mongolia, but it also maintains numerous apomorphic characters (Hou, 1996). *Eoenantiornithes* is the earliest record of the family which does not survive beyond the Cretaceous. The derived faunal characteristics, diversity, and extreme quantity of specimens expresses a strong degree of diversity and radiation. From a general perspective, its age should represent the Early Cretaceous.

The *Cathayornis* Avifauna is represented by eight genera and nine species including the Sauriurae *Sinornis santensis*, *Boluochia zhengi*, *Cathayornis yendica*, *C. caudatus*, *Lonchengornis sanyanensis*, *Cuspirorsrisornis houi*, and *Largirostrornis sexdentornis*, in addition to the Ornithurae *Chaoyangia beishanensis*, and *Songlingornis linghensis*. The entire assemblage is produced from the Jiufotang Fm. at Boluochi and neighboring regions of Chaoyang Co. in Liaoning, and is much more taxonomically diverse than the *Confuciusornis* Fauna.

Outside of China, Cretaceous birds are also recovered from Mongolia, Spain, Australia, North America, and Argentina. The abundance of Enantiornithidae is characteristic for the Cretaceous, and the majority of the six genera and seven species of Sauriurae in the *Cathayornis* Fauna represent this family, among which, *Sinornis* and *Cathayornis* appear extremely close to *Iberomesornis*, *Concornis*, and *Noguerornis* from the Early Cretaceous Barremian Stage of Spain. The *Cathayornis* Fauna ornithurines *Chaoyangia* and *Songlingornis* also maintain several derived characters approaching extant forms. The general complexion of this fauna and its comparison to other derived faunas indicate its age should be Early Cretaceous.

In summary, the Jehol Biota is a composition of several vertebrate faunas: The *Lycoptera* Ichthyofauna, the *Psittacosaurus* Herpetofauna, the *Confuciusornis* Avifauna, and the *Cathayornis* Avifauna. The Biota is both more derived and prolific than the assemblages from the Late Jurassic Solnhofen Limestone of Germany represented by *Archaeopteryx* and *Compsognathus*. This implies that after the Late Jurassic extinctions, the Early Cretaceous represented a significant evolutionary and radiation event.

Stratigraphic sequence and isotopic dating

The Jehol Biota is distributed within grabens of western Liaoning Province which represent a segment of the Late Mesozoic northeast Asian graben basin system (Li et al., 1987), during which time igneous activity was abnormally intense and widespread. The Yixian Fm. is composed predominantly of basalts interbedded with three to four sedimentary units (Chen et al., 1980; Wu et
al., 1989). Intense igneous and orogenic activity subsequent to the deposition of the Cretaceous
deposits have provided increasing difficulties in the correlation of stratigraphic sequences between
basins, the establishment of stratigraphic sections, and the sampling and diagnosis of radiometric
dates. Numerous workers have conducted chronological studies of these lithologies (Wang and
Diao, 1984; Gu, 1995; Smith et al., 1995; and Chen et al., 1997). $^{40}\text{Argon}/^{39}\text{Argon}$ dating on the
basalts and tuffs in the Yixian Fm., in combination with new discoveries of fossil vertebrates,
allow a preliminary establishment of a biochronologic and stratigraphic sequence for the vertebrates
of the Jehol Biota.

Smith et al. (1995) and Swisher et al., (1998) conducted $^{40}\text{Argon}/^{39}\text{Argon}$ dating on
volcanic and other pyroclastic deposits in the Yixian Fm. at Sihetun and Jianshangou, Beipiao;
Jingangshan, Yixian Co.; and Ershilipu and Daxinfangzi, Lingyuan Co. The samples from the
Yixian Fm. at Beipiao were selected from a unit 230 m above the base of the Formation, and
yielded a date of 121.4±0.6 Ma (Smith et al., 1995). In the third vertebrate bearing unit of the
lower Yixian Fm. at Sihetun (Wang et al., 1998), a date of 125.42±0.08 Ma was obtained from 18
samples of euhedral sanidine feldspars in the tephra from unit P1T-2, (3.4 m above Unit 18, the
$\text{Confuciusornis sanctus}$ bed). A date of 125.52±0.07 Ma was obtained from 24 samples of
euhedral sanidine feldspars from the tephras of P4T-1 (50 cm above the unit that produced
$\text{Zhangheotherium quinquecuspids}$) in the Jianshangou section (Swisher et al., 1998). Further
refinement of these samples is currently being conducted although it is not expected there will be a
significant adjustment to the age (Swisher, pers. com. 1998). These dates thus constrain the age
of the $\text{Confuciusornis-Sinosauropteryx-Zhangheotherium}$ Complex.

A radiometric date of 122.9±0.03 Ma was obtained at Anshanyan, Daxinfangzi, Lingyuan
Co. (Smith et al., 1995) and dates of 122.2±0.2 Ma and 122.5±0.3 Ma were obtained from the
interbedded lacustrine sediments basically equivalent to Daxinfangzi but from a unit slightly higher
than at Anshanyan (Smith et al., 1995), providing an age for the $\text{Monjurosuchus-Hyphalosaurus-
Liaoxiornis}$ Complex at Daxinfangzi and Dawangzhang, Lingyuan Co.

Dates of 121.4±1.1 Ma and 121.6±0.4 Ma were obtained from biotite and plagioclase
sampled from an interbedded pyroclastic angular conglomerate at Jingangshan, Yixian Co.,
providing an age for the $\text{Lycoptera muroii-Manchurochelys manchouensis}$ Complex (Smith et al.,
1995). The Jingangshan diabase date of 120.9±0.4-120.8±0.4 (Smith et al., 1995) closely
approaches the ages of the interbedded sediments and thus the unit represents a distinct but nearly
contemporaneous facies.

The basalts approximately 10 m above the third interbedded deposit (equivalent to the
Dakangbao Unit [Chen et al., 1980]) in the Zoujiagou section provide dates of 121.3±2.3-
121.4±0.7 Ma. This approaches that of the lacustrine sediments at Ershilipu, Lingyuan Co., and
is consistent with the sediments at Jingangshan.

Currently, there is no accurate radiometric date from the Jiufotang Fm., however, there is
an $^{40}\text{Argon}/^{39}\text{Argon}$ date of 110±0.52 from basalts overlying sediments correlated to the Jiufotang
Fm. which produce a Jehol Biota at Tebch, Inner Mongolia (Eberth et al., 1993). This date
provides an upper constraint for the Jiufotang Fm. and the $\text{Cathayornis-Chaoyangia-Psittacosaurus}$
Complex contained therein.

Chen and Chen (1997) conducted a systematic study of the Yixian Co. region in which
they dated pyroclastic deposits using K-Ar, Rb-Sr, and Ar-Ar dating techniques. They obtained
dates of 133±5.0 Ma at Shangdijiagou, 129±0.3 Ma at Zhuangchengzi, 125.5±0.1 Ma at
Sanbailong, 124.5±4.9 Ma at Zhujiagou, and 119.9±10.0 Ma Hejiagou. Thus the Yixian Fm. is
generally bracketed between 120-133 Ma, which is basically consistent with Smith et al. (1995),
and Swisher et al. (1998).
The Yixian Fm. is dominated by basalts interbedded with three to four lacustrine facies which produce the prolific Jehol Biota (Chen et al., 1980; Wu et al., 1989). Chen et al. (1980), identified four sedimentary units in ascending order as the Jianshangou Unit, the Shanyuan Unit, the Dakangbao Unit, and the Jingangshan Unit. Wu et al. (1989) later recognized three sedimentary units they identified as the Daobazi Unit, Zhuanchengzi Unit and the Jingangshan Unit. They correlated the lower Daobazi to the Jianshangou of Chen et al. (1980), the upper Jingangshan they retained as such, but the stratigraphic relationships of the middle Shanyuan and Dakangbao to the Zhuanchengzi unit were left unclear. Furthermore, Chen (1988) and Chen et al. (1980) recognized a Daxinfangzi Unit which they correlated to the Jianshangou Unit and recognized it as the most basal sediments of the Yixian Fm. Large quantities of fossil vertebrates are produced from the Jianshangou, Daxinfangzi, and Jingangshan beds which represent three vertebrate complexes. From the perspective of the vertebrates, the Jianshangou Unit is the most prolific, is characterized by its *Confuciusornis* Fauna and associated small theropods, and is associated with radiometric dates. Stratigraphically, this should represent the most basal portion of the Yixian Fm. The vertebrates from the Daxinfangzi Fm. include several taxa retained from the underlying Jianshangou beds in addition to first occurrences of *Protopsephurus, Monjurosuchus, Hyphalosaurus, and Liaoxiornis*. The fish *Protopsephurus* is extremely abundant in the Jiufotang Fm. and its associated radiometric date clearly indicates it is younger than the Jianshangou beds. Vertebrates from the Jingangshan unit are few, however, they include the first occurrence of the characteristic species *Lycoptera muroii* which may be correlated to the upper Jiufotang Fm., and thus this unit undoubtedly represents the uppermost unit of the Yixian Fm. as its associated radiometric date indicates.

The remaining sedimentary units have yet to produce fossil vertebrates and thus cannot be correlated, although radiometric data provides a foundation to arrange the stratigraphic sequence as follows: Although it is unclear where the samples were taken that provided the 120.0±0.3 Ma date for the Zhuanchengzi volcanics, the date still reflects a generally archaic age for the sediments and as such they should be correlated to the Jianshangou beds. Basalts 10 m above the Dakangbao beds provide an Ar/Ar date of 121.3±2.3 - 121.4±0.7 Ma (Smith et al. 1995). This postdates the Daxinfangzi beds in Lingyan Co. and more closely correlates to the Jingangshan beds, however, further field work is required to substantiate this interpretation.

It is undisputed that the Jiufotang Fm. extends into later stages than the Yixian Fm. and the vertebrate complexes contained therein are quite distinct. The Jiufotang Fm. is characterized by the first occurrences of the fishes *Jianichthys, Longdeichthys, Sinamia zdanskyi, Huashia* and the *Cathayornis* Avifauna. This is quite distinct from the three complexes produced from the Yixian Fm.

Gradstein et al. (1995) applied radiometric dating and vertebrate complexes to calibrate their Mesozoic Geologic Time scale, in which they recognize the Jurassic-Cretaceous boundary at 144.2 Ma. In the Jehol Geologic Biota, the sequence of vertebrate complexes, the stratigraphic sequence, and associated radiometric dates provide the following correlations: the Lower Yixian Fm. *Confuciusornis-Sinosauropteryx-Zhangheotherium* Complex from Jianshangou and Sihetun are middle Barremian in age. The middle Yixian Fm. *Monjurosuchus-Hyphalosaurus-Liaoxiornis* Complex from Daxinfangzi and Dawangzhang and the upper Yixian Fm. *Lycoptera muroii-Manchurochelys manchouensis* Complex from Jingangshan are late Barremian in age. The Jiufotang Fm. *Cathayornis-Chaoyangia-Psittacosaurus* Complex is Aptian in Age. As such, the Yixian and Jiufotang fms. span the late Valanginian to Aptian.
Conclusions

1. Four complexes are recognized in the vertebrates of the Jehol Biota: the lower Yixian Fm. *Confuciusornis-Sinosauropteryx-Zhangheotherium* Complex from the Sihetun-Jianshangou units, the middle Yixian Fm. *Monjurosuchus-Hyphalosaurus-Liaoxiornis* Complex from the Daxinfangzi-Dawangzhang units, the upper Yixian Fm. *Lycoptera muroii-Manchurochelys manchouensis* Complex from the Jingangshan unit, and the Jiufotang Fm. *Cathayornis-Chaoyangia-Psittacosaurus* Complex.

2. The fish and reptiles in the vertebrate complexes of western Liaoning Province represent the *Lycoptera* Ichthyofauna and the *Psittacosaurus* Herpetofauna. There are two distinct avian faunas: the Yixian Fm. *Confuciusornis* Avifauna and the Jiufotang Fm. *Cathayornis* Avifauna. These vertebrate faunas are all Early Cretaceous.

3. The Yixian Fm. pyroclastics and marls provide $^{40}$Argon/$^{39}$Argon dates of 125.42±0.08-125.52±0.07 Ma for the *Confuciusornis-Sinosauropteryx-Zhangheotherium* Complex assigning it to the middle Barremian Stage. The *Monjurosuchus-Hyphalosaurus-Liaoxiornis* Complex is 122.2±0.2-122.5±0.3 Ma assigning it to the late Barremian Stage. The *Lycoptera Muroii-Manchurochelys manchouensis* Complex is 121.4±1.1-121.6±0.4 Ma assigning it to the late Barremian Stage. The *Cathayornis-Chaoyangia-Psittacosaurus* Complex predates 110±0.52 Ma assigning it to the Aptian Age.

4. The ages of the Yixian and Jiufotang fms. are Early Cretaceous late Valanginian through Barremian and Aptian respectively.

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