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A New Boreopterid Pterodactyloid Pterosaur from the Early Cretaceous Yixian Formation of Liaoning Province, Northeastern China

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Abstract: A new boreopterid pterosaur: *Zhenyuanopterus longirostris* gen. et sp. nov. from the Yixian Formation of western Liaoning is erected, based on the complete skeleton with a skull and lower jaws preserved. It is characterized by: a large boreopterid pterosaur with a high number of teeth, where the anterior teeth are much larger than posterior ones; the length of the dorsal + sacral vertebrae is nearly half the length of the skull; ratio of the length of the humerus to metacarpal IV is approximately 91% and the, humerus, femur and third wing phalanx are all equal in length and the feet are specially small. It represents the largest boroepterid pterosaur discovered from western Liaoning and its surrounding areas so far

Key words: *Zhenyuanopterus*, Boroepteridae, Ornithocheiroidae, Yixian Formation, western Liaoning

1 Introduction

The Ornithocheiroidea was defined as *Istiodactylus, Pteranodon longiceps*, their most recent common ancestor, and all its descendants. It mainly consists of Ornithocheiridae and Pteranodontidae (See Unwin, 2003). Although the definition is also somewhat different to that proposed by Kellner (2003), the definition proposed by Unwin is accepted here. *Boreopterus* was initially assigned to the Ornithocheiridae (Lü and Ji, 2005), but later, it was assigned to the family Boreopteridae (Lü et al., 2006b), which include the closely related form *Feilongus* from the same sequence (Wang et al., 2005). Boreopteridae is considered to belong to Ornithocheiroidea (Lü et al., 2006b).

Compared with other pterosaurs found from western Liaoning and its surrounding areas, the ornithocheiroid pterosaurs are rare. The ornithocheiroid pterosaurs found from Liaoning include *Liaoningopterus* from the Jiufotang Formation (Wang and Zhou, 2003), *Yixianopterus* from the Yixian Formation (Lü et al., 2006a), and *Boreopterus* from the Yixian Formation (Lü and Ji, 2005).

This paper focuses on the Chinese boreopterid pterosaurs alone and is not intended to cover other ornithocheiroid pterosaurs. Herein described is a new boreopterid pterosaur: *Zhenyuanopterus longirostris* gen. et sp. nov. from the Yixian Formation of Huangbanjigou, Shangyuan, Beipiao City of western Liaoning (Fig. 1). *Zhenyuanopterus* is the largest boreopterid pterosaur discovered from western Liaoning and its surrounding areas so far.

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2 Systematic Paleontology

Pterosauria Kaup, 1834

Pterodactyloidea Plieninger, 1901

Ornithocheiroidea Seeley, 1891

Boreopteridae Lü, Ji, Ji and Yuan, 2006

Zhenyuanopterus gen. nov. (Fig. 2, Plate I)

Etymology: Zhenyuan, the Chinese pinyin for Mr. Sun Zhenyuan, who offered the beautiful specimen for scientific study; *-pterus*, Greek word for “wing,” a common suffix of pterosaur taxa.

Diagnosis: As for species.

Zhenyuanopterus longirostris sp. nov.

Holotype: A complete skeleton with a skull and lower jaws (GLGMV 0001). The specimen is stored in Guilin Longshan Geological Museum, Gulin City, Guangxi Zhuang Autonomous Region.

Type locality and horizon: Huangbanjigou of Shangyuan, Beipiao City, Yixian Formation (Chen et al., 2005).

Etymology: *longirostris*, Latin word, means long snouted, indicating that the new pterosaur with a long rostrum.

Diagnosis: A large boreopterid pterosaur (wing span about 4 meters) identified by the following characters:

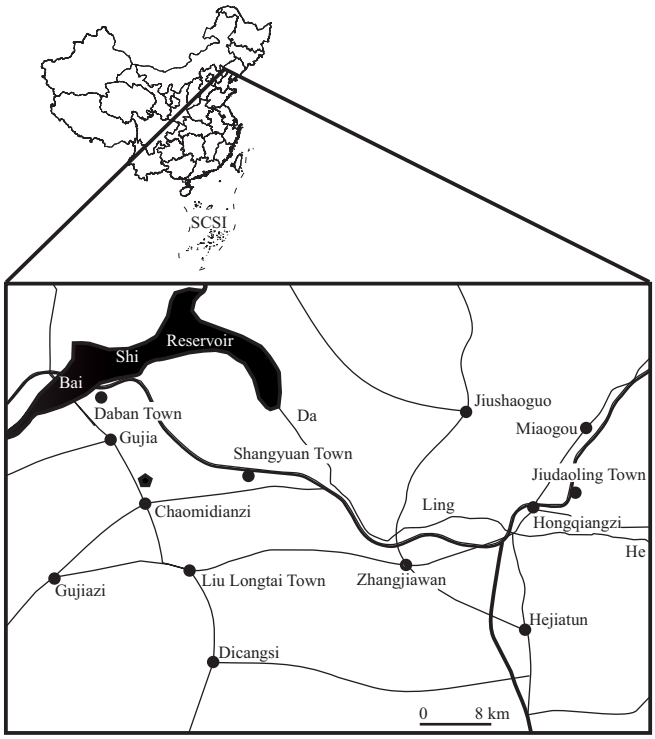

Fig.1. The map of the fossil locality. The solid pentagon represents the fossil site.

numbers of teeth in the whole upper and lower jaw the same, that is about 86 respectively; the longest teeth more than 10 times longer than the smallest; the length of the dorsal + sacral vertebrae nearly the half of skull length; length ratio of humerus to metacarpal IV about 91%; the third wing phalanx, humerus, femur are equal in length; the feet especially small.

3 Description

The specimen is well-preserved, complete and articulated (Fig. 2; Plate I; Table 1). The skull and lower jaw are exposed their right lateral sides. The postcranial skeletal elements are exposed in dorsal view.

The skull and lower jaws are well-preserved and naturally articulated (Plate IB). The prenarial rostrum is relatively long with a concave dorsal margin. A distinct crest (premaxillary crest) is present above the anterior part of the nasoantorbital opening although it is slightly displaced as a result of taphonomic alteration. The premaxilla and maxilla are completely fused anteriorly. The frontal is triangular in lateral view. The nasal is slender and very long, almost reaching the ventral margin of the nasoantorbital opening. The lacrimal and dorsal process of the jugal form the vertical anterior margin of the orbit. The lacrimal foramen is circular. The nasoantorbital opening is relatively large. The tooth row extends far back, and it almost occupies the whole ventral margin of the upper jaw. The length of the ventral margin of the nasoantrobital opening is 15 cm, but the tooth-bearing portion is 9 cm. Thus, the posterior part of the dentition occupies 60% the ventral margin of the nasoantorbital opening (Plate IB). The orbit is in the shape of an inverted and acute triangle. The position of the quadrate relative to the ventral margin of the skull is inclined about 120° backwards. The posterior region of the skull is rounded with the squamosal displaced ventrally. The sclerotic ring is well-preserved. Its diameter is approximate 2 cm.

The rostral end of the dentary is slightly expanded ventrally. The deepest portion of the dentary is near the conjunction of both branches of the lower jaw. The mandibular symphysis is 27.8 cm long, occupying more than half length of the lower jaw (56%).

There are 43 upper jaw teeth on each side, thus 86 teeth are present in total upper jaw. The anterior 22 teeth have sharp tips and are considerably longer than the posterior ones. Some replacement teeth are also present in both the upper and lower jaws. The longest is 5 cm and shortest is

Table 1 Measurements (in cm) of *Zhenyuanopterus longirostris* (GLGMV 0001) gen. et sp. nov.

Elements	Length	Width
Skull (from squamosal to the tip of the upper jaw)	54.5	-
Skull (from quadrate articulation point for lower jaw to the tip of the upper jaw)	48.5	-
Dentition	44	-
Prenarial rostrum	30	-
Nasoantorbital opening	15	-
Orbit	4.5	3
Mandible	49.5	-
Cervical 2	5.5	-
Cervical 3	8	-
Cervical 4,5	-	-
Cervical 6	6	-
Dorsal + sacral	27	-
Caudal series	13	-
Scapula	8	1.7 (shaft)
Coracoid	6	1.5 (shaft)
Humerus	21	2.5 (shaft)
Deltopectoral crest	5	2
Ulna	26.2	1.9
Radius	26	1
Pteroid	11.5	-
Metacarpal IV	23	-
Wph1	36	2
Wph2	27.5	1.9
Wph3	21	1.5
Wph4	19	0.5
Femur	21	1
Tibitarsals	20	1.9
Metatarsals I-V	2;2.5;2.6;2.2;1.2	-
Digit1	1.5; 1(claw)	-
Digit 2	05; 1; 0.9	-
Digit 3	0.5; 0.1; 0.9; 0.9	-
Digit 4	0.9;0.2;0.7;0.9	-

Note: - – un-applicable or not preserved.

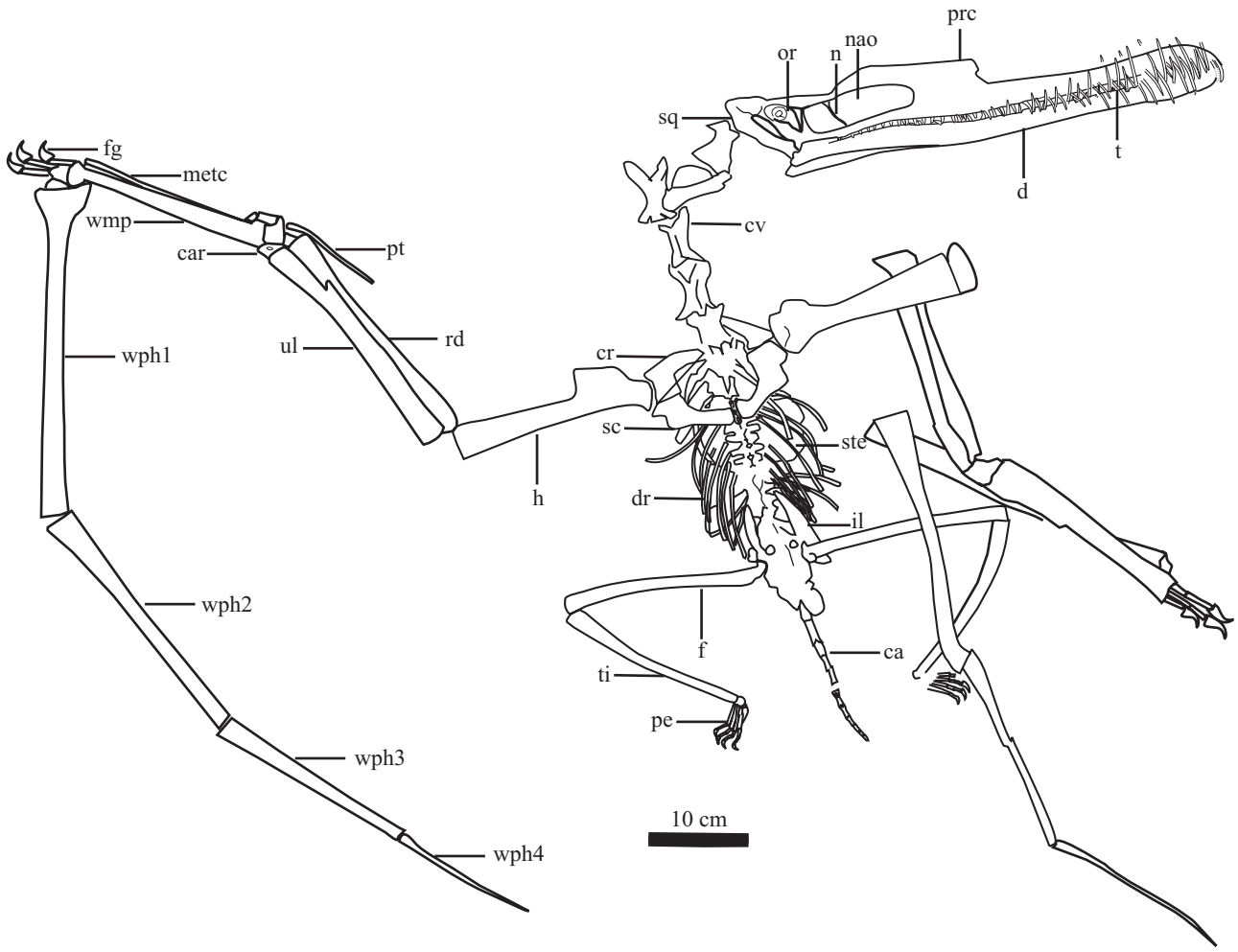

Fig. 2. Line drawings of the holotype *Zhenyuanopterus longirostris* (GLGMV 0001) gen. et sp. nov.
Abbreviations: nao, nasoantorbital opening; ca, caudal vertebrae; car., carpals; cr, coracoid; cv, cervical vertebrae; d, dentary; dr., dorsal ribs; f, femur; h, humerus; fg., fingers; il., ilium; metc., metacarpals; n., nasal; or., orbit; pe., pes; prc., premaxillary crest; pt. pteroid; rd., radius; sc., scapula; sq., squamosal; ste., sternum; t., teeth; ti., tibia; ul., ulna; wmp., wing metacarpal; wph1-4: wing phalanges 1-4.

0.5 cm (Plate IB). The more anterior teeth are relatively larger, but it is not clear which one are the longest during to the poor preservation near the anterior end of the rostrum. The third and fifth teeth of the lower jaw are the longest. The anterior 11 teeth of the lower jaw are almost perpendicular to the dorsal margin of the dentary. From the 12th to 21st, this angle is about 10 degrees. The teeth of the left side are not exposed. There is a tooth of lower jaw just anterior to the last tooth of the upper jaw, thus, it is inferred that the number of the lower jaw teeth is close to that of the upper jaw teeth. Therefore, there are also about 86 lower jaw teeth too.

The atlas and axis are not observed. There are six cervical vertebrae present, thus the number of the cervical vertebrae may be eight. The fifth of which is the longest. The neural spine is developed. They are tall and blade-like. There are twelve dorsal vertebrae, and their transverse processes are wide and plate-like in dorsal view. The neural spines of three anterior dorsal vertebrae between the distal ends of the scapulae are fused into a plate-like structure, which indicates that the centra of these dorsal vertebrae are fused into a notarium. The first dorsal rib is very large, broad and flat. The posterior dorsal ribs are slender however. There are 4 sacral vertebrae. The length of the dorsal + sacral vertebral column is nearly the half length of the skull. There are 13 caudal vertebrae preserved. The first four caudal vertebrae are considerably larger than the posterior ones. From the fifth caudal vertebra they become increasingly slender and the last one is thin and rod-like. The combined length of caudal vertebrae is shorter than the dorsal series.

The sternum is covered by anterior dorsal vertebrae and distal ends of scapulae. The anterior position of the large sternum is not clear, but its outline can be identified. It is wider than long (excluding the cristospine). The length (including the cristospine) and the width of the sternum are almost the same.

The scapula is longer than the coracoid, a reversal of the

usual ornithocheiroid condition (Uniwn, 2003). Thus, the scapula being longer than the coracoid here is a reversal. The scapula and coracoid are not fused. This implies that this is a juvenile animal which would potentially make this animal even bigger as an adult. The scapula is relatively short and stout with constricted shaft. It is less than 1/3 of the length of the humerus. The shaft of the scapula is slightly curved. The proximal end of the scapula is expanded. Posterior to the glenoid concavity, a distinct process (*processus scapularis*) is present on the ventrolateral margin of the scapula. The glenoid concavity is formed by the proximal portions of the scapula and coracoid. The proximal end of the coracoid is expanded too. The acrocoracoid process of the coracoid is well developed.

The shaft of the humerus is straight. The distal end of the humerus is slightly expanded. The deltopectoral crest of humerus is large and subtriangular with a proximally directed apex, although a small portion near the distal end is missing. The humeral head is smooth without pronounced ridge found in other large pterosaurs, such as *Santanadactylus* and *Anhanguera* (Kellner and Tomida, 200). There is no pneumatic foramen observed near the proximal end of the humerus. The length ratio of the deltopectoral crest to that of the humerus is about 0.24.

The ulna and radius are straight. The ulna is slightly longer than, and has a diameter nearly twice of that of the radius. The ulna is less than 133% of the length of the humerus and is similar in length to the combined length of dorsals and sacrals. The ulna is approximate 131% of the length of tibia. Some ridges are present near the distal end of the radius.

The proximal portion of the pteroid is expanded and curved. Its distal portion is straight with sharp distal end. The length ratio of the pteroid to the humerus is about 0.55.

The proximal carpals are fused into one irregular unit, but their sutures can be identified. There are four irregular bones between the proximal end of the metacarpal IV and the proximal carpals, it is inferred that these may be the distal carpals. Among them, there is a large, rectangular one which contacts with the proximal end of the wing metacarpal.

The distal ends of metacarpals I-III are preserved, but it is not clear whether these metacarpals reach the distal carpals or not. The fourth metacarpal is strong and slightly curved near its distal end. The manual claws are much larger than the pedal claws.

The wing phalanx 1 is the longest, with the second through fourth being progressively shorter. The length of the third wing phalange is equal to that of the femur and humerus.

The pelvic structure is not well-preserved. The anterior process of the ilium is long, covering four posterior dorsal vertebrae. The pubis and ischium are covered by other elements, thus cannot be seen clearly.

The femur is a long, slightly curved bone which both ends are moderately expanded. The greater trochanter is well developed. The femoral head is ball-shaped with a distinct neck. In medial view, the femoral head is perpendicular to the shaft of the femur.

The tibia is a slender and long bone. It is slightly shorter than the femur. It is curved with expanded proximal end. It tapers gradually towards the distal end. The fibula is preserved, but difficult to see its structure.

The astragalus and calcaneum are fused into a single unit which bears a straight margin articulating with the distal end of the tibia and a convex margin articulating with the distal tarsal in lateromedial view. Only one distal tarsal is preserved which is thin plate-like.

The feet are especially small. Metatarsal III is slightly longer than the metatarsal II. Metatarsal IV is longer than the metatarsal I but shorter than the metatarsal II. The digit formula is 2-3-4-5-0 with digit 2 the longest. The pedal claws are very small with a sharp tip.

4 Discussions and Conclusion

Zhenyuanopterus is assigned to Borepteridae based on the following characters: skull low with extremely elongated rostrum, teeth long and sharp, and anterior teeth longer than posterior ones, femur equal to tibia in length (Lü et al., 2006).

Zhenyuanopterus differs from *Boreopterus* (Lü and Ji, 2005) in that *Zhenyuanopterus* bears a larger skull and a larger number of teeth (the skull is more than twice the length of *Boreopterus*). There are about 172 teeth (upper jaw plus lower jaw) in *Zhenyuanopterus*, though *Boreopterus* has 108 (Lü and Ji, 2005). The ratio of the length of mandibular symphysis to the lower jaw length is 56% in *Zhenyuanopterus*, which is smaller than that of *Boreopterus* (it is approximately 65%; Lü and Ji, 2005). The third wing phalanx, humerus, and femur are equal in length in *Zhenyuanopterus*, whilst in *Boreopterus*, they are all of different lengths.

Zhenyuanopterus differs from *Feilongus* (Wang et al., 2005) in that the former bears much longer and stouter teeth than those of *Feilongus* (there are totally 76 teeth). While the teeth of *Feilongus* are confined to the anterior portion of the rostrum, they extend the full length of the jaws in *Zhenyuanopterus* which also has more robust teeth than the slender ones of *Feilongus*. The cervical vertebrae are relatively short in *Zhenyuanopterus*, whilst they are greatly elongated in *Feilongus* (personal observation on

the specimen (D3068) of Dalian Natural History Museum). However, the nasoantorbital opening of *Zhenyuanopterus* occupies 27.5% of the cranial length between the squamosal and the premaxilla, which is close to that of *Feilongus* (28.7%; Wang et al., 2005).

The morphology of the anterior teeth of *Boreopterus* (Lü and Ji, 2005), *Feilongus* (Wang et al., 2005) and *Zhenyuanopterus* are similar as they are long, slender, curved and sharp. These teeth are different from that of *Liaoningopterus* (Wang and Zhou, 2003), which are relatively stout. The characters of the skull shape and tooth morphologies of *Boreopterus*, *Feilongus* and *Zhenyuanopterus* clearly form a distinct clade - the Boreopteridae. At present, Boreopteridae includes three members: *Boreopterus* (Lü and Ji, 2005), *Feilongus* (Wang et al., 2005) and *Zhenyuanopterus*. *Boreopterus* and *Feilongus* are much smaller than *Zhenyuanopterus*.

At present, six genera of toothed pterosaurs were discovered from the Yixian Formation of Liaoning Province. They are *Haopterus* (Wang and Lü, 2001), *Boreopterus* (Lü and Ji, 2005) *Feilongus* (Wang et al., 2005), *Yixianopterus* (Lü et al., 2006a), *Gegepterus* (Wang et al., 2007) and *Zhenyuanopterus*, although they did not come from the same bed. The discovery of *Zhenyuanopterus* indicates that the high diversity of toothed pterodactyloid forms existed in the Early Cretaceous of Asia.

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Plate

IA. The photograph of *Zhenyuanopterus longirostris* (GLGMV 0001) gen. et sp. nov. Scale bar = 10 cm.

IB. Close-up of the skull of *Zhenyuanopterus longirostris* (GLGMV 0001) gen. et sp. nov. in right view. Scale bar = 10 cm.

Plate I