

A New Specimen of *Crichtonpelta benxiensis* (Dinosauria: Ankylosaurinae) from the Mid-Cretaceous of Liaoning Province, China

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Abstract: A new specimen of ankylosaurine dinosaur *Crichtonpelta benxiensis* is described. The new specimen is based on a nearly completely preserved skull from the same quarry as the holotype of the mid-Cretaceous Sunjiawan Formation in Shuangmiao, Beipiao City, Liaoning Province, China. Cladistic analysis incorporating new information from the new specimen resolves *Crichtonpelta benxiensis* is more advanced than basal members of Ankylosauridae (*Kunbarrasaurus*, *Liaoningosaurus*, *Chuangqilong*, *Cedarpelta*, *Gobisaurus* and *Shamosaurus*) and represents the first diverging branch of Ankylosaurinae. Comparisons to other mid-Cretaceous ankylosaurid-bearing dinosaur assemblages in northern China indicate a late Early Cretaceous to early Late Cretaceous age for the Shuangmiao dinosaur assemblage.

Key words: Shuangmiao, mid-Cretaceous, Ankylosauridae, Ankylosaurinae, *Crichtonpelta*

1 Introduction

A lot of vertebrate fossils and early angiosperm fossils are reported in the Cretaceous deposits of the western part of Liaoning Province, northeastern China (Zhou et al., 2003; Lü et al., 2007; Teng et al., 2014; Han et al., 2017), which have made this region famous all over the world. Such as a few phytophagous dinosaurs, including hadrosauroid *Jinzhouosaurus* (Wang and Xu, 2001), *Shuangmiaosaurus* (You et al., 2003), titanosauriform sauropod *Boreolosaurus* (You et al., 2004) and three genera of Ankylosauria *Liaoningosaurus* (Xu et al., 2001), *Crichtonsaurus benxiensis* (Lü et al., 2007) and *chuangqilong* (Han et al., 2014).

Crichtonpelta benxiensis is a new combination of ankylosaur dinosaur with the generic name proposed by Arbour and Currie (2016) to replace “*Crichtonsaurus*”. “*Crichtonsaurus bohlini*” was originally named by Dong (2002) and Lü et al. (2007) described a second species of it (*C. benxiensis*) based on material from the same quarry (Fig. 1). Arbour and Currie (2016) treated “*Crichtonsaurus bohlini*” as invalid. Here, a new nearly completely preserved skull of *Crichtonpelta benxiensis* from the same

quarry is described. The purpose of this study is to describe the new specimen and to reevaluate the phylogenetic affinity of *Crichtonpelta* based on additional information from the new specimen.

2 Methods

We examined the specimen by X-ray micro-computerized tomography. The scanning was carried out using the 450 kV micro-computerized tomography developed by the Institute of High Energy Physics, Chinese Academy of Sciences (CAS) and the Key Laboratory of Vertebrate Evolution and Human Origins, CAS. The specimen was scanned with beam energy of 440 kV and a flux of 1.5 mA at a detector resolution of 160 µm per pixel using a 360° rotation with a step size of 0.25° and an unfiltered aluminium reflection target. A total of 1440 transmission images were reconstructed in a 2048×2048 matrix of 2048 slices using a two-dimensional reconstruction software developed by the Institute of High Energy Physics, CAS.

In order to recover the systematic position of *Crichtonpelta benxiensis*, the data matrixes of Han et al. (2014) and Arbour and Currie (2016) are employed,

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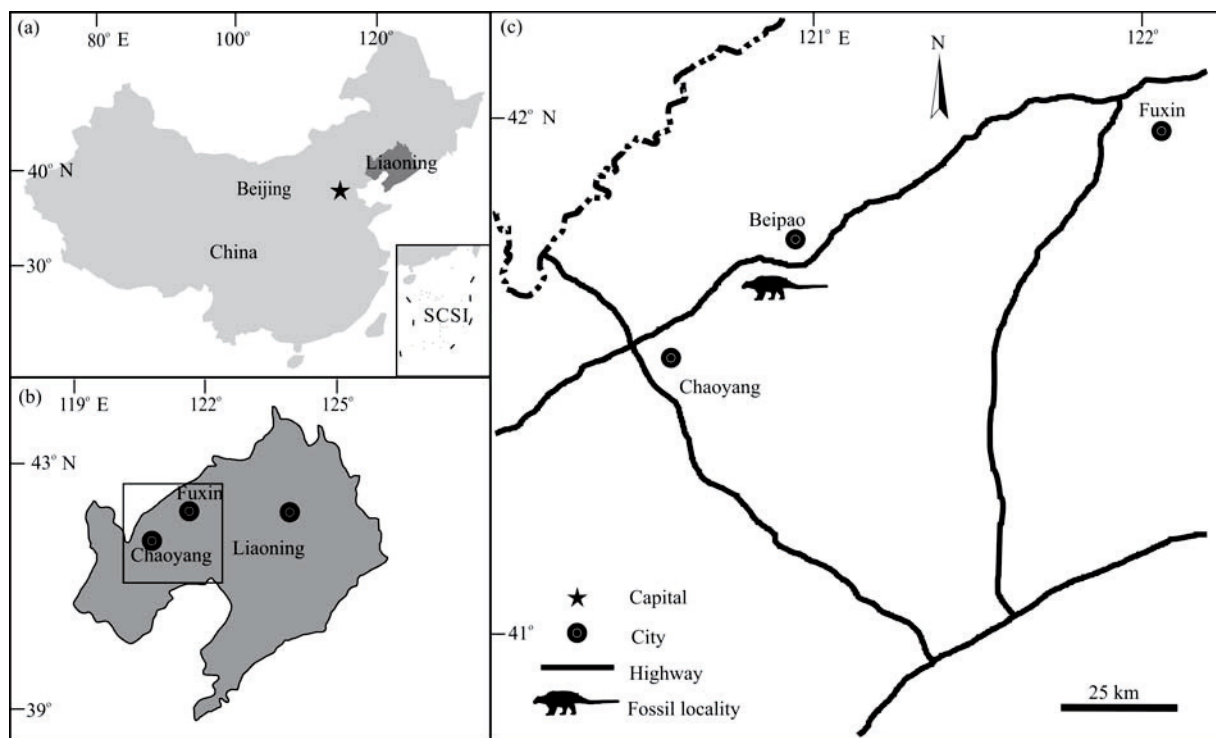


Fig. 1. Geographical map of *Crichtonpelta benxiensis* locality in Liaoning Province, China. (a), Fossil locality (black area) in northeastern China; (b) and (c), detailed position of fossil locality in Beipiao, Liaoning.

respectively. The former is largely based on Thompson et al. (2012). The new matrixes are assembled in Mesquite version 2.72 (Maddison and Maddison, 2011) and analyzed in TNT Version 1.1 (Goloboff et al., 2008). All characters were treated as unordered and equal weight. Parsimony analyses were conducted under the Traditional Search option with ten random seed and 1000 replicates of Wagner trees and the tree bisection reconnection (TBR) swapping algorithm. According to the review of Arbour and Currie (2016), *Zhongyuansaurus luoyangensis* is regarded as a junior synonym of *Gobisaurus domoculus*, while both *Shanxia tianzhenensis* and *Tianzhenosaurus youngi* are considered as junior synonyms of *Saichania chulsanensis*. Meanwhile, several taxa (*Antarctopelta oliveroi*, *Minmi paravertebral* and *Zhejiangosaurus lishuiensis*) are treated as nomina dubia. Following this, these taxa are removed from the current data matrixes. Note *Minmi* sp in Arbour and Currie (2016)'s matrix is now formally named as *Kunbarrasaurus ieversi* (Leahey et al., 2015). Codings for *Taohelong* from the Early Cretaceous Hekou Group of Lanzhou Basin in north-central China (Yang et al., 2013) is added to data matrix of Han et al., (2014).

3 Systematic Paleontology

Dinosauria Owen, 1842

Ornithischia Seeley, 1887

Thyreophora Nopcsa, 1915

Eurypoda Sereno, 1986

Ankylosauria Osborn, 1923

Ankylosauridae Brown, 1908

Ankylosaurinae Brown, 1908

Crichtonpelta Arbour and Currie, 2016

Crichtonpelta benxiensis (Lü et al., 2007) Arbour and Currie, 2016

New specimen: Geological Museum of China University of Geosciences (Beijing): G20090034, a nearly complete skull missing the anterior rostral portion.

Locality and horizon: Shuangmiao, Beipiao City, Liaoning Province. Sunjiawan Formation, late Early Cretaceous – early Late Cretaceous; late Albian (Jiang and Sha, 2006) and Cenomanian – Turonian (Dong, 2002).

Revised diagnosis: Differing from all other ankylosaurs in possessing the following unique combination of characters: rugose, amorphous frontonasal ornamentation not subdivided into discrete cranial caputegulae; lack of lacrimal incisures that give the skull an triangle-shaped outline in dorsal view; dorsal surface of the frontals and parietals not flat and having a distinct frontoparietal depression around the center on each side; lateral edges of the anterior and posterior supraorbitals forming a continuous supraorbital crest and not having distinct apices; nuchal crest possessing two distinct, transversely elongated prominences; apex of quadratojugal horn directing dorsally and posteriorly offset.

Comment: The new specimen is recovered from the same quarry as the holotype. Comparison to the holotype skull shows that the two skulls are generally similar to each other. It possesses all the revised diagnosis for *Crichtonpelta benxiensis* proposed by Arbour and Currie (2016), such as low and flat skull with closed antorbital and supratemporal fenestrae, triangular skull in dorsal view, present of squamosal and quadratojugal horns, a deep frontoparietal depression, and distinct, transversely elongated nuchal crests, as well as the autapomorphic dorsally directed apex of quadratojugal horn. Therefore, G20090034 can be assigned to *Crichtonpelta benxiensis*. However, the new specimen differs from the holotype in having slightly higher than wide oval orbit, which may be due to deformation.

4 Description

The new specimen is a nearly completely preserved skull missing the anterior rostral portion (Figs. 2–4). The preserved portion is 17 cm long from the broken nasal to the nuchal crest and 21 cm wide across the squamosal

horns, about the same size as the holotype. As in the holotype, cranial sutures are not visible and ornamentation is not divided into discrete caputegulae but is instead rugose and irregular (Arbour and Currie, 2016). In dorsal view, the skull roughly resembles an apically truncated equilateral triangle, and the maximum distance between the supraorbital caputegulae is less than the maximum distance across the squamosal horns. The skull table anterior to the orbit abruptly reduces in width. In lateral view, when the maxillary tooth rows are orientated in horizontal plane, the roof of the preserved rostral region is flat, similar to that in *Tarchia* and *Saichania* (Carpenter, 2004). The lateral temporal fenestra is obscured laterally by the squamosal and the quadratojugal but still visible posteriorly.

The anterior portion of the snout (the premaxillae, part of the maxillae and the nasals) is not preserved, and the position of the external nares is unclear. The maxillae extend posteriorly along ventrolateral border of the nasal. The lateral surface of the maxillae is convex and bears indistinct sculpturing. The posterior portion of the right maxilla preserves six alveoli, arranged in a single occlusal

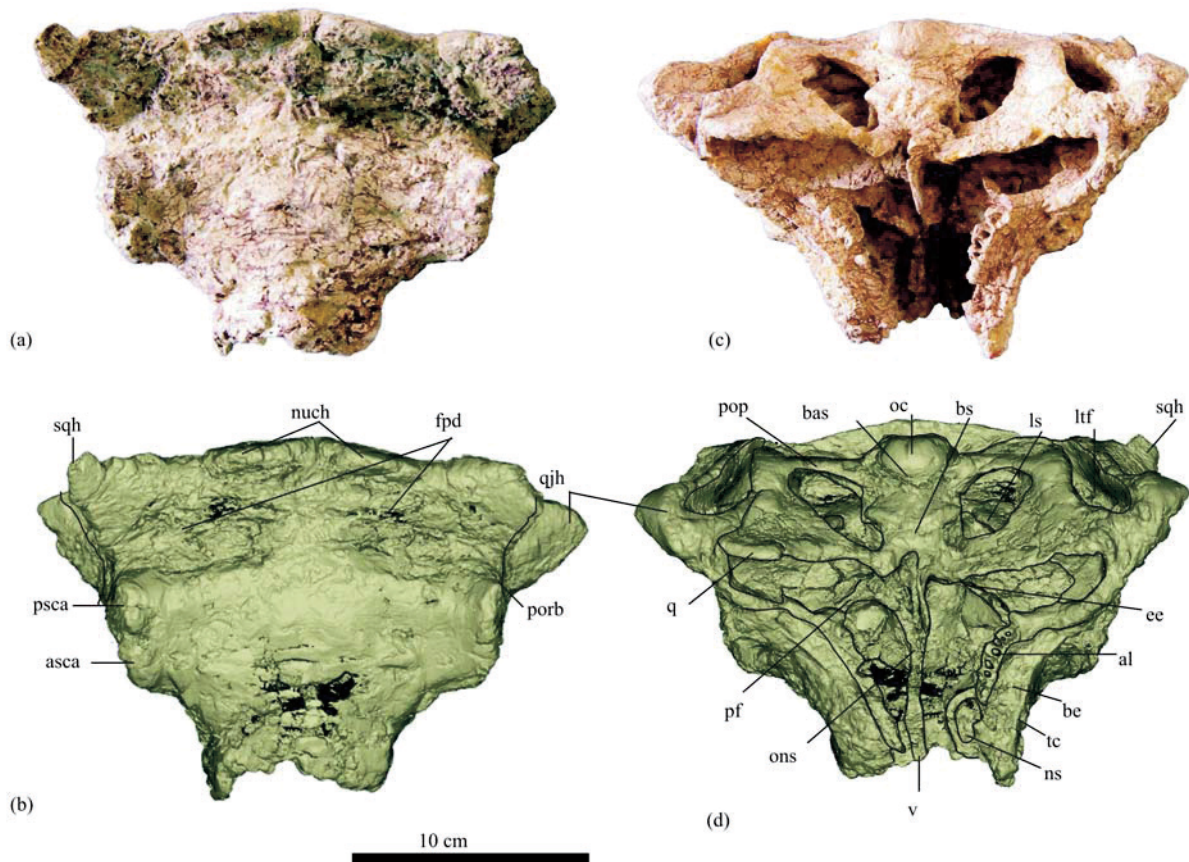


Fig. 2. Skull of *Crichtonpelta benxiensis* (G20090034) in dorsal (a, b) and ventral (c, d) views.

Abbreviations: al, alveolar; asca, anterior supraorbital caputegulum; bas, basioccipital; be, buccal emargination; bs, basisphenoid; ee, ectethmoid; fpd, frontal-parietal depression; ls, laterosphenoid; ltf, laterotemporal fenestra; mx, maxilla; ns, nasal sinus; nuch, nuchal crest; oc, occipital condyle; ons, osseous nasal septum; pf, pterygoid flange; pop, paroccipital process; porb, postorbital; psca, posterior supraorbital caputegulum; q, quadrate; qjh, quadratojugal horn; sqh, squamosal horn; tc, tomial crest; v, vomer.

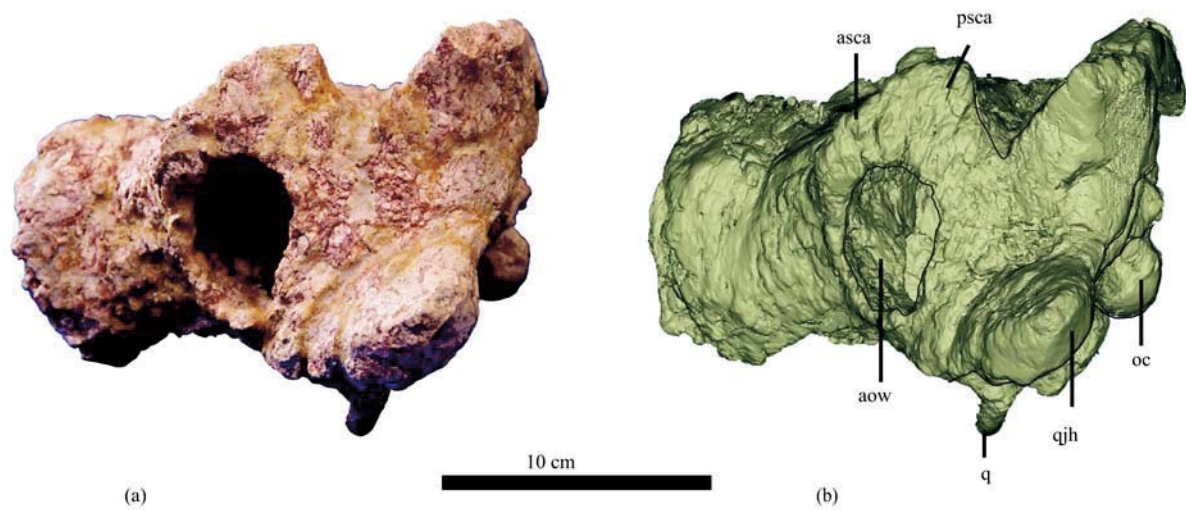


Fig. 3. Skull of *Crichtonpelta benxiensis* (G20090034) in left lateral view.

Abbreviations: aow, antorbital wall; asca, anterior supraorbital caputegulum; oc, occipital condyle; psca, posterior supraorbital caputegulum; q, quadrate; qjh, quadratojugal horn.

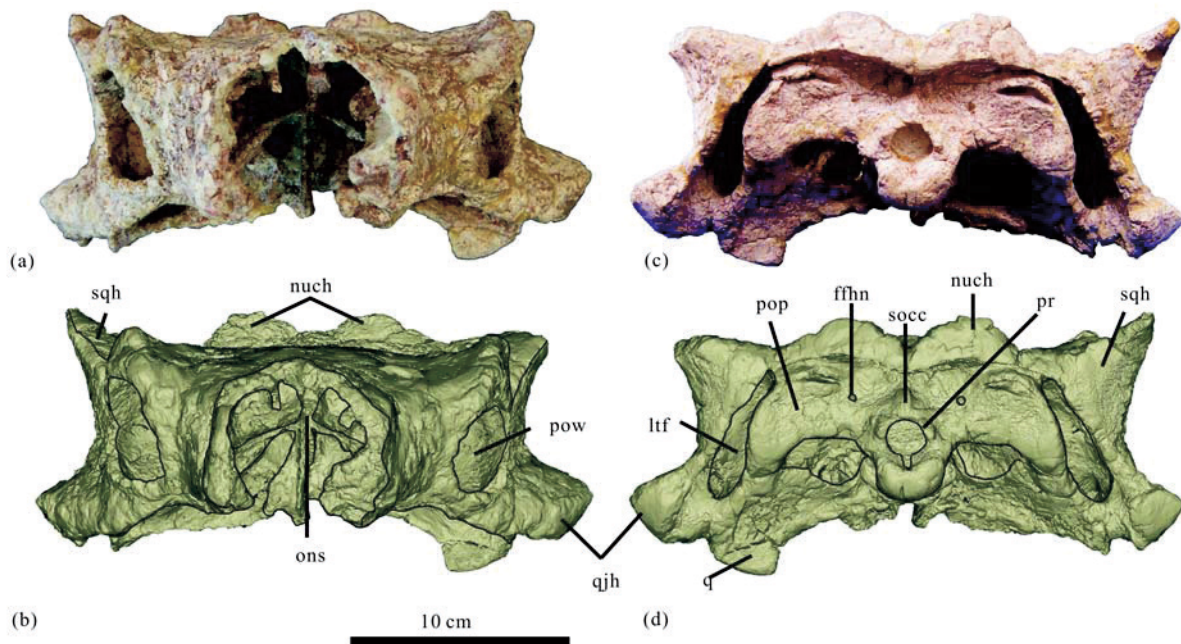


Fig. 4. Skull of *Crichtonpelta benxiensis* (G20090034) in anterior (a, b) and posterior (c, d) views.

Abbreviations: ffhn, foramen for the hypoglossal nerve; ltf, laterotemporal fenestra; nuch, nuchal crest; ons, osseous nasal septum; pow, postorbital wall; pr, prominences; q, quadrate; qjh, quadratojugal horn; pop, paroccipital process; q, quadrate; socc, supraoccipital; sqh, squamosal horn.

row. No teeth are preserved. Located lateral and parallel to the alveolar border is a concave buccal emargination. The tomial crest appears to be part of the maxilla, whereas in subadult *Pinacosaurus grangeri* (Maryańska, 1971) crania this tomial crest is formed by co-ossifying osteoderm. The nasals seem to form both the dorsal and part of the lateral surfaces of the rostrum as in most ankylosaur taxa. The dorsal surface of the nasals is rugose with irregular ornamentation, this is similar to the situation in *Gobisaurus* (Vickaryous et al., 2001) and *Shamosaurus* (Tumanova, 1983). The nasals form the osseous internasal

septum. Sinuses in each nasal represent the complex looping nasal passages (Witmer and Ridgely, 2008; Arbour and Currie, 2016), which can be seen on the ventral surface of the right nasal.

The orbit is oval in shape with its long-axis directing anteroventrally, this is similar to that of *Gobisaurus domoculus* (= *Zhongyuansaurus luoyangensis* Lü et al., 2007). The orbits are visible in anterior view, indicating that some stereoscopic vision was possible, similar to that of *Ankylosaurus magniventris* (Carpenter, 2004). The border of the orbit is markedly raised, as in *Saichania*

chulsanensis (Maryńska, 1977) and *Tarchia kielanae* (Maryńska, 1977), rather than flat as in *Ankylosaurus magniventris*, and both the accessory osseous antorbital and postorbital walls are well developed. The relatively deep jugal forms the ventral-most margin of the orbit cavity, as in *Zaraapelta nomadis* (Arbour et al., 2014). In lateral view, the anterior supraorbital caputegulum is smaller than the posterior one, and the boundaries between them are still visible. The lateral edges of the anterior and posterior caputegulae form a continuous supraorbital crest as in the holotype. This continuous supraorbital crest project dorsally rather than dorsolaterally. The middle supraorbital cannot be discerned in dorsal view.

In lateral view, a prominent 'V'-shaped notch is formed between the supraorbital caputegulae and the squamosal horn. The pyramidal squamosal horns project dorsolaterally and slightly caudally, but do not extend beyond the posterior margin of the skull in dorsal view. The transversely wide quadratojugal forms a bridge between the quadrate and the jugal, and forms the lower margin of the lateral temporal fenestra. The quadratojugal horn possesses a convex posterior margin in lateral view. In posterior view, the quadratojugal horn is triangular, relatively short mediolaterally compared with *Saichania* and *Tarchia*. It projects laterally rather than ventrolaterally, with the apex slightly dorsally upturned, which considered as a unique feature of *Crichtonpelta* (Arbour and Currie, 2016). The quadratojugal horn is smaller and blunter than the squamosal horn and does not obscure the articular condyle of the quadrate in lateral view, as in the basal member of Ankylosauridae (e.g. *Gobisaurus* and *Shamosaurus*). The quadrate is fused to the paroccipital process, quadratojugal, and pterygoid. It also forms the posterior margin of the lateral temporal fenestra.

The dorsal surface of the frontals and parietals is smooth without ornamentations, but a distinct frontoparietal depression is present around the center on each side. At the caudal end of the skull, the parietals form a nuchal shelf that is raised vertically into a pair of distinct, transversely elongated crests. These crests are separated by a midline notch and the posterior surfaces of the nuchal crests are vertical in relative to the dorsal surface of the parietals, forming a distinct convex arc in posterior view, which resembles the situation in *Saichania chulsanensis* and *Tarchia kielanae*. The nuchal shelf is

fused to the supraoccipital and paroccipital processes. In dorsal view, the nuchal shelf completely obscures the occiput, this is similar to the condition in *Pinacosaurus granger* and *Saichania chulsanensis*.

The occipital surface of the skull is broad and low. The supraoccipital is an unpaired median bone as a keystone dorsal to the foramen magnum, contacting the exoccipitals laterally and the parietals dorsally. The supraoccipital has a vertical and low midline ridge. Ventrally, it has a pair of low dorsal prominences at the dorsolateral edges of the foramen magnum. The paroccipital process extends laterally. It is fused with the quadrate at the lateral terminus where reaches its maximum dorsoventral height. The paroccipital process is slightly downturned with a concave ventral surface and the distal ends are below the level of the foramen magnum floor. Dorsolaterally to the paroccipital processes, there are a pair of crescent-shaped grooves. Dorsal to the lateral-most margin of the occipital condyle, there are a pair of foramina for the hypoglossal nerves perforating the exoccipitals along the occiput. The foramen magnum is large and circular in shape. The occipital condyle is formed only by the basioccipital and does not appear to receive any contributions from the exoccipitals, unlike the condition in *Pinacosaurus*. The occipital condyle projects posteroventrally. The basioccipital and basisphenoid are completely co-ossified.

The preserved proportion of the palatal region is not well preserved. The left vomer is missing, but the preserved portion of the right vomer is thin and delicate. It bisects the palatal region in the sagittal plane and contributes to the vertically orientated osseous nasal septum. The pterygoid flange projects anterolaterally and it appears that an interpterygoid vacuity was present. The ectethmoid seems to form the anterior wall of the orbit, and separates the orbit from the olfactory region.

5 Phylogenetic Analysis

Scores for *Crichtonpelta benxiensis* are revised in Han et al. (2014)'s matrix (Table 1). In Han et al. (2014)'s matrix 22 characters were scored, in contrast to our 15. Our less scores than Han et al. (2014)'s original is based on our observation of the new specimen and the cast of the holotype of *Crichtonpelta benxiensis*. The dataset now includes 46 taxa and 170 characters. This analysis

Table 1 Character scores for *Crichtonpelta benxiensis* in the date matrix of Han et al. (2014)

Characters	4	7	8	9	10	16	18	24	25	28	30	32	33	35	36
H	1	2	0	0	0	1	1	?	?	?	0	?	0	?	1
New scores	?	?	?	1	?	?	?	1	1	1	1	1	1	1	0
Characters	37	38	39	44	47	48	49	50	54	55	56	57	58	80	82
T	0	1	1	0	0	0	1	0	?	1	?	1	1	1	?
New scores	?	?	0	?	?	?	?	?	1	0	1	?	?	0	0

Abbreviations: H, character states in Han et al. (2014).

produced 1980 most parsimonious trees (MPTs) with tree length of 495 steps, Consistency Index of 0.37 and Retention Index of 0.673. The strict consensus tree recovers the monophyly for both Ankylosauridae and Nodosauridae, and *Crichtonpelta* is recovered as a member of Ankylosauridae (Fig. 5a).

In the strict consensus tree, Ankylosauridae is supported by 7 unambiguous synapomorphies: 33(0→1), 65(0→1), 112(0→1), 129(1→0), 142(0→1), 154(0→1), 155(0→1). Among them, four are present in *Crichtonpelta* (including referred specimens of Lü et al., 2007): 33(1), shape of quadrate is straight in lateral aspect; 65(1), maxillary and/or dentary tooth crown shape is rounded and bearing 13 or more denticles; 154(1), location of the fourth trochanter on the femoral shaft is over half-way down the femoral shaft; 155(1), the maximum distal width of the tibia is more than the maximum proximal width. In the 50% majority rule tree, *Crichtonpelta* is recovered as the most basal

diverging branching in Ankylosaurinae (Fig. 5b). Ankylosaurinae is supported by two unambiguous synapomorphies : 51(0→1) and 89(0→1). 51(1), paroccipital process extends laterally; 89(1), posterior projection of the nuchal shelf obscures occiput in dorsal view.

Based on our observation of the new specimen and the cast of the holotype of *Crichtonpelta benxiensis*, the scores for *Crichtonpelta benxiensis* in Arbour and Currie (2016)'s matrix are further revised (Table 2). We could score 11 characters for *Crichtonpelta benxiensis*, in contrast to 14 of Arbour and Currie (2016)'s original. Although with less scores our revised conservative version should reflect the current knowledge on *Crichtonpelta benxiensis* more accurately than previous one. Our new analysis produced 10000 most parsimonious trees (MPTs) with tree length of 417 steps. The strict consensus tree recovers the monophyly for both Ankylosauridae and

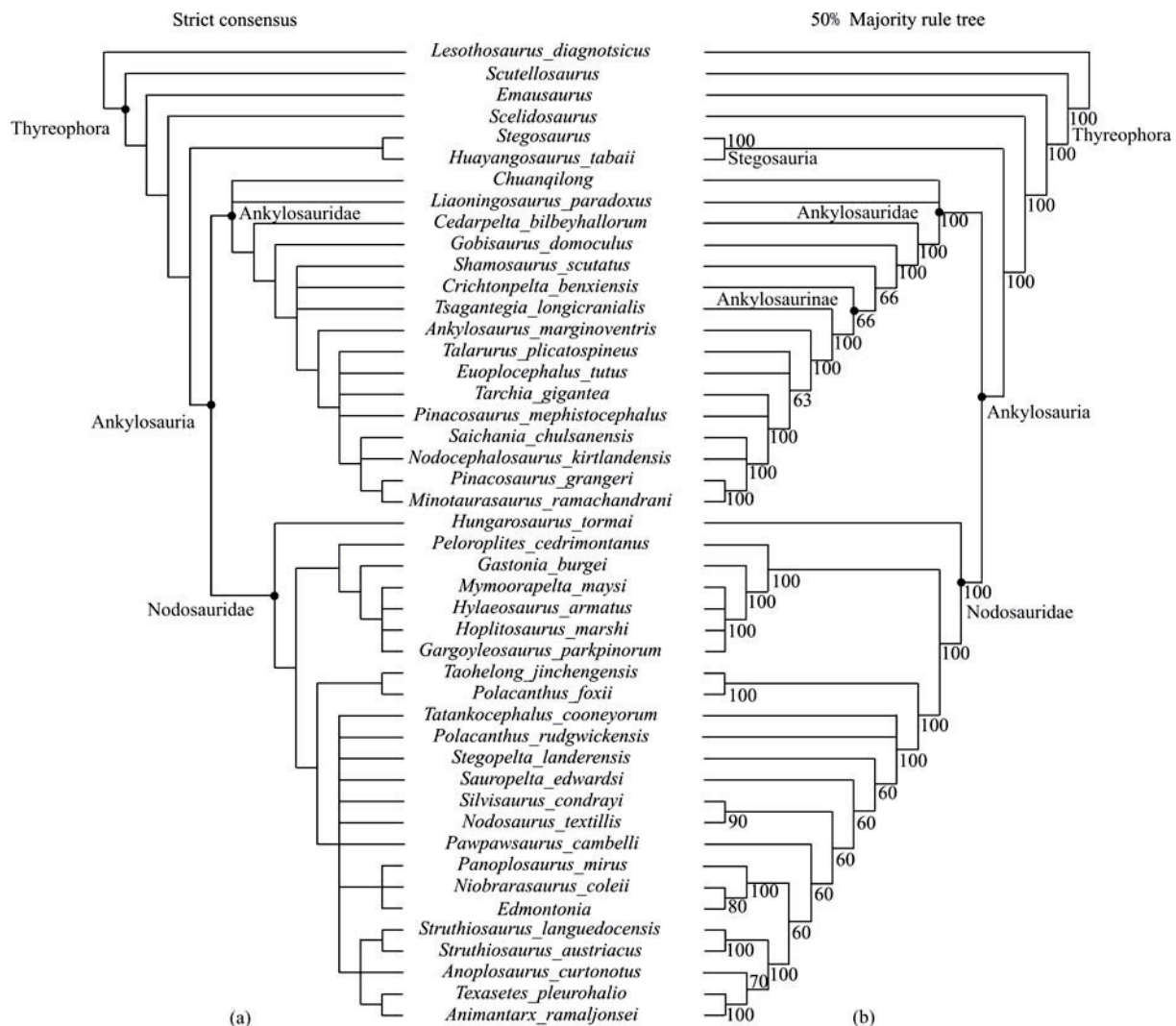


Fig. 5. Results of the phylogenetic analysis in Han et al. (2014)'s matrix.

(a), Strict consensus tree of 1980 MPTs recovered from a traditional (heuristic) search in TNT; (b), 50% majority rule tree; numbers under nodes represent the percentage of MPTs in which the node was recovered, only those relationships recovered in over 50% of the MPTs are shown.

Table 2 Character scores for *Crichtonpelta benxiensis* in the data matrix of Arbour and Currie (2016).

Characters	4	15	16	25	26	27	28	29	31	32	33	35	39	41	46	48	53	60	61	69	76
A	0	1	0	?	?	?	?	?	1	0	1	?	2	?	0	0	0	1	1	0	1
New scores	?	?	?	0	0	0	1	1	?	?	?	0	1	0	1	1	1	?	?	?	?

Abbreviations: A, character states in Arbour and Currie (2016).

Nodosauridae, and the 50% majority rule tree further results *Crichtonpelta* as the most basal member of Ankylosaurinae (Fig. 6). This result is generally similar to our above one based on Han et al. (2014)'s matrix.

6 Discussions

Crichtonpelta benxiensis shows a mixture of characters of Ankylosauridae. As in non-Ankylosaurinae ankylosaurids

(*Gobisaurus* and *Shamosaurus*), *Crichtonpelta* possesses relatively primitive ankylosaurid features, such as rugose, amorphous frontonasal ornamentation not subdivided into discrete cranial caputegulae and quadratojugal horn not obscuring the articular condyle of the quadrate in lateral view. More importantly, *Crichtonpelta* shows a number of key features of Ankylosaurinae, such as a larger, more triangular, pointed squamosal and quadratojugal horns, vertically raised nuchal shelf extending into a pair of

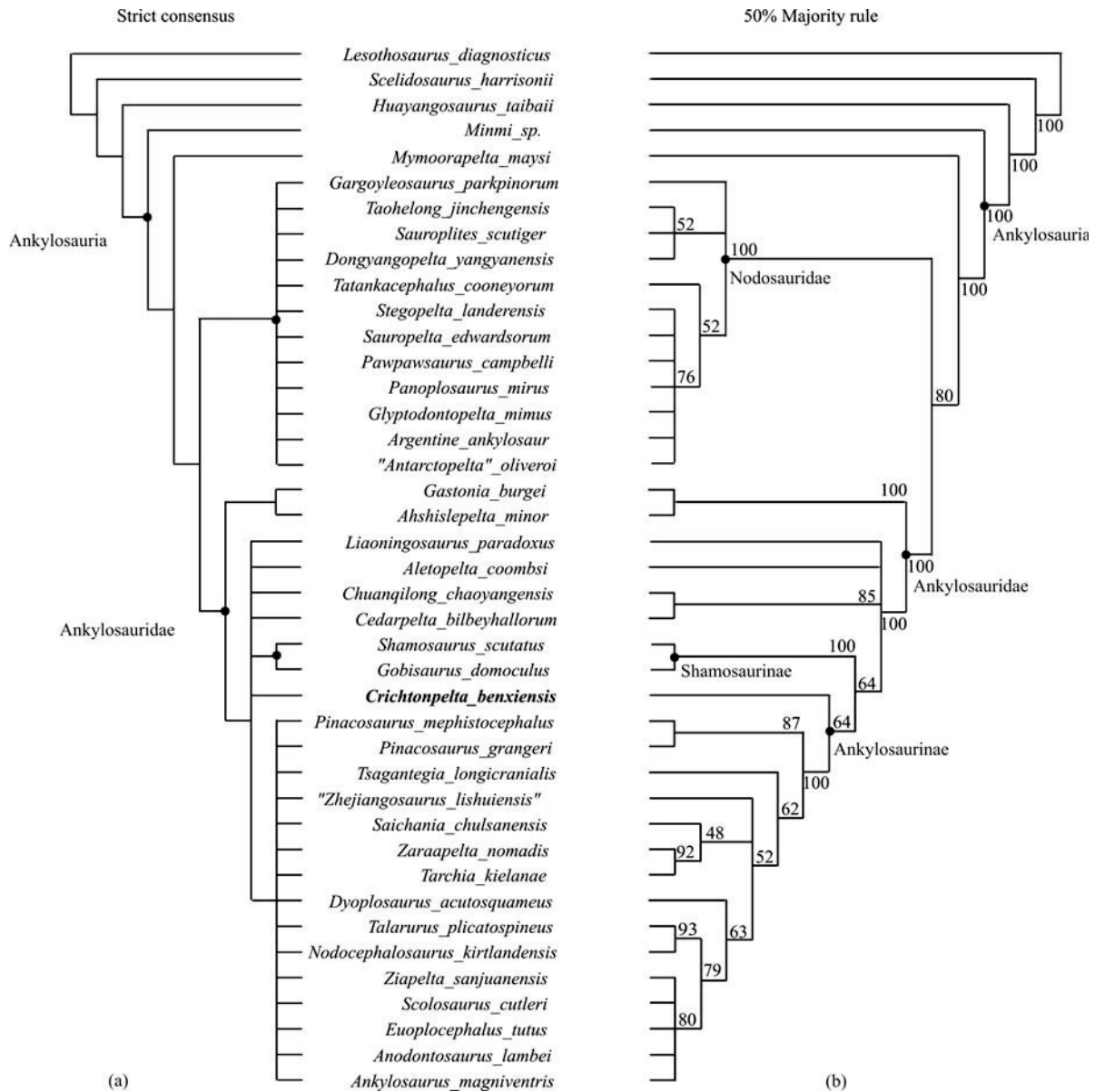


Fig. 6. Results of the phylogenetic analysis in Arbour and Currie (2016)'s matrix. (a), Strict consensus tree of 10000 MPTs recovered from a traditional (heuristic) search in TNT; (b), 50% majority rule tree; numbers above nodes represent the percentage of MPTs in which the node was recovered, only those relationships recovered in over 50% of the MPTs are shown.

distinct, transversely elongated crests, posterior projection of the nuchal shelf obscuring the occiput in dorsal view. However *Crichtonpelta* lacks many features in more advanced members of Ankylosaurinae, such as dorsoventrally short jugal (present in *Pinacosaurus*), lacrimal incisure (present in *Pinacosaurus grangeri*), and long squamosal horns (present in *Pinacosaurus mephistocephalus*, Godefroit et al., 1999).

Besides *Crichtonpelta*, two other dinosaurs, one hadrosauroid (*Shuangmiaosaurus gilmorei*) (You et al., 2003) and one titanosauriform sauropod (*Borealosaurus wimani*) (You et al., 2004) have also been reported from the same Shuangmiao quarry. Recently, a large theropod tooth has also been reported from the same quarry (Xie, 2015). The Shuangmiao dinosaur assemblage is unique, and cannot be compared to any other known dinosaur faunas directly.

Gobisaurus is recovered from the Maortu locality, Alashan Desert in Nei Mongol Autonomous Region (Inner Mongolia) (Vickaryous et al., 2001). The Maortu and nearby Dashuigou (Tashuikou) localities (about 15 km northeast of Maortu) has yield plenty of dinosaurs including two large-bodied theropods (*Chilantaisaurus tashuikouensis* and *Shaochilong maortuensis*) (Hu, 1964; Benson and Xu, 2008; Brusatte et al., 2009; Brusatte et al., 2010), one basal hadrosauroid (*Probactrosaurus gobiensis*) (Rozhdestvensky, 1966; Norman, 2002), one ankylosaurine (*Gobisaurus domoculus*) (Vickaryous et al., 2001) and an unnamed basal hadrosauriform (Pittman et al., 2015). All these dinosaurs are recovered from the Suhongtu Formation, which is late Early Cretaceous in age (Vickaryous et al., 2001; Li et al. 2015). In comparison to the Shuangmiao dinosaur assemblage, *Crichtonpelta* is more advanced than *Gobisaurus* as recovered by this study as well as by Thompson et al. (2012) and Arbour and Currie (2016), while *Shuangmiaosaurus* is much more advanced than *Probactrosaurus* (You et al., 2003; Wang et al., 2015). This may indicate a relatively late age for the Shuangmiao dinosaur assemblage, which is early Late Cretaceous.

“*Zhongyuansaurus luoyangensis*” (Xu et al., 2007) was regarded as a junior synonym of *Gobisaurus domoculus* by Arbour and Currie (2016). “*Zhongyuansaurus*” is the only dinosaur recovered from the Shangdonggou Formation in Ruyang Basin, Henan Province, which is about 1300 km southwest of Shuangmiao. The age of the Shangdonggou Formation was considered to be early Late Cretaceous (Xu et al., 2010), but recently revised as late Early Cretaceous (Albian) based on gastropod biostratigraphy (Pan et al., 2014). Therefore, the age of the *Crichtonpelta*-bearing Sunjiawan Formation may be younger than that of the “*Zhongyuansaurus*” (= *Gobisaurus*)-

bearing Shangdonggou Formation. However, caution should be taken because dinosaurs are not considered as good indicators in biostratigraphy. Nevertheless, the age of the Sunjiawan Formations can be assigned to from late Early Cretaceous to early Late Cretaceous.

7 Conclusions

Our study based on the new specimen provides further anatomical information on *Crichtonpelta benxiensis*, recovers it as the most basal member of Ankylosaurinae, and indicates a late Early Cretaceous to early Late Cretaceous age for the Shuangmiao dinosaur assemblage.

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