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New Nodosaurid Dinosaur from the Late Cretaceous of Lishui, Zhejiang Province, China

LÜ Junchang[1,*], JIN Xingsheng[2], SHENG Yiming[2], LI Yihong[2], WANG Guoping[3] and Yoichi AZUMA[4,2]

1 *Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China*
2 *Zhejiang Museum of Natural History, Hangzhou, Zhejiang 310012, China*
3 *Lishui Culture Department of Zhejiang Province, Lishui, Zhejiang 323000, China*
4 *Fukui Prefectural Dinosaur Museum 51-11 Terao, Muroko, Katsuyama 911-8601, Japan*

Abstract: A new genus and species of nodosaurid dinosaur: *Zhejiangosaurus lishuiensis* gen. et sp. nov. is erected herein. It is characterized by the sacrum consisting of at least three true sacral vertebrae, 5 caudal dorsal vertebrae fused to form the presacral rod, wide divergence of long slender preacetabular process of the ilium from the middle line of the body, and the fourth trochanter located at the femoral mid-length.

Key words: Nodosauridae, *Zhejiangosaurus*, Late Cretaceous, Lishui, Zhejiang Province

1 Introduction

Ankylosauria is a monophyletic clade of quadrupedal herbivorous dinosaurs characterized by the pervasive development of parasagittal rows of osteoderms across the dorsolateral surfaces of the body and an unusual skull architecture with small denticulate teeth and an external investment of cranial ornamentation (Vickaryous et al., 2004). The earliest discovery of true ankylosaurs from China was noted by Wiman (1929) and Gilmore (1933). Since then more specimens have been found (Young, 1935, 1964; Maryańska, 1977; Pang and Cheng, 1998; Godefroit et al., 1999; Vickaryous et al., 2001; Dong, 1993, 2002; Xu et al., 2001), and most of them are ankylosaurid dinosaur. In China, only one nodosaurid dinosaur was found so far (Xu et al., 2001). Herein described is a new nodosaurid dinosaur from the Upper Cretaceous Chaochuan Formation of Lishui, Zhejiang Province (Fig. 1). The specimen was found in March of 2000 and one of the authors (Jin Xingsheng) presided the excavation, which was carried out by the staffs from the Zhejiang Museum of Natural History and Lishui Culture Department of Zhejiang Province. The purpose of this paper is to describe the new specimen in detail and compare with other nodosaurid dinosaurs.

* Corresponding author. E-mail: lujc2008@126.com.

2 Systematic Paleontology

Thyreophora Nopcsa, 1915
Eurypoda Sereno, 1986
Order Ankylosauria Osborn, 1923
Family Nodosauridae Marsh, 1890
Zhejiangosaurus gen. nov.

Etymology: Zhejiang refers to Zhejiang Province, the Chinese administrative unit, which the fossil was found from.

Diagnosis: as for the only species.

Fig. 1. Map of the fossil locality.
Solid triangle indicates fossil locality.

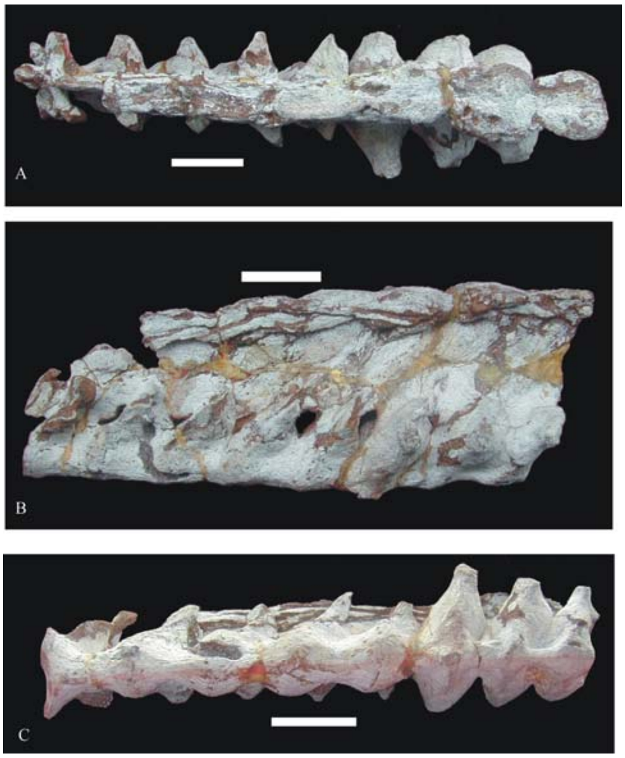

Fig. 2. Sacrum of *Zhejiangosaurus lishuiensis* gen. et sp. nov., in dorsal (A), lateral (B) and ventral views (C).
Scale bars = 10 cm.

Zhejiangosaurus lishuiensis sp. nov. (Figs. 2–7)

Etymology: The specific name refers to the Chinese administrative unit Lishui, which the holotype locality belongs to.

Holotype: an incomplete skeleton including sacrum consisting of 8 vertebrae, complete right ilium, proximal end of ischium and complete pubis. Partial left ilium, 2 complete hindlimbs, 14 caudal vertebrae and some unidentified bones. The specimen stored in the Zhejiang Natural History Museum (ZMNH M8718).

Locality and horizon: Liancheng, Lishui of Zhejiang Province. Chaochuan Formation (Cenomanian) (Cai and Yu, 2001). GPS data: 28° 28′36.4″ N, 119°51′54.3″ E.

Diagnosis: The sacrum consisting of at least three true sacral vertebrae, 5 caudal dorsal vertebrae fused to form the presacral rod, the preacetabular process of the ilium relatively longer and slender; the sacral ribs are oriented dorsolaterally and slightly posteriorly; the fourth trochanter located at the femoral mid-length; the fibular much slender than the tibia; the ratio of tibia to femoral length approximate 0.46.

3 Description

No cervical vertebrae and anterior dorsal vertebrae are preserved. Four connected distal part of neural spines of dorsal vertebrae are preserved. The distal end of the neural spine is expanded transversely, and its dorsal surface is concave.

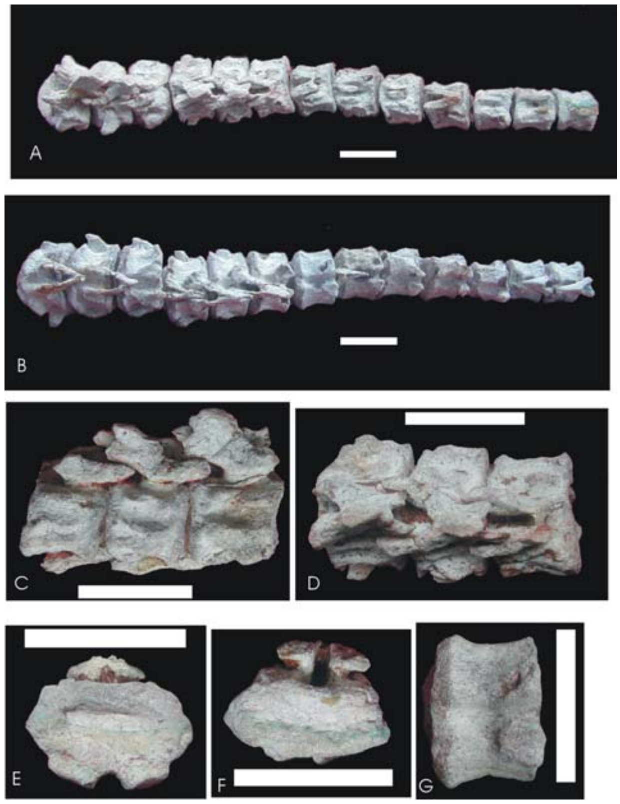

Fig. 3. The naturally articulated anterior caudal vertebrae in dorsal view (A) and ventral view (B); close-up of the anterior three caudal vertebrae in lateral view (C) and dorsal view (D); middle caudal vertebra in anterior (E), posterior (F) and ventral views (G).
Scale bars = 10 cm.

The synsacrum is composed of at least 8 vertebrae (Fig. 2). The sacral ribs and transverse processes are fused. They form a robust, dorsoventrally deep brace between the vertebral column and the ilium. Deep isolated concavities appear on the dorsal portion of the medial surface of the ilium for receiving the distal end of the sacral transverse process, therefore, the distal end of the transverse process strongly interlocked with the medial surface of the ilium, but not fused to the ilium. The braces extend dorsolaterally. The sacral ribs are oriented dorsolaterally and slightly posteriorly rather than horizontally seen in other ankylosaurs (Vickaryous et al., 2004). The last three braces are the widest, indicating that at least three sacral vertebrae present in this animal (the last centrum only preserved its proximal part, thus it is not sure it belongs to the last one or not). The anterior five are the dorsosacral vertebrae. The sacrum and the caudal dorsal vertebrae fused to form the presacral rod as in other ankylosaurs (Eaton, 1960; Ostrom, 1970). The ventral margins of the first five vertebrae are

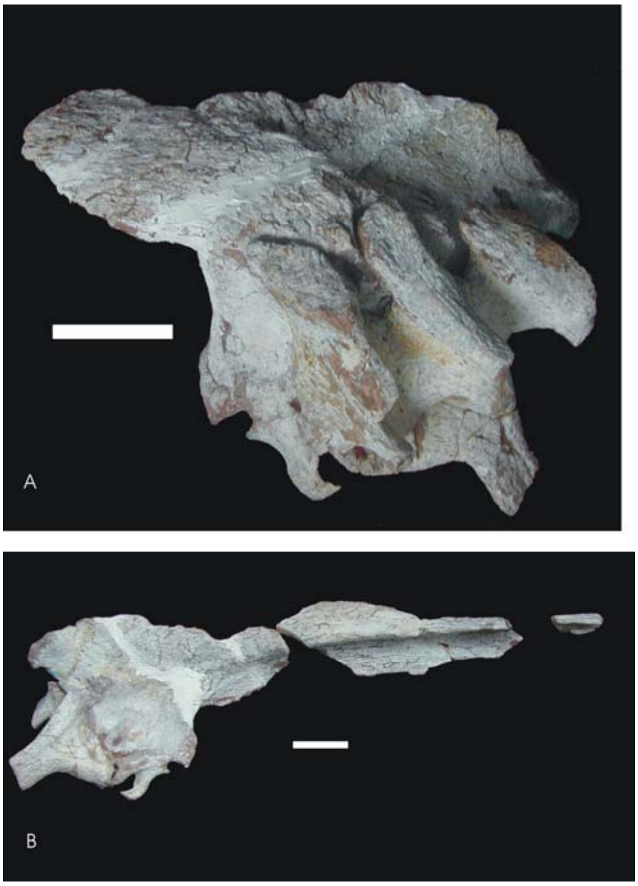

Fig. 4. Part of right pelvic girdle in medial view (A) and lateral view (B).
Scale bars = 10 cm.

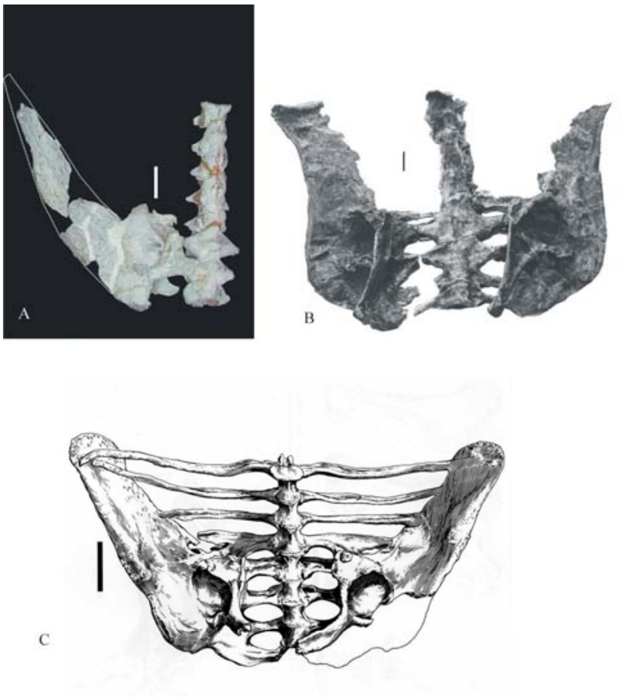

Fig. 5. Comparison of synsacrum and pelvis.
A. partial synsacrum and pelvis of *Zhejiangosaurus lishuiensis* gen. et sp. nov.; B. synsacrum and pelvis of *Struthiosaurus languedocensis* (from Garcia and Pereda- Suberbiola, 2003); C. synsacrum and pelvis of *Euoplocephalus* (from Coombs, 1978). Scale bars = 10 cm in A and B, 20 cm in C.

straight and the ventral margin is curved from the sixth vertebra in lateral view (Fig. 2B). The sutures between the centra are not clear. The adjacent neural spines and zygapophyses of the pressacral rod and the sacrum fused together, forming a continuous lamina along the synsacrum. The lamina becomes higher posteriorly (Fig. 2B). It is 25 cm high from the bottom of the sacral vertebra to the top of the osteoderm. Four osteoderms are present on top of the posterior portion of the lamina. The last one is densely fused with the top of the neural spine (Fig. 2A). The anterior surface of the first dorosacral vertebra is slightly concave. The width of the anterior articular end is greater than its height (104 mm wide and 64 mm high from the bottom to the lower margin of the neural canal). The lateral and ventral surfaces of vertebrae are rounded (Fig. 2C). The whole length of the preserved synsacrum is 63 cm. The length of each vertebra from anterior to posterior is as follows: 10, 9, 8.5, 9, 9, 7.5, 8, and 3.4 (preserved length) cm.

Caudal vertebrae: 13 caudal vertebrae are preserved (Fig. 3A, B) (Table 1). The exact position of these vertebrae in the tail is not clear. Most of them belong to anterior caudal vertebrae. The anterior six caudal vertebrae are naturally articulated. All the caudal vertebrae bear haemal arches, indicating that they are not postsacral rod vertebrae. The cross-sections of all the centra are hexagonal, although this is slightly exaggerated due to the preservation (Fig. 3E, F). The caudal ribs are present in some vertebrae, and they are oriented horizontally with slightly anteriorly. The cross section of the base of the caudal rib is triangular. The neural arches are short. The prezygapophyses extend 1/3 length of the centrum of the anterior caudal (Fig. 3C, D). A deep longitudinal groove presents on the ventral surface of the centrum, which are formed by a pair of parasagittal ridges extending posterior protruding haemal facets (Fig. 3G). This is similar to that of nodosaurid dinosaur found from North America (Coombs and Deméré, 1996) and *Hoplitosaurus* (?) sp. (Bodily, 1969). The distal ends of the neural spines are not preserved. Both articular ends of the anterior six caudal vertebrae are nearly flat, although in some centrum showing little concavities due to the preservation. A longitudinal ridge is present on the lateral surface of the posterior caudal vertebrae. One small incomplete caudal vertebra is preserved. One end is narrower than the other end. No indication of the tail-club is present.

The haemal arch is short with short shaft and widened branches. All haemal arches are fused to the caudal

Table 1 Length of the anterior caudal vertebrae of *Zhejiangosaurus lishuiensis* gen. et sp. nov.

Vertebrae	1	2	3	4	5	6	7	8	9	10	11	12	13
Length (cm)	6	6	6.5	7.5	6.4	6.5	6.5	6.5	6.5	6.5	6.5	6.5	7

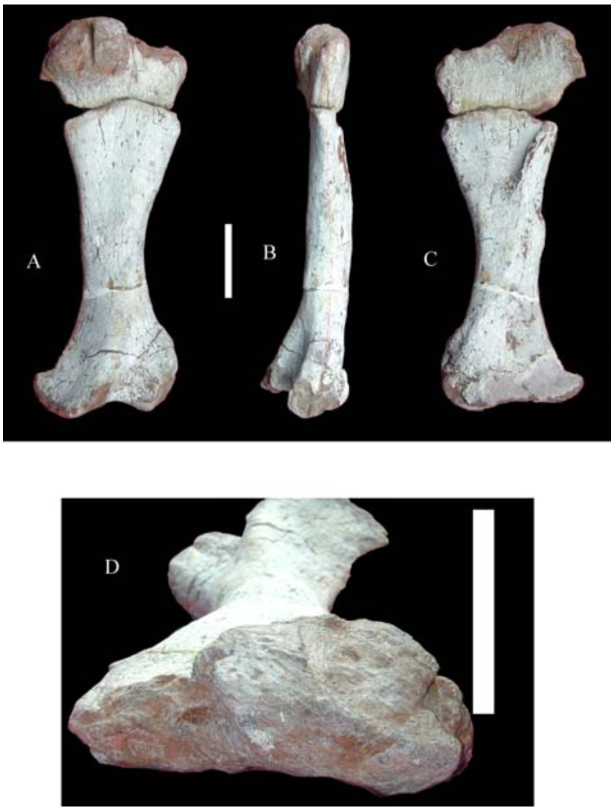

Fig. 6. Right femur of *Zhejiangosaurus lishuiensis* gen. et sp. nov. in anterior view (A), medial view (B), posterior view (C) and proximal end view (D).
Scale bars = 10 cm.

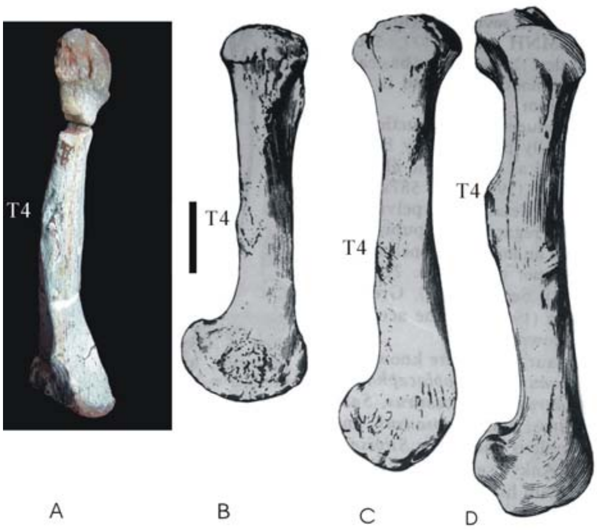

Fig. 8. Femora of Ankylosauria in medial views, showing the position of fourth trochanter (T4).
A. *Zhejiangosaurus lishuiensis* gen. et sp. nov. B. *Euoplocephalus*. C. *Ankylosaurus*. D. *Sauropelta*. B, C and D are from Coombs (1979). Scale bar = 10 cm.

Fig. 7. Right leg of *Zhejiangosaurus lishuiensis* gen. et sp. nov. in medial view (A) and in lateral view (B); Left leg of *Zhejiangosaurus lishuiensis* gen. et sp. nov. in medial review (C) and medial review (D) of the right tibia and pes of *Zhejiangosaurus lishuiensis* gen. et sp. nov.
Scale bars = 10 cm.

vertebrae (Fig. 3B). The haemal arch is fused to the ventral surface near the posterior end of the caudal vertebra.

Ilium (Fig. 4): The right ilium is almost complete except missing small portion of its anterior process, while the left ilium only preserved its central portion. The pubis, ischium and ilium are fused together, forming an imperforate acetubulum. As in other ankylosaurids, dorsal to the acetabulum, part of the ilium is rotated horizontally, projecting above the articulation with the femur. Just above the posterodorsal end of the ischium, a distinct process appears on the lateral surface of the ilium, together with the ischium, demarcating the posterior margin of the acetabulum. Posteroventral to the process, there is a large concavity, whose function is not clear. The postacetabular process is short. The dorsal margin of postacetabular process of the ilium is twisted, extending dorsolaterally, while its lower part extends medially. A distinct tuberosity appears on the distal end, and this process is horizontal to

Table 2 Measurements of the elements of the hindlimb of *Zhejiangosaurus lishuiensis* gen. et sp. nov. (in cm)

	Length	Proximal width	Distal width	Shaft diameter
Femur	52.5	19.5	15.2	8
Tibia	24	18	17	7
Fibular	21	6.3	6.6	3
Metatasal II	5	-	-	-
Metatasal III	7.5	-	-	-
Metatasal IV	5.5	-	-	-
Digit II: 1, 2,3	2, 1.5, 7.5	-	-	-
Digit III:1,2,3	3,-,-	-	-	-
Digit IV: 1,2,3	3-,-,-	-	-	-

the process which forms the margin of the acetabulum. Medially, the ilium contacts three sacral ribs. The preacetabular process is long. It is widely divergent from the presacral rod in dorsal and ventral view (Fig. 5A). In lateral view, it covers at least all the fused dorsosarcral vertebrae. The mediodorsal surface of the preacetabular process is convex, and a distinct ridge originates from the base of the preacetabular process, extending horizontally to the end of the process, and forming a deep longitudinal concavity on the ventral surface.

Ischium (Fig. 4): The proximal portion of the ischium is preserved. The dorsolateral surface of the ischium forms part of the cup-like acetabulum. The ischium does not bear obturator process. The shaft of the ischium is plat-like with rectangular cross section. The medial surface of the proximal end of the ischium is slightly convex. The fragments of three sacral ribs are attached to the medial surface of the ilium and the proximal end of the ischium, which is similar to the case in *Animantarx* (Carpenter et al., 1999).

Pubis (Fig. 4): The pubis is very small, and strongly fused with the ilium. It is hook-like, with a notch on its posterior margin.

Femur (Figs. 6, 7): Both legs (femur-tibia-metatarsals-phalanges) are naturally articulated, and both the left and right femora are almost complete (Table 2). As in other ankylosaurs, the femur is generally straight and massive (Fig. 6B), with poorly defined proximal trochanters (Coombs, 1979; Vickaryous et al., 2004). The shape of the femoral head is not clear (Fig. 6A), due to the erosion. In proximal view, the posterior margin of the proximal end is nearly straight, whilst its anterior and medial margins are convex (Fig. 6D). The distolateral surface of the femoral shaft is smooth without large scar for the *M. gastrocnemius* observed in *Ankylosaurus magniventris* (Carpenter, 2004). The fourth trochanter is present as a ridge on the medial margin of the approximately mid-shaft of the femur (Fig. 8A), which is similar to that of Nodosauridae, while in Ankylosauridae, the fourth trochanter is located distally to the femoral mid-length (Coombs, 1979). Just above the level of the fourth trochanter, the posterior surface of the femoral shaft is flat (Fig. 6C), while its anterior surface is slightly concave. Distally, both medial and lateral condyles are distinct. The medial condyle is wider anteroposteriorly than that of the lateral condyle. Wide shallow groove appears on both the anterior and posterior surfaces between the medial and lateral condyles (Fig. 6A, C).

Tibia and fibula (Fig. 7): The tibia is stout. The shaft of the tibia is straight, although the outline of the tibia shows little torsion due to the preservation. The proximal end is broadly expanded craniocaudally, whilst it distal end is broadly expanded mediolaterally. This is a notch on the middle of the lateral border of the proximal end for receiving the fibula. The tibia-astragalus is fused with no trace of fusion. The fibula is much slenderer than the tibia (Fig. 7B) and it is strongly curved laterally in the anteroposterior view, and this may be caused by the preservation. The shaft of the fibula is smooth without scar-like tubercle seen in other ankylosaurs (Coombs, 1979). Both the proximal and distal ends of the fibula are dilated. But the distal end is wider than proximal end in diameter. The medial surface of the distal end of the fibula is concave, contacting with the expanded distal end of the tibia. The fibula-calcaneum junction is fused without any trace of fusion.

Pes: Two complete pedes show that the pes has three metatarsals (Fig. 7D). The pes is tridactyl as that of *Euoplocephalus* (Vickaryous et al., 2004). Although some pedal phalanges of both pedes are not naturally articulated and dispersed in some toes. Three pedal phalanges (including the ungual) present in the medial one indicate that it is the second toe. The second metatarsal is stouter than the other two. The third metatarsal is the longest and the fourth metatarsal is the shortest. The proximal ends of the metatarsals are slightly concave, and their distal ends are not clear. The second phalange of the second toe is small and much reduced proximodistally. The pedal ungual is wider proximally than distally. The dorsal surface is sculptured with pits and small short grooves. Small short notches are present on the proximal margin of the ungual. Three phalanges of the third toe are preserved, the ungual is displaced from its original place, and thus the third phalange of this toe may be covered by the third ungual. One phalange of the fourth toe is preserved, the number of the phalanges is not clear, but it is probably 5 as in other anykylosaurs which bear three pedal toes.

Osteoderm: Four osteoderms are preserved with the corresponding neural spine (Fig. 2A). The osteoderm is round with 9 cm in diameter. A shallow longitudinal groove appears on the middle of dorsal surface. The dorsal surface of the osteoderm is coarse.

4 Discussion and Conclusion

The suborder Ankylosauria is divided into families Ankylosauridae and Nodosauridae (Coombs, 1978). It is easy to identify these two groups according to skull shapes. Ankylosaurid skulls are wide, roughly triangular in dorsal view with broad, blunt anterior end (Coombs, 1978), and these include *Gargoyleosaurus* (Carpenter et al., 1998), *Gastonia* (Kirtland, 1998), *Gobisaurus* (Vickaryous et al., 2001), *Pinacosaurus* (Godefroit et al., 1999), *Tianzhenosaurus* (Pang and Cheng, 1998), *Ankylosaurus* (Brown, 1908), while the skulls of nodosaurid dinosaurs are elongate and pyriform in dorsal view with a narrower, more pointed anterior end than in ankylosaurids, and the skull length always exceeds the maximum skull width (Coombs, 1978), and these include *Panoplosaurus* (Lambe, 1919), and *Edmontonia* (Sternberg, 1928), *Silvisaurus* (Eaton, 1960), *Pawpawsaurus* (Lee, 1996), *Animantarx* (Carpenter et al., 1999), *Cedarpelta* (Carpenter et al., 2001) and a partial nodosaur skull from Japan (Hayakawa et al., 2005). However, the skull of *Zhejiangosaurus lishuiensis* is not preserved, thus the assignment of *Zhejiangosaurus lishuiensis* can be only based on their postcranial skeleton. It is impossible to compare with *Pawpawsaurus* (Lee, 1996) and *Panoplosaurus* (Lambe, 1919), in which only the skull or other parts are preserved, but not preserved in *Zhejiangosaurus*.

Although the skeleton of *Zhejiangosaurus lishuiensis* is not complete, the characters of the tail, femur and synsacrum and pelvic girdle show that it is much more similar to nodosaurid dinosaurs rather than ankylosaurid dinosaurs. The tail of *Zhejiangosaurus lishuiensi* is not complete, but the posterior caudal vertebrae bearing longitudinal ridges present on their lateral surfaces is similar to these of the taxa without the tail club mentioned by Ostrom (1970) and Vickaryous et al. (2004). A small and short centrum may represent the most distal caudal which is similar to the taxa without tail club (Vickaryous et al., 2004) and the fourth trochanter is located proximal to the femoral mid-length. The position of the trochanter on the femur is more similar to these of nodosaurid dinosaurs rather than ankylosaurid dinosaurs (Fig. 8), such as *Ankylosaurus magniventris* (Brown, 1908). The fourth trochanter is proximal to the femoral mid-length in *Zhejiangosaurus lishuiensis*. According to Coombs (1979), the position of the fourth trochanter is correlated with tail size and function, therefore, the tail of *Zhejiangosaurus lishuiensis* is short and has no active function as in other nodosaurids. The synsacrum of *Zhejiangosaurus lishuiensis* consists of at least three true sacral vertebrae and 5 caudal dorsal vertebrae fused to form the presacral rob, which is different from that of *Edmontonia*, but similar to that of *Silvisaurus* (Eaton, 1960). The synsarcum of *Edmontonia* is made up of four caudal vertebrae and three sacral vertebrae (Carpenter, 1990). The elongated and narrow preacetabular process of the ilum is widely divergent from the presacral rod in dorsal and ventral view in *Zhejiangosaurus lishuiensis*, which is similar to that *Edmontonia* (Carpenter, 1990), but differs from that of *Sauropelta*, which is relatively short and wide (Coombs, 1978).

The synsacrum and pelvis of *Zhejiangosaurus lishuiensis* are also different from those of ankylosaurs with these parts preserved. Compared with the synsacrum and pelvis of *Struthiosaurus* (Garcia and Pereda-Suberbiola, 2003) and *Euoplocephalus* (Fig. 5), the shape of the ilium in *Zhejiangosaurus lishuiensis* differs from those of *Struthiosaurus* and *Euoplocephalus* in that the lateral margin of the ilium is convex laterally in *Zhejiangosaurus lishuiensis* in ventral view. The lateral margin of the ilium of *Struthiosaurus* is curved laterally, whilst it is straight in *Euoplocephalus*. Therefore, based on these characters, *Zhejiangosaurus lishuiensis* is assigned to nodosaurid dinosaur. It represents the first large-sized nodosaurid dinosaur found from China so far.

Zhongyuansaurus luoyangensis, an indisputable nodosaurid ankylosaur was recently described by Xu et al. (2007). It displays typical nodosaurid characters of the skull and distalmost caudal vertebrae in the skull with a length larger than width and the tail without a club. The discovery of nodosaurids *Zhongyuansaurus* and *Zhejiangosaurus* further supports the idea that nodosaurid dinosaurs do exist in Asia, although both genera are not directly compared due to the lack of comparable elements between them.

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