Early Middle Jurassic dinosaur footprints from Zizhou County, Shaanxi, China (Postprint)

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Abstract

Four types of footprints of carnivorous dinosaurs have been found from the Yan' an Formation of early Middle Jurassic in Zizhou County, Shaanxi, China. From the top to bottom interval, the four types of footprints discovered at five layers in a 1.7 m thick stratum are as follows: 1) the large tridactyl footprints in the fifth layer (e, top) belong to Zizhoupus wangi ichnogen. et ichnosp. nov.; 2) the medium tridactyl footprints in the third and fourth layers (c–d) belong to Changpeipus longweimaoensis ichnosp. nov.; 3) small tridactyl or tetradactyl footprints in the second layer (b) belong to Shensipus xiaoliheensis ichnosp. nov. and 4) small tridactyl footprints in the first layer (a, bottom) belong to Shensipus tungchuanensis.

Full Text

Preamble

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Early Middle Jurassic Dinosaur Footprints from Zizhou County, Shaanxi, China

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Abstract

Four distinct types of carnivorous dinosaur footprints have been discovered in the early Middle Jurassic Yan'an Formation in Zizhou County, Shaanxi Province, China. These footprints occur across five stratigraphic layers within a 1.7-meter-thick section. From top to bottom, they are: (1) large tridactyl footprints in

the fifth layer (e, top) assigned to *Zizhoupus wangi* ichnogen. et ichnosp. nov.; (2) medium tridactyl footprints in the third and fourth layers (c–d) assigned to *Changpeipus longweimaoensis* ichnosp. nov.; (3) small tridactyl or tetradactyl footprints in the second layer (b) assigned to *Shensipus xiaoliheensis* ichnosp. nov.; and (4) small tridactyl footprints in the first layer (a, bottom) assigned to *Shensipus tungchuanensis*.

Keywords: Zizhou, Shaanxi, Middle Jurassic, Yan' an Formation, dinosaur footprints

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1. Introduction

Shaanxi Province holds historical significance as the site where Teilhard de Chardin and C. C. Young (1929) discovered the first dinosaur track in China. Since that pioneering find, more than 63 forms of dinosaur tracks from over 50 localities spanning the Upper Triassic to Upper Cretaceous have been documented across China (Chen et al., 2006; Matsukawa et al., 1995; Zhen et al., 1996; Lockley et al., 2002, 2003, 2013; Kuang et al., 2013). In most regions, numerous footprints occur on single bedding planes, similar to the bird and dinosaur tracks described from Texas (Lee, 1997).

The Longweimao tracksite is located in Longweimao Village, Dianshi Town, Zizhou County, Shaanxi Province (N37°39 03.26 , E109°48 36.49 , Fig. 1 [Figure 1: see original paper]). Local resident Mr. Wang Jun discovered the footprints in June 2012 while excavating a cave dwelling near the village. He observed that footprints in the lower levels were smaller, while those in the upper levels were larger.

The 1.7-meter-thick track-bearing stratum can be divided into five distinct layers (Fig. 2 [Figure 2: see original paper]). These layers range from 2–10 cm thick and consist of fine-grained sandstone belonging to the lower Middle Jurassic Yan' an Formation (Bureau of Geology and Mineral Resources of Shaanxi Province, 1989). Rock colors vary from gray to gray-yellow, and bedding plane structures including plant fragment imprints, ripple marks, mud cracks, worm trails, and footprints are visible on some surfaces. The underlying stratum comprises pebble-bearing gritstone with cross-bedding, oblique bedding, and parallel bedding. Based on lithological characteristics, this interval can be assigned to the Baotashan Sandstone of the lower portion of the early Middle Jurassic Yan' an Formation (Yang, 2008).

We identified 51 dinosaur footprints across a ~10 m^2 bedding plane distributed through five stratigraphic levels (Layers a–e). Most tracks are scattered, though a few form trackways of two or more footprints. The footprints can be grouped into four types: (1) large tridactyl tracks (Layer e); (2) medium tridactyl tracks

(Layers c, d); (3) small tridactyl or tetradactyl tracks (Layer b); and (4) small tridactyl tracks (Layer a).

During 2013–2014, Xing et al. (2015) investigated other track sites in the Zizhou area and reported new localities. They documented medium- to large-sized theropod footprints similar to the ichnogenera *Kayentapus* and *Eubrontes*, as well as trackways of small bipedal ornithischians referred to as *Anomoepus* isp. However, our study differs significantly in that the tracks were discovered in multiple layers at a single locality, showing a regular size increase through the stratigraphic sequence. This pattern necessitates further investigation.

Abbreviations: NWUV refers to specimen numbers from the Institute of Cenozoic Geology and Environment, Department of Geology, Northwest University.

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2. Systematic Descriptions

Class Reptilia
Order Sauroschia
Suborder Theropoda Marsh, 1881
Ichnofamily Eubrontidae Lull, 1904

***Zizhoupus* ichnogen. nov.**

Type species: *Zizhoupus wangi* ichnogen. et ichnosp. nov.

Etymology: The genus name *Zizhoupus* derives from Zizhou County where the footprints were discovered. The species epithet honors Mr. Wang Jun, who discovered the footprints and contacted the authors for study and evaluation.

Diagnosis: Large asymmetric bipedal walking tracks with tridactyl digit impressions. Claw marks at the distal ends of digits and oblong phalangeal pads are clearly visible. Footprints exceed 40 cm in length and are longer than wide. The average divarication angle between digits II and IV is 68°, with a pace length of 156 cm. Digit III shows inward rotation relative to the pes axis, with the average divarication angle between III–IV being twice that between II–III.

***Zizhoupus wangi* ichnogen. et ichnosp. nov. (Fig. 3 [Figure 3: see original paper]; Tables 1–2)**

Holotype: One large positive right track with tridactyl digit impressions, NWUV 1404 (field number: 12zz14).

Paratypes: One large negative (concave) left track with tridactyl digit impressions, NWUV 1405 (field number: 12zz15).

Referred materials: One half of a large positive (convex) track with tridactyl digit impressions, NWUV 1406 (field number: C 9); two negative footprints, field numbers: C 45, 46 (Fig. 2A, preserved in situ at Longweimao field site).

Horizon and locality: Layer e of Longweimao site, Zizhou County, Shaanxi Province, Yan' an Formation, early Middle Jurassic.

Diagnosis: Same as for the ichnogenus above.

Description: Three scattered footprints—two positive (convex) and one negative (concave)—were collected from the top of the section, Layer e (Fig. 2), with two additional negative (concave) footprints preserved in situ. NWUV 1404 (Fig. 3) closely matches NWUV 1405 in size and shape. Digit III is the longest, with divarication angles of II 21° III 46° IV. The footprint measures 40 cm long and 36.8 cm wide, with an aspect ratio of 1.09. The two negative (concave) footprints (C 45, 46) preserved in situ form a trackway pace (Fig. 2B) measuring 156 cm in length. Their sizes and shapes are consistent with NWUV 1404–1406 (Table 1). The middle digit (III) slants slightly outward. The right claw of C 45 is oriented at approximately 250°, while the left claw of C 46 is oriented at approximately 240°.

Discussion: Lockley et al. (2003, 2013) reviewed Mesozoic dinosaur footprints from China and revised several ichnotaxonomic assignments: *Youngichnus xiyangensis* to *Eubrontes xiyangensis*, *Megaichnites jizhaoshiensis* to *Kayentapus jizhaoshiensis*, *Jinlijingpus nianpanshanensis* to *Eubrontes nianpanshanensis*, and *Chonglongpus hei* to *Gigandipus hei*. Large carnosaurian footprints previously reported from China include *E. platypus* from the Jurassic, *E. xiyangensis*, *Changpeipus carbonicus*, *K. jizhaoshiensis*, *E. nianpanshanensis*, *G. hei* (Zhen et al., 1996; Yang and Yang, 1987), *Lufengopus dongi* (Lü et al., 2006), and *Chapus lockleyi* from the Lower Cretaceous (Li et al., 2006).

Zizhoupus differs from *G. hei* in being bipedal and tridactyl. It differs from bipedal tridactyl *Kayentapus*, *Changpeipus*, and *Eubrontes* in its larger size (length >40 cm), greater divarication angles between digits (>60° between II-IV), and oblong phalangeal pads. It also differs from *E. platypus* and *E. xiyangensis* in having a narrower posterior foot margin. *Zizhoupus* is easily distinguished from *Chapus* by smaller digit divarications, shorter pace, the paw-like tracks of *Chapus*, and its older stratigraphic age (K , Lower Cretaceous). Detailed comparisons are presented in Table 2 .

HI3, a tridactyl bipedal dinosaur footprint from the Huo tracksite, resembles *Zizhoupus* but is slightly smaller (Xing et al., 2015).

***Changpeipus longweimaoensis* ichnosp. nov. (Fig. 4 [Figure 4: see original paper]; Table 3)**

Holotype: One medium-sized positive right track with tridactyl digit impressions, NWUV 1407 (field number: 12zz01).

Paratypes: One medium-sized positive right track with tridactyl digit impressions, NWUV 1408 (field number: 12zz13).

Referred materials: Two negative and one positive tracks with tridactyl digit impressions, field numbers: C 5, 6, 66 (preserved in situ at Longweimao field site).

Horizon and locality: Layers c–d of Longweimao site, Zizhou County, Shaanxi Province, Yan' an Formation, early Middle Jurassic.

Diagnosis: Asymmetric bipedal walking tracks with tridactyl digit impressions. Claw marks at the distal ends of digits and oblong phalangeal pads are clearly visible. Footprints range from 23.4–32.4 cm in length (28.1 cm average) and are longer than wide. The divarication angle between digits II–IV ranges from 55°–64° (59° average).

Etymology: The species epithet *longweimaoensis* derives from Longweimao Village where the footprints were discovered.

Description: The holotype (NWUV 1407, Fig. 4) and paratypes are scattered positive (convex) footprints preserved on fine-grained sandstone. They represent medium-sized theropod dinosaur footprints with tridactyl digits, where digit II is the shortest. Oblong phalangeal pads are clearly visible, with the holotype being better preserved than the others. Measurements are provided in Table 3.

Discussion: According to Zhen et al. (1996), *Changpeipus* typically includes medium-sized footprints (e.g., *C. carbonicus* footprint length 29.2–38.3 cm) with narrow posterior margins and large interdigital angles. The five tracks described here (NWUV 1407, 1408, C 5, 6, 66) are medium-sized bipedal tridactyl footprints with large interdigital angles and a short digit II. Footprint lengths range from 23.4–32.4 cm (average 28.1 cm) and widths from 17.5–27.9 cm (average 22.9 cm). The angle between digits II and IV ranges from 55°–64° (average 59°). These features clearly align with *Changpeipus* (Young, 1960, 1979; Zhen et al., 1996; Lü et al., 2007; Xing et al., 2009a).

All *Changpeipus* fossils have been recovered from Jurassic formations, including *C. carbonicus* from the Early, Middle, and Upper Jurassic; *C. xuiana* from the Middle Jurassic; and the tracks described herein from the lower part of the Middle Jurassic.

The Longweimao footprints differ from other *Changpeipus* species as follows: they lack the tarsal impression present posterior to the footprint in *C. xuiana* (Lü et al., 2007). The length-width ratio of Longweimao footprints ranges from 1.06–1.41 (average 1.23), differing from *C. xuiana* (average 1.9) and *C. carbonicus* (average 1.58) (Zhen et al., 1996). The cf. *Changpeipus* isp. from the Lower Jurassic of Xinjiang is much shorter and wider, with a length-width ratio of only 0.44 (Young, 1960, 1979; Zhen et al., 1996; Xing et al., 2014).

Differences between *C. longweimaoensis* and *C. pareschequier* include: the interdigital divarications of *C. longweimaoensis* (II 26° III 34° IV) differ from those of *C. pareschequier* (II 28° III 28° IV); the phalangeal pad formula is x-2-3-4-x in *C. longweimaoensis* versus x-2-3-2-x in *C. pareschequier*. Longweimao footprints also differ from *C. pareschequier* in lacking the round metatarsophalangeal pad

and subequal divarication angles between II–III and III–IV (Xing et al., 2009a). Additionally, the Longweimao footprints from the Middle Jurassic are stratigraphically younger than *C. pareschequier* from the Lower Jurassic of Yunnan (Xing et al., 2009a). Consequently, we classify these tracks as a new species: *Changpeipus longweimaoensis* ichnosp. nov.

Coelurosauria indet. Ichnogenus *Shensipus* Young, 1966

***Shensipus xiaoliheensis* ichnosp. nov. (Fig. 5 [Figure 5: see original paper]; Table 4) Holotype:** One slab with two negative tracks with tridactyl digit impressions, NWUV 1409 (field number: 12zz03).

Paratypes: One slab with two positive tetradactyl tracks, NWUV 1410 (field number: 12zz02).

Referred materials: 11 slabs bearing 24 small tridactyl digit impressions (five stored in the Department of Geology, Northwest University as NWUV 1411–1415, and others observed in situ as C1–4, 8, 48, 64).

Horizon and locality: Layer b of Longweimao site, Zizhou County, Shaanxi Province, Yan' an Formation, early Middle Jurassic.

Etymology: The species epithet *xiaoliheensis* derives from the Xiaolihe River Basin where the footprints were discovered.

Diagnosis: Small theropod dinosaur footprints with tridactyl or tetradactyl digits. The pes is functionally tridactyl with a medially-directed hallux sometimes impressed. Digit III is the longest, and digit IV is longer than digit II. Phalangeal pads are indistinct. Footprint lengths range from 9.6–21.3 cm (13.8 cm average). The aspect ratio is 1.11, and the average divarication angle between digits II–IV is 74°.

Description: The holotype (NWUV 1409) and paratype (NWUV 1410) are preserved in fine-grained sandstone (Fig. 5). The holotype exhibits tridactyl digits, with digit III being the longest and bearing two pads. Digits III and IV are slightly longer, with three or four pads. The angle between digits II and III is slightly smaller than that between III and IV. The paratype is a positive (convex) tetradactyl track with a small hallux impression (I?). Digit I measures 3 cm long with a claw mark at its distal end and is oriented opposite to digit IV, making the angle between digits I and IV approach 180°. Digits II, III, and IV are similar in size and shape. Among referred materials (NWUV 1411–1415), only NWUV 1415 shows an indistinct hallux impression. All these footprints occur in Layer b (Fig. 2). Measurement data are presented in Table 4.

Discussion: Compared with other dinosaur footprints from China, the specimens from Layer b of the Longweimao site most closely resemble *Shensipus*, leading us to assign them to this genus. These footprints represent a new *Shensipus* species based on the following: (1) *S. xiaoliheensis* footprint lengths vary

between 10–20 cm; (2) the shape resembles small theropod footprints such as *Shensipus* but shows different interdigital angle variation. The average divarication angle II-IV for *Shensipus* from Zizhou is 74° (Table 4), which is less than the 90° reported for *S. tungchuanensis* from Tongchuan (Young, 1966; Zhen et al., 1996) and the 102° measured for *S. tungchuanensis* in this study (Table 5); (3) occasional tetradactyl impressions (hallux) occur, which are absent in *S. tungchuanensis*; (4) since only a few footprints show the hallux, while most others resemble *Shensipus* in shape and size, we classify them as a new species: *S. xiaoliheensis* ichnosp. nov.

Xing et al. (2015) re-assigned *Shensipus tungchuanensis* Young, 1966 to the ichnogenus *Anomoepus* Hitchcock, 1848 as *Anomoepus tungchuanensis* (Young, 1966) comb. nov., inferring that these tracks belong to *Anomoepus* based on their similarity to tracks reported by Li et al. (2012: fig. 12B [Figure 12: see original paper]) and others from the Huo tracksite. Xing et al. (2015) considered *S. tungchuanensis* a subjective junior synonym of *Anomoepus* sensu lato and thus proposed the new combination *A. tungchuanensis*.

Xing et al. (2015) stated that "All these characteristics, notably the wide digit divarication, length/width ratio, short step, and inward rotation, are characteristic of *Anomoepus* (Lockley and Gierlinski, 2006)." However, the actual quote from Lockley and Gierlinski (2006, p. 182) reads: "The long step of *A. cuneatus* (pes length: step ratio of 1:5.6 to 1:8 and pes width: step ratio of 1:7.7 to 1:10.7) described by Lull (1953) from the Newark Supergroup is also similar to the ratio recorded for *Anomoepus* from the Lisbon Valley Oilfield site (about 1:8), and the exceptional ratio of between 1:18.3 and 1:19.9 recorded for *Hopiichnus*."

Lockley et al. (2013) considered *Shensipus* a distinctive and potentially valid ichnotaxon of uncertain affinity. We concur with this assessment and therefore retain the original classification (Young, 1966) in our study.

***Shensipus tungchuanensis* Young, 1966 (Fig. 6 [Figure 6: see original paper]; Table 5) Materials:** Four slabs of small scattered tridactyl footprints, NWUV 1416 (field number: 12zz23); C 55, 69, 70 (observed in situ); and one slab approximately 1 m × 0.8 m bearing nine small tridactyl footprints, field number: C 34 (observed in situ). All footprints originate from Layer a (bottom) of the section.

Description: C 34 is a large slab with three rows of nine negative footprints. NWUV 1416 is a positive (convex) small tridactyl footprint with indistinct phalangeal pads and slender digits. The heel is small (Fig. 6). The foot measures 9.4 cm long, with a 92° angle between digits II and IV. Measurement data are presented in Table 5. The other specimens (C 55, 69, 70) are scattered slabs each bearing a single footprint. Based on measurements from 12 footprints (Table 5), lengths range from 5–10.1 cm (average 7.8 cm) and widths from 7.9–13.4 cm (average 9.4 cm). The central digit (III) is longest, while digit II is shortest.

Discussion: *Shensipus tungchuanensis* is characterized by bipedal tridactyl

footprints with very slender digits. The angles between digits II–III and III–IV are large (II 32° III 58° IV). Footprints are 9–10 cm long with a 9.7 cm pace from the Middle Jurassic (Young, 1966; Zhen et al., 1996). The features described above—footprints less than 10 cm long, slender clawed digits, and interdigital angles II–IV exceeding 90°—are consistent with *S. tungchuanensis* footprints from the Jurassic. We therefore assign these footprints to *S. tungchuanensis*.

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3. Discussion

Body Size, Height, and Gait of the Trackmakers

Previous studies indicate that hip height approximates leg length, being about four times foot length in mammals (Alexander, 1976), and that body length is approximately 2.63–3.5 times hip height (Xing et al., 2009b; Li et al., 2006). Based on measurements of the newly discovered footprints, the smallest tracks (*Shensipus tungchuanensis*) represent an animal with a hip height of 31.2 cm and body length of 0.8–1.1 m. The larger *S. xiaoliheensis* ichnosp. nov. trackmaker stood approximately 55.2 cm high and measured 1.5–1.9 m long. The *Changpeipus longweimaoensis* ichnosp. nov. trackmaker reached 1.1 m in hip height and 3–3.9 m in body length, representing a medium-sized dinosaur. The largest footprint, *Zizhoupus wangi* ichnogen. et ichnosp. nov., represents a large dinosaur 4.6–6.1 m long with a hip height of 1.75 m.

Geological Age

The Middle Jurassic Yan' an Formation in the Yan' an-Fugu area of northern Shaanxi Province reaches 200–300 m in thickness (Bureau of Geology and Mineral Resources of Shaanxi Province, 1989). The Yan' an Formation near the Dalihe River is approximately 220 m thick (Yang, 2008). According to the latest International Stratigraphic Chart, the Middle Jurassic spans approximately 174.1–163.5 Ma (International Commission on Stratigraphy, 2015), representing a duration of about 10.6 million years. The estimated depositional rate in the study area averages 100,000 years per 2.1 m. The Longweimao site section spans less than 100,000 years for the 1.7-m-thick interval.

Most dinosaur footprint sites yield specimens from a single layer at one locality. However, the Longweimao tracksite preserves footprints in five layers at one locality, with footprint sizes increasing regularly upward. This pattern of multi-layer footprint preservation with systematic size variation through the stratigraphic sequence is rare and has not been reported in previous studies.

The adjacent area documented by Xing et al. (2015) differs substantially from our findings, possibly due to investigation of different stratigraphic layers. Our study describes five distinct layers within a 1.7-m interval at a single locality, whereas Xing et al. (2015) based their work on single layers from other locations. This discrepancy may account for both similar and divergent features,

which is expected given the significant vertical and horizontal variation typical of continental strata. Further evidence is needed for verification.

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Note: Figure translations are in progress. See original paper for figures.