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 frst layer (a, bottom) belong to Shensipus tungchuanensis.

Full Text

Preamble

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, China. Within a 1.7 m thick stratigraphic interval, the footprints occur at five successive layers, displaying the following sequence from top to bottom: (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 location where Teilhard de Chardin and C. C. Young (1929) discovered the first dinosaur track in China. Since that pioneering discovery, more than 63 morphotypes 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). Most regions exhibit numerous footprints on single bedding planes, similar to the bird and dinosaur tracks described from Texas (Lee, 1997).

At one locality in the Yan'an Formation (Middle Jurassic), four distinct footprint types have been identified across five layers within a 1.7 m thick stratum. These tracks differ significantly from most previously described dinosaur footprints in China. The tracksite is located at Longweimao village, Dianshi Town, Zizhou County, Shaanxi Province (N37°39 03.26 , E109°48 36.49 , [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 astutely observed that footprints in lower levels were smaller, while those in upper levels were larger.

The 1.7 m thick track-bearing stratum can be divided into five distinct layers ([Figure 2: see original paper]), each 2–10 cm thick and composed of fine-grained sandstone. These horizons belong to the lower Middle Jurassic Yan' an Formation (Bureau of Geology and Mineral Resources of Shaanxi Province, 1989). Rock colors range from gray to gray-yellow, and various bedding plane structures are preserved, including plant fragment imprints, ripple marks, mud cracks, worm trails, and footprints. The underlying substrate consists of pebble-bearing gritstone with cross-bedding, oblique bedding, and parallel bedding structures. 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 distributed across a ~10 m^2 bedding plane at five stratigraphic levels (Layers a–e). Most tracks are scattered, though a few form trackways comprising two or more footprints. The footprints can be grouped into four distinct morphotypes: (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, reporting new localities with medium- to large-sized theropod footprints similar to the ichnogenera *Kayentapus* and *Eubrontes*, as well as trackways of small bipedal ornithischians referred to *Anomoepus* isp. However, our study differs fundamentally in documenting tracks from multiple layers at a single locality, revealing a regular stratigraphic size progression in dinosaur footprints. This pattern has not been reported by Xing et al. (2015), necessitating further investigation.

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

2 Systematic Descriptions

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

***Zizhoupus* ichnogen. nov.**

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

Etymology: The ichnogenus name *Zizhoupus* derives from Zizhou County, the region where the footprints were discovered. The specific epithet *wangi* 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 preserved. Footprint length exceeds 40 cm, with length greater than width. The average divarication angle between digits II and IV is 68°, and pace length is 156 cm. Digit III exhibits inward rotation relative to the pes axis, with the average divarication angle between digits III–IV being twice that between II–III.

***Zizhoupus wangi* ichnogen. et ichnosp. nov. ([Figure 3: see original paper]; -)**

Holotype: One large positive (convex) 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 ([Figure 2: see original paper], 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.

Description: Three scattered footprints—two positive (convex) and one negative (concave)—were collected from the top of the section, Layer e ([Figure 2: see original paper]), with two additional negative (concave) footprints preserved in situ. NWUV 1404 ([Figure 3: see original paper]) and NWUV 1405 are similar in size and shape. Digit III is the longest, with divarication angles of II 21° III 46° IV. The footprint measures 40 cm in length and 36.8 cm in width, yielding an aspect ratio of 1.09. The two in situ negative footprints (C 45, 46) form a trackway pace ([Figure 2B: see original paper]) measuring 156 cm in length, with footprint dimensions consistent with NWUV 1404–1406 (). The middle digit (III) slants slightly outward. The orientation of the right claw of C 45 is approximately 250°, while the left claw of C 46 is about 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 presence of oblong phalangeal pads. It also differs from *E. platypus* and *E. xiyangensis* in having a narrower posterior foot region. *Zizhoupus* is easily distinguished from *Chapus* by smaller interdigital divarications, shorter pace, the paw-like tracks of *Chapus*, and its older stratigraphic age (K , Lower Cretaceous). Detailed comparisons are presented in .

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

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

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 digit distal ends and oblong phalangeal pads are clearly preserved. Footprint length ranges from 23.4–32.4 cm (average 28.1 cm), with length exceeding width. Divarication angle II–IV measures 55°–64° (average 59°).

Etymology: The specific epithet *longweimaoensis* derives from Longweimao village, the locality where the footprints were discovered.

Description: The holotype (NWUV 1407, [Figure 4: see original paper]) and paratypes are scattered positive (convex) footprints preserved on fine-grained sandstone. These medium-sized theropod dinosaur footprints exhibit tridactyl digits, with digit II being the shortest. Oblong phalangeal pads are clearly visible. The holotype is better preserved than other specimens. Measurements are provided in .

Discussion: According to Zhen et al. (1996), *Changpeipus* typically includes medium-sized footprints (e.g., *C. carbonicus* footprint length 29.2–38.3 cm) characterized by narrow posterior footprints 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 and widths from 17.5–27.9 cm, with II–IV angles of 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 Middle Jurassic.

The Longweimao tracks differ from other *Changpeipus* species in several respects: 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), contrasting with *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: 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 II-III and III-IV divarication angles (Xing et al., 2009a). Additionally, Longweimao footprints from the Middle Jurassic are stratigraphically younger than *C. pareschequier* from the Lower Jurassic of Yunnan (Xing et al.,

2009a). Consequently, we designate these tracks as a new species: *Changpeipus longweimaoensis* ichnosp. nov.

Coelurosauria indet. Ichnogenus *Shensipus* Young, 1966

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

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

Referred materials: Eleven slabs with 24 small tridactyl digit impressions (five stored in the Department of Geology, Northwest University as NWUV 1411–1415; remainder 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 specific 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 (average 13.8 cm), with an aspect ratio of 1.11. The average divarication angle II–IV is 74°.

Description: The holotype (NWUV 1409) and paratype (NWUV 1410) are preserved in fine-grained sandstone ([Figure 5: see original paper]). 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 respectively. 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 imprint (I?). Digit I measures 3 cm long with a claw mark at its distal end, oriented opposite to digit IV such that the I–IV angle approaches 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 imprint. All these footprints occur in Layer b ([Figure 2: see original paper]). Measurement data are presented in .

Discussion: Compared with other dinosaur footprints from China, the size and shape of specimens from Layer b of Longweimao site most closely resemble *Shensipus*. We assign them to a new species based on the following criteria: (1) *S. xiaoliheensis* footprint length varies between 10–20 cm; (2) the shape resembles small theropod footprints such as *Shensipus* but exhibits different interdigital angles. The average II–IV divarication angle for *Shensipus* from Zizhou is 74° (), smaller than the 90° reported for *S. tungchuanensis* from Tongchuan (Young,

1966; Zhen et al., 1996) and the 102° observed in *S. tungchuanensis* in this study (); (3) occasional tetradactyl impressions (hallux) occur, which are absent in *S. tungchuanensis*; (4) since most footprints lack a hallux but are otherwise similar in shape and size to *Shensipus*, 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., based on similarities to tracks reported by Li et al. (2012: fig. 12B) and others from the Huo tracksite. They considered *S. tungchuanensis* a subjective junior synonym of *Anomoepus* sensu lato. However, Lockley et al. (2013) regarded *Shensipus* as a distinctive and potentially valid ichnotaxon of uncertain affinity, a view we endorse. We therefore retain the original classification (Young, 1966) in our study.

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

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

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 ([Figure 6: see original paper]). The footprint is 9.4 cm long with a 92° angle between digits II and IV. Measurements are provided in . Specimens C 55, 69, 70 are scattered slabs each bearing a single footprint. Based on 12 measured footprints (), lengths range from 5–10.1 cm (average 7.8 cm) and widths from 7.9–13.4 cm (average 9.4 cm). Digit III is the longest, and digit II is the shortest.

Discussion: *Shensipus tungchuanensis* is characterized by bipedal tridactyl footprints with very slender digits. The II–III and III–IV angles are large (II 32° III 58° IV). Footprints are 9–10 cm long with a 9.7 cm pace length from the Middle Jurassic (Young, 1966; Zhen et al., 1996). The features observed here—footprints less than 10 cm long, slender clawed digits, and II–IV angles exceeding 90°—are consistent with *S. tungchuanensis* from the Jurassic. We therefore assign these footprints to *S. tungchuanensis*.

3 Discussion

Body Size, Height, and Gait of Trackmakers

Previous studies indicate that hip height approximates leg length, being about four times foot length in mammals (Alexander, 1976), while 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 (*Shensipus tungchuanensis*) represents an animal with a hip height of 31.2 cm and body length of 0.8–1.1 m. The larger *S. xiaoliheensis* trackmaker stood approximately 55.2 cm tall and measured 1.5–1.9 m in length. The *Changpeipus longweimaoensis* 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*, indicates 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 is approximately 200–300 m thick (Bureau of Geology and Mineral Resources of Shaanxi Province, 1989). Near the Dalihe River, the Yan' an Formation reaches about 220 m in thickness (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 approximately 100,000 years per 2.1 m of sediment. The 1.7 m thick section at Longweimao thus represents less than 100,000 years of deposition.

Most dinosaur footprint sites yield specimens from a single layer at one locality. However, at Longweimao, footprints occur in five distinct layers at one site, with footprint sizes increasing stratigraphically upward. Such multi-layer footprint assemblages showing regular size progression through a stratigraphic sequence are exceptionally rare and have not been reported in previous studies.

The adjacent area investigated by Xing et al. (2015) differs markedly from our study, likely due to examination of different stratigraphic layers. We documented five distinct layers within a 1.7 m interval at one locality, whereas Xing et al. (2015) focused on single layers at other locations. This discrepancy may account for both similarities and differences in observed features, which is expected given the substantial vertical and lateral variability typical of continental strata. Additional evidence is required for further verification.

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