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ORIGINAL RESEARCH

A Review of two Middle Jurassic Theropod Tracksites Discovered in the 1980s from Sichuan Basin

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ABSTRACT

Tracks from two sites in the Middle Jurassic Xintiangou Formation in the Wuma Village area, Wuhuang Township, Zizhong have been known and intermittently studied and excavated since the 1980s. The track-bearing surfaces were exposed by a combination of natural weathering and deliberate excavation by residents in a rural agricultural area. The surfaces were used as "threshing floors" for the processing of agricultural crops in an area subject to weathering under a humid sub-tropical climatic regime. Despite the negative effects of weathering on the quality of track preservation, the sites are historically significant in Chinese ichnology as the type areas for many controversially named theropod ichnotaxa. Subsequent researchers challenged the ichnotaxonomy as provincial and over-split, suggesting that many of the tracks, belong to well-known Lower Jurassic ichnogenera. The present study reviews these two sites, providing new information, and confirming that the tracks belong to the ichnogenera *Grallator*, *Eubrontes* and *Kayentpus* which are typical of the globally widespread Lower Jurassic tetrapod biochron. This suggests the Middle Jurassic ichnofauna in Sichuan is like Lower Jurassic ichnofaunas elsewhere. Previous efforts to transfer the ichnospecies to globally, better-known ichnogenera were important in reducing ichnogenus diversity, but did not reduce ichnosepcies diversity. Herein the ichnotaxa are reviewed and it is shown that the ichnospecies names have no utility for comparative study or in assessing assemblage diversity, or biochron composition. It is therefore proposed that the multiple ichnospecies names proposed based on tracks from these two localities can mostly be accommodated under the labels *Grallator* isp. indet., and *Eubrontes* isp. indet.

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1. Introduction

One of the main issues in the study of China's dinosaur tracks is the problem of ichnotaxonomic 'over-splitting' (Lockley et al., 2013), which is more severe among Jurassic taxa than those from the Cretaceous (Lockley et al., 2014). Lockley et al. (2013) attempted to solve the problem, and began a review of Jurassic tracks from the Sichuan Basin by assessing ichnotaxonomy of Lower and Middle Jurassic theropod tracks reported in the 1980s and 1990s, notably by Yang and Yang (1987) and Zhen *et al*. (1986, 1996), from Sichuan and other provinces of China. The over-splitting problem identified by Lockley *et al*. (2013) is simply stated: prior to 2013, 25 theropod tracks had been named from the Lower and Middle Jurassic of China, see summary by Lockley *et al*. (2013), although in the rest of the world the global Lower Jurassic Biochron (*sensu* Lucas, 2007) revealed no more than three commonly reported theropod tracks: *Grallator, Eubrontes* and *Kayentapus* (plus a few other less common ichnogenera). This led to scrutiny of sites from which multiple, provincially-restricted theropod ichnotaxa were named. Of immediate relevance in this regard, this review considers two track sites in Wuhuang Township, Zizhong County (Lockley et al., 2003).

The Wumacun site, or Wumacun site A (GPS: 29°43'27.96" N, 104°47'32.38"E) (Fig. 1) is located in Qingganglin, Wuma Village, Wuhuang Township, Zizhong County, near the center of the Sichuan Basin. It contains 155 tracks of six distinct types and comprising 14 trackways. This site was exposed in the 1970s, when farmers were clearing topsoil to make a rock surface into a threshing ground on which to dry and prepare agricultural produce. In the autumn of 1981, the Chongqing Museum of Natural History found the Wumacun site and collected roughly 90 tracks. The Jizhuashi site, also known as the Wumacun site B (GPS: 29°43'19.88"N, 104°47'35.46"E), is about 260 m south of the Wumacun site. This site is a large fallen rock with more than 30 tracks on the bedding plane, including two large trackways and four small trackways. It is also relevant to note that the Wumacun sites (A and B) are located only about 15 km southeast of the Nianpanshan site (Lockley and Matsukawa, 2009) which contains two of the typical Lower Jurassic tetrapod footprint biochron tracks: *Anomopeus* and *Eubrontes* (formerly *Jinlijingpus*). The track bearing surfaces at both the Wumacun site A and Nianpanshan have been used for agricultural purposes which, in combination with the regional climatic regime has led to the deterioration of tracks making ichnotaxonomic identification difficult. These facts justified the removal of tracks in 1981 in order to preserve them. However, excavation compromises the integrity of the track-bearing surfaces. Despite these problems, efforts have been made since the 1980s to reinvestigate these sites (Lockley et al., 2003; Lockley & Maksukawa, 2009; Xing et al., 2016), and the collected track specimens (Li, 2015), in order to understand the morphology of tracks and make ichnotaxonomic identifications. This paper is a further contribution to this effort with reference to the Wumancun sites, and aims to evaluate the utility of ichnospecies and ichnogenus labels for assessing assemblage diversity of tetrapod footprints which is essential to get correct for global correlations and the understanding of biochron composition (Lucas, 2007).

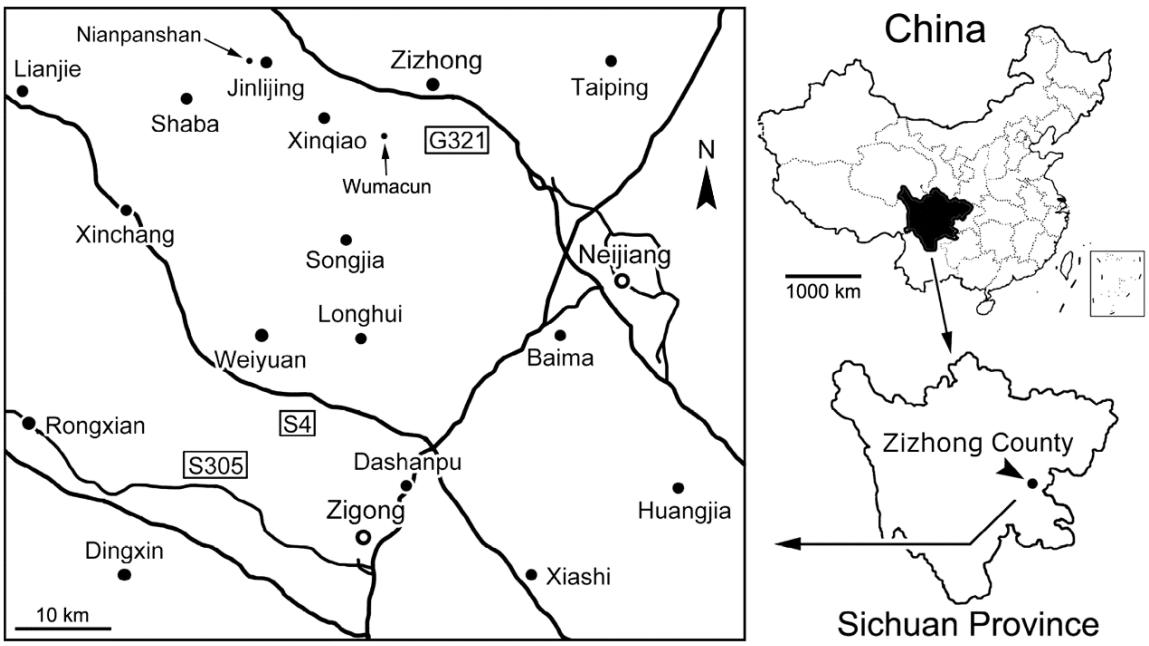

Figure 1. Map showing the location of Wumacun tracksites in the Middle Jurassic Xintiangou Formation of Sichuan Province, China.

Yang and Yang (1987) described and named six theropod ichnotaxa from the Wumacun and Jizhuashi sites: i.e., *Zizhongpus wumaensis, Tuojiangpus shuinanensis, Chonglongpus hei* and *Chuanchengpus wuhuangensis* from the Wumacun site and *Megaichnites jizhaoshiensis* and *Chongqingpus microiscus* from the Jizhuashi site. None of these tracks were defined with adequate reference to any of the common, ichnotaxa such as *Eubrontes* and *Grallator* which are internationally widespread in the Lower and perhaps Middle Jurassic. This raises a number of questions pertaining to what are a valid ichnotaxonomic labels to apply to the assemblage in order make a realistic assessment of morphological diversity, and meaningful correlations.

Institutional abbreviations

V (also CFNY, CFZW) = Chongqing Museum of Natural History, Chongqing, China
JZS = Jizhuashi site (= Wumacun site B), Zizhong County, Sichuan Province, China

2. The Local Geological Setting

Tracks from the Wumacun site and Jizhuashi site are preserved in the lower Middle Jurassic Xintiangou Formation (Aalenian–Bajocian, Huang, 2019) (Fig. 2) (Yang & Yang, 1987), which is widely distributed in the Sichuan Basin. The Xintiangou Formation in the Zizhong area is ~150–490 m thick, with a tendency to thicken from southwest to northeast. It overlays, mostly conformably, the Daanzhai Member of Ziliujing Formation. Only the bottom of the Xintiangou Formation is exposed in the Zizhong area. Dinosaur tracks from the Wumacun site are located four meters above the underlying Daanzhai Member of the Ziliujing Formation on a yellow sandstone surface with a dip of 8°. A 1.5 m thick sandy conglomerate layer comprises the base of the Xintiangou Formation. Overlying the conglomerate layer is a 2.5 meter thick light gray fine–medium grained feldspathic quartz sandstone layer, of which the weathering grey-yellow surface is a part. The lower part of the Daanzhai Member is comprised of thin to medium-thick bedded limestone interbedded with gray-green mudstone. It is overlain by a layer of purple-red and gray-green mudstone, which is about 9 m thick. Dinosaur tracks from the Jizhuashi site are situated on a large fallen rock, which can be assumed to belong to the lowest strata of the Xintiangou Formation, based on the lithology and nearby strata.

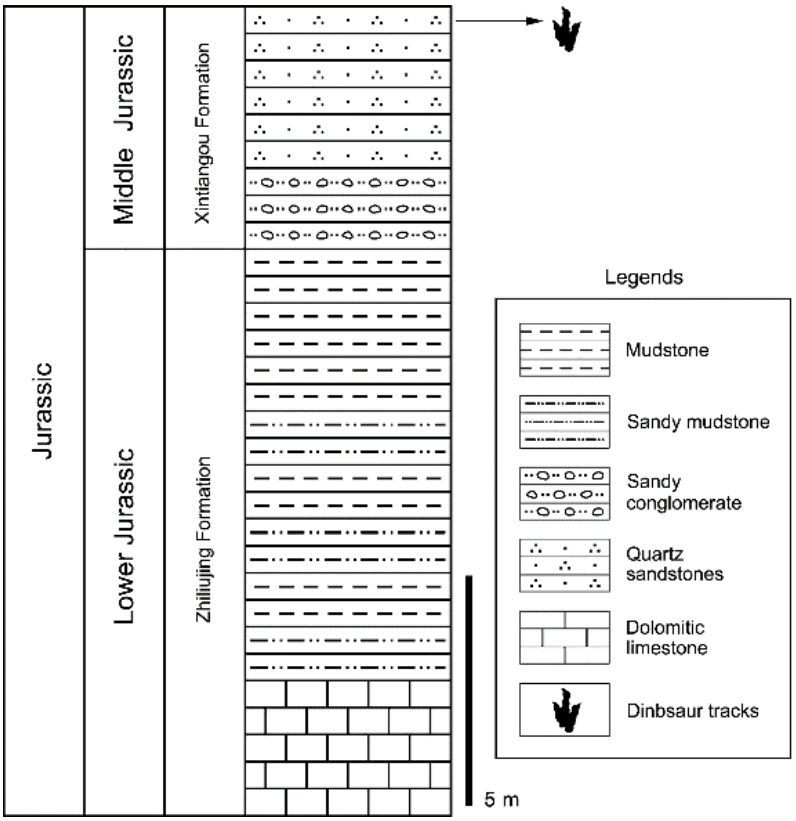

Figure 2. Stratigraphic section showing position of track-bearing level of Wumacun site.

3. Material and methods

A virtual 3D model of the *in situ* specimen, JZS-T2-L3, from the Jizhuashi site was created, followed photogrammetry methods outlined by others (Xing et al., 2018a). Here, 16 photographs, taken with a Canon EOS 5D Mark III (EF24-105mm f/4L IS USM, 70mm), processed through Agisoft Metashape Professional (v.1.5.0). The surface topography of the 3D model was visualised using elevation and contour filters in Paraview (version 5.0.0 64 bit; Ahrens et al., 2005) and ambient occlusion filters in CloudCompare (v2.6.1 64 bit; www.cloudcompare.org).

4. Wumacun site

After nearly forty years of natural weathering, the Wumacun site is now covered with dense grasses (Fig. 3). Yang and Yang (1987) named *Zizhongpus wumaensis* (T1 and T2), *Tuojiangpus shuinanensis* (T3–T5), *Chonglongpus hei* (T6) and *Chuanchengpus wuhuangensis* (T7 and T8) from this site (Fig. 4), while three other trackways (T9–T11) were not described. Lockley *et al*. (2003) described one unusual case of crouching traces (T11). These traces reveal metatarsal traces and a sub-triangular ischial callosity impression associated with *Eubrontes*-like tracks. They also indicated the location of tracks that had been excavated. Many possible tail traces are also preserved at the tracksite, which can be observed in the field. However, it was difficult to determine the relationship between these trail traces and the trackways because most of the trackways had disappeared, therefore, these trail traces are not re-described herein.

Figure 3. Photograph of the Wumacun site from Sichuan Province, China.

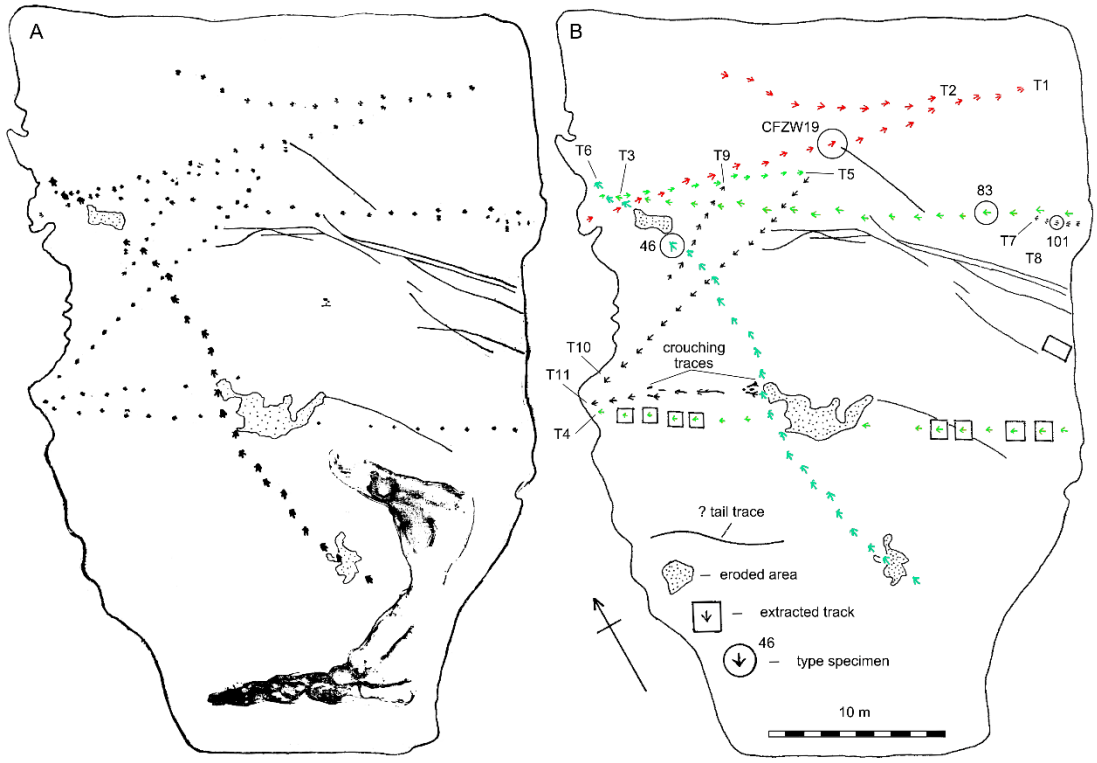

Figure 4. Map of track-bearing level at Wumacun site with trackways. A from Yang and Yang (1987). B from Lockley et al. (2003). Here trackway numbers T1–T11 superimposed on the 2003 map for purposes of the present analysis. Note that the 2003 map shows where tracks were excavated from an un-numbers trackway and where crouching traces in trackway T11 are located.

4.1 Eubrontes isp indet. 1

Yang and Yang (1987) named *Zizhongpus wumaensis* based on a complete natural mold of a pes track, cataloged as CFZW19, from Wumacun site and now preserved in the Chongqing Museum of Natural History (Fig. 5, Table. 1). Yang and Yang (1987) provided the following diagnostic features, translated as follows: "one of the large-sized Anchisauripodidae ichnogenera, bipedal, tridactyl, and digitigrade, with elongated phalangeal pads, large proximal ends, sharp distal ends and nail shape. Digit III is longer than digits II and IV. Three digits are very splayed. Especially, digit IV is far from digit III, digit II curves inward, and digit IV curves outward. The length is greater than the width. And there is no metatarsophalangeal pad impression, manus print or trail."

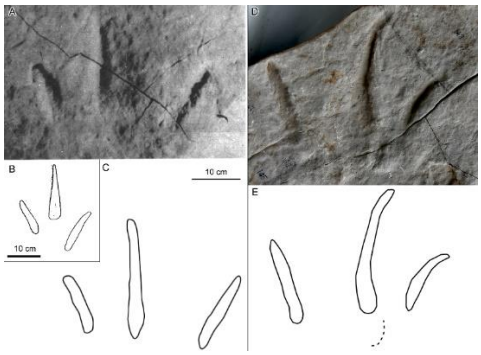

Figure 5. The interpretative outline drawings and photograph of *Zizhongpus wumaensis*. A and B, type specimen CFZW19 from Yang and Yang (1987). C, new interpretative outline drawing based on A. D and E, specimen V-1393-1 from the same trackway.

	L	W	II-IV	PL	SL	PA	L/W	M
WMC-TI1	13.4	8.5	58	—	—	—	1.6	0.72
WMC-TI2	19.5	10.7	67	—	—	—	1.8	1.06
WMC-TI3	37.4	19.6	45	—	—	—	1.9	0.72
WMC-TI4	33.4	17.4	44	—	—	—	1.9	0.67
CFZW19	25.0	36.2	109	—	—	—	0.7	0.33
V-1393-1	25.7	37.1	107	—	—	—	0.7	0.33
CFZW83	30.4	22.0	52	—	—	—	1.4	0.38
V-1396-3	30.7	22.6	50	—	—	—	1.4	0.38
CFZW46	49.8	40.3	58	—	—	—	1.2	0.39
CFZW47	48.5	37.0	57	—	—	—	1.3	0.38
CFZW101	10.4	5.2	45	—	—	—	2.0	0.78
V-1399-2	10.0	6.1	52	—	—	—	1.6	0.62
JZS-T1-R1	27.0	21.0	57	107.0	215.0	172	1.3	0.33
JZS-T1-L1	29.0	22.0	57	108.5	215.5	161	1.3	0.42
JZS-T1-R2	30.0	22.0	51	110.0	—	—	1.4	0.54
JZS-T1-L2	31.0	24.0	61	—	—	—	—	—
JZS-T1-R3	31.8	23.0	57	—	—	—	1.4	0.50
JZS-T1-L3	31.5	24.0	56	111.0	—	—	1.3	0.46
JZS-T1-R4	—	23.5	65	—	217.0	—	—	—
JZS-T1-L4	36.8	21.9	50	—	—	—	1.7	0.61
JZS-T1-R5	—	21.0	—			—	—	0.40
Mean	31.0	22.5	57	109.1	215.8	167	1.4	0.47
JZS-T2-R1	27.5	21.5	62	103.0	—	—	1.3	0.45
JZS-T2-L1	27.0	22.0	52	—	—	—	—	—
JZS-T2-R3	27.5	17.0	61	104.0	204.0	159	1.6	0.54
JZS-T2-L3	29.5	23.0	62	103.5	204.0	162	1.3	0.39
JZS-T2-R4	29.0	18.5	56	103.0	—	—	1.6	0.65
JZS-T2-L4	—	23.0	64	—	—	—	—	—
Mean	28.1	20.8	60	103.4	204.0	161	1.4	0.51
JZS-T3-L1	12.1	5.8	38	69.5	142.2	174	2.1	0.75
JZS-T3-R1	10.6	5.4	44	72.9	—	—	2.0	0.72
JZS-T3-L2	12.2	5.8	40	—	—	—	2.1	0.60
Mean	11.6	5.7	41	71.2	142.2	174	2.1	0.69
JZS-T4-L1	13.3	8.1	52	70.3	—	—	1.6	0.60
JZS-T4-R1	13.8	7.7	50	—	—	—	1.8	0.50
Mean	13.5	7.9	51	70.3			1.7	0.55
					—	—		
CFZW176	12.2	8.1	59	—	—	—	1.5	0.62
V-1400	11.5	8.5	70	—	—	—	1.4	0.63

Table. 1. Measurements (in cm) of the theropod tracks from the Wumacun and Jizhuashi sites, Sichuan Province, China (**Note**: **Abbreviations**: L: Maximum length; W: Maximum; II–IV: The interdigital divarication digit II–IV; PL: Pace length; SL: Stride length; PA: Pace angulation; L/W is dimensionless; M: Mesaxony).

Lockley *et al*. (2003) considered the morphological features of *Zizhongpus wumaensis* to be similar to that of *Megaichnites jizhaoshiensis* (Yang & Yang, 1987) from the Jizhuashi site and to be, indistinguishable from a large grallatorid or *Kayentapus*-like form. On this basis, Lockley *et al*. (2003) assigned it to cf. *Kayentapus* isp. Lockley *et al*. (2013) also assigned *Zizhongpus wumaensis* to *Kayentapus wumaensis*. Li (2015) also considered *Zizhongpus wumaensis* to be invalid but proposed assigning it to *Megaichnites* (*Kayentapus*) *jizhaoshiensis.*

However, these previous considerations and reclassifications were probably based on an inaccurate interpretative outline drawing from Yang and Yang (1987). Yang and Yang (1987) gave the measurement data in their description of the model specimen: the footprint is 30 cm in length and 35–38 cm in width, although the imprint of the heel is clearly missing. This explains why a *Kayentapus*-like track might appear wider than long rather than longer than wide. The digit traces are all narrow: digit II is 11–13 cm long, digit III is 22–24 cm long, and digit IV is 17.5–18.5 cm long. Based on these values, the length/width ratio of the track is 0.8–0.9, however, the footprint in the original interpretative outline drawing (Fig. 5B) is distinctly longer than it is wide, the length/width ratio is ~1.2. Zhen *et al*. (1996) and Lockley *et al*. (2003, 2013) based their assessments on this figure.

According to the photographs of the type specimen provided by Yang and Yang (1987), CFZW19 is 25 cm in length and 36.2 cm in width, digit II is 12.7 cm long, digit III is 24.7cm long, digit IV is 17.2 cm long, and the length/width ratio is 0.7. Chen Wei from Chongqing Museum of Natural History provided the photographs of one left track V-1393-1 (C-1053) from the same trackway, although its exact position within the trackway is uncertain. This left track, V-1393-1, is 25.7 cm long, with a length/width ratio of 0.7. The two tracks both have three relatively narrow digits, but with no digit pad impression. The length/width ratio for the anterior triangle of both is 0.33. The ends of the digits of V-1393-1 deepen, especially that of digit II. The divarication angles between digits II and IV are very wide (109° and 107° for CFZW19 and V-1393-1).

The morphological features of CFZW19 and V-1393-1, with only narrow digit traces and no heel, indicate that they are probably extramophological variants, possibly undertracks or slightly collapsed digit traces. Yang and Yang (1987) believed that the morphology of *Zizhongpus* was due to the small digits and light weight of the trackmaker, without considering the possibility that they were extramorphological variants. Yang and Yang (1987) mentioned 29 tracks of this morphology, composing two trackways, one consists of 10 tracks, and the other consists of 19 tracks. A total of 25 tracks were collected by the museum. The footprints of these two trackways were roughly equal in size. At their initial (proximal) registration points, the two trackways are close to each other, about 1 or 2 m apart, then one heads north and the other west. The pace length of the trackway containing CFZW19 is 139 cm.

The mesaxony of the *Zizhongpus* CFZW19 and V-1393-1tracks is moderate (0.33), which is similar to footprints of the ichno- or morphofamily Eubrontidae (*Eubrontes*: 0.58, Lockley, 2009; *Kayentapus*: 0.52, Lockley et al., 2011). The morphology of *Zizhongpus* is inferred to reflect the undertracks of *Eubrontes* or *Kayentapus*, e.g., *Kayentapus* from Chongqing (Xing et al., 2020). Thus, *Zizhongpus wumaensis* is here considered to be invalid, due to lack of sufficient diagnostic features, and can be assigned to the *Eubrontes* isp. indet.

4.2 Eubrontes isp indet. 2

Yang and Yang (1987) named *Tuojiangpus shuinanensis* based on a complete natural mold of a pes track, cataloged as CFZW83 from Wumacun site, and now preserved in the Chongqing Museum of Natural History. Yang and Yang (1987) provided the following diagnosis features, translated as follows: "bipedal, tridactyl, digitgrade, phalangeal pad formula of 2-3-4, large digit III, strong digit II, and slender digit IV. Digits II, III curve inwards, and digit IV curves outwards. Digits II–IV have sharp and curved claws. There is no manus print."

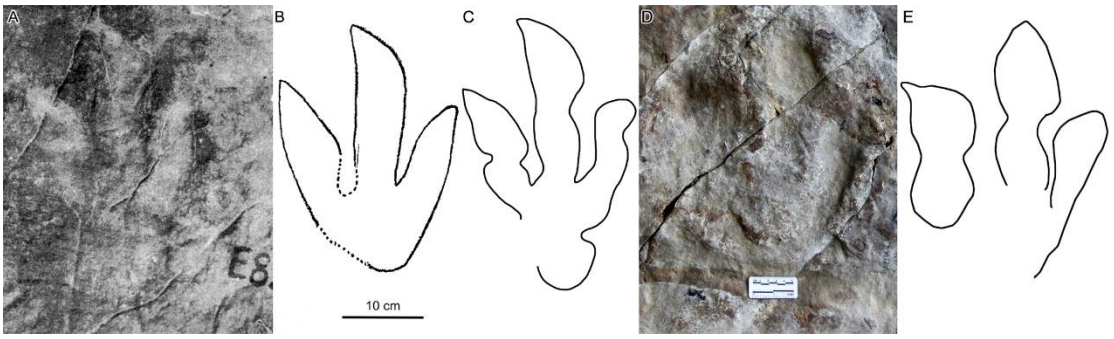

Figure 6. The interpretative outline drawings and photograph of *Tuojiangpus shuinanensis*. A and B, type specimen CFZW83 from Yang and Yang (1987). C, revised interpretative outline drawing of CFZW83; D and E, specimen V-1396-3 from the same trackway.

Yang and Yang (1987) argued that *Tuojiangpus shuinanensis* belongs to the ichnofamily Anchisauropodidae. Lockley *et al*. (2003) regarded CFZW83 as badly preserved and lacking details of the phalangeal pad and referred it to cf. *Eubrontes* isp. Lockley *et al*. (2013) considered it to be undiagnostic material and considered *Tuojiangpus shuinanensis* to be a *nomen dubium*. Li (2015) assigned CFZW83 to *Eubrontes* isp.

According to the photographs of the type specimen provided by Yang and Yang (1987), CFZW83 is 30.4 cm in length and 22 cm in width, with a length/width ratio of 1.4. The track is very shallow, phalangeal pads cannot be identified, and heel traces are not visible. CHEN Wei, from the Chongqing Museum of Natural History, provided the photographs of one right track, V-1396-3 (C-1056), from the same trackway, although its exact position within the trackway is unclear. Li (2015) used a photograph of V-1396-3 and considered it to be CFZW83. However, a comparison of the photograph of V-1396-3 with the photograph of CFZW83 provided by Yang and Yang (1987) shows a large discrepancy in details, indicating that they are probably of two different tracks. V-1396-3 is 32.0 cm in length, with a length/width ratio of 1.3. The ends of the digits of V-1396-3 deepen, especially in the case of digit II. The length/width ratio for the anterior triangle of CFZW83 and V-1396-3 are 0.48 and 0.42 respectively. The divarication angles between digits II and IV are wide (47° and 56° for CFZW83 and V-1396-3).

CFZW83 and V-1396-3 are very shallow with no visible heel traces, these traits indicate that they are extramorphological variants, probably undertracks. Yang and Yang (1987) mentioned 65 tracks of this morphology, composing three trackways. Two of the trackways are orientated from west to east, and one is orientated from east to west. Forty tracks were collected by the museum. The pace length of the trackway containing CFZW83 is 145 cm. Yang and Yang (1987) considered the ratio of the pace length to the track length of *Tuojiangpus shuinanensis* to be 4.7: 1, similar to that of *Grallator*.

The mesaxony of the *Tuojiangpus* CFZW83 and V-1396-3 tracks is moderate (0.38), which is similar to footprints of the ichno- or morphofamily Eubrontidae. The morphology of *Tuojiangpus* is similar to that of undertracks of *Eubrontes*. *Tuojiangpus* is here considered invalid, due to lack of sufficient diagnostic features, and can be assigned to the *Eubrontes* isp. indet.

4.3 Gigandipus morphotype

Ichnofamily Gigandipodidae Lull, 1904
Gigandipus hei n. comb. (Yang & Yang, 1987) Lockley *et al*., 2013
Fig. 7

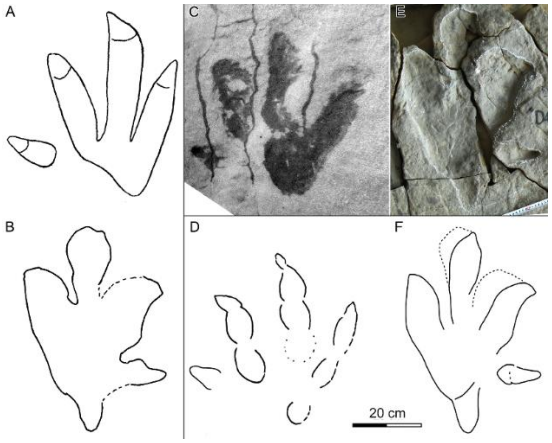

Figure 7. The interpretative outline drawings and photograph of *Gigandipus hei*. A and C, type specimen CFZW46 from Yang and Yang (1987), were transformed in Photoshop to an elevation view.

B and E, specimen CFZW47 from the same trackway from Li (2015). D, new interpretative outline drawing from Lockley *et al*. (2003), digit I is added herein. F, interpretative outline drawing from the CFZW47 from Xing et al. (2014).

Holotype: A complete natural mold of a pes track, cataloged as CFZW46, preserved in the Chongqing Museum of Natural History
Paratype: A complete natural mold of a pes track, cataloged as CFZW47 (V-1397-1, C-1037), preserved in the Chongqing Museum of Natural History
Type horizon and locality: Xintiangou Formation, Middle Jurassic. Wumacun site, Zizhong County, Sichuan Province, China.
Emended diagnosis: A large-sized functionally tridactyl, tetradactyl footprint with a relatively strong medially-directed hallux trace and pes length/width ratio of 1.2, the length/width ratio for the anterior triangle is 0.39. Tridactyl portion of footprint sub-symmetrical with a divarication angle between traces of digits II and III about equal to the angle between digits III and IV. Step about 2.4 times footprint length.
Re-description: 27 tracks of *Gigandipus hei* compose one trackway, 13 of them were collected by the Chongqing Museum of Natural History. According to the photographs of the type specimen provided by Yang and Yang (1987) and outline drawings from Xing *et al*. (2014), CFZW46 is 49.8 cm in length, 40.3 cm in width, and has a length/width ratio of 1.2. The medially directed hallux is very distinct, with a length of 10 cm. Heels are relatively shallow, and the ends of digits are deeper. Digit II and III traces are more robust (wider), and digit IV is slenderer. There are two and three phalangeal pads in digit II and III traces respectively, digit IV is inferred to have at least three phalangeal pads which re not clearly registered. The divarication angle between traces of digits II and III is subequal to the angle between digits III and IV, which is 29°. The angle between the axis of the hallux and the track axis is 58°. The length/width ratio for the anterior triangle is 0.39. The pace length is 120 cm, 2.4 times the length of the track. CFZW47 is badly preserved, and has no visible phalangeal pads, it is 48.5 cm long, with a length/width ratio of 1.3. The metatarsal pads are 9.5 cm, which increases the total track length to 58 cm. It has a well-preserved medially directed hallux, which is 12.7cm long. The angle between the axis of the hallux and the track axis of is 90°. Digits II and III both preserve transverse drag marks.

Discussion

Yang and Yang (1987) assigned *Chonglongpus hei* to the ichnofamily Gigandipodidae based on the following characteristics translated as: "large size" and "tracks are bipedal and tetradactyl; the halluces are low on the leg, mostly on the ground, with the tip of the hallux extending sideways and semi-roated; digit II is more developed, with the length close to digit IV; digits I–IV have claws curving inwards; digit III is longer than the lateral two digits; the whole footprint is longer than it is wide; trails are preserved; there is no manus print". Li (2015) provided the following diagnostic features: bipedal, tetradactyl, anterolaterally directed hallux, interdigital divarication of 65° (I–II), 17° (II–III) and 22° (III–IV), divarication angle between digits II and IV of 37°, track length of 49 cm, width of 37 cm, pace length of 120 cm, trackway width of 30cm. However, these characteristics are insufficient to distinguish it from other members of the Gigandipodidae.

Lockley *et al*. (2003) considered *Chonglongpus hei* to be a large, *Eubrontes*-like track, and, due to the medially directed hallux and typical 2-3-4 phalangeal formula for digits II, III, and IV, assigned it to *Gigandipus hei.* Lockley *et al*. (2003) provided new an interpretative outline drawing, but without a digit I trace. Xing *et al*. (2014) updated the interpretative outline drawing, however, CFZW46 was misspelled as "CFZW48" in the manuscript. Lockley *et al*. (2013) and Li (2015) followed this classification but did not provide a new diagnosis.

Medium–large sized theropod tracks preserving digit I are not common in China: known instances include *Chongqingpus nananensis* from the Upper Jurassic Shangshaximiao Formation of Chongqing (Xing et al., 2013), *Eubrontes zigongensis* from the Lower Jurassic Zhenzhuchong Formation of Weiyuan County, Sichuan Province (Xing et al., 2014), and *Gigandipus chiappei* from the Jiaguan Formation, Lower Cretaceous of Guizhou Province (Xing et al., 2018b). The biggest differences between these tracks and *Gigandipus hei* are the orientation and the morphology of digit I. *Chongqingpus nananensis* and *Eubrontes zigongensis* have a short and thin antero-medially directed hallux trace, and *Gigandipus chiappei* has a strong and posteromedially directed hallux.

Medium-large sized theropod tracks preserving digit I are also not common in the global record. Type *Gigandipus* was originally described by Hitchcock (1856) from the Lower Jurassic of New England, and has since rarely been reported

elsewhere: see Milner *et al*. (2009) for a Lower Jurassic occurrence in Utah, and relevant discussion of the possibility that *Gigandipus* is a variant of *Eubrontes* with hallux trace registered. As noted above, ichnogenus *Gigandipus* has only been reported once from the Cretaceous, from the Jiaguan Formation of Guizhou Province (Xing et al., 2018b). However, recently a large tetradactyl track, with prominent hallux traces was reported and named as *Ordexallopus zhanglifui* from the Lower Cretaceous Jingchuan Formation (Lockley et al., 2018). These authors compared this ichnotaxon with *Gigandipus* to demonstrated the difference notably in the much greater divarication angle of *O. zhanglifui*. Hallux traces associated with small theropod tracks are reported sporadically from the global track record, but have rarely been used for formal ichnotaxonmy. On the other hand, *Gigandipus* and *Ordexallopus* raise interesting question about the importance of hallux traces in large theropod tracks from both the Jurassic and Cretaceous. In the case of the Lower Jurassic the difference between Chinese *Eubrontes* and *Gigandipus* suggests that different trackmaker taxa are represented. Among other features the size differences are notable.

4.4 *Grallator* isp. indet.

Yang and Yang (1987) named *Chuanchengpus wuhuangensis* based on a complete natural mold of a pes track, cataloged as CFZW101 from the Wumacun site (Fig. 8). This track is preserved in the Chongqing Museum of Natural History. There are six additional referenced specimens also preserved in the Chongqing Museum of Natural History: CFZW97, 98, 99, 100, 102, 103.

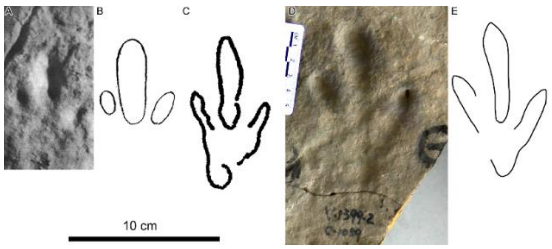

Figure 8. Interpretative outline drawings and photograph of *Chuanchengpus wuhuangensis*. A and B, type specimen CFZW101 from Yang and Yang (1987). C, new interpretative outline drawing from Lockley *et al*. (2003). D and E, specimen V-1399-2 from the same trackway.

Yang and Yang (1987) considered *Chuanchengpus wuhuangensis* to be dinosaur tracks, but gave no more detailed classification. Yang and Yang (1987) proposed the following diagnostic features, in translation: "bipedal, tridactyl, digitgrade, fairly thick and long digit III, oval digit II, long, oval digit IV; proximal part of digit III most posterior, followed by digit IV and digit II; no manus prints and trails". Lockley *et al*. (2003) pointed out that Yang and Yang (1987) did not realize heel traces were present in the badly-preserved tracks. Based on this recognition, Lockley *et al*. (2003) noted that the type specimen of *C. wuhuangensis* has a morphology typical of *Grallator*, and provided a new interpretative outline drawing, and re-assigned *C. wuhuangensis* to *Grallator* isp. Lockley *et al*. (2013) assigned *C. wuhuangensis* to *Grallator wuhuangensis*. Li (2015) followed this viewpoint and gave the following list of diagnosis features: " bipedal, tridactyl, digitgrade, the digit III longer than lateral digits, stocky medial digit trace, no manus prints or trails, interdigital divarication of 16° (II–III) and 20° (III–IV), track length of 7 cm, width of 5.5 cm, pace length of 41 cm, trackway width of 30 cm". These measurements, including track length were taken directly from Yang and Yang (1987). However, as Yang and Yang (1987) did not recognize the heel (and therefore did not include its length in their measurements): thus, these measurements are erroneous. These features are all insufficient to distinguish the tracks from other members of the Grallatoridae.

According to the new interpretative outline drawing provided by Lockley *et al*. (2003), CFZW101 is the smallest track at Wumacun site, with a length of 10.4 cm, and a length/width ratio of 2.0. The photographs provided by Li (2015) are quite different from the original photographs from Yang and Yang (1987) and are probably not of the type specimens. This new specimen is designated V-1399-2 (C-1059)., and the interpretative outline drawing is reproduced herein. The track is 10 cm long, with a length/width ratio of 1.6. The ends of the digit traces deepen, especially in digit II. The length/width ratio for the anterior triangle of CFZW101 and V-1399-2 is 0.78 and 0.62, respectively. The divarication angles between digits II and IV are wide (45° for CFZW101 and 52° for V-1399-2).

The length/width ratio and mesaxony of *Chuanchengpus* are both similar to those of footprints of the ichno- or morphofamily Grallatoridae. *Chuanchengpus* is similar to the undertracks of Grallatoridae in morphology. Due to lack of sufficient diagnosis features, *Chuanchengpus* is here considered to be invalid and can be assigned to the *Grallator* isp indet.

Yang and Yang (1987) also mentioned two trackways of *Chuanchengpus* at Wumacun site, with same morphology and separated by a distance of one or two meters, across a 10-square-meter area in the northeast corner of the tracksite. The tracks of both trackways were reported to share an eastern orientation. However, the authors represented only one trackway on the footprint map (Fig. 4).

Yang *et al*. (2012) named a second ichnospecies of *Chuanchengpus*: *Chuanchengpus shenglingensis*, based on a small tridactyl trackway consisting of 26 tracks from the Middle Jurassic Xiashaximiao Formation, Nianpanshan tracksite, Zizhong County, Sichuan Province. Li (2015) agreed the type species of *Chuanchengpus*, *C. wuhuangensis* already assigned *C. wuhuangensis* to *Grallator* (Lockley et al., 2013), so changed *C. shenglingensis* to the new type species of *Chuanchengpus*. However, Yang *et al*. (2012) and Li (2015) did not realize that Fig. 6F of Lockley *et al*. (2003) was so-called *C. shenglingensis*, and considered it to belong to *Anomoepus*. Xing *et al*. (2016) restudied all tracks from the Nianpanshan site, considered *Chuanchengpus shenglingensis* a *nomen dubium*, and assigned it to *Anomoepus* isp. This most recent interpretation is followed here.

4.5 Grallatorid tracks

Few tracks at the Wumacun site remain visible. It is perhaps pertinent to note that use of bedding plane surfaces as threshing floors leads to deterioration of, and tracks exposed on such surfaces! Of the remaining tracks, four well-preserved tridactyl tracks are designated as WMC-TI1-4 (Fig. 9). These tracks are located about 6 m north of the T3 trackway and are not shown on the footprint distribution map of Yang and Yang (1987).

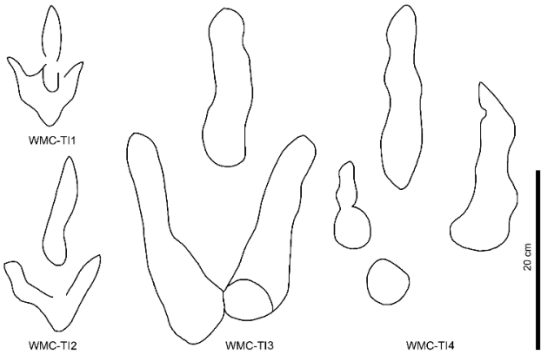

Figure 9. The interpretative outline drawings of Grallatorid tracks from Wumacun site.

WMC-TI1–4 are typical tridactyl theropod tracks. They mostly have no visible phalangeal pads. WMC-TI1 is the smallest, with a length of 13.4 cm, and WMC-TI3 is the largest, with a length of 37.4 cm. The length/width ratio of these four tracks is 1.6–1.9, the length/width ratio for the anterior triangle is 0.67–1.06. On the whole they resemble *Grallator* (TI1 and TI2) and large-sized Grallatoridae (TI3 and TI4).

5. Jizhuashi site

5.1 Eubrontes isp indet. 1

Yang and Yang (1987) named *Megaichnites jizhaoshiensis* based on a complete natural mold of a pes track, cataloged as CFZW161, from the Jizhuashi site and now preserved in the Chongqing Museum of Natural History. In addition, there is one referenced specimen: CFZW164 (V-1398-1, C-1058), also preserved in the Chongqing Museum of Natural History. All the *M. jizhaoshiensis* tracks preserved in the Chongqing Museum of Natural History were excavated in 1981, at the same time as the Wumacun excavation. Other tracks remain in situ (Fig. 10–14). Yang and Yang (1987) provided the diagnosis of *M. jizhaoshiensis* in translation as: "bipedal, tridactyl, digitgrade, phalangeal pad formula of 2-3-4; broad phalangeal pad that is enlarged anteriorly and narrowed posteriorly; digits II–IV with blunt peach-tip-like claws; the proximal parts of digits II and IV brought together and positioned posteriorly; digit III midway between digits II and IV and positioned anterior; anchor-shaped; moderate interdigital divarication".

Figure 10. Photograph of the Jizhuashi site from Sichuan Province, China. The white objects on the bedding plane are cement. Chongqing Museum of Natural History backfilled the pits where the footprints had been excavated with cement.

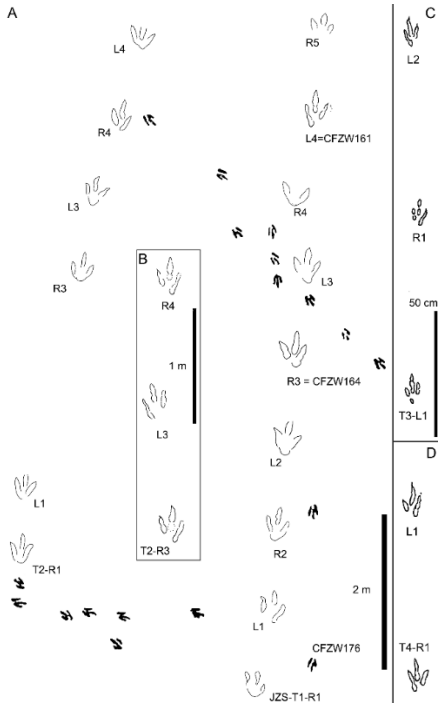

Figure 11. Map of track-bearing level at Jizhuashi site with trackways. A, JZS-T1 and T2 catalogued by the authors, the solid small tracks from Yang and Yang (1987). B, interpretative outline drawings of T2 from Lockley *et al*. (2003). C and D, small tracks from Lockley *et al*. (2003).

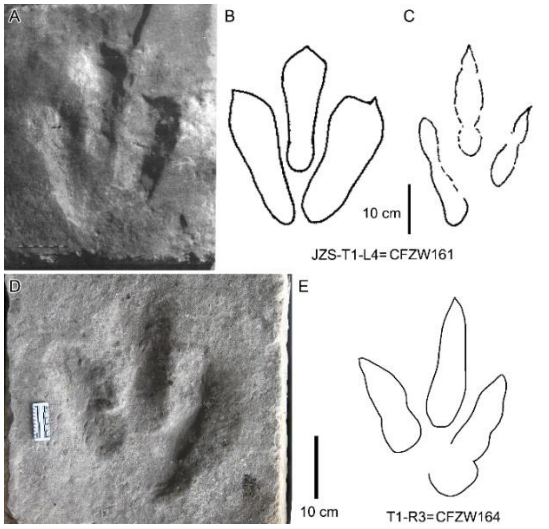

Figure 12. The interpretative outline drawings and photograph of *Megaichnites jizhaoshiensis*. A and B, type specimen CFZW161 from Yang and Yang (1987). C, new interpretative outline drawing from Lockley et al. (2003). D and E, specimen CFZW164 from the same trackway.

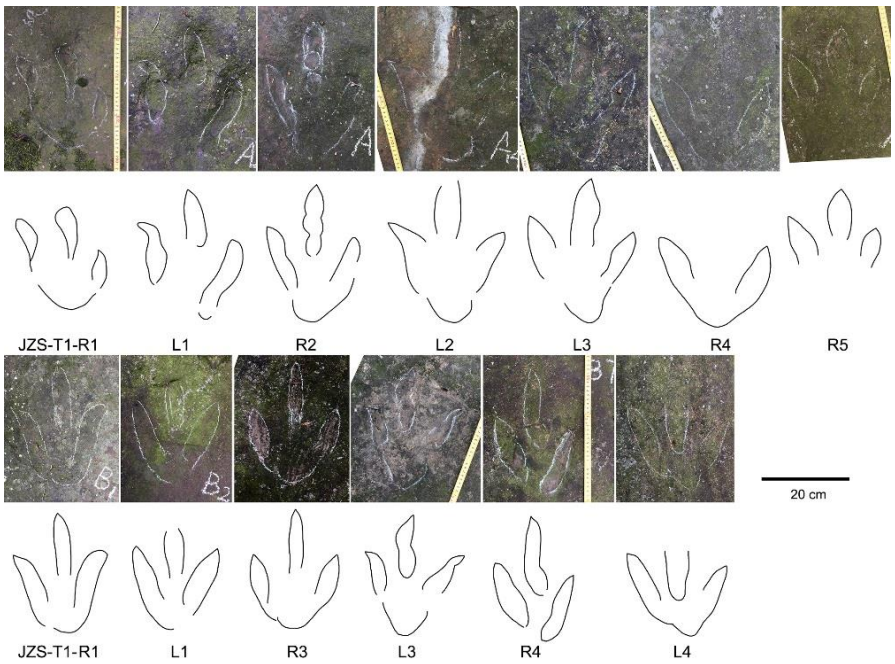

Figure 13. The interpretative outline drawings and photograph of Eubrontidae trackways from the Jizhuashi site, Sichuan Province, China.

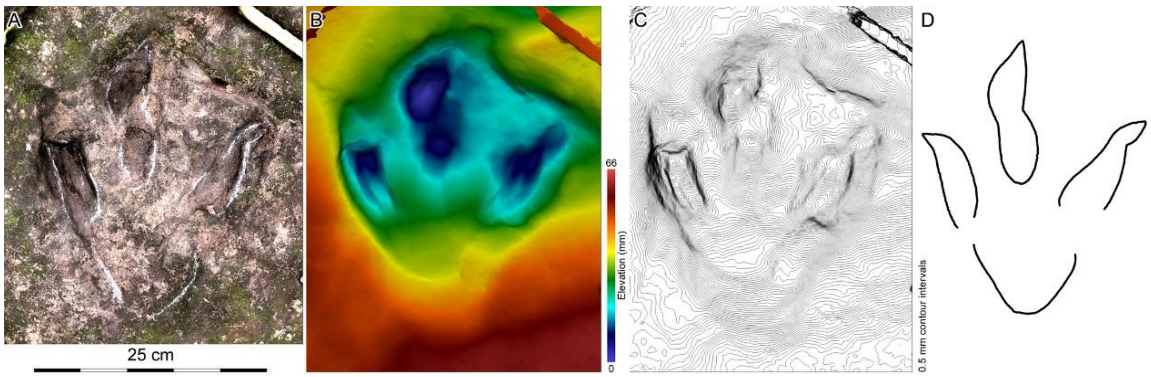

Figure 14. The photograph (A), 3D images (B and C), and interpretative outline drawing (D) of Eubrontidae JZS-T2-L3 from Jizhuashi site, Sichuan Province, China.

Lockley *et al*. (2003) provided a new interpretive outline drawing, directly from the original track and considered *Megaichnites* as having a more typical theropod track configuration, with phalangeal pad impressions. The track was recognized as resembling that of a large grallatorid, eubrontid or possibly *Kayentapus*, and was assigned to cf. *Kayentapus* sp. (Lockley et al., 2003). Lockley et al. (2013) assigned it to *Kayentapus jizhaoshiensis*. Li (2015) suggested that *Kayentapus jizhaoshiensis* was distinguishable from other ichnospecies of *Kayentapus* mainly by the larger individual size. Li (2015) provided the following diagnostic features:" bipedal, tridactyl, digitgrade, phalangeal pad formula of 2-3-4, ungual, interdigital divarication of 25° (II–III) and 28° (III–IV), the track length of 38.5 cm, and the width of 28 cm ". These features are insufficient to distinguish it from other members of *Kayentapus*. It is noteworthy that the photograph of *Megaichnites jizhaoshiensis* provided by Li (2015) is not of the type specimen, but a referred specimen CFZW164.

The main authors investigated the Jizhuashi site in July 2017 and catalogued the trackway containing CFZW164 (along with eight other tracks) as JZS-T1. A nearly parallel trackway, 2 m apart from JZS-T1, is designated as JZS-T2, and consists of six tracks. All of the footprints from JZS-T1 are tridactyl theropod tracks, with an average length of 31 cm. Several have three divergent digits, wide divarication angles (57°) and high pace angulation (167°). Taking the well-preserved JZS-T1-R3

(CFZW164) track as an example, the length is 31.8 cm and the length/width ratio is 1.4. Digit III projects the farthest anteriorly, followed by digits II and IV. Digit traces display a sharp and distal claw mark. Most digit impressions reveal distinct pad impressions, with the formula x-2-3-4-x. The digit traces indicate relatively wide divarication angles between digits II and IV (57°). The divarication angle between digits II and III is slightly larger than that between digits III and IV. The proximal region of digit IV forms a round metatarsophalangeal trace region close to the axis of digit III. JZS-T1-L4 (CFZW161) is relatively poorly-preserved, and three digits are obviously divergent. Other tracks in the same trackway are similar to JZS-T1-R3 in morphology. Overall, the trackways are narrow (pace angulation about 167°) and are characterized by long step lengths (109.1 cm on average). JZS-T1 has low to medium mesaxony, and the anterior triangle length/width ratios is 0.47.

Tracks from trackway JZS-T2 are similar to those of JZS-T1 in morphology, but smaller in size than the latter, with a mean length of 28.1 cm, the length/width ratio is 1.4 and the anterior triangle length/width ratios is 0.51. The digit traces indicate relatively wide divarication angles between digits II and IV (60°). The best-preserved track is JZS-T2-L3. The 3D image shows the three digits are the deepest and the heel is very shallow. Two phalangeal pads can be observed in both digit II and III, while the phalangeal pad traces for digit IV are not discernable. The digit traces each display a sharp distal claw mark. The trackways are narrow (pace angulation about 161°) and are characterised by long step lengths (103.4 cm on average).

Most features of JZS-T1 and T2, such as size, mesaxony and interdigital divarication, are consistent with the Jurassic and early Cretaceous *Eubrontes* of China. Type *Kayentapus hopii* (Welles, 1971) from Arizona, is characterized by the absence of a hallux impression and the preservation of the metatarsophalangeal pad of digit IV well separated from the rest of the digit impressions (Welles, 1971; Lockley et al., 2011). However, features of JZS-T1 are not uniform and obvious, which may be due to its preservation. Besides, the interdigital divarication of JZS-T1 is less than that of *Kayentapus* in China (such as Chongqing *Kayentapus*, ~70°, Xing et al., 2020) and closer to *Eubrontes*. Thus, *Megaichnites jizhaoshiensis* is considered to be invalid due to a lack of sufficient diagnosis features, and can be assigned to *Eubrontes* isp indet.

5.2 Grallator isp indet. 2

There are four small-sized trackways at the Jizhuashi site, consisting of at least 18 tracks. Yang and Yang (1987) named *Chongqingpus microiscus* based on a complete natural mold of a pes track, cataloged as CFZW176 from the Jizhuashi site and now preserved in the Chongqing Museum of Natural History (Fig. 15). The Chongqing Museum of Natural History collected at least one additional specimen from the Jizhuashi site, which is designated V-1400 (C-1062). The main authors did not discover small-sized tracks in the 2017 investigation, which may be due to weathering or coverage by moss.

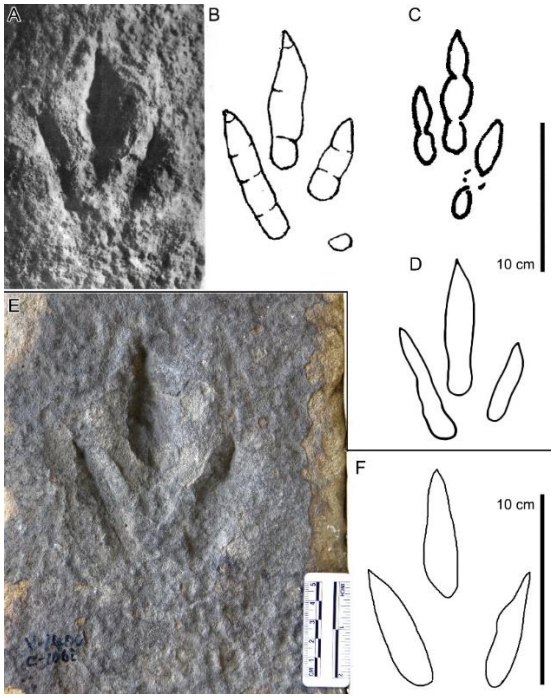

Figure 15. The interpretative outline drawings and photograph of *Chongqingpus microiscus*. A and B, type specimen CFZW161 from Yang and Yang (1987). C, interpretative outline drawing from Lockley *et al*. (2003). D, new interpretative outline drawing from this text. E and F, specimen V-1400 from the same trackway.

Yang and Yang (1987) considered *Chongqingpus microiscus* to belong to the Anchisauropodidae. Yang and Yang (1987) proposed the following diagnostic features, in translation: "interdigital divarication of 20° (II–III) and 24° (III–IV), divarication angle between digits II and IV of 40°, 10 mm long of digit I, 71 mm long of digit II, 100 mm of digit III, 105 mm of digit IV, the track length of 145 mm, the width of 85 mm, and narrow gauge

". Lockley *et al*. (2003) pointed out that the type specimen of *C. microiscus* is a classic example of a small *Grallator* (foot length 9–12 cm), provided a new interpretative outline drawing, and re-assigned *C. microiscus* to *Grallator* isp. It is notable that the digit I of *C. microiscus* was unmarked in the interpretative outline drawing. Actually, this trait is invisible or very ambiguous according to the photos provided by Yang and Yang (1987). Lockley *et al*. (2013) also assigned *C. microiscus* to *Grallator microiscus*, and did not recognize a hallux trace. Li (2015) followed this classification, and regard V-1400 as a paratype, but did not use the interpretative outline drawing updated by Lockley *et al*. (2003). Li (2015) proposed new diagnosis features: "bipedal, tridactyl, interdigital divarication of 20° (II–III) and 24° (III–IV), the track length of 14.5 cm, the width of 8.5 cm, small or no hallux trace, no trail, narrow gauge". Li (2015) also considered the lateral divarication angle (II–IV) of *C. microiscus* (44 °) to be outside the range of *Grallator*. However, these traits are insufficient to distinguish it from other members of Grallatoridae, because the interdigital divarication of the Chinese *Grallator* is generally greater than that of recorded in North America (Xing et al., 2016).Yang and Yang (1987) believed that *C. microiscus* is similar to *Chongqingpus nananensis* in morphology. Xing *et al*. (2013) reviewed *C. nananensis*, and suggested that the medium-sized track (mean track length ~29 cm) may best be accommodated in the ichnogenus *Kayentapus*, and may in some cases preserve ill-defined hallux traces.

The new interpretative outline drawing provided by Lockley *et al*. (2003) displays two trackways, designated JZS-T3 and T4. The two trackways show distinctive features of *Grallator*, including small individual track size (the mean length of T3 is 11.6 cm and the mean length of T4 is 13.5 cm); high length/width ratio (2.1 and 1.7, respectively); medium mesaxony, and the anterior triangle length/width ratios is 0.69 and 0.55, respectively. Digit traces each display a sharp distal claw mark. Most digit impressions reveal distinct pad impressions, with the formula x-2-3-4-x. The trackways are narrow (pace angulation about 173° for T3) and are characterized by long step lengths (71.2 cm and 70.3 cm on average).

According to the figures of CFZW176 and photographs of the V-1400 specimen (Yang & Yang, 1987), *C. microiscus* shows some difference from JZS-T3 and T4, mainly in the lower length/width ratio and relatively wide divarication angles between digits II and IV. The length/width ratio in CFZW176 and V-1400 is 1.5 and 1.4, apparently lower than that of JZS-T3. Phalangeal pad traces are not visible. However, the anterior triangle length/width ratios are almost consistent with those of JZS-T3 and T4 tracks. The length/width ratio and mesaxony of *Chuanchengpus* are both similar in morphology to footprints of the ichno- or morphofamily Grallatoridae. *C. microiscus* are quite similar to the Jurassic and Cretaceous Grallatoridae or *Grallator* type of China. *C. microiscus* is considered invalid because it lacks sufficient diagnostic features and can be assigned to *Grallator* isp. indet.

6. Discussion and conclusions

One of the results of the transfer of diverse, ill-conceived ichnospecies like *Zizhongpus wumaensis, Tuojiangpus shuinanensis, Chonglongpus hei* and *Chuanchengpus wuhuangensis* from the Wumacun site and *Megaichnites jizhaoshiensis* and *Chongqingpus microiscus* from the Jizhuashi site into classifications under a small number of more widely recognized ichnogenera like *Grallator*, *Eubrontes* and *Kayentapus* is to reduce the ichnogeneric diversity without reducing the ichnospecies diversity! The question then arises: how useful are the ichnospecies names, except as historical curiosities? To take just one example, the Wumacun track *Chongqingpus microiscus* was transferred to *Grallator microiscus* by Lockley *et al*. (2013) because the former ichnotaxon is not distinguishable, at the ichnogenus level, from a variety of tracks classified under ichnogenus *Grallator*. However, the original diagnosis and description of *C. microiscus* (Yang & Yang, 1987) contains no information that distinguishes it from *Grallator*, at the ichnospecies level: i.e., the value of the trivial name *microiscus* is highly questionable and would not help ichnologists distinguish it from other *Grallator* ichnospecies. Therefore, there is no reason to identify the track at any level below *Grallator* isp. indet. This argument does not entirely remove these multiple species from the historical archives, or prevent them from being reassessed, however the argument does draw attention to the fact that the ichnospecies name has no comparative value and should not be used as to measure diversity. In short, the process of synonymizing the over-split Jurassic ichnotaxonomy involves both the first step of rejection of invalid ichnogenus names as done by Lockley *et al*. (2013) and the second step of rejection or questioning of invalid ichnospecies names, as done here.

Regarding the main Wumacun site, the tracks

named *Zizhongpus wumaensis* (T1 and T2) which Lockley *et al*. (2013) transferred to *Kayentapus wumaensis* is here referred to the *Eubrontes* isp indet. *Tuojiangpus shuinanensis* (T3–T5) which Lockley *et al*. (2013) considered undiagnostic is also referred to the *Eubrontes* isp indet. *Chonglongpus hei* (T6) is referred to *Gigandipus hei*, consistent with the revision of Lockley *et al*. (2013), *Chuanchengpus wuhuangensis* is here assigned to *Grallator* isp indet.

Regarding the Jizhuashi site *Megaichnites jizhaoshiensis* which Lockley *et al*. (2013) transferred to *Kayentapus jizhaoshiensis* is here referred to *Eubrontes* isp. indet., and, as noted above, *Chongqingpus microiscus* is referred to *Grallator* isp. indet.

The track-bearing units reported from the Jurassic of China have traditionally been divided on the basis of inferred age into Lower and Middle Jurassic assemblages. Thus, in the Lower Jurassic Fengjiahe Formation of Yunnan Province the original literature (Zhen et al., 1986) suggests the presence of six ichnospecies each in a different ichnogenus (implied diversity of six) whereas in the study area Yang and Yang (1987) reported nine ichnospecies in seven different ichnogenera (implied diversity of nine) from the Middle Jurassic Xintiagou and Lower Shaximiao Formations: see Lockley *et al*. (2013) for summary. This would imply that the Lower and Middle Jurassic of China yielded diverse ichnofaunas that were entirely different from one another, as well as from any equivalent aged ichnofaunas elsewhere in the world. Because this original ichnotaxonomy is was so provincial and misleading with respect to the widespread Lower Jurassic tetrapod footprint biochron (sensu Lucas, 2007), Lockley *et al*. (2013), took the initial step of synonymizing the Yunnan ichnofaunal list to suggest the six ichnotaxa belonged in only three ichnogenera (*Grallator, Eubrontes* and *Kayentapus*) while the nine middle Jurassic ichnotaxa from Sichuan represented the same three ichnogenera, plus *Gigandipus*, as well as *Anomoepus* (Lockley et al., 2003; Lockley & Matsukawa, 2009). These ichnotaxonomc revisions change our understanding and interpretation of the Jurassic tetrapod ichnofaunas of China entirely.

The Lower Jurassic global biochron of Lucas (2007) is characterized by the dinosaurian ichnogenera *Grallator, Eubrontes, Kayentapus, Anomoepus* and *Otozoum*. The four former ichnogenera are now known to be common in China in the Middle as well as the Lower Jurassic. Lucas (2007) defined two Jurassic tetrapod biochrons: a Lower Jurassic biochron, as defined above, and a combined Middle and Upper Jurassic biochron characterized by quite different ichnogenera. The latter was primarily defined on the basis of assemblages from North America and Europe, not China. It therefore appears to be an open question as to why the Middle and Lower Jurassic assemblages (biochrons) are the same in China but different in other regions. Either there are unresolved questions regarding the age of these ichnofaunas in different regions, or there were paleoenvironmental or facies control factors that allowed for the prolonged survival of the Lower Jurassic ichnofaunas into the Middle Jurassic in China.

Given that the Wumacun and Jizhuashi ichnofaunas are comprised of the ichnogenera *Grallator, Eubrontes,* and possibly, *Kayentapus* and, *Anomoepus* they correspond closely to the Lower Jurassic tetrapod footprint biochron even though in China these ichnogenera are reported as Middle Jurassic in age. The original list of ichnospecies for these sites proposed by Yang and Yang (1987) is shown to have no utility for characterizing the ichnofauna, whereas the more generalized list of ichnotaxa is consistent with what is known of the distribution of theropod ichnogenera in the Early Jurassic Biochron, which evidently persist into the Middle Jurassic of China.

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