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Large theropod trackway from the Lower Jurassic Zhenzhuchong Formation of Weiyuan County, Sichuan Province, China: Review, new observations and special preservation

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Abstract

The well-preserved theropod track *Weiyuanpus zigongensis*, recently assigned to *Eubrontes zigongensis*, was not described in exhaustive detail at the time of its original discovery in 2007. Among the morphological details not described was an antero-medially directed hallux seen in five of the six tracks that make up the type trackway. Hallux traces are only rarely reported in large Lower Jurassic theropod tracks such as *Eubrontes* and *Gigandipus*, and their presence or absence may be the result of one or both of two factors: track depth and/or differences in hallux configuration in the trackmakers. Here we argue that *E. zigongensis* is one of the best preserved examples of a eubrontid track, which can be morphologically distinguished from other *Eubrontes* ichnospecies by the presence of well-defined hallux traces.

Keywords: *Eubrontes*; *Weiyuanpus*; Hallux; Theropod; Sichuan Basin

1. Introduction

Compared with the rich record of Early Jurassic theropod tracks in North America (Farlow and Lockley, 1993; Olsen et al., 1998), contemporaneous theropod tracks in China are relatively rare. In recent years, however, the Early Jurassic theropod track record in China has been increasingly recognized, such as those at Lufeng in Yunnan Province (Xing et al., 2009a), Wusu of Xinjiang (Xing et al., 2014), and Shenmu (Li et al., 2012) and Zizhou (Xing et al., in press) of Shaanxi. Lockley et al. (2013) concluded that the only five of the 20 named Chinese theropod track ichnogenera from the Early and Middle Jurassic of China are valid: *Changpeipus*, *Eubrontes*, *Grallator*, *Gigandipus*, and *Kayentapus*.

According to the report of the villagers and the No. 2 geological survey team of the Sichuan Bureau of Geology and Mineral Resources, in 1985, Yuan-Ji Li and Ming-Zhang Li, villagers from Shaba Village (Rongsheng Township, Weiyuan County) of Sichuan Province reported dinosaur tracks. Shi-Da Zhu, Ren-Yan Gao, and Guang-Zhao Peng from Zigong Dinosaur Museum successfully excavated the dinosaur trackways with six tracks at the Shaba tracksite (Fig. 1). The specimens are currently housed at Zigong Dinosaur Museum. Gao (2007) preliminarily described these tracks and named them *Weiyuanpus zigongensis*. Lockley et al. (2013) assigned *W. zigongensis* to *Eubrontes zigongensis* n. comb. Xing et al. (2013a) also considered *Weiyuanpus* as a junior synonym of *Eubrontes* but because they have not formally been re-diagnosed, it is considered here a valid ichnotaxon.

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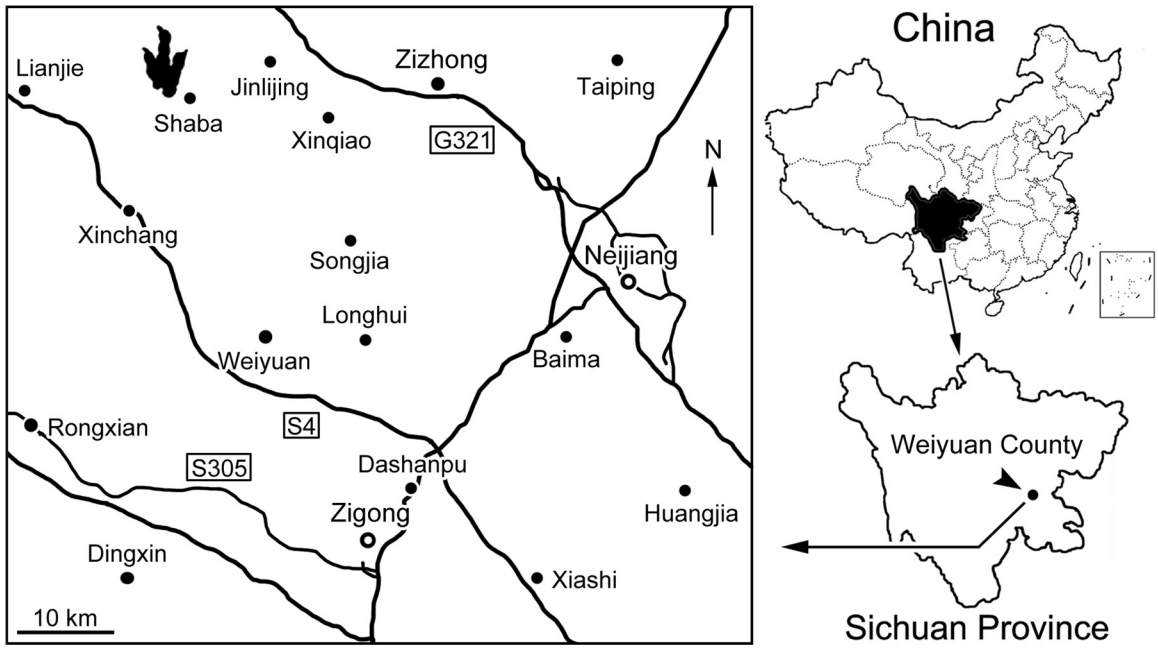

Fig. 1. Map showing the position of the footprint locality (footprint icon), the Shaba tracksite, Weiyuan County, Sichuan Province, China.

In March 2014, together with Yi Wang, the curator of Zigong Dinosaur Museum, the first author of this paper investigated the site, but no track-bearing outcrops were found. However, they studied the specimens from the site at the Zigong Dinosaur Museum. Herein we offer a detailed description of these tracks.

The local people believed that these tracks were left by ghosts, coinciding with the local Ghost culture derived from Qin Dynasty (BC 221–207) in the Sichuan Basin (Du, 2009). In the neighboring Guizhou Province, *Chirotherium* tracks are considered strange "ghostly handprints" (Xing et al., 2013b). This offers another of many examples of how some tetrapod footprints influenced the formation of Chinese folk legends (Xing et al., 2011).

Institutional abbreviations: AC, Hitchcock Ichnology Collection at the Pratt Museum of Amherst College, Amherst Massachusetts, USA; CFZW (also CFNY), Chongqing Museum of Natural History, Chongqing, China; CHABU, Chabu tracksite, Inner Mongolia, China; LDM, Lufeng Dinosaurian Museum, Lufeng, Yunnan, China; SGDS, St. George Dinosaur Discovery Site at Johnson Farm, Utah, USA; ZDM, Zigong Dinosaur Museum, Sichuan, China.

2. Geologic setting

The Sichuan Basin contains Early, Middle, and Late Jurassic vertebrate faunas in a 3000+ meter thick sequence (Lucas, 2001). Peng et al. (2005) described the dinosaur fauna from Zigong area, establishing a biostratigraphic sequence based on vertebrate fossils. This scheme identifies two formations (Zhenzhuchong and Ziliujing) as Lower Jurassic, two (Xintiangou and Xiashaximiao) as Middle Jurassic, and three (Shangshaximiao, Suining, and Penglaizhen) as Upper Jurassic.

The Shaba tracksite is located 15 km east of Lianjie Town (Fig. 1), now covered by terraced fields. The Weiyuan Anticline, a structure within the Sichuan Basin, is a hemispherically dome-shaped anticline with the background of flat and weakly folded strata in central Sichuan. The track-bearing sandstones are situated at the north end of the Weiyuan Anticline in the lower Zhenzhuchong Formation (Gao, 2007) (Fig. 2). The Zhenzhuchong Formation strata are distributed around the Weiyuan Anticline within Weiyuan area in a ring, with a thickness of 42 m (Xia and Li, 1988). The yellow-pale fine feldspathic quartz sandstones and purple mudstones exhibit an unequal-thickness interbed dominated by mudstones. The track-bearing sandstones are 3.6 m in thickness and the tracks are preserved on the top surface of this unit. The tracks were exposed by weathering and erosion.

3. Methods

Photogrammetric images were produced from multiple digital photographs (Canon EOS 5D Mark III) which were converted into scaled, highly accurate 3D textured mesh models using Agisoft Photoscan Professional v. 1.0.4. The mesh models were then imported into Cloud Compare v. 2.5.3. where the models were rendered with accurately scaled color topographic profiles.

4. Systematic ichnology

Theropoda Marsh, 1881
Eubrontidae Lull, 1904
Eubrontes zigongensis n. comb. (Gao, 2007) Lockley et al., 2013

Holotype: A complete natural mold of a pes track, cataloged as ZDM 0032-F2 from the Shaba tracksite (Figs. 3 and 4; Table 1). The specimen is stored in the Zigong Dinosaur Museum.

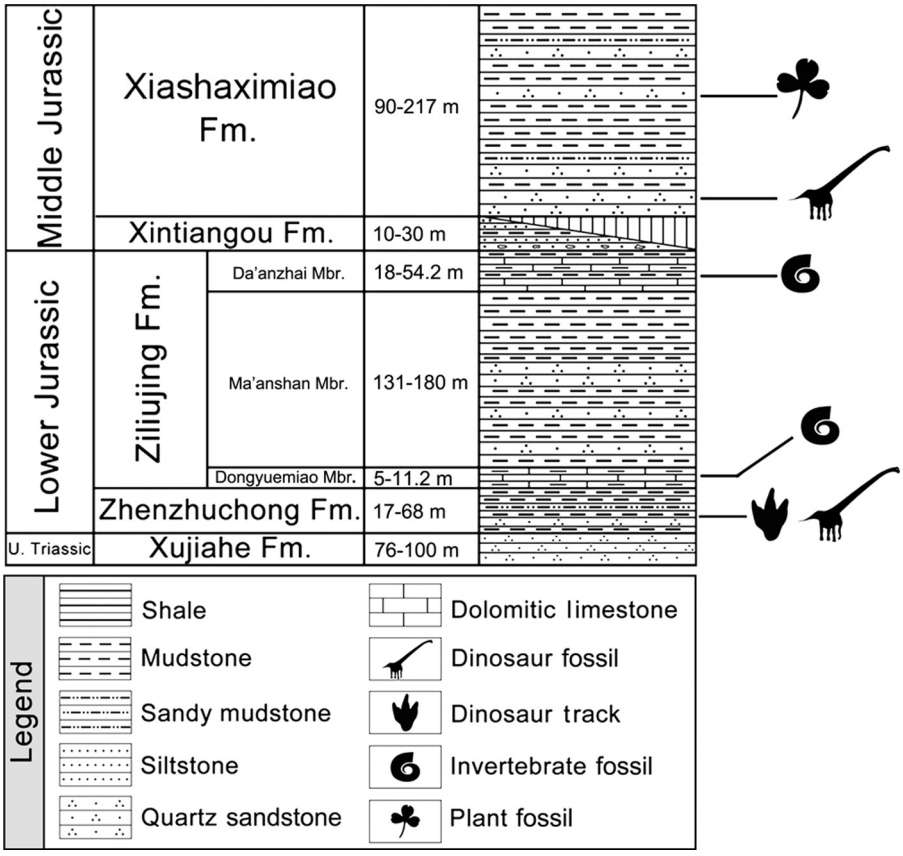

Fig. 2. Stratigraphic section of the Jurassic in the study area with the position of footprints and body fossil remains (after Xing et al., 2013a).

Paratypes: Specimens ZDM 0032-F1, F3–F6 (Figs. 3–5; Table 1) in the same trackway as the holotype. As with the holotype, these specimens are stored in the Zigong Dinosaur Museum.

Type horizon and locality: Zhenzhuchong Formation, Lower Jurassic. Shaba tracksite, Weiyuan County, Sichuan Province, China.

Emended diagnosis: A relatively large-sized functionally tridactyl, tetradactyl footprint with a short and thin anteromedially directed hallux trace and pes L/W ratio of 1.4. Tridactyl portion of footprint nearly symmetrical with a divarication angle between traces of digits II and III about equal to the angle between digits III and IV. Step about three times footprint length, mean pace angulation high, about 165°.

Description: The mean length and width from ZDM 0032-F1–F6 are 42.1 cm and 30.5 cm, respectively. The mean length/width ratio calculated from ZDM 0032-F1–F6 is 1.4. ZDM 0032-F2 exemplifies the *Eubrontes zigongensis* morphology. The axis of the hallux impression is nearly parallel to the digit II impression, and the angle between the midline of the hallux and the track axis is 63°. Digit III projects the farthest anteriorly, followed by digits II and IV. Two distinct metatarsophalangeal pad traces can be seen: a smaller one posterior to digit II and another larger one posterior to digit IV. The former

Table 1
Measurements (in cm) of the theropod tracks from Shaba tracksite, Weiyuan County, Sichuan Province, China.

Number: ZDM 0032	R/L	ML	MW	LD I	LD II	LD III	LD IV	II–III	III–IV	II–IV	SL	PL	PA	L/W
F1	R	>36.0	29.5	–	>22.5	26.5	>24.5	–	–	–	244.2	122.0	165°	–
F2	L	43.0	33.0	7.5	29.0	29.0	31.5	30°	28°	58°	243.7	125.0	166°	1.3
F3	R	44.0	30.0	3.5	29.0	30.5	30.0	29°	26°	55°	243.2	123.0	166°	1.5
F4	L	41.5	31.0	5.0	28.5	27.0	31.5	28°	28°	56°	244.1	126.0	164°	1.3
F5	R	40.0	28.5	5.0	30.5	24.5	31.5	23°	28°	51°	–	124.0	–	1.4
F6	L	42.0	30.0	3.0	29.0	27.5	34.5	24°	29°	53°	–	–	–	1.4
Mean	–	42.1	30.5	4.8	29.2	27.7	31.8	27°	28°	55°	243.8	124.0	165°	1.4

Abbreviations: R/L: right/left; ML: maximum length; MW: maximum width (measured as the distance between the tips of digits II and IV); LD I: length of digit I; LD II: length of digit II; LD III: length of digit III; LD IV: length of digit IV; II–III: angle between digits II and III; III–IV: angle between digits III and IV; II–IV: angle between digits II and IV; SL: stride length; PL: pace length; PA: pace angulation; L/W: maximum length/maximum width.

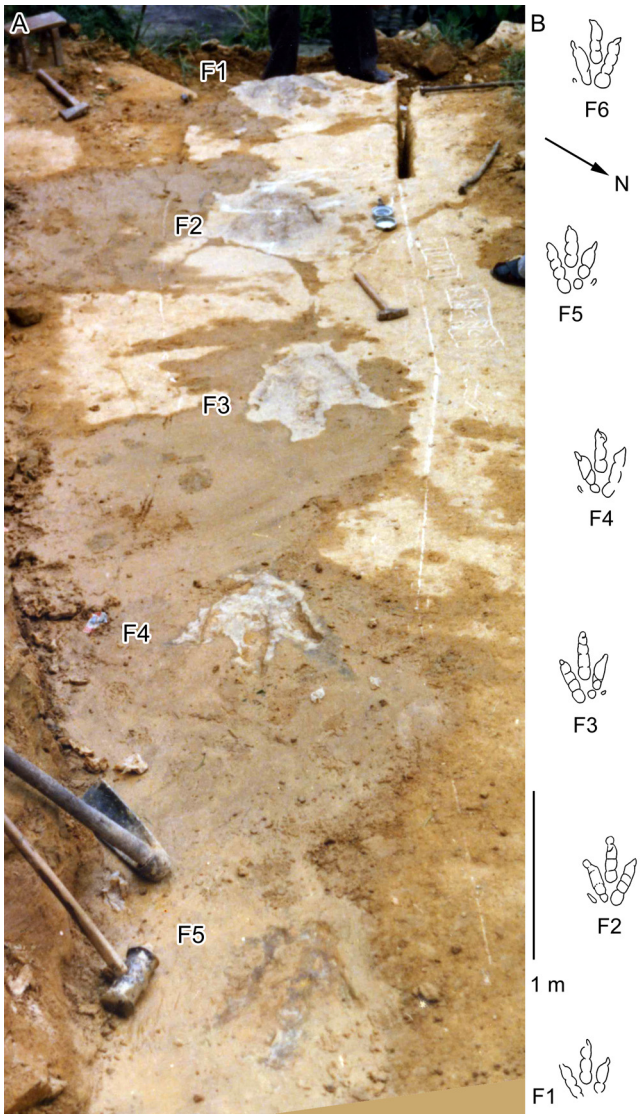

Fig. 3. *Eubrontes zigongensis* n. comb. trackway (ZDM 0032) at the Shaba tracksite. (A) In situ surface. (B) Sketch.

is adjacent to the trace of the first, proximal pad of digit II and separated from this by a distinct crease. The latter is round and blunt and positioned near the line with the axis of digit III, but closer to digit IV. The deep, concave digit impressions retain pad impressions that have a formula (including metatarsophalangeal pads II and IV) of 1-3-3-4-x. Each digit has a sharp claw mark, and digit II has the clearest and longest mark. In general, the digits have relatively wide divarication angles between digit II and IV (58°). The divarication angle between digits II and III (30°) is almost equal to the one between digits III and IV (28°).

The morphological characteristics of other tracks of ZDM 0032 are generally consistent with those of ZDM 0032-F2. Except for the incomplete ZDM 0032-F1, the other five tracks preserve halluces. The outer trackway width of ZDM 0032 trackway, measured from the outside margin of the pes, is 42–50 cm. The average pace angulation is 165°, and the footprint length to pace length ratio is 1:2.95.

The stride length relative to pes length of the type trackway of *Eubrontes zigongensis* allows us to calculate speed (v) using the formula of Alexander (1976): $v = 0.25g^{0.5} \times \mathrm{SL}^{1.67} \times h^{-1.17}$ where g is the gravitational acceleration in m/s, SL the stride length, and h is the hip height, estimated at 4.9 times foot length, using the ratio for large theropods proposed by Thulborn (1990). We estimate a speed of ~1.49 m/s or ~5.36 km/h. The body length of the track maker of the *Eubrontes zigongensis* is approximately 5.4 m, calculated using the average hip height to body length ratio of 1:2.63 (Xing et al., 2009b).

Comparison: The most striking characters of *Eubrontes zigongensis* ZDM 0032 are the axis of the hallux impression being nearly parallel to the digit II impression, and the presence of a distinct metatarsophalangeal pad trace posterior to digit II. The latter character is common in *Eubrontes* tracks, such as the type specimens of *Eubrontes* AC 151 (Olsen et al., 1998) (Fig. 6). This characteristic also distinguishes *Eubrontes zigongensis* from *Chongqingpus*, the middle-large theropod tracks with hallux (Xing et al., 2013a); and the common ichnogenus *Kayentapus* from the Early–Middle Jurassic (Lockley et al., 2011).

The hallux of ZDM 0032, a feature not described by Gao (2007), is significant. Plaster replicas of ZDM 0032 are on display at the Zigong Dinosaur Museum and other exhibitions all over the globe. Restricted by the limits of the molding and casting process and long-term neglect, the hallux traces on these models are indistinct. The hallux position may be variable owing to preservation, rather than inherent morphological differences (Gatesy et al., 1999). However, the positions of the halluces on the tracks of ZDM 0032 are consistent in five of the six tracks where they occur. The preservation of a hallux is rare for *Eubrontes*. Well-preserved specimens include the natural casts SGDS.8, SGDS.24, SGDS.50 from the Lower Jurassic Moenave Formation of southwestern Utah, USA (Milner et al., 2006, figs. 14C, 17). The deeper tracks were left by a trackmaker walking on soft sediment so that the hallux and metatarsal impressions were preserved. The positions of the halluces are generally consistent with ZDM 0032.

Theropod track ichnotaxa with distinctive hallux impressions and similar morphologies to *Eubrontes* include *Gigandipus* from the Lower Jurassic of Turner's Falls, Connecticut (Hitchcock, 1856) (Fig. 6). Bock (1952) and Harris et al. (1996) believed that *Gigandipus* is an extra morphological variant of *Eubrontes* in which the track maker's foot sank deep enough into the substrate to bring the anatomically elevated hallux into contact with the substrate, but some *Eubrontes* tracks lacking hallux impressions are apparently deeper than some *Gigandipus* tracks (Weems, 1992). This implies hallux length may vary among large Lower Jurassic theropod trackmakers, presumably because they represent either different species, with different hallux lengths, or a species in which hallux length varied. Because these two ichnogenera are similar in morphology, still, it is widely considered that in at least some instances, the two ichnotaxa are synonymous (Weems, 2003; Rainforth, 2005; Milner et al., 2009). *Gigandipus* usually has a medially-directed hallux (Hitchcock, 1856; Lull, 1953), and *Eubrontes* and ZDM 0032 have a more anteriorly-directed hallux (Fig. 6).

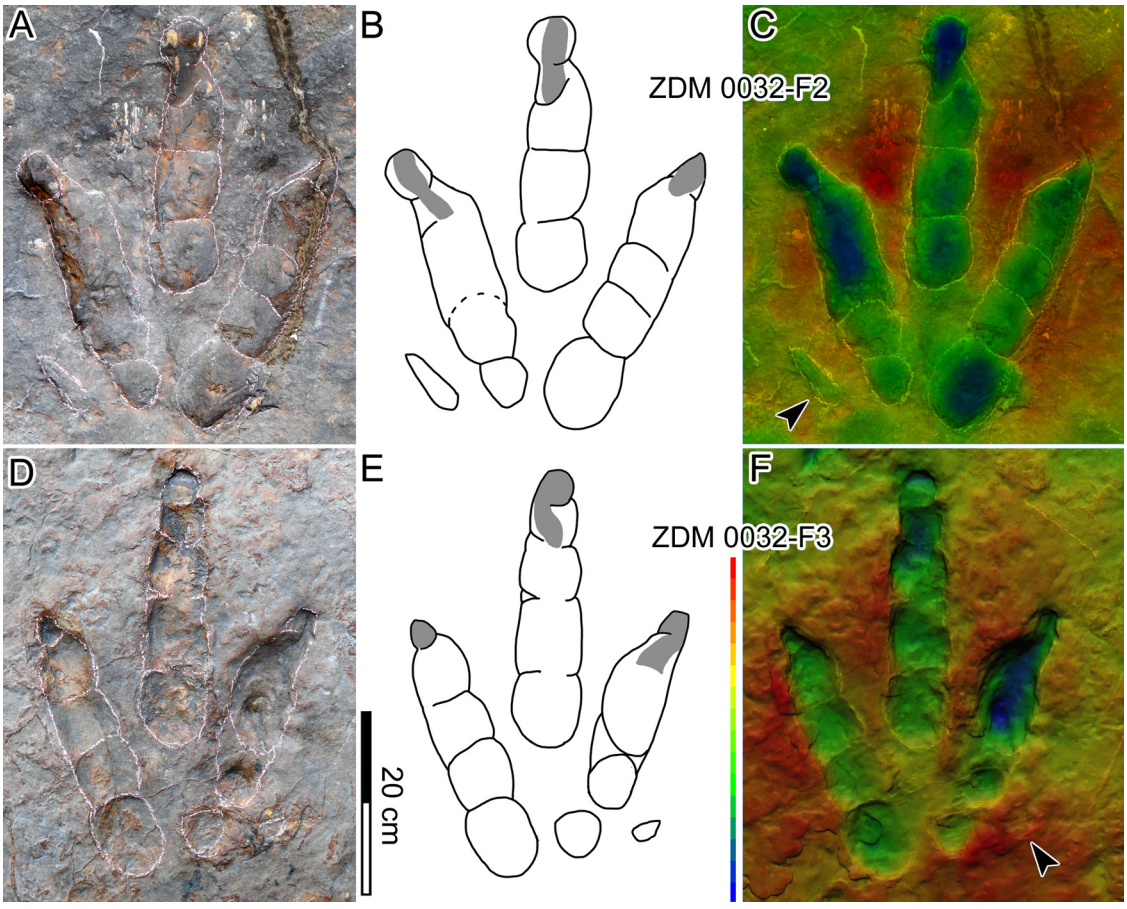

Fig. 4. Photographs (A and D), sketches (B and E) and the 3D models (C and F) of *Eubrontes zigongensis* ZDM 0032-F2 and F3. Arrows indicate hallux impressions.

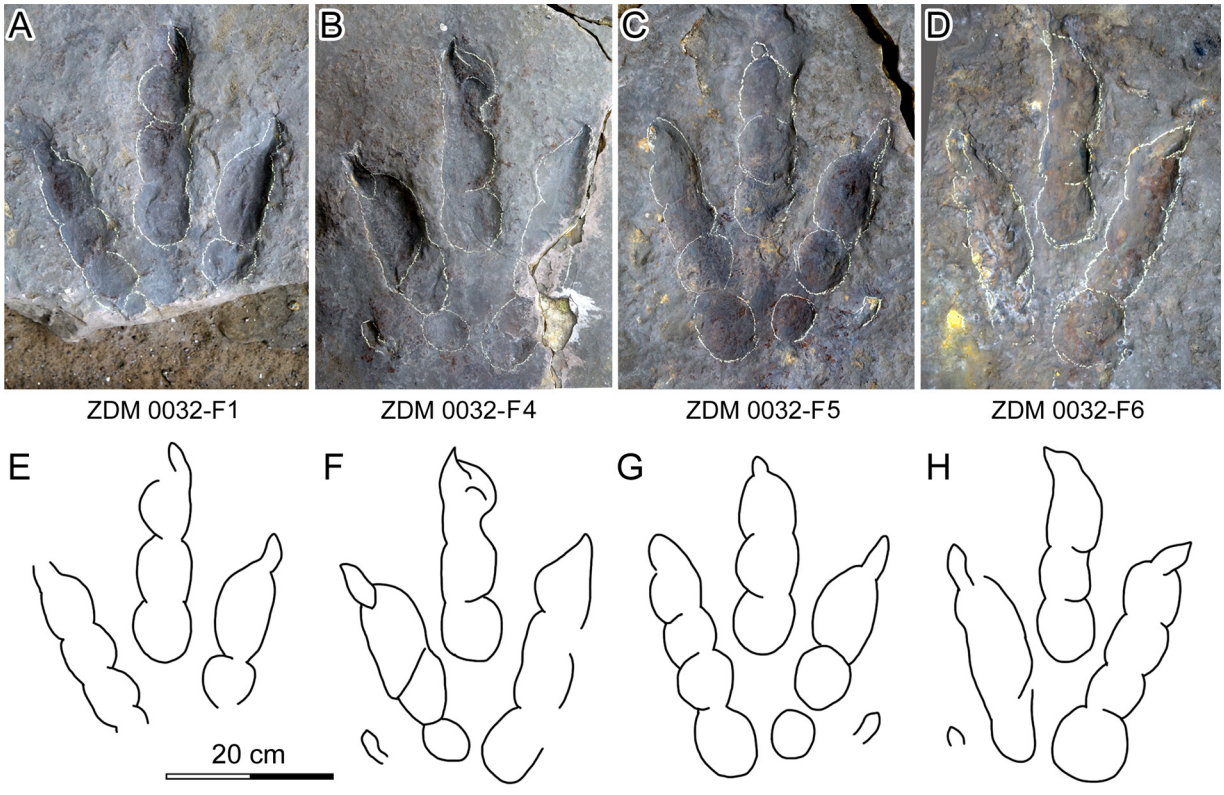

Fig. 5. Photographs (A–D) and sketches (E–H) of *Eubrontes zigongensis* ZDM 0032-F1 and F4–6.

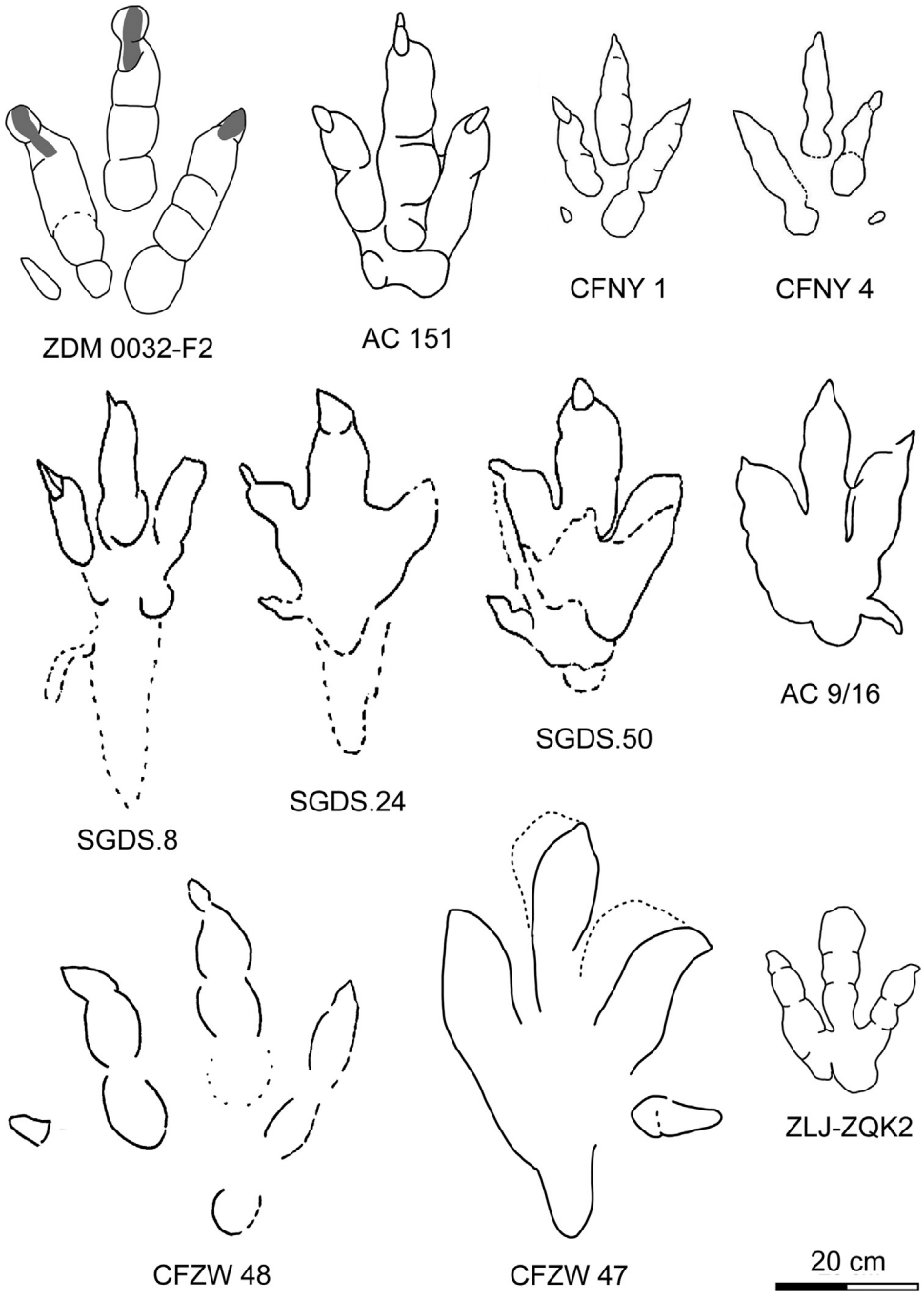

Fig. 6. Sketches of theropod footprints from the Early–Middle Jurassic of China and North America. ZDM 0032-F2, well-preserved track from the type trackway of *E. zigongensis*; AC 151, type of *Eubrontes giganteus* from the Lower Jurassic of Massachusetts (after Olsen et al., 1998, fig. 5A); CFNY1 (holotype) and CFNY4 (paratype) of *Chongqingpus nananensis* from the Upper Jurassic of Chongqing (after Xing et al., 2013b, figs. 6, 7); SGDS.8, SGDS.24, SGDS.50, *Eubrontes* track casts with hallux traces from the Lower Jurassic Moenave Formation of Utah (after Milner et al., 2006, fig. 17B); AC 9/16, type of *Gigandipus caudatus* from the Lower Jurassic of Connecticut (after Lull, 1953); CFZW 48 (holotype) and CFZW 47 (paratype) of *Gigandipus hei* from the Middle Jurassic of Zizhong, Sichuan Province; ZLJ-ZQK2, type of *Eubrontes pareschequier* from the Lower Jurassic of Lufeng, Yunnan Province (after Xing et al., 2014, fig. 12E).

The Chinese Early–Middle Jurassic tracks similar to ZDM 0032 primarily include *Gigandipus hei* (Yang and Yang, 1987; Lockley et al., 2003), *Chongqingpus* (Xing et al., 2013a), and *Eubrontes pareschequier* (= *Changpeipus pareschequier*) (Xing et al., 2009a, 2014) (Fig. 6).

Among them, the single large track *Gigandipus hei* (approximately 49 cm long) also bears a hallux impression (Yang and Yang, 1987). Compared with the holotype CFZW 48 and the referred specimen CFZW 47, the medially-directed hallux of *G. hei* differs from *Eubrontes* and ZDM 0032; the position of the hallux in *Chongqingpus* is consistent with that of ZDM 0032, but lacks a metatarsophalangeal pad trace posterior to digit II. *Eubrontes pareschequier* (= *Changpeipus pareschequier*) resembles ZDM 0032 in morphology, but lacks a hallux

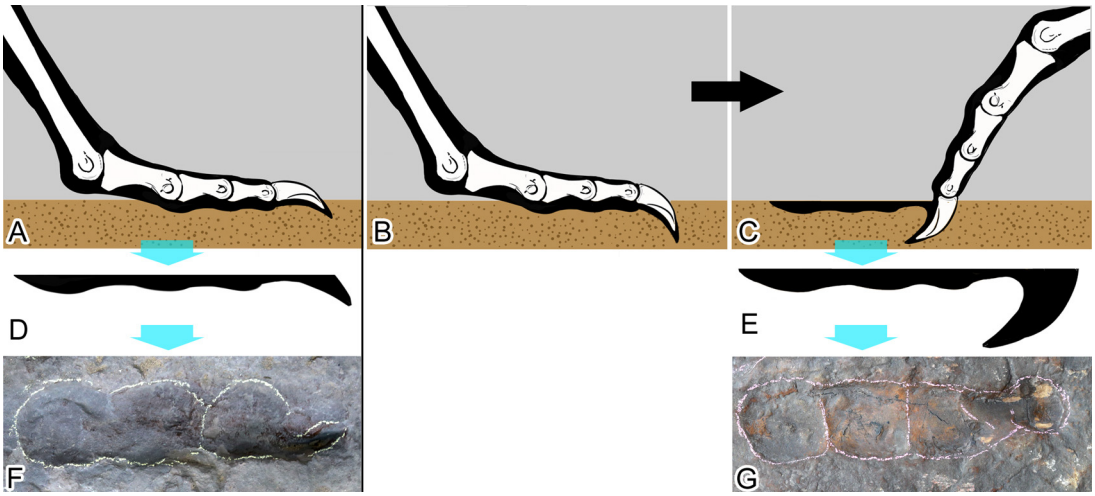

Fig. 7. Flexed-ungual locomotion in the *Eubrontes zigongensis* ZDM 0032 trackway (revised from Wilson et al., 2009, fig. 4A). (A) Trackmaker leaving common impression; (B) claw of trackmaker inserting the sediments deeply; (C) pulling out of the sediments; (D) close-up of track in (A); (E) close-up of track in (C); (F) digit III of ZDM 0032-F1, corresponding to the impression of (A) and (D); (G) digit III of ZDM 0032-F2, corresponding to the impression of (C) and (E). Silhouette morphology and proportions based on the pes skeleton of *Sinosaurus triassicus* LDM–L10. Digit pads based on the pad impressions of *Concavenator corcovatus* MCCM-LH 6666 (Ortega et al., 2010, SP4).

impression. As is stated above, the hallux impression in ZDM 0032 is relatively shallow (Fig. 4C and F). *Eubrontes pareschequier* has well-preserved digits (Xing et al., 2009a, pl. IB); however, the absence of a hallux impression in *E. pareschequier* is still due to the taphonomical or preservation factors (the hallux impressions are too shallow to preserve).

5. Peculiarities of preservation

The well-preserved ZDM 0032-F2 offers some interesting details. Remarkably, round impressions were observed at the distal digits II and III. Together with the distal concavities at the ends of the second pad of digit II and the third pad of digit III, these impressions constitute claw marks (Fig. 4C).

These marks have been considered previously to have been caused by the trackmaker inserting his claws deeply into the substrate (Wilson et al., 2009, fig. 4A, tr.17–22 from a same trackway). Digits II and III of ZDM 0032-F2 support this interpretation. In a moderately firm substrate, digital pads and claws leave impressions that more or less adequately reflect their anatomy (Fig. 7A–C). In softer sediments they first leave a "normally" shaped impression but then continue to penetrate deeper into the substrate, thereby producing a round impression that corresponds to the cross-section of the claws (Fig. 7D–G). When the trackmaker withdrew the pes from the substrate, sediments retracted and flew back. These round claw impressions are still the deepest parts of the track. In ZDM 0032, it is obvious that the tracks with round claw impressions (F2 and F3) comprise one step. It is assumed that the two tracks were made on a softer substrate and that the claws of the trackmaker sank deeply into the sediment. A similar taphonomy is also seen in the holotype of *Chapus* CHABU-8-42 (Li et al., 2006), in which the round claw impressions at the distal end of digits II and III are discernable. These characteristics, because they are largely a function of the physical properties of the substrate, are not employed as diagnostic ichnotaxonomic features for identification.

6. Zhenzhuchong vertebrate fauna and trackmakers

6.1. Body fossils

The Zhenzhuchong Formation includes a series of shallow lake facies sediments from the Early Jurassic (Peng et al., 2005). Body fossils from the Zhenzhuchong Formation are rare and consist of the following:

(1) In 1973, an incomplete prosauropod, *Anchisaurus*, was discovered by the No. 108 geological survey team of Guizhou Province in the Xinchang Basin, Dafang County, northern Guizhou. The specimen includes a nearly complete skull and is approximately 1.7 m long (Dong, 1996). Some theropod material was simultaneously discovered, presumed to be *Sinosaurus* sp. (Dong et al., 1983). Unfortunately these specimens have not been formally described yet.
(2) In 1977, a single prosauropod skeleton material was discovered by Chinese Academy of Geology at Huangshiban Commune, Weiyuan County, which was assigned to plateosaurids (Dong et al., 1983).
(3) In 1978, Zhiming Dong collected an ungual at Hulin Village, Huangshiban Commune, Weiyuan County, which can be assigned to *Lufengosaurus* (Dong et al., 1983).

6.2. Ichnofossils

Yang and Yang (1987) reported a wide gauge sauropod trackway from the Dazu tracksite in the Zhenzhuchong Formation. They were later mentioned by Matsukawa et al. (2006) and briefly described by Lockley and Matsukawa (2009, fig. 7). This may be the oldest sauropod trackway known from China.

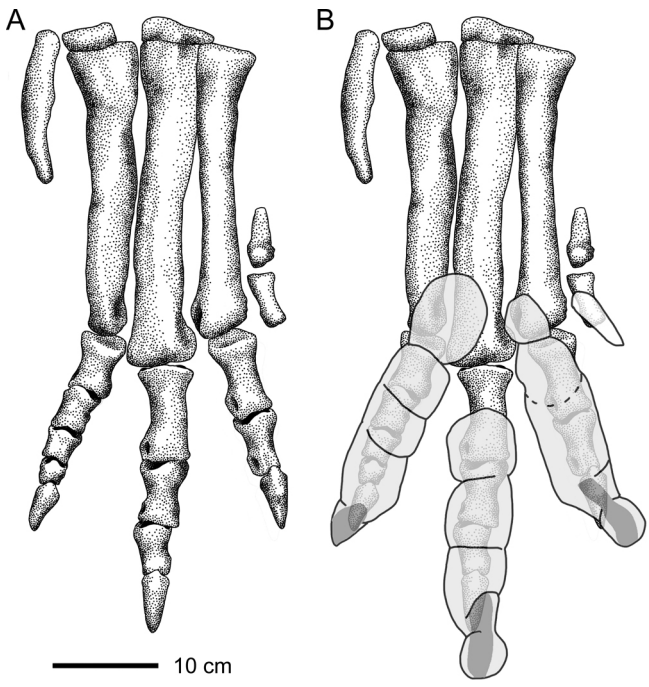

Fig. 8. (A) Pes skeleton of *Sinosaurus triassicus* LDM–L10. (B) Pes skeleton superimposed on *Eubrontes zigongensis* ZDM 0032-F2.

These body fossils and track records indicate that a typical *Lufengosaurus* fauna (*Lufengosaurus*, *Anchisaurus*, and *Sinosaurus*) and basal sauropods characterize the Zhenzhuchong Formation. The fauna is comparable with the fauna from the Lufeng Formation of the Lufeng Basin, Yunnan.

The body length of the trackmaker of *Eubrontes zigongensis* is approximately 5.4 m, which is similar to the 5.5 m estimated body length of *Sinosaurus triassicus* (= "*Dilophosaurus sinensis*") (Hu, 1993; Xing et al., 2013c). *Sinosaurus* sp. is known from the Zhenzhuchong Formation of Dafang County (although it has not been described yet), but the holotype of *Sinosaurus triassicus* (Lower Jurassic Lufeng Formation), LDM–L10 (which, based on a nearly complete skeleton, was approximately 4.5 m long), preserves complete feet (Fig. 8A). By comparing the footprint ZDM 0032-F2 with the foot of LDM–L10 (Fig. 8B), the morphology of the track is consistent with that of the pes skeleton. Although the pes of early theropods tends to be morphologically conservative in evolutionary terms, the co-occurrence of *Sinosaurus* skeletal remains and appropriate footprints in the same unit suggests an affiliation of both.

Remarkably, *Sinosaurus triassicus* is an Early Jurassic theropod characterized by twin hatchet-shaped nasolacrimal crests similar to those of its North American relative *Dilophosaurus* (Hu, 1993; Xing et al., 2013c). Recent phylogenetic analyses show that *Sinosaurus triassicus* is not the most basal dilophosaurid (Smith et al., 2007), but is more closely related to Averostra than to *Coelophysis bauri* and *Dilophosaurus wetherilli* (Rauhut, 2003; Xing, 2012; Xing et al., 2013c). After the record from North America, it seems that supposed *Dilophosaurus wetherilli* tracks correspond to *Kayentapus* tracks that show relatively widely divaricated and slender digits (Welles, 1971; Lockley et al., 2011).

7. Conclusions

The new combination *Eubrontes zigongensis* (*Weiyuanpus zigongensis* after Gao, 2007) is a highly distinctive Early Jurassic, large theropod ichnotaxon. The material also represents one of the best-preserved theropod tracks from China and therefore is well suitable for detailed comparative analyses. Although functionally tridactyl, the majority of tracks in the type trackway are tetradactyl, indicating an anteromedially directed hallux, which touched the substrate lightly. Had the hallux traces been described in detail in the original description of *W. zigongensis* (Gao, 2007) it is possible that the ichnotaxon would have been retained as distinctive and not so readily referred to *Eubrontes* (Lockley et al., 2013). However, a detailed review of the occurrence of hallux traces in *Eubrontes* and the quite similar, if not synonymous, ichnogenus *Gigandipus* reveals no compelling evidence for the erection of a new ichnogenus (*Weiyuanpus*) on the basis of relatively inconspicuous hallux traces. However, retaining the ichnospecies "*zigongensis*" is justified on the basis of the repetition of hallux traces with a distinctive orientation. It is also noteworthy that the size and foot morphology of *Sinosaurus triassicus* is highly consistent with *Eubrontes zigongensis*.

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