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Wide-gauge sauropod trackways from the Early Jurassic of Sichuan, China: oldest sauropod trackways from Asia with special emphasis on a specimen showing a narrow turn

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Abstract An Early Jurassic sauropod dinosaur tracksite in the Lower Jurassic Zhenzhuchong Formation at the Changhebian site in Dazu County, Sichuan, is known to have yielded the trackway of a turning sauropod. A re-study of the site shows that all in all there are more than 100 tracks organized in at least three sauropod trackways. The narrow turn in one of the trackways is confirmed and analyzed in greater detail. All of the trackways show a wide gauge similar to *Brontopodus*-type trackways, but simultaneously exhibit high heteropody typical for *Parabrontopodus*-type trackways. The relative length of pes digits I, II and III is difficult to determine, but is suggestive of a primitive condition where digit I is less well developed than in *Brontopodus*. Thus far, they are the stratigraphically oldest sauropod trackways known from Asia being Hettangian in age. Previously, the trackway with the narrow turn was reported as the first turning sauropod trackway from Asia, but recently several other turning trackways have been reported suggesting that this behaviour is more commonly found than previously assumed and is now documented from the Early Jurassic to Late Cretaceous. Most of these examples show tight turns of between $\sim 90^{\circ}$ and as much as 180° suggesting that despite their large size sauropods could quite easily and abruptly change their direction of movement.

Keywords Sauropod tracks · Turning trackway · China · Dinosaur locomotion · Zhenzhuchong Formation · Early Jurassic

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Abbreviations

CHB	Changhebian track locality, Chongqing, China
CUGB	China University of Geosciences, Beijing
L/R	Left/right
P	Pes
M	Manus
S	Sauropod
P′ML	Maximum length of pes
M′ML	Maximum length of manus
WAM	Width of the manus angulation pattern
WAP	Width of the pes angulation pattern

1 Introduction

The locomotion of sauropod dinosaurs is a challenging question that can only be answered by integrating both data from skeletal remains and trackways. Preserved narrow- and wide-gauge sauropod trackways are essential for understanding the different gait of these tetrapods that, solely from skeletons, would remain widely obscure. This is also true for exceptional behaviour, for example when making sharp turns during walking. In Asia, most sauropod tracks are known from the Early Cretaceous, such as the large assemblages of tracks described from Korea (e.g., Lockley et al. 2006; Kim and Lockley 2012) and China (e.g., Lockley et al. 2002; 2014; Xing et al. 2014a), but also smaller assemblages as those from Thailand (Le Loeuff et al. 2002). By comparison the record of Jurassic sauropods tracks, especially Early Jurassic sauropod tracks, is scarce. In China, Early Cretaceous trackways of medium-sized ($50 \leq$ P'ML <75 cm) and large sauropods (P'ML >75 cm) nearly all have a medium to wide gauge pattern and have been referred to *Brontopodus*-type trackways (Xing et al. 2014a), while trackways of small sauropods have a narrow to medium gauge and are generally referred to *Parabrontopodus*-type trackways (Xing et al. 2015a). China's so far scarce Early Jurassic sauropod track record is comprised primarily of *Parabrontopodus*-type trackways from the Lower Jurassic Ma'anshan Member of the Ziliujing Formation of Zigong City, Sichuan (Xing et al. 2014b); *Liujianpus shunan* and cf. *Brontopodus*-type trackwayss from the Lower Jurassic Daanzhai Member of Ziliujing Formation of Sichuan Province (Xing et al. 2015b); and sauropod trackways from the Changhebian tracksite, Chongqing (this paper). Additionally, a poorly-preserved Late Triassic *Eosauropus* trackway is known from the uppermost part of Xujiahe Formation of Longguan, Zigong City, Sichuan (Xing et al. 2014c).

In 1985, Yang Xinglong and Yang Daihuan from the Chongqing Nature Museum found nearly a hundred tracks of quadrupedal dinosaurs on top of a siltstone layer of the Lower Jurassic Zhenzhuchong Formation in Changhebian Village (GPS: 29°27′4.12″N, 105°46′59.92″E: see Fig. 1), Youting Town, Dazu County, Chongqing Municipality. Yang and Yang (1987) briefly reported this discovery when describing dinosaur tracks from the Sichuan Basin and suggested that prosauropods or stegosaurs were the most likely trackmakers. Following a brief study of the site in 2001 by Sino-Japanese-American expeditions, Lockley and Matsukawa (2009) published a partial map showing an area where a wide-gauge trackway exhibits a sharp left turn and they identified this trackway as of sauropod origin, stating that this appears to be the oldest sauropod trackway known from Asia. However, they did not provide a full description or discussion of the tracksite and all the three visible trackway segments. The main author of this paper investigated the locality again in 2011 and 2015, and the purpose of the present paper is to present a detailed update, description, and interpretation of this important Early Jurassic tracksite. Furthermore, the study gives rare insights into trackway pattern and gait variability of early sauropods when changing walking direction and performing a narrow turn.

2 Geographical and geological setting

The Sichuan Basin contains Early, Middle, and Late Jurassic vertebrate fossils within a more than 3000 m thick depositional sequence (Lucas 2001). Peng et al. (2005) described the dinosaur fauna from Zigong area and established a biostratigraphic correlation scheme based on vertebrate fossils. In this scheme, two formations (Zhenzhuchong and Ziliujing) are identified as Early Jurassic, two (Xintiangou and Xiashaximiao) as Middle Jurassic, and three (Shangshaximiao, Suining, and Penglaizhen) as Late Jurassic.

Dazu County is located in the southeast of Sichuan Basin. The Changhebian tracksite is located 5 km northeast of Youting Town. The strata at the site mainly consist of (from bottom to top): abundant fluviatile sandstones from the Upper Triassic Xujiahe Formation which includes six members, with coal seams in the third and fifth members in the Youting area. Medium-thick layered siltstones, and fine-grained feldspar quartzitic sandstones with interbedded sandy mudstone form the Lower Jurassic Zhenzhuchong Formation (Hettangian) (Fig. 2). This sequence is capped by Holocene clays.

The Zhenzhuchong Formation is a 17–68 m thick sequence of shallow lacustrine deposits (Peng et al. 2005), and the tracks are located in the layered siltstones. Abundant plant fossils have been found in the Zhenzhuchong Formation in the northeastern part of the Sichuan Basin, with flora assemblages characterized by ferns, cycads and conifers. This floral assemblage significantly differs from the underlying Upper Triassic Xujiahe Formation (which consists of lycopods, bryophytes and articulatae) and shows features characteristic of the Early Jurassic (Liu et al. 2009). *Qiyangia lilingensis* (bivalve) and *Palaeolimnadia baitianbaensis* (conchostracans) also suggest that the Zhenzhuchong Formation is Early Jurassic in age (Chen et al., 2006). Chen et al. (2006) proposed that the Zhenzhuchong Formation of the Sichuan Basin and the Lower Lufeng Formation from Yunnan Province further south, are comparable to each other, while Barrett et al. (2007) suggested that the latter is ?Hettangian–?Sinemurian in age.

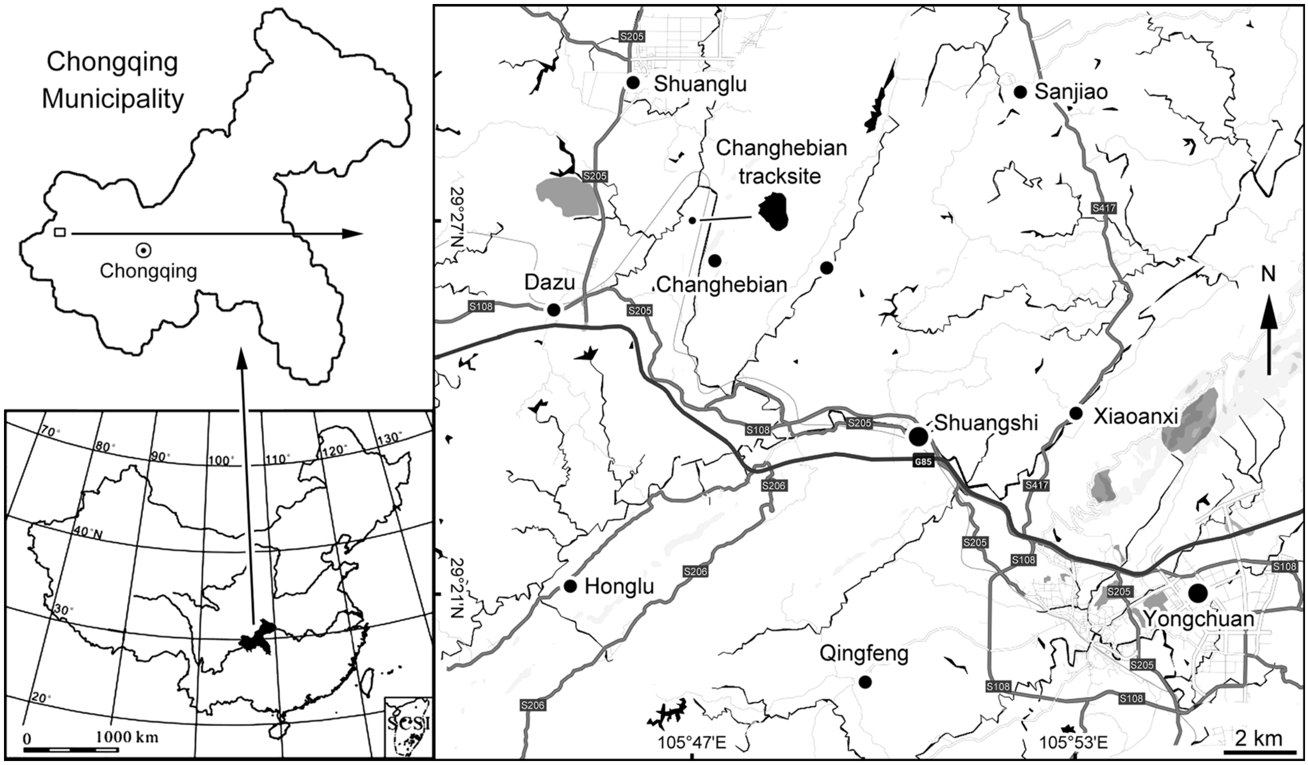

Fig. 1 Geographical setting of the study area and the Changhebian sauropod tracksite in Dazu County, Sichuan Province, China

The Zhenzhuchong vertebrate fauna includes the typical *Lufengosaurus* (prosauropod) fauna (Peng et al. 2005; Xing et al. 2014b). Dong et al. (1983) have described several fragmentary *Lufengosaurus* remains from the southwest portion and southern margin of Sichuan Basin.

3 Materials and methods

3.1 Generalities

The beds of the Changhebian tracksite are inclined at approximately 45°, which required specialized mountaineering equipment to traverse and study the site in detail (Fig. 3). Therefore the China National Mountaineering Team and Zigong Search and Rescue Team contributed to the investigation. By anchoring ropes at the top of the outcrop, we accessed the tracks and catalogued and outlined them one by one with chalk. The entire tracksite was traced on a large-sized transparency film as well. These original drawings (CUGB-T20150720) are kept in the China University of Geosciences, Beijing. We copied the original transparency film, cut it into 1 m-wide strips, scanned these strips with a Hewlett-Packard Development Company (HP) SD Pro 44-in Scanner and constructed a complete digital map by Adobe Photoshop CS6 (see supplementary material). Using the ratios of width of the pes angulation pattern/maximum length of pes (WAP/P'ML) and width of the manus angulation pattern/maximum length of manus (WAM/M'ML), gauge (trackway width) was calculated for both pes and manus tracks (see Marty 2008; Marty et al. 2010a, b); Table 1). Marty (2008) and Marty et al. (2010a, b) have suggested that 1.0 can be used as an arbitrary threshold to distinguish narrow-gauge from medium-gauge trackways, while 1.2 can be used to divide medium-gauge and wide-gauge trackways, and a value above than 2.0 represents a very wide gauge. As noted by Xing et al. (2016), these categories are somewhat arbitrary divisions between the polar extremes of narrow- and wide-gauge trackways as originally defined by Farlow (1992) and Lockley et al. (1994), who did not, however, quantify these categories.

The protection of the tracksite as a geological park is currently under discussion and study with local authorities.

3.2 The trackways

3.2.1 Material, horizon and locality

Trackway CHB-S1 comprises 28 pes and 16 manus tracks; trackway CHB-S2 22 pes and 11 manus tracks; trackway CHB-S3 7 pes and 7 manus tracks. All tracks remain in situ.

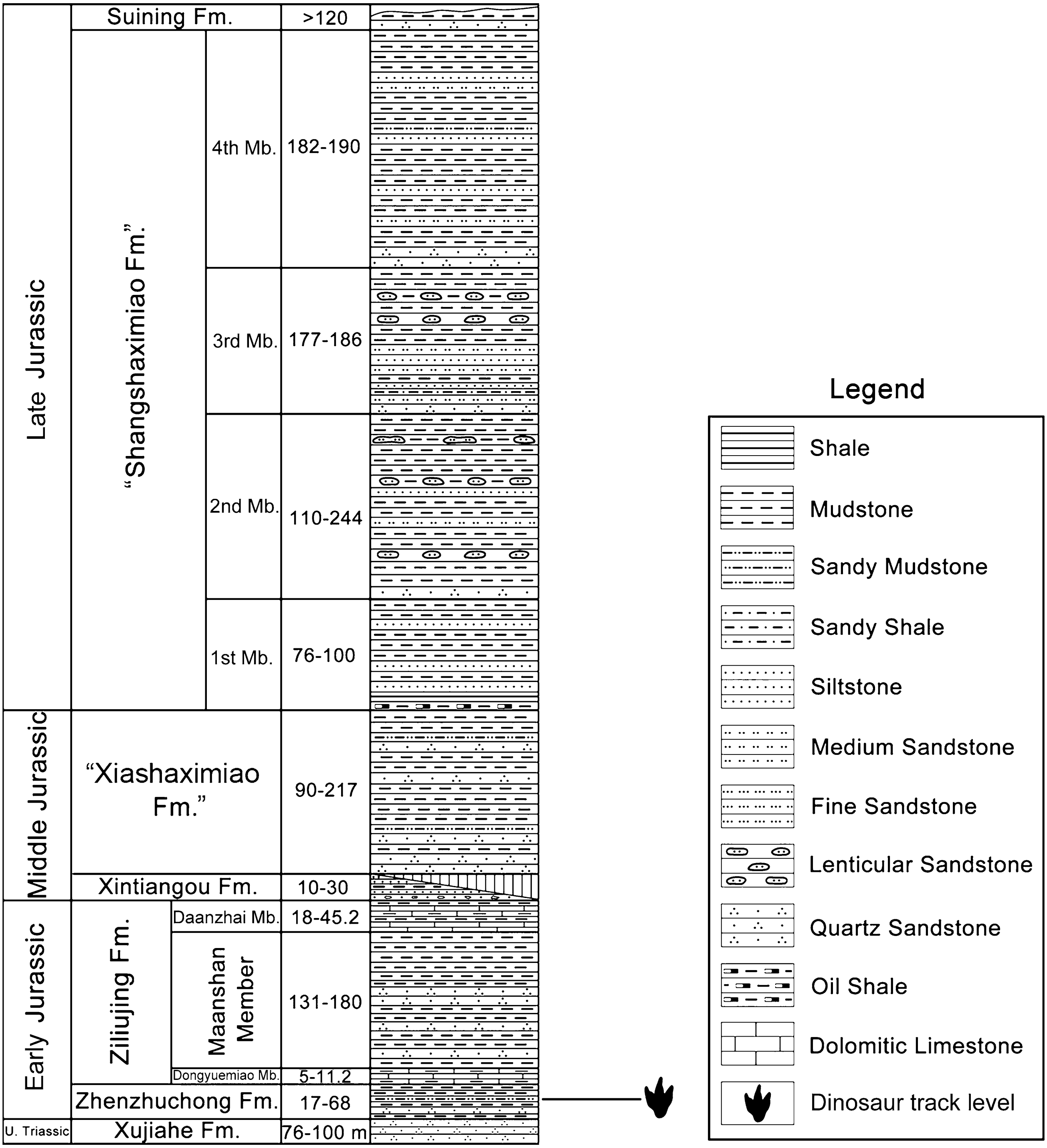

Fig. 2 Stratigraphic section of the Jurassic in the study area with the position of the sauropod track level of the Changhebian tracksite in the Lower Jurassic Zhenzhuchong Formation

The trackways occur in the following horizon and location: Zhenzhuchong Formation (Early Jurassic), Changhebian Village, Youting Town, Dazu County, Chongqing Municipality, China.

3.2.2 *Description*

Trackways CHB-S1, S2 & S3 are 15, 13.5, and 3.5 m long, respectively. Trackway CHB-S2 is the best preserved and

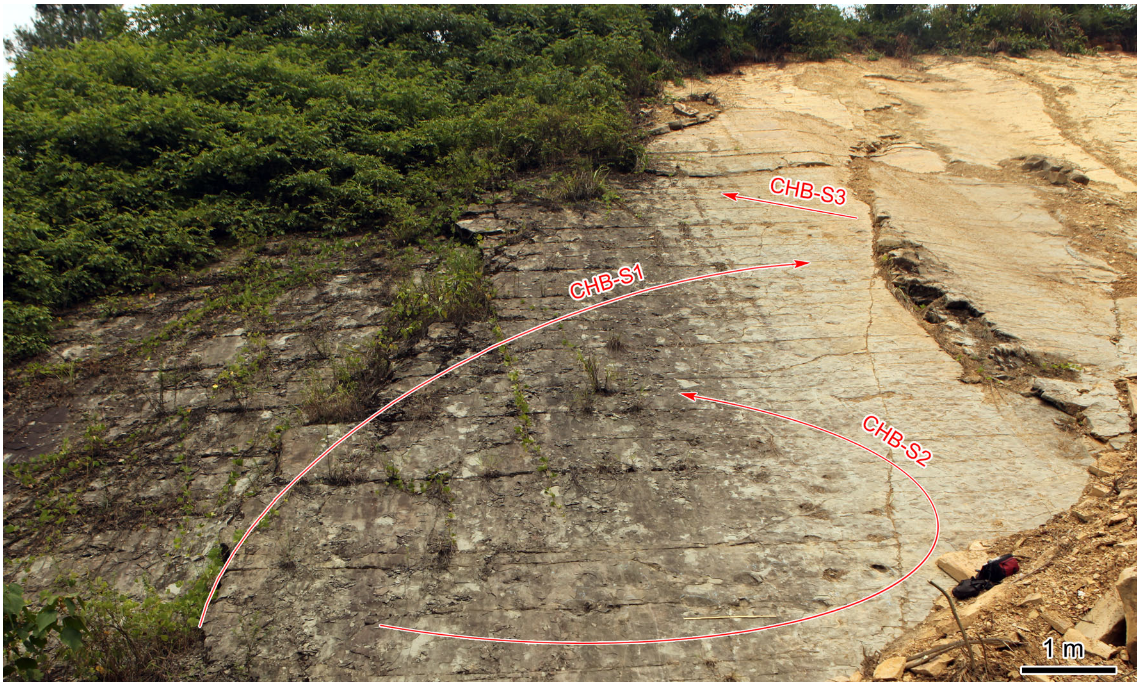

Fig. 3 Photograph of the Changhebian tracksite, Chongqing, China showing the steeply inclined track-bearing surface. The narrow turn of trackway CHB-S2 is clearly visible on the *lower right*. Trackways CHB-S1 and CHB-S3 are partially visible to the *left* of the normal fault, in the *middle part* of the photograph

exhibits a pronounced left turn towards the NW (Fig. 4, 5, 6). The CHB-S1 tracks are similar to the better-preserved CHB-S2 tracks, but slightly smaller in size. Trackway CHB-S3 is severely weathered; thus the morphology of the CHB-S1 or CHB-S3 tracks is not described in greater detail. However, the tracks of the S1 and S3 trackways are generally consistent with those from CHB-S2 from a morphological point of view and the three trackways are also similar regarding size (the average pes length of S1–S3 is 33.9, 35.9, and 34 cm) and trackway configuration. All three trackways represent quadrupedal progression, exhibiting all pes and corresponding manus tracks with only a few exceptions. Trackway S1 makes a small turn to the right but this turn is not nearly as tight and pronounced as the left turn in S2.

The average pes length of CHB-S2 is 35.9 cm, the average width 27.7 cm, and the average L/W ratio is 1.3. The average manus length is 12.5 cm, the average width 24.4 cm, and the average L/W ratio is 0.5 (Table 1). The pes tracks of CHB-S2 are oval in shape and the manus crescent shaped. Most of the manus and pes tracks are rotated outwards relative to the trackway midline, and most of the time have a similar outward rotation, which is not "extremely" pronounced (see Figs. 4, 5, 6). Manus tracks are generally located in front of pes tracks, but some exceptions occur, notably within the turn, where some left manus tracks are located more inside with respect to the preceding pes track. The average outward rotation values for the manus and pes tracks are approximately 22° and 39°, respectively. The WAP/P'ML is 1.4, characterizing this trackway as wide-gauge sensu Marty (2008). The best-preserved pes–manus couple is CHB-S2-LP9 and LM9 (Fig. 6). The pes print LP9 is oval in shape, with a metatarso-phalangeal region narrower than the anterior region. Large, forwardly-directed claw mark impressions of digits I–III are present. The manus track LM9 is crescent shaped, digit I and V impressions are preserved, while the middle digit II and II impressions and the metacarpo-phalangeal region are indistinct. The heteropody (manus:pes area ratio) is high with a value of 1:3.1. The average pes pace angulation is 98°, while the average manus pace angulation is 80°.

CHB-S2 is a sauropod trackway with a very pronounced, narrow turn to the left (Figs. 3, 4). The turn itself is very narrow and consists of eleven pes and ten manus tracks: LP4-LM4 to LP9-LM9. In the middle of the turn, from RP5-RM5 on until approximately RP8, the trackway becomes much narrower (WAP/P'ML = 1.0) than in the non-turning part, where the trackway is clearly wide-gauge (WAP/P'ML = 1.2–1.7).

In the turning sequence, CHB-S2-LP6 and RP6 are almost parallel to each other, as are LP7 and RP7, which are also located very close to each other. LM6 is absent due to weathering, while LM7 is located close to the posterior part of LP8. The tracks between RP5 and RP7 are all located very close to each other, possibly indicating a

Table 1 Measurements of sauropod trackway parameters from Changhebian site, Chongqing, China

Number CHB-	ML (cm)	MW (cm)	R (°)	PL (cm)	SL (cm)	PA (°)	ML/MW	WAP&WAM	WAP/P'ML&WAM/M'MW
S1-LP1	33.0	–	14	62.0	106.0	112	–	35.5	1.1
S1-LM1	10.0	18.5	29	66.5	111.0	105	0.5	37.5	2.0
S1-RP1	35.0	26.5	−3	66.0	104.0	98	1.3	42.0	1.2
S1-RM1	8.5	18.5	65	73.0	102.0	94	0.5	42.5	2.3
S1-LP2	32.5	20.0	19	72.0	102.5	103	1.6	38.0	1.2
S1-LM2	10.0	17.5	18	66.5	100.0	104	0.6	33.8	1.9
S1-RP2	30.0	23.0	−11	58.5	100.0	103	1.3	40.0	1.3
S1-RM2	9.5	19.0	10	60.0	102.0	101	0.5	36.0	1.9
S1-LP3	31.0	25.0	30	69.0	98.0	92	1.2	41.5	1.3
S1-LM3	8.5	23.5	4	72.0	98.0	86	0.4	46.0	2.0
S1-RP3	28.5	21.0	23	67.0	81.0	83	1.4	42.0	1.5
S1-RM3	10.5	21.5	45	72.0	101.0	89	0.5	46.0	2.1
S1-LP4	34.5	28.5	33	55.0	100.0	106	1.2	43.5	1.3
S1-LM4	8.0	19.0	68	72.0	99.5	99	0.4	36.0	1.9
S1-RP4	37.0	28.0	20	70.0	97.0	96	1.3	50.0	1.4
S1-RM4	10.0	22.0	15	58.5	93.0	90	0.5	40.0	1.8
S1-LP5	34.5	24.5	62	60.0	101.0	106	1.4	43.5	1.3
S1-LM5	13.0	21.0	–	72.0	–	–	0.6	–	–
S1-RP5	34.0	21.0	42	66.0	114.0	119	1.6	40.5	1.2
S1-RM5	10.0	20.0	–	–	–	–	0.5	–	–
S1-LP6	31.0	23.5	46	66.5	100.0	108	1.3	43.5	1.4
S1-LM6	–	–	–	–	–	–	–	–	–
S1-RP6	36.5	23.5	36	57.0	95.0	99	1.6	45.0	1.2
S1-RM6	–	–	–	–	–	–	–	–	–
S1-LP7	37.0	24.0	26	68.0	86.5	86	1.5	50.0	1.4
S1-LM7	10.0	20.0	24	–	92.0		0.5	–	–
S1-RP7	27.5	22.0	31	58.0	59.5	59	1.3	57.5	2.1
S1-RM7	–	–	–	–	–	–	–	–	–
S1-LP8	34.0	27.0	53	62.0	107.0	115	1.3	40.0	1.2
S1-LM8	14.0	23.0	–	–	124.0	–	0.6	–	–
S1-RP8	46.5	25.5	−9	65.0	123.0	108	1.8	44.5	1.0
S1-RM8	–	–	–	–	–	–	–	–	–
S1-LP9	35.0	29.5	49	86.0	108.5	94	1.2	47.0	1.3
S1-LM9	10.0	22.0	–	–	–	–	0.5	–	–
S1-RP9	43.0	26.0	–	60.0	–	–	1.7	–	–
S1-RM9	–	–	–	–	–	–	–	–	–
S1-LP10	32.0	22.0	21	–	109.0	–	1.5	–	–
S1-LM10	–	–	–	–	–	–	–	–	–
S1-RP10	–	–	–	–	–	–	–	–	–
S1-RM10	–	–	–	–	–	–	–	–	–
S1-LP11	25.0	20.0	41	94.0	116.0	97	1.3	50.0	2.0
S1-LM11	–	–	–	–	–	–	–	–	–
S1-RP11	32.5	18.5	24	58.0	95.5	86	1.8	50.0	1.5
S1-RM11	13.5	21.5	–	–	–	–	0.6	–	–
S1-LP12	32.0	28.0	25	80.0	124.0	114	1.1	44.0	1.4
S1-LM12	–	–	–	–	–	–	–	–	–
S1-RP12	26.5	19.5	21	68.0	104.5	105	1.4	44.0	1.7
S1-RM12	–	–	–	–	–	–	–	–	–

Table 1 continued

Number CHB-	ML (cm)	MW (cm)	R (°)	PL (cm)	SL (cm)	PA (°)	ML/MW	WAP&WAM	WAP/P’ML&WAM/M’MW
S1-LP13	32.5	28.0	33	64.0	101.0	95	1.2	46.0	1.4
S1-LM13	–	–	–	–	–	–	–	–	–
S1-RP13	40.0	29.0	12	73.0	109.0	96	1.4	49.0	1.2
S1-RM13	–	–	–	–	–	–	–	–	–
S1-LP14	37.0	31.0	22	74.0	100.0	100	1.2	38.0	1.0
S1-LM14	10.0	19.5	–	–	110.0	–	0.5	–	–
S1-RP14	36.5	30.0	–	56.0	–	–	1.2	–	–
S1-RM14	–	–	–	–	–	–	–	–	–
S1-LP15	37.0	28.0	–	–	–	–	1.3	–	–
S1-LM15	12.5	19.0	–	–	–	–	0.7	–	–
Mean-P	33.9	24.9	|28|	66.7	101.7	99	1.4	44.4	1.4
Mean-M	10.5	20.3	31	68.1	103.0	96	0.5	39.7	2.0
S.d.-P	4.6	3.6	17.8	9.3	13.1	12.7	0.2	5.0	0.3
S.d.-M	1.8	1.8	23.4	5.6	9.1	7.3	0.1	4.7	0.2
S2-LP1	–	–	–	–	–	–	–	–	–
S2-LM1	13.0	23.0	71	71.0	119.0	99	0.6	50.5	2.2
S2-RP1	40.0	27.0	23	68.0	139.0	117	1.5	49.0	1.2
S2-RM1	8.0	25.5	–	85.5	–	–	0.3	–	–
S2-LP2	37.0	24.0	26	94.0	140.0	113	1.5	50.0	1.4
S2-LM2	11.0	30.0	64	–	119.0	–	0.4	–	–
S2-RP2	36.5	27.5	12	73.0	137.0	113	1.3	46.0	1.3
S2-RM2	–	–	–	–	–	–	–	–	–
S2-LP3	34.0	24.5	10	91.0	131.0	99	1.4	54.0	1.6
S2-LM3	11.0	20.0	26	100.0	151.0	103	0.6	61.0	3.1
S2-RP3	29.5	29.0	17	81.0	132.0	103	1.0	50.5	1.7
S2-RM3	13.0	22.5	45	93.5	140.5	102	0.6	56.0	2.5
S2-LP4	33.0	22.5	−20	88.0	124.0	103	1.5	51.0	1.5
S2-LM4	15.0	24.0	−19	87.0	120.0	89	0.6	61.5	2.6
S2-RP4	38.0	29.0	15	70.0	131.0	106	1.3	54.5	1.4
S2-RM4	23.0	27.0	45	84.5	118.0	81	0.9	68.5	2.5
S2-LP5	41.0	31.0	20	93.0	110.0	85	1.3	66.0	1.6
S2-LM5	13.0	21.5	–	96.0	–	–	0.6	–	–
S2-RP5	42.5	29.0	52	67.0	90.0	100	1.5	42.0	1.0
S2-RM5	10.0	22.5	34	–	85.5	–	0.4	–	–
S2-LP6	36.0	30.5	−4	50.0	60.0	54	1.2	54.0	1.5
S2-LM6	–	–	–	–	–	–	–	–	–
S2-RP6	30.5	33.5	37	73.5	69.0	68	0.9	42.0	1.4
S2-RM6	13.0	27.5	32	100.0	67.5	35	0.5	–	–
S2-LP7	35.0	28.5	−4	37.0	81.0	41	1.2	37.5	1.1
S2-LM7	8.5	17.5	29	46.0	62.0	16	0.5	–	–
S2-RP7	33.5	28.5	16	105.0	135.0	113	1.2	43.0	1.3
S2-RM7	15.0	23.0	20	105.0	146.0	101	0.7	30.0	1.3
S2-LP8	39.0	28.0	13	53.0	104.0	88	1.4	52.5	1.3
S2-LM8	9.5	22.5	−15	84.0	125.5	69	0.4	76.5	3.4
S2-RP8	30.5	30.5	60	91.0	126.0	106	1.0	50.0	1.6
S2-RM8	12.0	29.5	82	128.0	137.0	82	0.4	63.0	2.1
S2-LP9	37.0	27.0	22	66.0	128.0	97	1.4	55.5	1.5
S2-LM9	13.5	28.5	9	71.0	121.0	71	0.5	65.5	2.3

Table 1 continued

Number CHB-	ML (cm)	MW (cm)	R (°)	PL (cm)	SL (cm)	PA (°)	ML/MW	WAP&WAM	WAP/P'ML&WAM/M'MW
S2-RP9	33.5	25.0	6	102.0	150.0	116	1.3	50.0	1.5
S2-RM9	16.0	28.5	43	123.5	148.5	87	0.6	72.5	2.5
S2-LP10	44.0	27.5	12	74.0	139.0	112	1.6	54.0	1.2
S2-LM10	10.0	20.5	−47	90.0	132.0	79	0.5	76.0	3.7
S2-RP10	33.5	28.0	21	93.0	140.0	110	1.2	55.0	1.6
S2-RM10	14.5	25.5	38	114.5	145.0	90	0.6	66.0	2.6
S2-LP11	33.0	25.5	44	78.0	121.0	109	1.3	48.5	1.5
S2-LM11	11.5	22.0	40	88.0	127.5	91	0.5	60.0	2.7
S2-RP11	34.5	27.5	–	71.0	–	–	1.3	–	–
S2-RM11	12.0	30.0	–	91.0	–	–	0.4	–	–
S2-LP12	37.5	26.5	–	–	–	–	1.4	–	–
S2-LM12	10.5	21.0	–	–	–	–	0.5	–	–
Mean-P	35.9	27.7	|22|	77.1	119.4	98	1.3	50.3	1.4
Mean-M	12.5	24.4	|39|	92.1	121.5	80	0.5	62.1	2.6
S.d.-P	3.8	2.5	18.9	17.4	25.6	21.0	0.2	6.2	0.2
S.d.-M	3.2	3.6	32.8	19.3	26.6	24.6	0.1	12.2	0.6

ML maximum length, *MW* maximum, *R* rotation, *PL* pace length, *SL* stride length, PA pace angulation, *WAP* width of the angulation pattern of the pes (calculated value), *WAM* width of the angulation pattern of the manus (calculated value), *ML/MW, WAP/P'ML and WAM/M'MW* ratios are dimensionless, *S.d.* Standard deviation, "| |" indicating absolute value, "–" indicating missing data

slowing down in the middle of the turn. Another unusual feature is that some of the left pes tracks are turned inwards in the turning sequence, such as LP4, LP6, and LP7, while right pes tracks have a positive (outward) rotation throughout the turn and the entire trackway. Also the left manus tracks LM4, LM8 and LM10 are rotated inwards, while all right manus tracks are rotated outwards. This feature is similar to other turning sauropod trackways, like the TDGZ-S1 trackway from Tangdigezhuang tracksite, Shandong Province, China (Xing et al. 2015a), and this is obviously related to the turn.

For sauropods, Alexander (1976) first suggested that hip height was equal to 4 times of the foot length, whereas, later, Thulborn (1990) estimated hip height to be better estimated at 5.9 times the foot length. The relative stride length ratios of the CHB-S1 and S2 trackways are between 0.51–0.75, 0.56–0.83. Using the equation to estimate speed from trackways (Alexander 1976), the mean locomotion speed of the trackmakers was between 1.3–2.02 (CHB-S1) and 1.58–2.48 km/h (CHB-S2), indicating a slow walk.

4 Discussion

4.1 Ichnotaxonomy

Gauge is often used to distinguish the two typical, major groups (narrow gauge mainly in the Jurassic; wide gauge mainly in the Cretaceous) sauropod trackways (Farlow 1992; Lockley et al. 1994; Wilson and Carrano 1999; Santos et al. 2009; Marty et al. 2010a; Castanera et al. 2014), even if some trackways show changes from narrow to wide gauge along trackway course (e.g., Marty et al. 2010b; Castanera et al. 2012).

The three trackways from the Changhebian site are all wide-gauge trackways, apart from the turn in trackway CBH-S2. Regarding the wide gauge and the rather moderate outward rotation of manus tracks, the Changhebian sauropod trackways resemble the *Brontopodus*-type trackways. The high degree of heteropody on the other hand is typical for *Parabrontopodus* narrow-gauge trackways (Lockley et al. 1994), while the configuration of the three prominent and forwardly-directed digit impressions is not as the type description of *Parabrontopodus* stating that the digits are 'strongly outwardly rotated' (Lockley et al., 1994).

On the other hand, the Changhebian sauropod trackways also differ from the recently named sauropod medium-gauge ichnotaxon *Liujianpus* (Xing et al. 2015d) from the Lower Jurassic Ziliujing Formation. *Liujianpus* shows a combination of features shared with both *Otozoum* and *Brontopodus* (Rainforth 2003; Lockley et al. 1994) and has elongate pes digit traces oriented subparallel to the pes axis and a sub-circular manus with five discrete blunt digit traces. A small wide-gauge "*Brontopodus*-type" trackway JYS11 (Xing et al. 2015b) was found at the same site as *Liujianpus.* JYS11 has a mean pes length of 26.4 cm and is quite similar to the Changhebian sauropod trackways regarding track morphology.

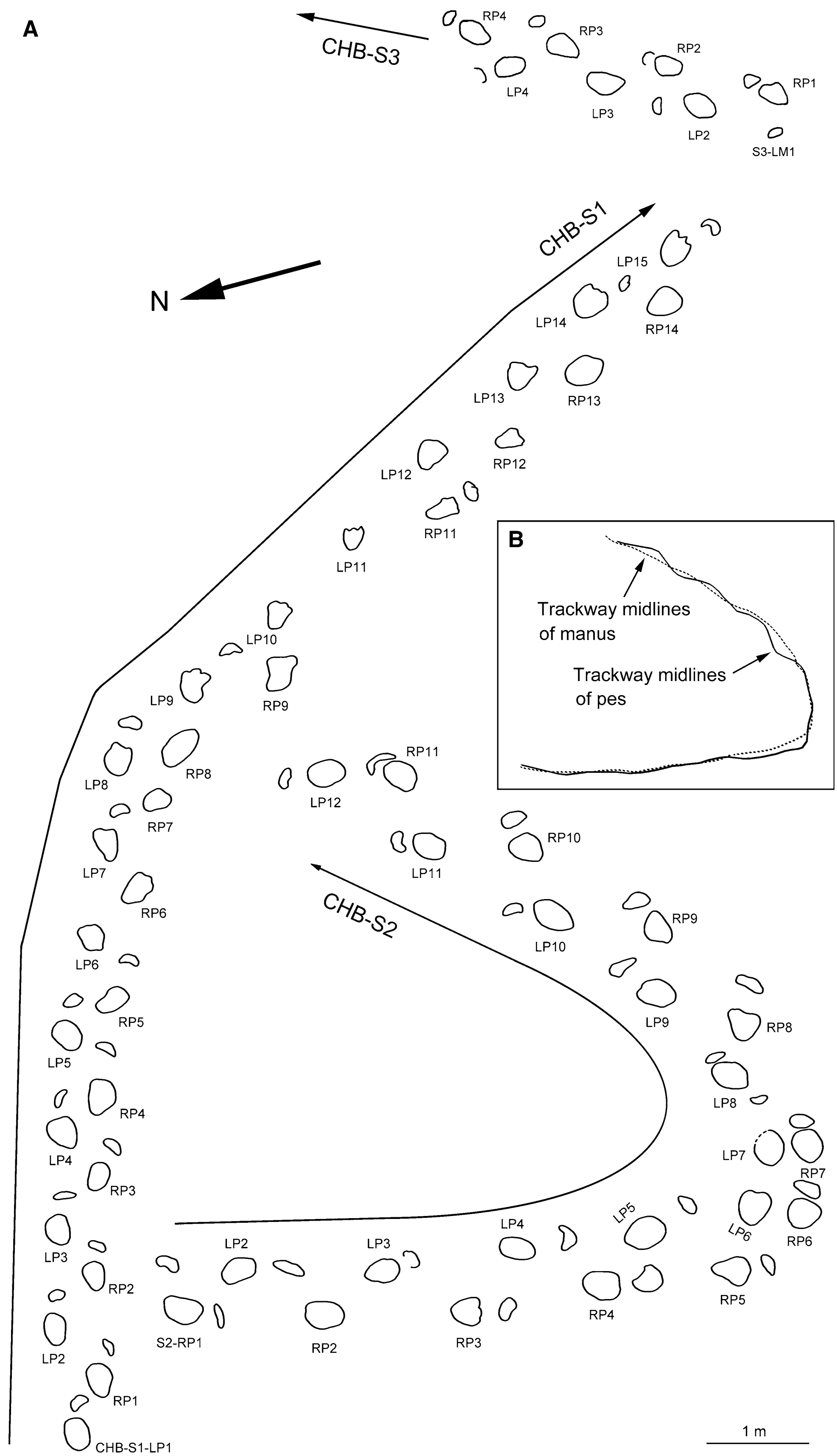

Fig. 4 Map with interpretative outline drawings (*A*) of the track-bearing level at the Changhebian site; and trackway midlines (*B*) of pes (*solid line*) and manus (*dashed line*), exhibiting the off-tracking phenomenon of the manus with regards to the pes. (Trackway midline defined by linking the midpoint of the *line* between centres of the *left* and *right* tracks)

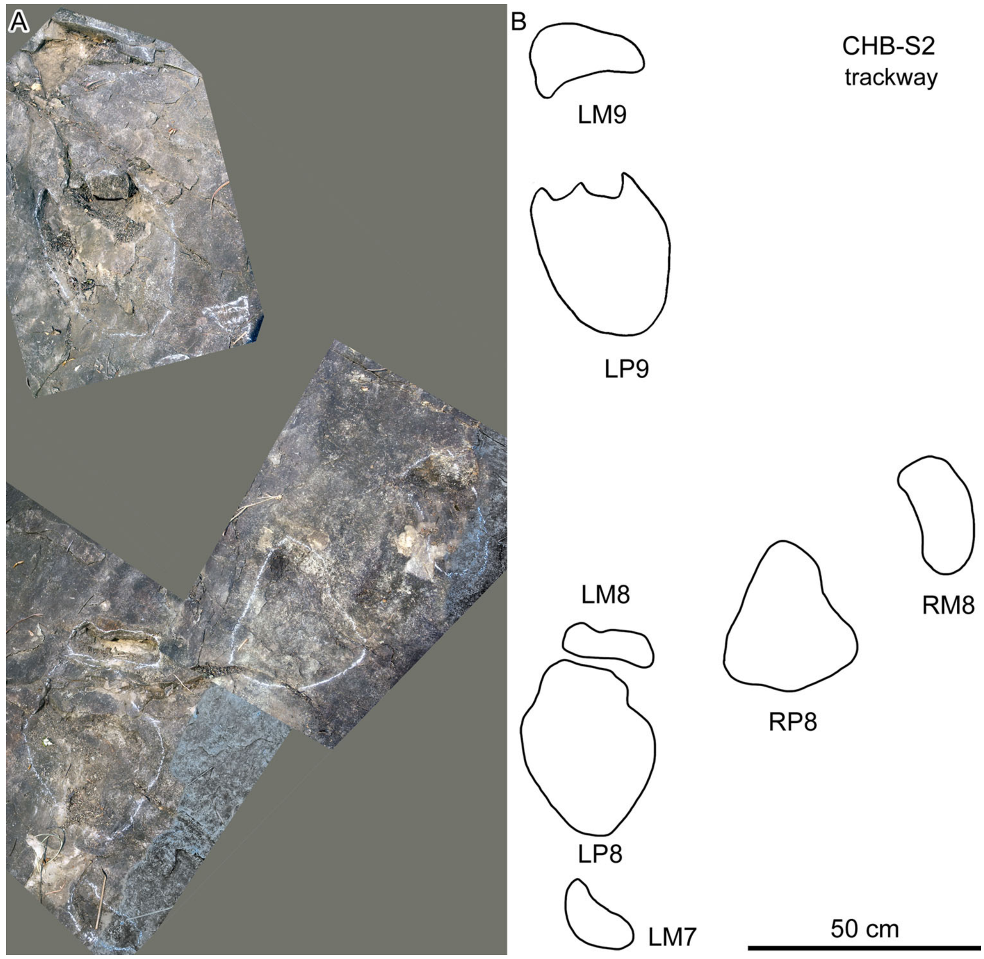

Fig. 5 Photograph and outline drawing of well-preserved tracks from trackway CHB-S2, right after the narrow turn. The external position of RM8 and the atypical close position of LM7 to the rear part of LP8 are related to the turn

It is also noteworthy that even some other Early Jurassic prosauropod trackways have a wide gauge (Ishigaki 1988; Farlow 1992; Lockley 2001).

Finally, the Changhebian sauropod trackways are clearly distinct from Late Jurassic–Early Cretaceous Chinese *Parabrontopodus*-type trackways, which are narrow to medium gauge and have a more pronounced outward-rotated manus (Xing et al. 2015a).

For these reasons and because the Changhebian trackways share typical characteristics of both *Parabrontopodus* and *Brontopodus*, we refrain from assigning these trackways to one of these ichnotaxa. Nonetheless, we believe that the Changhebian trackways—despite their wide gauge—are more closely related to *Parabrontopodus, Lavinipes* or other unnamed sauropod trackways from the Early Jurassic (see also Fig. 9 of Avanzini et al. 2003), as they have a high heteropody.

We easily rule out a thyreophoran origin (*Deltapodus* and *Shenmuichnus* ichnotaxa), as *Deltapodus* typically has three round and blunt digits and a pronounced narrowing of the heel (Whyte and Romano 2001; Xing et al. 2013) and this is not the case in the Changhebian trackways. *Shenmuichnus* tracks are clearly tridactyl (Li et al. 2012).

The occurrence of Early Jurassic wide-gauge, "*Brontopodus*-type" trackways suggests that several basal eusauropods, such as *Patagosaurus*, *Volkheimeria*, *Cetiosaurus*, *Cetiosauriscus*, and *Turiasaurus* (Upchurch et al. 2004; Royo-Torres et al. 2006), could possibly have left wide-gauge trackways. Wilson and Carrano (1999) and Santos et al. (2009) have inferred some wide gauge-trackmaker features, such as: wider sacra, limb morphologies suggesting an outwardly-angled limb posture, and increased eccentricity of the femoral midshaft.

Present evidence indicates a great diversity of Early Jurassic sauropodomorphs in Southwest China (Sichuan and Chongqing). Skeletal fossils include *Lufengosaurus* (prosauropod) (Dong et al. 1983), and the track records narrow-gauge *Parabrontopodus* tracks (Xing et al. 2015a), *Liujianpus* tracks, and wide-gauge *Brontopodus*-type tracks (Xing et al. 2015b).

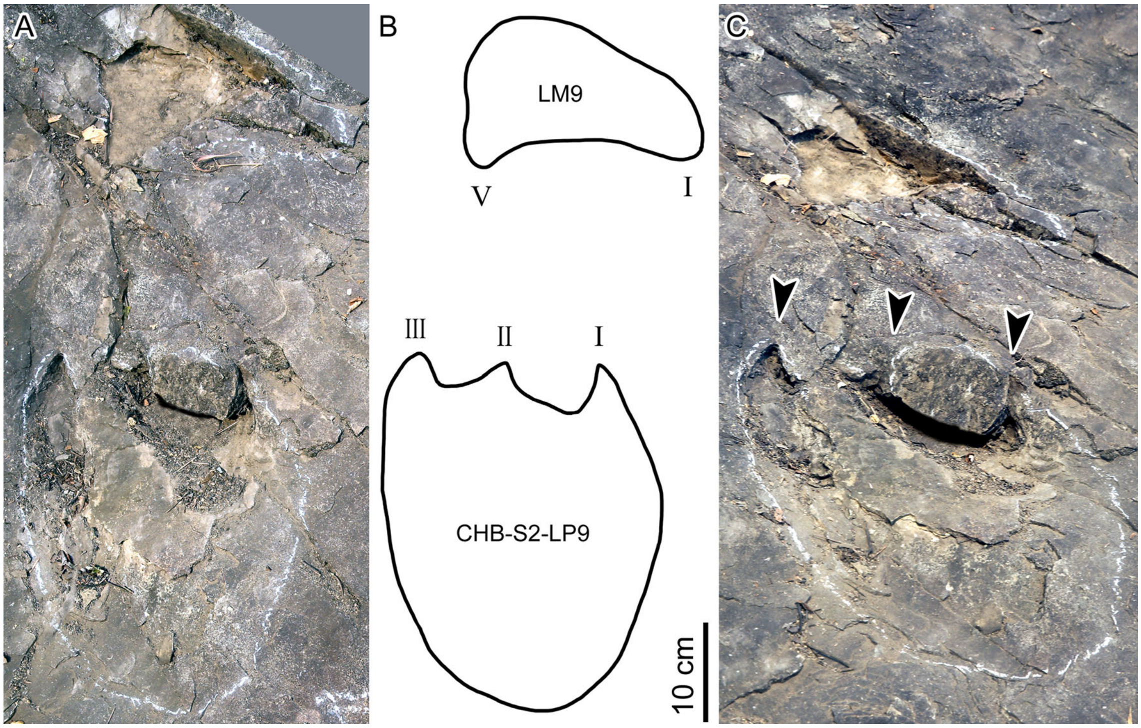

Fig. 6 Photograph (**a**), outline drawing (**b**), and low-angle light photograph (**c**) of the well-preserved pes-manus couple LP9-LM9 of trackway CHB-S2. Note the three well-developed and forwardly-oriented digit I-III impressions on the *left* pes track LP9. Digit *I* and *V* (not *IV*?) impressions are visible on the manus track LM9

4.2 Trackmaker identification

The sauropodomorph dinosaurs are well known in southern China from the Early Jurassic. For example, the basal sauropodomorph *Lufengosaurus* (Young 1941) and *Yunnanosaurus* (Young 1942) are abundant in Yunnan Province, and also have several records in Sichuan Province (Dong 1984). Sauropod remains are far less common, but include, for example, the basal sauropod *Gongxianosaurus* (He et al. 1998) and the eusauropod *Tonganosaurus* (Li et al. 2010).

Where tracks are sufficiently well preserved it should be easy to differentiate *Lufengosaurus*-like trackmakers from those that have left *Brontopodus*-type trackways. Tracks of the former genus have digit I impressions shorter than digit III, that tend to be oriented anteriorly, whereas the latter have digit I traces larger than digit III, with stringer outward rotation. The track LP9 shown in Figs. 5 and 6 indicates that digit I is shorter than digit III, and more prosauropod-like than typical sauropod tracks (*Brontopodus* type). However, it is probable that in comparison with more derived sauropods, the more basal sauropods would have had digit I less strongly developed in comparison with digit III. For example in the pes of *Shunosaurus* digit I is shorter than digit II and about the same length as digit II (Zhang 1988). Wright (2005, p. 256) illustrated hypothetical footprints made by different sauropod groups but noted that "no basal sauropod (e.g., *Vulcanodon*) tracks have been discovered." Moreover, her reconstruction of a possible *Vulcanodon* track is much more like a prosauropod track (e.g., *Otozoum* or *Liujianpus*) than any confirmed *Brontopodus*-like sauropod track.

4.3 Turn of trackway CHB-S2

Ishigaki and Matsumoto (2009) have reported what they called an "off-tracking phenomenon" for the trackway 'Tu' of the Iouaridène tracksite (Late Jurassic, Morocco). Sauropod trackway no. 6 of the Zhaojue tracksite, Sichuan Province (Xing et al. 2015b), and trackway TDGZ-S1 from the Tangdigezhuang tracksite, Shandong Province, China (Xing et al. 2015c) also show a similar "off-tracking" phenomenon, and Xing et al. (2015c) also discuss "off-tracking" in further detail. CHB-S2 has a much less obvious "off-tracking" and this may be related to the very tight turn and abrupt change in direction. An explanation could be that the animal slowed down to almost standing still before changing the direction. This would also explain why the tracks between RP5 and RP7 are located very close to each other. Accordingly, "off-tracking" may only have occurred sauropods make rather large and continuous turns without too much of deceleration. However, a verification of such hypotheses requires more detailed studies that aim to show a quantitative correlation between variations in stride length and trackway curvature, and that cite appropriate behavioral support (in extant quadrupeds) for a correlation between stride length and speed.

4.4 Overview on turning sauropod trackways

Recent studies have shown that turning sauropod trackways are more common than previously known. The first report appears to have been an unpublished 1987 photo of trackways from the Upper Cretaceous (Maastrichtian) Fumanya region of Spain (Vila et al. 2008) which shows three turns, the first two being relatively abrupt (sharp) turns approximating 90° and the third, also abrupt (sharp) and almost 180°.

The second report is the Lommiswil tracksite in the Jura Mountains in Switzerland. Published in Meyer 1990 (Fig. 2, trackway 6), and 1993 (Fig. 4, unnumbered trackway) are two wide-gauge (partially pes-only) sauropod trackways with abrupt and round turns.

The third report, from the Morrison Formation (Late Jurassic) at the Valley City site in Utah (Lockley and Hunt 1995, Fig. 4.45), later named the Copper Ridge site, shows a turn of nearly 90°. The initial report of the Changhebian site discussed here thus appears to have been the fourth and the oldest report of a sauropod turn, providing evidence of a turn of about 120–130°.

More recently, a large site from the Lower Cretaceous Feitianshan Formation of the Zhaojue area, Sichuan, yielded a turning trackway with an abrupt 180° turn (Xing et al. 2015b), and a site from the Early Cretaceous Dasheng Group, of Shandong Province a rather wide or broad semicircular turn of almost 180° (Xing et al. 2015c). Another trackway with even two quite pronounced turns is figured in Castanera et al. 2014 (Fig. 2, trackway PM-N5-P2). Several Late Jurassic turning trackways were excavated and documented by the Palaeontology A16 on Highway A16, but most of these are not published as yet, but see Stevens et al. 2016, Fig. 13.7 for an example of a sauropod trackway with a very narrow and round turn. Trackways with rather slight turns are more frequent, as almost no trackway is really straight. Good examples of trackways with rather slight turns are "G7" and "PM-N5-P3" shown in Fig. 2 in Castanera et al. (2014).

Notable among these reports are the very sharp or abrupt (~180°) turns reported at the Spanish site (Castanera et al. 2012) and at the Zhaojue site. In comparison the turn made by the Changhebian sauropod is less pronounced (~120–130°) as is the one from Utah (~80°). In the global sauropod trackway record there are many sites where sauropod trackways deviate from straight lines. However, in the samples cited here, all the trackways show turns of between ~89° and ~180° in short distances of no more than about 3–5 m.

We consider the sample too small to draw any new conclusions about sauropod turning behaviour and locomotion at present. At least, it is evident that despite their large size sauropods could make abrupt and narrow turns over a few meters only. A larger sample of well-preserved trackways of narrow and wide gauge sauropod making turns with different curvatures, analysed with more sophisticated and statistical analysis tools (see also Stevens et al. 2016) would be required to draw any further conclusions about the gaits involved in such turns.

To summarize, these reports span sites dating from the Early Jurassic to Late Cretaceous. Although the sample is still small this represents a wide time span and the records are from three different continents.

5 Conclusions

1. It's confirmed that the Changhebian tracksite reveals the oldest sauropod dinosaur trackways in Asia.
2. The trackways share typical characteristics of wide-gauge *Brontopodus*-type (wide gauge) and narrow-gauge *Parabrontopodus*-type trackways (high heteropody) and include one example of an individual that made an abrupt and narrow turn (~120°–130°).
3. The relative length of pes digits I, II and III is difficult to determine, but is suggestive of a primitive condition where digit I is less well developed than in *Brontopodus*-type pes tracks.
4. This is another example that shows that trackway gauge is related to behaviour and may change along a single trackway course, in the present case within the turn.
5. This is the oldest example of a trackway of a turning sauropod, which combined with several other well-documented examples, shows that various groups of sauropod trackmakers ranging in age from Early Jurassic to Late Cretaceous, were capable to do tight turns over a couple of meters only.
6. Trackways of turning sauropods are now widely distributed in time (Early Jurassic to Late Cretaceous) and space (Asia, Europe and North America). Although they are still not often reported, they seem to be more common than previously assumed and will be important in analyses on sauropod locomotion from trackways.

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