Biosis: Biological Systems (2021) 2(1), 217-228
https://doi.org/10.37819/biosis.002.01.0093

Lower Cretaceous Dinosaur Trackways Exposed by Water Erosion in Sichuan Province, China

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ABSTRACT

A newly discovered saurischian dominated tracksite in the Lower Cretaceous Jiaguan Formation in southeastern Sichuan province reveals 13 sauropod trackway segments representing ichnogenus *Brontopodus* and three theropod trackways. This is a typical Type 1 Jiaguan Formation deposit dominated by tetrapod tracks with no significant tetrapod body fossils. The tracks occur in a river channel exposure of feldspathic quartz sandstone about 20–25 m wide and ~ 60 m long. The trackways are exposed on both banks but eroded away in the central channel area. The sauropod tracks represent relatively small animals with pes print lengths ranging from 24.5 cm to 33.9 cm. The theropod trackways include a large example (footprint length 46.5 cm with metatarsal traces) and two smaller parallel trackways with footprint lengths less than 20 cm. The author also discussed the erosion of tracks and trackway by water erosion, especially their morphological changes.

ARTICLE HISTORY

Received: 20-02-2021
Revised: 28-02-2021
Accepted: 11-03-2021

KEYWORDS

Jiaguan formation
Saurischians
Sauropod tracks
Theropod tracks
Brontopodus

1 Introduction

Fossil deposits assemblages can be divided into five types according to their relative abundances of tracks and bones (Lockley, 1991; Lockley & Hunt, 1994). Type 1 deposits contain only tracks, Type 2 are dominated by tracks, Type 3 have bones and tracks in almost the same number, Type 4 are dominated by bones, and Type 5 contain only bones. The Jurassic red beds of Sichuan Basin have yielded abundant tracks and bones in roughly equal abundance, and so belonging to Type 3. However, in the Early Cretaceous, the fossil assemblages of Sichuan Basin are differently composed indicating a change to Type 1 and Type 2. Moreover, track and skeletal records both indicate that sauropods flourished in the Jurassic Sichuan Basin, while ornithopods were less common (Peng et al., 2005). In the Early Cretaceous Sichuan Basin, the Jiaguan Formation was dominated by saurischians tracks (non-avian theropods and sauropods), however, some track assemblages from the Jiaguan Formation indicate that the abundance of ornithopods was locally as high as that of sauropods in fluvial and lacustrine environments (Xing et al., 2016a). All sauropod tracks from the Jiaguan Formation have been assigned to ichnogenus *Brontopodus*, while theropod tracks show higher diversity.

On July 14, 2020, the staff of the Natural Resources Station of Huangjing Town, Gulin County, discovered a large number of regular indentations on a 3000 m^2 slab in Changtan, Huangjing Laolin Scenic Area, Huangjing Town, Gulin County (Fig. 1). On August 26, 2020, the main authors (LX, GP, YY, and BT) visited the track site and confirmed that these indentations are dinosaur tracks. Thirteen sauropod trackways and three theropod trackways were found in an area of 1322 m^2. The morphology of these tracks and the alteration caused by water currents are evaluated below.

2. Materials and methods

All tracks including those inundated by water from the Changtan site were outlined with white crayon and photographed (Fig. 2). The tracks in partially inundated areas were traced on large sheets of transparent plastics. No natural casts were collected.

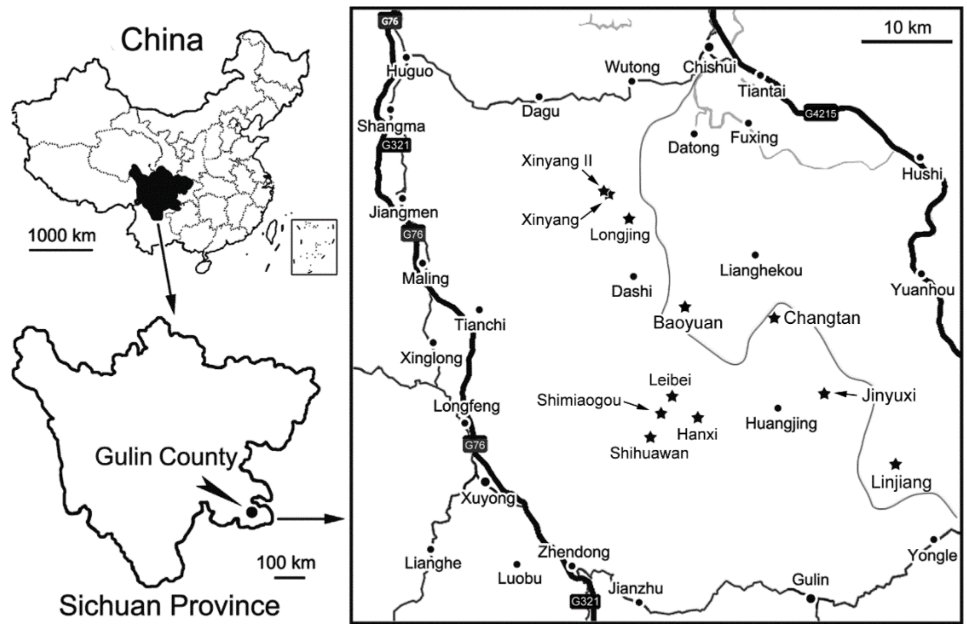

Figure 1. Geographical setting showing the location (star icon) of the Lower Cretaceous dinosaur tracksites in Sichuan Province, China.

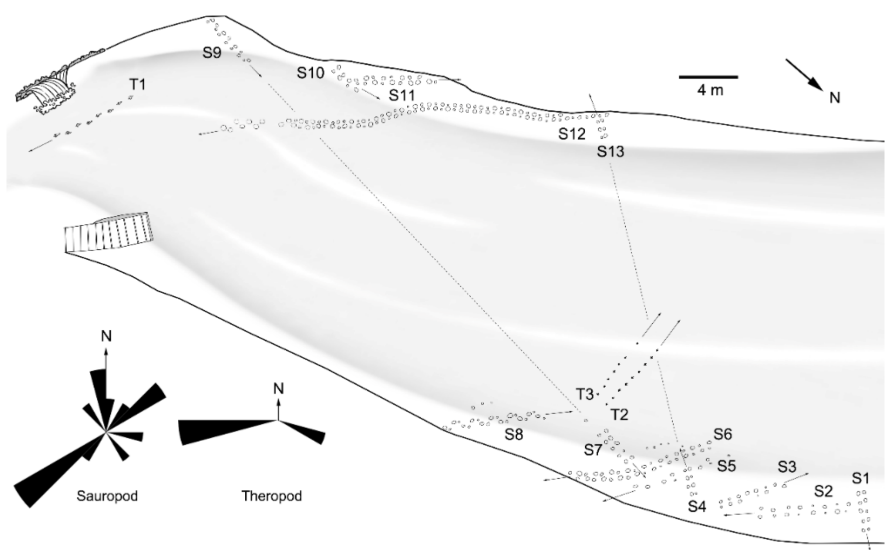

Figure 2. The distribution map of dinosaur trackways and the rose diagram of the sauropod and theropod trackways orientations at Changtan site of Sichuan Province, China.

The whole exposed surface was photographically recorded using a remote controlled four axis quadcopter (DJI Inspire 1: weight: 3400 g; max service ceiling above sea level: 4500 m; max flight time: 15 min; max wind speed resistance: 10 m/s and with DJI GO App, iOS 8.0 or later) with a 12 mega–pixel camera (model X5, with a 15 mm lens). After taking off from the ground, the DJI Inspire 1 was controlled remotely, and it provided real–time HD video through a mobile APP (DJI GO version 3.1.23).

Maximum length (L), maximum width (W), pace length (PL), stride length (SL), pace angulation (PA) and rotation of tracks (R) were measured according to the standard procedures of Leonardi (1987) and Lockley and Hunt (1995). For the trackways of sauropod, gauge (trackway width) was quantified for pes and manus tracks using the ratios WAP/P'L and WAM/M'L (Marty et al., 2010). Hip heights and speed estimations of the theropod, and sauropod trackmakers were derived from the trackways following the methods of Alexander (1976), Thulborn (1990), and González Riga (2011).

3. Geological setting

The Changtan track site is located at the southern edge of the Sichuan Basin (GPS: 28°18'44.63"N, 105°46'13.50"E). Based on the report of a regional geological survey, the Cretaceous strata in the Changtan area belong to the Jiaguan Formation (Xing et al., 2016a). The lithology and chronology of the Jiaguan Formation have been described in detail in a previous paper by the main authors (Xing et al., 2016a). The Jiaguan Formation is comprised of thick, brick-red, feldspathic, quartz-sandstone (Sichuan Provincial Bureau of Geology aviation regional Geological Survey team, 1976). It was deposited unconformably above the red mudstones of the Lower Cretaceous Tianmashan Formation or the Upper Jurassic Penglaizhen Formation and in conformable contact with the sandy conglomerate and mudstone of the overlying Upper Cretaceous Guankou Formation (Gu & Liu, 1997).

The tracksite is associated with the feldspathic quartz sandstone of the Upper Member of the Jiaguan Formation. The Upper Member is 345–1000 m thick and is comprised of feldspathic quartz sandstone interbedded with thin layers of lenticular mudstone and siltstone. The sediments of the Jiaguan Formation are alluvial fan, riverain and desert deposits (Geng, 2011). Chen (2009) argued that the Upper Member represents a meandering stream deposit interbedded with deposition from small, braided rivers. The track-bearing surface is exposed on both sides of the river, but due to erosion, the tracks appear to have been eroded away

4. Sauropod tracks

4.1 Description

There are a total of 13 sauropod trackways at the Changtan site, distributed on both sides of the river (Figs. 3, 4; Table. 1). The tracks of the S13 trackway are badly damaged, thus only tracks from the S1−S12 trackways were measured. The length of pes prints ranges from 24.5 cm to 33.9 cm. The S8 trackway is described in detail due to its better preservation.

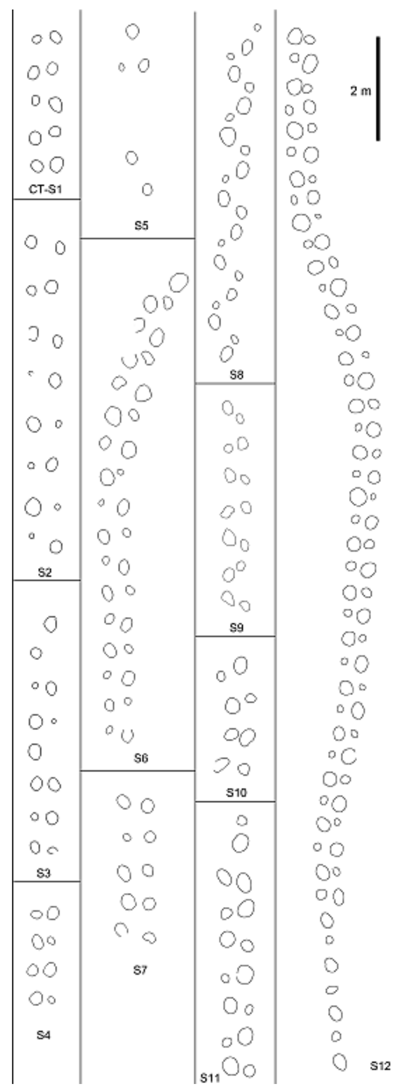

Figure 3. Interpretive outline drawing of sauropod trackways at Changtan site of Sichuan Province, China.

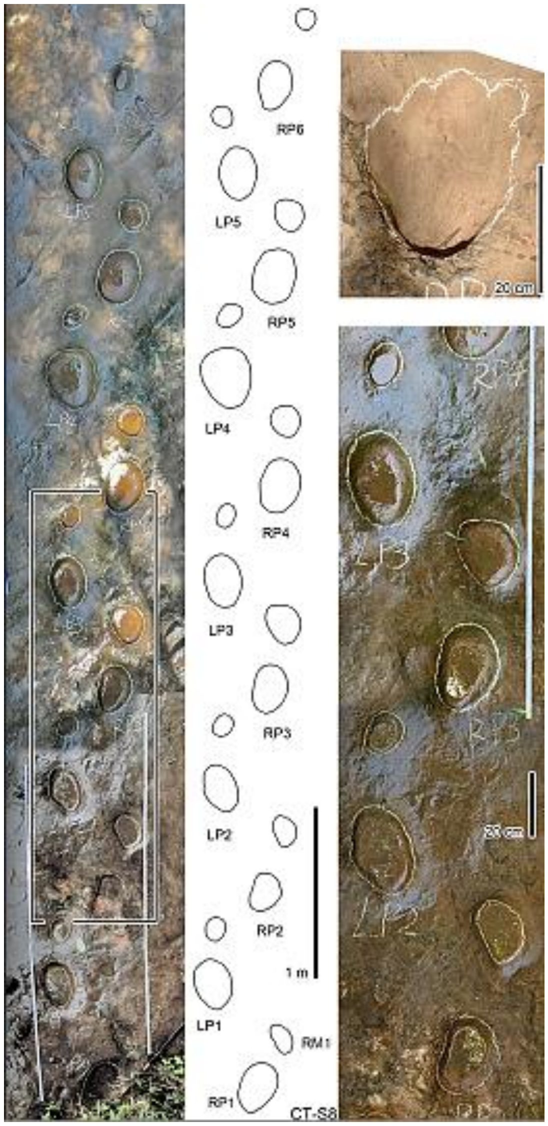

Figure 4. Photograph (A, C) and interpretive outline drawing (B) of well-preserved sauropod trackway CT-S8 and a close-up photograph of well-preserved CT-S3-RP5 (D)

The mean length of the manus and pes prints from the CT-S8 trackway is 13.4 cm and 29.9 cm, respectively. The manus impressions lie anterior to those of the pes. The average length/width ratios of the manus and pes impressions are 0.8 and 1.4, respectively. Taking the best-preserved examples RP2 and RM2, the manus prints are oval-shaped and the marks of digit I and V and the metacarpophalangeal regions are distinct, while the pes prints are oval, and the marks of digits I−IV are indistinct and the metatarsophalangeal region is smoothly curved. The manus and pes impressions are rotated approximately 53° and 21° outward from the trackway axis, respectively. The pace angulation of the pes is 130°.

Only one pes track of S1−S12 trackways, CT-S3-RP5, shows relatively distinct digit traces. The length and width of the pes from the CT-S3-RP5 track is 27.9 cm and 23.0 cm, respectively, making the length/width ratio 1.2. The pes prints are oval, the marks of digits I−IV are distinct and developed. However, it is extraordinary that the digit IV area is quite developed, while the digit I area is weaker. The metatarsophalangeal region is smoothly curved.

4.2 Comparison and discussion

The pes and manus morphology and trackway configurations of the Changtan site quadruped trackways are typical of sauropods (Lockley, 1999, 2001; Lockley & Hunt, 1995). Most sauropod trackways in China are wide- (or medium-) gauge and are, therefore, referred to the ichnogenus *Brontopodus* (Lockley et al., 2002a).

The WAP/P'ML ratios of the S1−S13 trackways are variable. Except for the badly-preserved CT-S5 and S13, measurement data for all trackways (eleven in total) were recorded. Marty et al. (2010) considered a WAP/P'L ratio of 1 to be the demarcation point between narrow- and medium-gauge trackway trackways with a value of 1.2 to be between medium- and wide-gauge, and trackways with a value above 2 to typically be wide-gauge. By this standard, CT-S8 and CT-S10 (each with a value of 0.9) are narrow-gauge; CT-S11 and CT-S12 (1.0) and CT-S4 (1.1) are between narrow- and medium-gauge; CT-S3 and CT-S9 (1.2) are between medium- and wide-gauge; and CT-S6 (1.3), CT-S2 (1.4), CT-S1 (1.6), and CT-S7 (1.8) are wide-gauge. Overall, the S1−S13 trackways are medium–wide gauge, which is similar to other sauropod trackways from the Jiaguan Formation (Xing et al., 2016a). The wide-gauge of the *Brontopodus*-type trackways suggests that the tracks were left by titanosaurian sauropods (Wilson & Carrano, 1999; Lockley et al., 2002a).

The heteropody (ratio of manus to pes size) of the S1−S12 tracks is 1: 1.5 –1:3.6, which is notably variable and will be discussed in detail in 'Preservation.' Otherwise, S1−S12 shows the typical features of *Brontopodus*, including*:* 1) a medium to wide-gauge; 2) pes tracks that are longer than wide, and are large and outwardly directed; 3) U-shaped manus traces; and 4) a high degree (1:3 in *Brontopodus birdi*) of heteropody (Farlow et al., 1989; Lockley et al., 1994; Santos et al., 2009).

Table 1. Measurements (in centimeter, degree and square centimeter) of the sauropod trackways from Changtan site, Sichuan Province, China.

	L	W	R	PL	SL	PA	L/W	WAP	WAP/ P'L	A	H
CT-S1-M	20.3	18.9	26	69.5	121.6	122	1.1	—	—	307.6	—
CT-S1-P	26.4	21.9	|28|	75.4	124.0	110	1.2	46.0	1.6	472.3	1.8
CT-S2-M	14.0	15.2	|36|	94.7	158.2	113	1.0	—	—	181.9	—
CT-S2-P	26.9	22.9	31	92.7	168.2	131	1.2	39.2	1.4	497.7	3.4
CT-S3-M	16.2	16.8	|27|	73.6	125.8	119	1.0	—	—	246.9	—
CT-S3-P	24.5	21.5	|22|	68.5	131.1	129	1.2	29.5	1.2	416.5	2.4
CT-S4-M	14.8	18.5	47	64.2	111.4	118	0.8	—	—	224.2	—
CT-S4-P	26.2	22.0	37	62.0	110.2	128	1.2	26.8	1.1	461.5	2.0
CT-S5-M	8.4	15.3	—	—	—	—	0.5	—	—	106.3	—
CT-S5-P	25.2	19.8	—	70.4	—	—	1.3	—	—	393.9	—
CT-S6-M	15.9	17.2	36	69.9	112.1	107	1.0	—	—	232.9	—
CT-S6-P	31.1	23.7	|20|	67.7	112.1	113	1.3	38.0	1.3	591.0	2.6
CT-S7-M	22.0	22.4	29	75.0	126.4	116	1.0	—	—	398.4	—
CT-S7-P	27.7	21.3	33	80.5	125.9	102	1.3	53.1	1.8	458.5	1.5
CT-S8-M	13.4	16.5	53	70.9	120.5	118	0.8	—	—	177.7	—
CT-S8-P	29.9	21.5	21	65.4	119.0	130	1.4	27.7	0.9	518.6	3.3
CT-S9-M	15.6	21.6	55	67.6	121.2	125	0.7	—	—	277.2	—
CT-S9-P	25.1	19.5	32	67.4	121.1	131	1.3	27.9	1.2	393.6	1.5
CT-S10-M	19.4	21.5	29	73.6	125.6	117	0.9	—	—	327.0	—
CT-S10-P	29.3	26.1	33	72.8	127.8	131	1.1	29.0	0.9	631.9	2.2
CT-S11-M	18.8	22.9	46	73.6	122.2	111	0.8	—	—	358.6	—
CT-S11-P	33.9	27.3	24	69.4	122.2	123	1.3	33.3	1.0	750.6	2.5
CT-S12-M	14.3	16.2	42	57.8	91.0	104	0.9	—	—	184.9	—
CT-S12-P	29.0	25.4	32	53.5	90.9	116	1.2	27.8	1.0	594.5	3.6

Abbreviations: L: Maximum length; W: Maximum width; R: Rotation; PL: Pace length; SL: Stride length; PA: Pace angulation; WAP: Width of the angulation pattern of the pes (calculated value); L/W and WAP/P'L are dimensionless; A: area; H: heteropody; CT-Sx-M: manus data of CT-Sx trackway; CT-Sx-P: pes data of CT-Sx trackway.

For sauropods, Alexander (1976) first suggested that hip height be estimated as h=4 × foot length, whereas, later, Thulborn (1990) estimated hip height as h=5.9 × foot length. González Riga (2011) estimated hip height as h=4.586 × foot length (pes length). Based on the formula of Thulborn and González Riga, the SL/h ratios of the CT-S1–S4, S6–S12 sauropod trackway are between 0.53–1.06 (h=5.9) and 0.68–1.36 (h=4.586) (Table. 2). Using the equation to estimate speed from trackways (Alexander, 1976), the locomotion speed of the trackmakers of CT-S1–S4 and S6–S12 is between 1.28–3.91 km/h and 1.72–5.25 km/h, respectively, and accordingly suggests walking. The speed of the S2 trackmaker is significantly higher than that of others, and S12 is the slowest. Nevertheless, these tracks are consistent with most Chinese *Brontopodus*-type trackways (Xing et al., 2016a, 2016b).

	h=5.9		h=4.586	
	SL/h	v (km/h)	SL/h	v (km/h)
CT-S1	0.80	2.40	1.02	3.23
CT-S2	1.06	3.91	1.36	5.25
CT-S3	0.91	2.87	1.17	3.86
CT-S4	0.71	1.99	0.92	2.68
CT-S6	0.61	1.67	0.79	2.25
CT-S7	0.77	2.34	0.99	3.14
CT-S8	0.67	1.94	0.87	2.60
CT-S9	0.82	2.45	1.05	3.29
CT-S10	0.74	2.24	0.95	3.00
CT-S11	0.61	1.75	0.79	2.35
CT-S12	0.53	1.28	0.68	1.72

Table 2. The speed of the sauropod trackmakers of Changtan site, Sichuan Province, China.

5. Theropod tracks

5.1. Description

Of the three trackways, T1 consists of at least eight tracks. T2 and T3 have at least nine and seven tracks, respectively (Figs. 5–7; Table. 3).

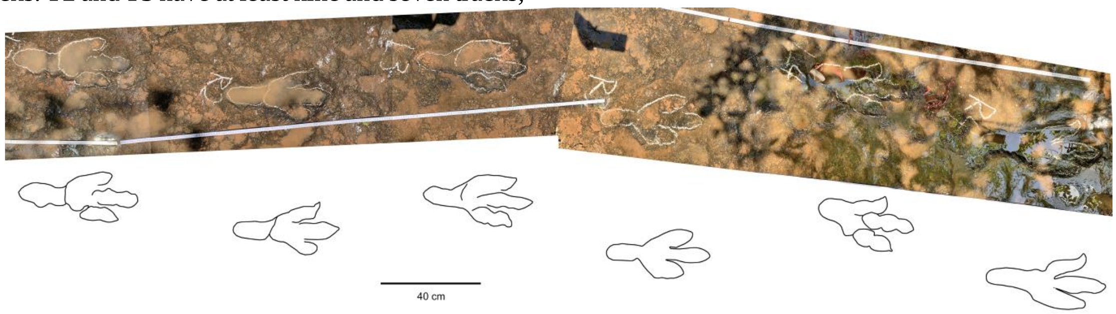

Figure 5. Photograph and interpretive outline drawing of well-preserved theropod trackway CT-T1 at Changtan site of Sichuan Province, China.

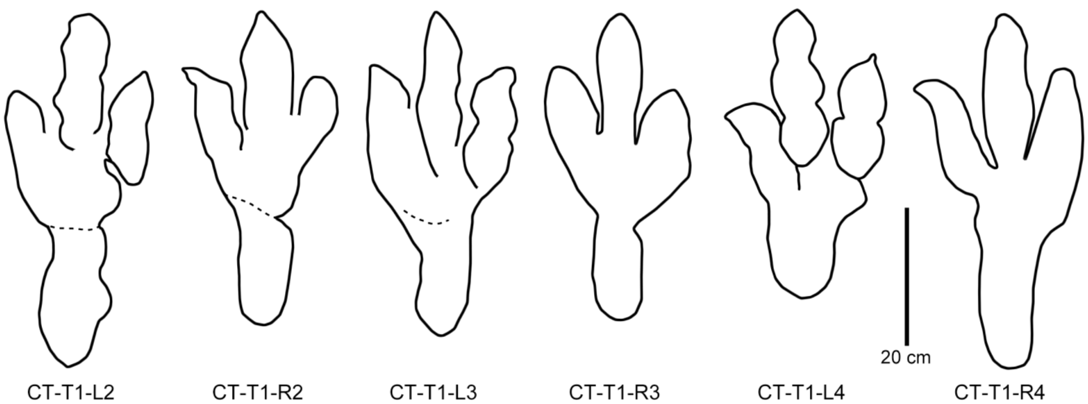

Figure 6. Interpretive outline drawing of CT-T1 theropod tracks at Changtan site of Sichuan Province, China.

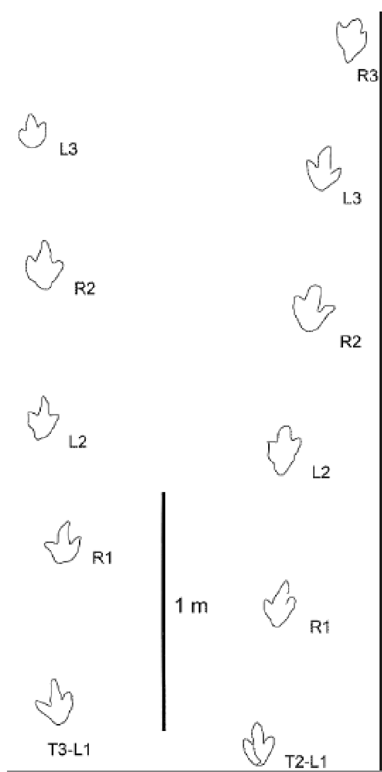

Figure 7. The distribution map of CT-T2 and T3 at Changtan site of Sichuan Province, China.

Table 3. Measurements (in cm) of the theropod tracks from the Changtan site, Sichuan Province, China.

	L	W	L'	PL	SL	PA	II-IV	L/W	M
CT-T1-L1	35.0	23.5	46.0	81.0	160.0	171	—	1.5	—
CT-T1-R1	36.5	21.0	50.0	79.5	159.5	158	—	1.7	—
CT-T1-L2	30.0	19.5	46.5	83.0	162.0	162	48	1.5	0.52
CT-T1-R2	30.0	19.5	44.5	81.0	157.0	154	52	1.5	0.53
CT-T1-L3	31.5	19.5	46.5	80.0	162.0	156	49	1.6	0.43
CT-T1-R3	30.5	18.5	45.5	85.5	163.5	153	47	1.6	0.53
CT-T1-L4	32.5	22.5	43.5	82.5	—	—	57	1.4	0.48
CT-T1-R4	34.5	19.5	49.5	—	—	—	51	1.8	0.43
Mean	32.6	20.4	46.5	81.8	160.7	159	51	1.6	0.49
CT-T2-L1	17.9	12.5	—	60.8	125.2	167	58	1.4	0.52
CT-T2-R1	19.4	11.9	—	65.2	124.9	169	56	1.6	0.58
CT-T2-L2	21.0	13.1	—	60.3	118.5	168	48	1.6	0.45
CT-T2-R2	19.7	17.1	—	58.8	113.0	168	66	1.2	0.41
CT-T2-L3	19.0	13.9	—	54.8	—	—	64	1.4	0.57
CT-T2-R3	18.6	12.4	—	—	—	—	42	1.5	0.32
Mean	19.3	13.5	—	60.0	120.4	168	56	1.4	0.48
CT-T3-L1	18.7	14.1	—	66.5	118.7	162	63	1.3	0.47
CT-T3-R1	17.7	15.4	—	53.6	117.8	165	81	1.1	0.48
CT-T3-L2	18.1	12.2	—	65.2	118.2	171	60	1.5	0.59
CT-T3-R2	20.3	13.6	—	53.4	—	—	59	1.5	0.55
CT-T3-L3	14.3	9.8	—	—	—	—	63	1.5	0.48
Mean	17.8	13.0	—	59.7	118.3	166	65	1.4	0.52

Abbreviations: L: Maximum length; W: Maximum width; L': Length of the footprint with metatarsal traces; PL: Pace length; SL: Stride length; PA: Pace angulation; II-IV: The interdigital divarication II–IV; L/W is dimensionless; M: Mesaxony.

CT-T1 is well-preserved, the mean length and width for CT-T1-L1–R2 are 32.6 cm and 20.4 cm, respectively. The mean length/width ratio is 1.6. Each track has elongated metatarsal traces, which average 14 cm in length, ranging 11 cm–16.5 cm. Including the metatarsal traces, the mean length of the track is 46.5 cm. Several tracks show dividing lines (crease traces) between the proximal ends of the metatarsal pads and the metatarsophalangeal pads of digit IV.

CT-T1-L4 exemplifies the morphology. Digit III traces project the farthest anteriorly, followed by digits II and IV. One round and blunt metatarophalangeal pad trace posterior to digit II can be seen. There is no clear boundary between the metatarophalangeal pad trace and the elongate metatarsal pad (~11cm) of digit IV. However, in R2, the metatarophalangeal pad trace should be very close to the line of the axis of digit III. The deep, concave impressions of digits II-III retain pad impressions that have a formula (including metatarsophalangeal pad II) of x-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 (51°). The divarication angle between digits II and III (23°) is smaller than that between digits III and IV (28°).

The other tracks from CT-T1 are consistent with CT-T1-L4 in their general features. The divarication angles between digit II and IV range from 47° to 57°. The average pace angulation is 159°, and the footprint length to pace length ratio is 1:2.5.

Two small-size trackways, CT-T2 and T3, are nearly parallel, between which the distance increases from 72 cm to 107 cm. CT-T2 measures 19.3 cm in total length, slightly longer than CT-T3 (17.8 cm). The length/ width ratio of both of CT-T2 and T3 are 1.4. In CT-T3, the best preserved, digit III projects the farthest anteriorly (followed by digits II and IV), the metatarsophalangeal area trace of digit IV is round and blunt and positioned near the axis of digit III, the digits have relatively wide divarication angles between digits II and IV (65°), the phalangeal pad traces are unclear, each digit impression ends in a sharp claw mark, the average pace angulation is 166°, and the footprint length to pace length ratio is 1:3.4. CT-T2 is similar to T3 in morphology. In CT-T2 L2 and R3 may have partial metatarsal pads, the divarication angles between digits II and IV are lower (56°), the average pace angulation is 168°, and the footprint length to pace length ratio is 1:3.1.

5.2 Comparison and discussion

Theropod tracks with long metatarsal pads are common in the Jiaguan Formation, such as the Baoyuan specimens (Xing et al., 2011), Hanxi specimens (Xing et al., 2015), and Linjiang specimens (Xing et al., 2018). Among the best known theropod tracks with metatarsal pads are those from the Lower Cretaceous Glen Rose Formation of Glen Rose, Texas (Kuban, 1989). The Texas tracks are very similar to the specimens from the Jiaguan Formation.

It is puzzling that such tracks with long metatarsal pads, which are very rare in other Early Cretaceous tracksites of China, occur so frequently in the Jiaguan Formation. Thus, we must consider possible explanations. In the first instance it appears special sedimentation conditions can be ruled out as there is no evidence that Jiaguan Formation deposits are sedimentologically unique or unusual. In this regard, Jiaguan stream deposits interbedded with deposition from small braided rivers (Chen, 2009) have no additional observable effect on other trackmakers, including small tridactyl dinosaurs and sauropods. If stepping into deep and soft sediments, the feet of trackmakers would leave their metatarsal traces, and their digit traces would also likely reveal changes attributable to the same sedimentological conditions, yet we see fairly "normal" digit area traces (Gatesy et al., 1999). Another possibility is that the Jiaguan Formation was host to a special (behaviorally-unusually) group of medium-to-large sized theropods that occasionally assumed a particular gait in which the metatarsals touched the sediments (Kuban, 1989), but without strongly affecting their speeds (Xing et al., 2015). However, to the best of the authors' knowledge no similar behavior is common among any extant birds (Xing et al., 2015).

Xing *et al*. (2011) first discovered the theropod tracks with metatarsal pads from the Jiaguan Formation and assigned them to cf. *Irenesauripus* isp. The main reasons for this diagnosis were that the majority of the divarication angles between digits III and IV are greater than between digits II and III and phalangeal pad impressions are typically weak to absent (Gangloff et al., 2004). However, *Irenesauripus* tracks are large (38–53 cm, Sternberg, 1932), with slender digits and an overall lily shape (V-shaped posteriorly) (Lockley et al., 2011), which is similar to Jurassic *Kayentapus*. Xing et al. (2011) assigned the Baoyuan specimens to cf. *Irenesauripus* isp., which was mainly due to the wide divarication angle and slender digits of the best preserved BYA2 specimen. However, this trait is not replicated in other theropod tracks with metatarsal pads from the Jiaguan Formation. The Baoyuan specimens are the best preserved and four of them have digit I traces, which is absent in CT-T1.

The average length/ width ratio and anterior triangle length/ width ratio of CT-T1 is 1.6 and 0.49, which are typical for the morphofamily Eubrontidae (1.7 and 0.37–0.58, Olsen et al., 1998; Lockley, 2009). Occasionally, *Eubrontes* shows a digit I trace, as in *Eubrontes zigongensis* from the Lower Jurassic Zhenzhuchong Formation of Sichuan Province, China (Xing et al., 2014). In summary, we reclassify the theropod tracks with metatarsal pads from the Jiaguan Formation as *Eubrontes* morphotype tracks. In this regard, recent studies have recognized well preserved *Eubrontes* in the Jiaguan Formation of China under the new ichnospecies name *E. nobitai* (Xing et al., 2021). This conclusion recognizes that although *Eubrontes* is abundant in the Lower Jurassic and characteristic of the global Lower Jurassic Biochron defined by Lucas (2007), the ichnogenus occurs sporadically elsewhere in the post-Lower Jurassic track record. The present study confirms this conclusion. In a related study (Lockley and Milner, in review) the temporal distribution of Eubrontes in space and time is reviewed and compared with the distribution of other large theropod track ichnotaxa.

CT-T2 and T3 have similar average length/ width ratio and anterior triangle length/ width ratio with CT-T1, which is 1.4 and 0.48 (T2), 1.4 and 0.52 (T3) respectively. These tracks are assignable to small-sized *Eubrontes* morphotype tracks. Small-size *Eubrontes* morphotype tracks are common in the Jiaguan Formation (Xing et al., 2016a). For small theropods (length less than 25 cm) and large theropods (ML greater than 0.25m), Thulborn (1990) suggested that hip height h=4.5 × foot length and 4.9 × foot length. The SL/h ratios of the CT-T1 to T3 trackways are 1.01, 1.39 and 1.48 respectively, indicating a walking gait. The speed of these trackmakers is 3.60, 4.54 and 4.83 km/h respectively, which indicates the trackmakers were not strongly affected by the muddy sediments.

6. Preservation

At the Changtan site, the river flows continuously throughout the year, with the largest waterflow occurring from May to July and the least in winter. Before 2018, only the area in the middle of the stream-bed bedrock was naturally exposed. In 2018, when the local government refurbished the scenic area, the bedrock was expanded by excavators and the alluvial cover on both sides of the river were removed, exposing abundant tracks. Erosion from the flowing river likely explains the lack of visible tracks in the middle of the bedrock exposure.

Prior to the erosion of the middle portion of track-bearing surface it is likely that many more trackways would have been the preserved, than are visible today on the west and east banks of the river. The location and orientation of the sauropod trackways gives some clues to the original distribution of trackways. For example the orientation of trackways S9 and S7 have both the same orientation and the same alignment, from south to north, despite a gap of ~43 m (Fig. 8). Likewise the orientation and alignment of trackway segments S4 and S13 from northeast to southwest, is the same despite a gap of ~27 m.

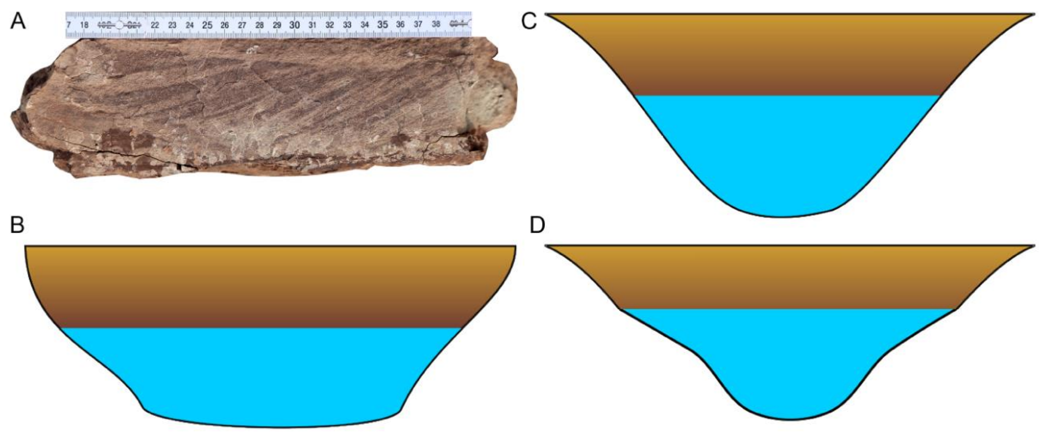

Figure 8. A: a cross section of natural sauropod pes cast of Qingquansi site VII, Shangdong Province. B–D cross sections of Changtan sauropod casts. The blue area indicates water.

There are 13 sauropod trackways for which orientations can be measured, five on the west bank and eight on the east bank. Collectively there appear to be two preferred trends one involves three trackways heading due north and another oriented towards the NNE. Two other aforementioned trackway segments S4 and S13, which may represent the same trackway, are oriented to the SSE, at 180^{o} to the NNE-oriented trackway. The second trend is revealed by six trackways, four oriented towards the SE, and two oriented to the NW. This is a fairly clear bimodal trend. It is intertsing the the three theropod trackways reveal a bimodal East-West trend (two closely parallel to the west and one slightly south of east: i.e., ESE)

Most tracks have been eroded by the currents, with the sauropod tracks suffering the most pronounced changes. The Changtan sauropod tracks are bowl-shaped, with smooth, low inclination inner walls and angled at about 30° from the bottom to the bedding plane surface. Such low angle track walls can either be explained as characteristic features of transmitted tracks, or erosion of true tracks, or erosion of transmitted tracks. Clearly the location of the tracks in a river channel area has caused significant the erosion of the tracks whether not the unweathered surface originally exposed true tracks or some form of transmitted tracks.

The eroded tracks have distinct, round pits in their middle that occur in no consistent pattern, and evidently represent the erosion of tracks in a process similar to pothole formation, although in this case the tracks served as preformed potholes, naturally predisposed to enlargement in the middle of the river, where erosion was most intense. As track enlargement proceeded with time, left and right tracks join together into single depressions that have almost destroyed the original track morphologies.

Erosion appears to have been consistent in altering the morphology of similar tracks. In CT-S2, for instance, the manus print is surprisingly small, with a heteropody of 3.4, significantly higher than most other tracks from the same area. One possibility is as that the whole trackway was eroded, the upper part of the track was most eroded, and the lower part, was less modified by erosion: compare the blue and brown areas of Fig. 8C-D. CT-S2 has a heteropody of 3.6, and some manus prints are also very small, similar to CT-S12. In accounting for this pronouncd heteropody we cannot rule out other factors. For example, Cretaceous trackways from the Humaca site in Bolivia (Lockley et al., 2002b) were shown to have track walls that had partially collapsed, so that the perimeters on the bedding plane surface were smaller than at the deeper level of the track floors.

However, the pattern of some trackways is more likely due to trackmaker behavior than erosion. In CT-S8, for example, the left manus print is distinctly smaller (11.7 cm in length, 126.2 m^2 in area), the right one is larger (14.8 cm in length, 220.6 m^2 in area). It is notable that the left manus tracks are situated, more medially, in front of the pes tracks, whereas those on the right side are more laterally situated, more to the lateral margins of the trackway. Thus, the trackway is asymmetric and could reflect a subtle individual behavioral or gait irregularity, or possibly a feature of the substrate such as slope.

Theropod tracks on sandstone bedding planes appear to be less eroded, with no clear patterns, although the edges of the tracks are gradually being destroyed. In CT-T2 and T3 trackways, the further the track is toward the center of the river, the higher the degree of erosion.

10. Conclusion

In recent years numerous tracksites have been reported from the Lower Cretaceous Jiaguan Formation in Sichuan Province. The first summary presented by Xing and Lockley (2016) and Xing *et al*. (2016) listed 14 named sites yielding an estimated total of more than 300 individual trackmakers. Since then other named sites have been reported including the the Gaoqing-Yongsheng and Huibu sites (Xing et al., 2017), the Linjiang site (Xing et al., 2018), the Jinyuxi site (Xing et al., in review) and the present Changtan site. Thus, to date there are at least 19 known sites which is a 50% increase in site reports in less than five years. To date 15 of these sites are heavily saurischian (sauropod and theropod) dominated making the Changtan site typical of the formation. As the Jiaguan Formation is almost devoid of useful tetrapod body fossils it remains a Type 1 deposit, consistently yielding evidence of saurischian dominated faunas. This renders the ichnofauna the only important source of information on the tetrapod fauna.

Acknowledgments

This research was funded by the National Natural Science Foundation of China (No. 41772008), and the 111 project (B20011), China.

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