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EARLY CRETACEOUS SAUROPOD AND ORNITHOPOD TRACKWAYS FROM A STREAM COURSE IN SICHUAN BASIN, SOUTHWEST CHINA

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Abstract— The newly discovered dinosaur tracksite in the Lower Cretaceous Jiaguan Formation of Sichuan Province herein named the Longjing tracksite reveals at least four diagnostic trackways; three attributable to sauropods and one to an ornithopod. All trackways occur on a sandstone bedding plane in a river bed, and consequently are subject to constant erosion. The individual tracks are rounded to oval dish shaped impressions (concave epireliefs) that may have been underprints prior to exhumation and erosion. However the trackway configurations are clear with the sauropod trackways showing quadrupedal progression, outward rotation of the pes and typical low pace angulation ~100°, but poor preservation of manus traces. By contrast ornithopod trackways represent bipeds with a quadripartite pes morphology, inward pes rotation and higher pace angulation between 138° and 157°. Ichnotaxonomically, the sauropod trackways cannot be determined with certainty but are slightly similar to co-eval specimens from nearby Hanxi and Xinyang tracksites that have been assigned to cf. *Brontopodus*. The ornithopod trackway that lacks a manus imprint is assigned to *Caririchnium*, a characteristic ichnogenus from the Early Cretaceous.

INTRODUCTION

Since the first report of dinosaur footprints from the Jiaguan Formation of the Sichuan Basin (Zhen et al., 1994), this unit has become important for the study of dinosaur faunas in southwestern China. Tetrapods represented by footprints from this formation include ornithopods, sauropods, theropods, birds, and pterosaurs (Zhen et al., 1994; Xing et al, 2007, 2011a, 2013).

The main locality, the Lotus tracksite, is located at the southeastern border of the Sichuan Basin in Qijiang District, Chongqing Municipality (Xing et al., 2007). This tracksite comprises two assemblages: (1) the *Wupus-Pteraichnus* ichnoassemblage, which is dominated by multiple and mainly parallel trackways of a small tridactyl trackmaker (*Wupus*) and by five pterosaurs trackways (*Pteraichnus*); and (2) the *Caririchnium* ichnoassemblage, which is dominated by ornithopod tracks (*Caririchnium lotus*) (Xing et al. 2013a). The Baoyuan tracksite at the southern border of the Sichuan Basin preserves several theropod trackways (cf. *Irenesauripus* isp.) with imprints showing traces of the metatarsal pad (Xing et al., 2011a).

During fieldwork in 2014, another three tracksites (Hanxi, Xinyang, and Longjing) were discovered in the Jiaguan Formation in close geographic proximity to each other (Fig. 1). The Longjing tracksite, described here, is located 23.5 km northwest of the Hanxi tracksite, and the Xinyang tracksite is a further 3.5 km northwest of the Longjing tracksite. The previously described Baoyuan tracksite (Xing et al., 2011a) is located roughly halfway between the Hanxi and Longjing tracksites. Interestingly, the kinds of dinosaur footprints recorded at each of the three new sites differ. The Hanxi tracksite shows footprints of sauropods, larger theropods (*Eubrontes* type), and small ornithopods (cf. *Ornithopodichnus*). The Xinyang tracksite footprints of sauropods, larger theropods (*Eubrontes* type), and small-sized theropods. Finally, the Longjing tracksite shows footprints of sauropods and medium-sized ornithopods. This suggests a high diversity of dinosaurs in this area. On the other hand, this difference may also suggest the possibility of substrate influence on vertebrate trackmakers. For example, based on the western Canada tracksites, McCrea et al. (2014) considered, it was biped-dominant vs. quadruped-dominant, where the quadrupeds were dominant on low energy surfaces with high organic content with bipeds rare or entirely absent; bipeds were dominant on high energy surfaces with low organic content, but the quadrupeds were still there in numbers. In 2013, during a trip to Longjing Village, Dashi Township, Tao Yang, an employee of the Publicity Department of Xuyong County, listened to reports of rhinoceros footprints from local villagers that were forwarded to the major authors of this paper (XL, PG and YY) who studied the tracksite in September, 2014. The "rhinoceros" interpretation by the locals is related to the name of the area which is Xiniutuo (meaning: rhinoceros bay) reflecting running waters flowing into the Shawan River and the tracksite which is completely flooded (Fig. 2). These tracks of quadrupeds were made by sauropods or large-ornithopods, and they are another significant example of track fossils giving rise to folk legends (Xing et al., 2011b).

Abbreviations: L / R = Left / right; O = Ornithopod; S = Sauropod; LJ = Longjing tracksite, Xuyong, Sichuan Province, China.

GEOLOGICAL SETTING

The Longjing tracksite is located at the southern margin of the Sichuan Basin (GPS: 28°24'53.83"N, 105°36'27.10"E). According to the 1:20000 regional geological survey report of Xuyong Mapping (H-48-XXXIV), the Cretaceous strata of the Xuyong region belong to the Jiaguan Formation, which is characterized by a set of thick, brick-red, feldspathic, quartz sandstones (Sichuan Provincial Bureau of Geology aviation regional Geological Survey team, 1976) (Fig. 3). The age of the Jiaguan Formation has been estimated to be between 117 Ma and 85 Ma (Aptian–Santonian) by Li (1995) and between 140 and 85 Ma (Berriasian–Santonian) by Gou and Zhao (2001), these age both based on the results of electron spin resonance (ESR). Recent pollen studies indicate a Barremian–Albian age for the Jiaguan Formation (Chen, 2009). The Longjing tracksite is an exposure of the upper member of the Jiaguan Formation and displays current ripples and abundant mud cracks.

MATERIALS AND METHODS

The site is covered by shallow, fast flowing water. Therefore a temporary dam was constructed upstream to redirect the water and facilitate study and measuring of the tracks. In order to document complete trackways, photos were edited using Adobe Photoshop photomerge. Latex molds of two best perserved ornithopod tracks LJ-O1-R1 and LJ-O1-R2 were made, and reposited at Xuyong County Bureau of Land and Resources, Sichuan, China.

Speed of trackmakers was calculated using the formula of Alexander (1976). For sauropods, Alexander (1976) first suggested that hip height h = 4×foot length, whereas, later, Thulborn (1990) estimated h = 5.9×foot length. The relative stride length (SL/h) may be used to determine whether the animal is walking (SL/h≤ 2.0), trotting (2<SL/h<2.9), or running (SL/h≥2.9) (Alexander, 1976; Thulborn, 1990). For the ornithopod trackway we used the calculations of Thulborn (1990) for small ornithopods (ML < 25 cm) with the hip height h= 4.6 ML. It is important to note that calculations of hip height refer to a posture with straight legs. The natural posture as well as spaces for joints of limb elements might alter these values (see McCrea et al., 2014).

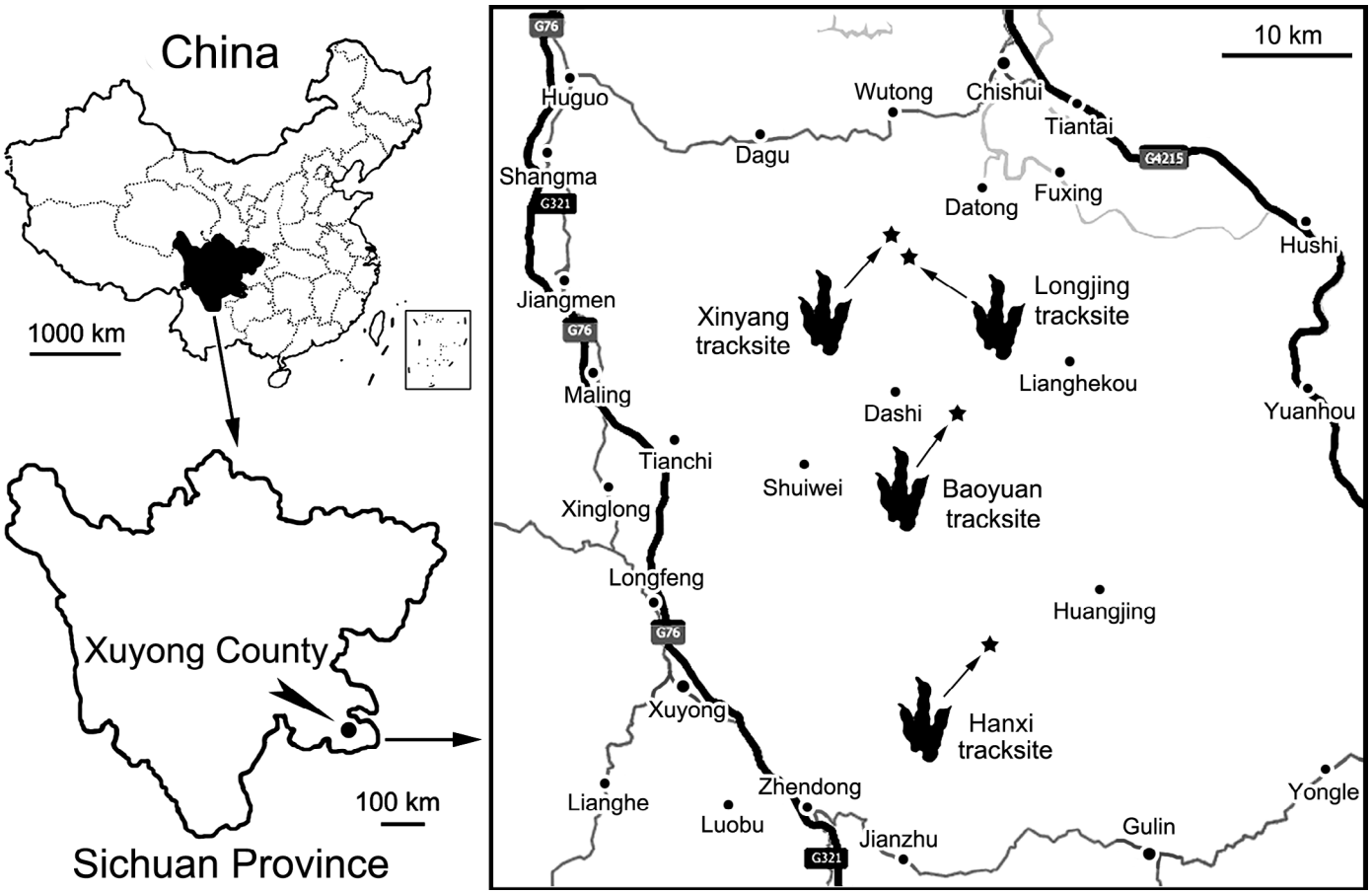

FIGURE 1. Map showing the position of Lower Cretaceous footprint localities in southeastern Sichuan Province, China (pentagram icon) with the Lower Cretaceous Longjing tracksite described in this paper, and the Xiyang, Baoyuan (Xing et al., 2011a), and Hanxi tracksites.

DINOSAUR TRACKS

Sauropod Tracks

Description

The Longjing tracksite preserves at least three trackways of large quadrupeds: LJ-S1–S3 (Figs. 2, 4–5) (Table 1). All tracks and trackways remain *in situ.* LJ-S1 (Figs. 4A–D, 5A–B) is the longest trackway and includes twenty pes traces spanning a distance of more than 10 m. Long-term erosion by the river has made the digits of the pes tracks indistinct. Moreover, the tracks are preserved as smooth rounded to oval dish shaped impressions characteristic of underprints. However, as it was impossible to find exposures of an overlying bed, that might reveal the true tracks, this interpretation is not proven, but based on the smooth topography of the tracks. The length/width ratios of the pes impressions are ~1.2, and the long axis of each pes impression is rotated approximately 24° outward from the trackway axis. The average pes pace angulation is 109°. LJ-S1 also includes numerous shallow manus prints, unfortunately, these prints have been eroded by the flowing water and most are almost unidentifiable with little morphological detail. In general, the combination of the original mode of preservation, probably as underprints on this surface, and recent river erosion makes the quality of preservation suboptimal. However, the trackway patterns are sufficiently diagnostic to differentiate the three sauropod trackways from the ornithopod trackway (described below).

LJ-S2 is shorter than LJ-S1 in length (Table. 1) and with only 2–3 manus impressions. The manus impressions of LJ-S2 lie anteromedially to the pes impressions. Taking the best-preserved manus-pes association LP1–LM1 (Fig. 5C–D) as a representative example, the length/width ratios of the manus and pes impressions are 1.0 and 1.4 respectively. The rounded manus shows indistinct digit marks. The pes impression is oval, while the digits are indistinct, and the metatarso-phalangeal region is smoothly curved. LP1–LM1 have a high degree of heteropody (relatively small manus trace compared with the pes trace) (1:1.7 of XY-S1). LJ-S3, which is not figured here, only preserves two pes traces. They are are morphologically similar to those of LJ-S1.

The SL/h ratios of the LJ sauropod trackway are calculated between 0.43–0.63 and accordingly suggest walking, and the mean locomotion speed of the trackmaker is estimated to have been between 1.12–1.76 km/h.

Comparisons

Most sauropod trackways in China are wide- (or medium-) gauge and are therefore referred to the ichnogenus *Brontopodus* (Lockley et al., 2002). Recently discovered sauropod trackways from Hanxi and Xinyang are consistent with the characteristics (e.g. length/width ratios, heteropody, etc.) of *Brontopodus* type tracks from the Lower Cretaceous of the USA (Farlow et al., 1989; Lockley et al., 1994), but are narrow-gauge and thus have been provisionally classified as cf. *Brontopodus* (Xing et al., in prep. a, b). The distribution of pressure (load) through the sediment is spread downwards and outwards (see Allen, 1989; Manning, 2004, p. 104), an inference that implies that underprints are wider than the true tracks that generated them from higher levels. This conclusion is fairly obvious but has rarely been stated explicitly. However, some authors (Thulborn 1990; Lockley 1991) have noted that such undertracks have more diffuse margins with increasing depth. This could be the case in the Longjing trackways that are quite similar in shape and size to those from Hanxi and Xinyang. Length/width ratio values for pes tracks are within the ranges for *Brontopodus*, however, trackways have a narrow-gauge pattern and partly show a high degree of heteropody (see above). This is another example for the combination of typical *Brontopodus* and *Parabrontopodus* patterns in some Cretaceous sauropod trackways, a phenomenon further explored in a future study. Therefore, we refer the sauropod tracks from the Longjing tracksite tentatively to cf. *Brontopodus*.

Ornithopod Tracks

Description

The Longjing tracksite preserves at least one distinct pes-only ornithopod trackway, cataloged as LJ-O1, with eleven pes prints (Figs. 6–7). A second tridactyl trackway is present, but currently impossible

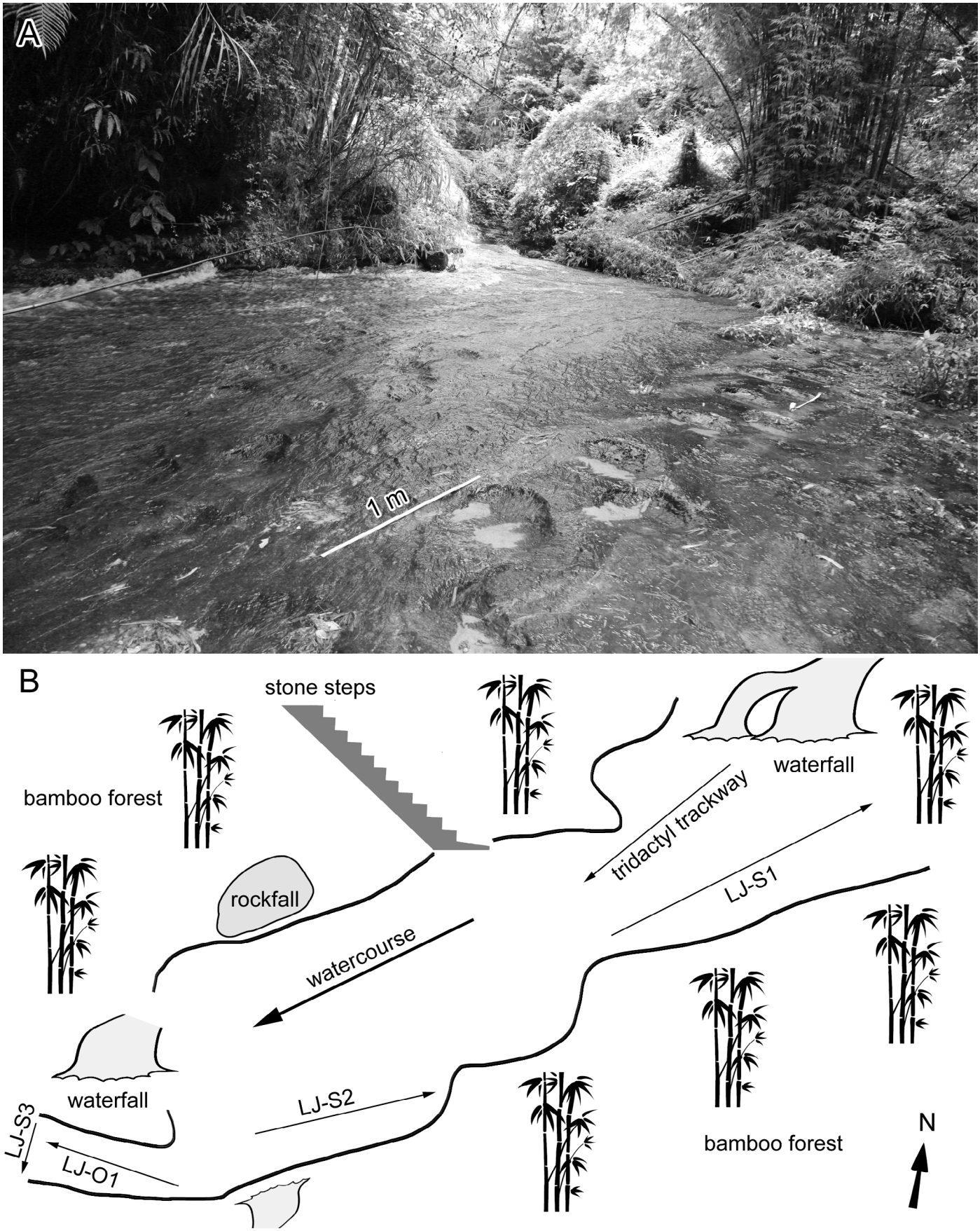

FIGURE 2. Photograph (A) and map (B) of Longjing tracksite, Southwest China. Notice the track surface which is flooded by the river.

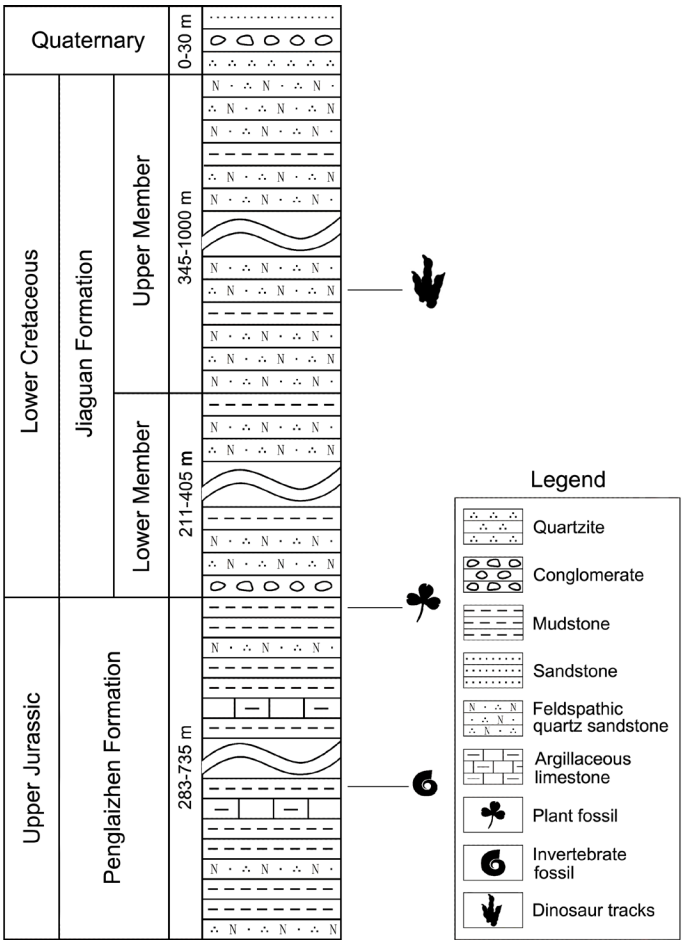

FIGURE 3. Stratigraphic section of the Jurassic–Cretaceous in the study area with the position of footprints and body fossil remains.

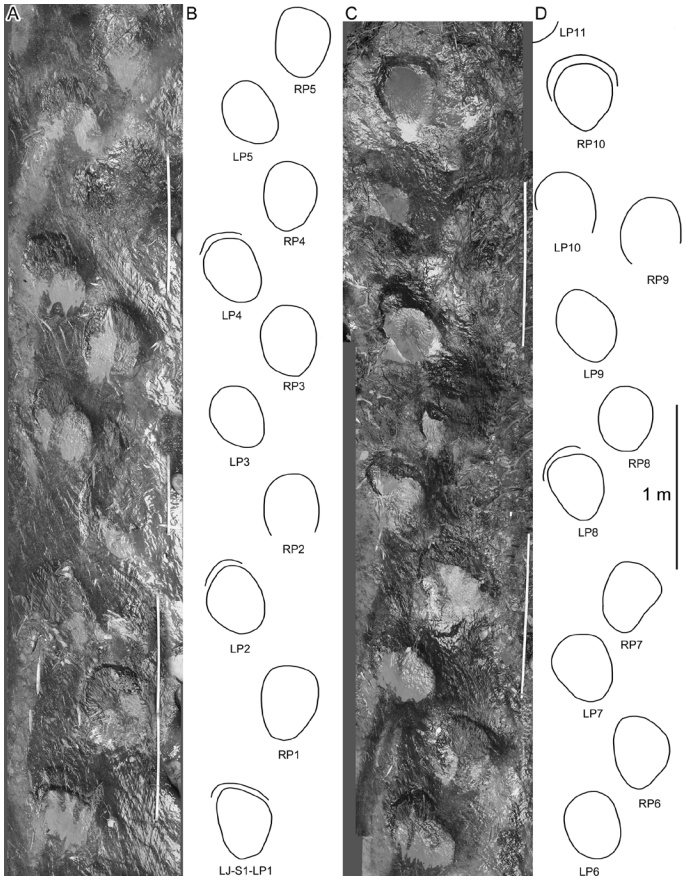

FIGURE 4. Photographs (**A** and **C**) and sketches (**B** and **D**) of sauropod trackway LJ-S1 from the Longjing tracksite, southeastern Sichuan Province, China.

to diagnose due to the fast water flow and severe erosion. All tracks remain *in situ*.

The pes traces of LJ-O1 are mesaxonic, functionally tridactyl, plantigrade, and have a mean length of 22.8 cm and an average and median length/width ratio of 1.4 (ranging between 1.2 and 1.5). O1-R1 (Fig. 7) is the best-preserved representative of LJ-O1. The pes trace of O1-R1 shows a quadripartite morphology, consisting of impressions of three digits and a heel pad separated by pronounced ridges. The ML/MW ratio is 1.4 while the anterior triangle length/width ratio (mesaxony) is 0.34. Based on the outline of the pad impressions the digit II trace appears the shortest, while the trace of digit IV appears the longest. Claw traces or ungual marks are absent or indistinctly preserved. The heel is transverse oval in shape. There is a distinct space between the three digit traces and the heel trace. The interdigital divarication of II–IV is 46°. The average pace angulation of LJ-O1 is 149° (range between 138° and 157°). The pes traces show consistent inward rotation, mean 9°–10°.

The progression of the trackmaker is calculated as follows: The SL/h ratio of LJ-O1 is 0.91 and accordingly suggests a walking gait; using the formula of Alexander (1976), the speed of LJ-O1 is 2.48 km/s, slightly lower than 3.02–6.01 km/s of the Zhaojue specimens.

Comparisons

Lower Cretaceous ornithopod trackways are well-known from Europe, North America, and East Asia. To date, four valid ornithopod ichnogenera have been named from the Lower Cretaceous: *Amblydactylus* (two ichnospecies), *Caririchnium* (three ichnospecies), *Iguanodontipus* (one ichnospecies), and *Ornithopodichnus* (one ichnospecies) (Lockley et al., 2014). *Amblydactylus* is the trackway of a quadrupedal or facultatively bipedal ornithopod. It was originally described by Sternberg (1932) based on material from the Gething Formation of North America. Pes imprints are about twice the size of those of *Iguantodontipus*, an ichnogenus of similar morphology, that was introduced by Sarjeant et al. (1998) based on footprints from the Lower Cretaceous of Great Britain. The latter was considered to be synonymous with *Amblydactylus* by Lucas et al. (2011), but a distinct ichnogenus by Lockley at al. (2014). *Ornithopodichnus* was originally described from the Cretaceous Jindong Formation of Korea by Kim et al. (2009) and is characterized by small to large pes imprints with week mesaxony (relative length/width of anterior triangle) compared with *Amblydactylus*, *Iguanodontipus* and *Caririchnium* that show moderate mesaxony. *Ornithopodichnus* is known from trackways of both bipedal and quadrupedal trackmakers.

LJ-O1 resembles *Caririchnium*, an ichnogenus originally described from the Antenor Navarro Formation, Brazil, and defined by Leonardi (1984). Lockley et al. (2014) described the pes trace of *Caririchnium* as possessing a sub symmetric, quadripartite morphology consisting of impressions of three digits, and a heel pad separated by pronounced ridges. Either, the pes was functionally plantigrade, or the impression of the heel pad the result of exceptionally soft substrate. The ridges represent what, in life, were concave-up creases separated by convex-down pads. The ungual traces reported in Leonardi (1984) occur within, not distal to, the traces of digits II–IV.

The length/width ratio and mesaxony values of LJ-O1 are similar to those of the three *Caririchnium* ichnospecies (Lockley et al., 2014) and Morphotype A from the Zhaojue (Sichuan) tracksite (Xing et al., 2014) (Table 3). *Caririchnium lotus* is known from the Jiaguan Formation of Qijiang (Chongqing Municipality) (Xing et al., 2007) and the Zhaojue specimens are from the slightly older Feitianshan Formation (Berriasian–Barremian) (Xing et al., 2014). This indicates that the *Caririchnium* type is fairly widespread in the Lower Cretaceous strata of southwestern China.

Caririchnium lotus tracks are divided into small (19–23 cm in length), medium (25–30 cm), and large (37–40 cm) size classes (Xing

TABLE 1.Measurements (in cm) of the sauropod trackways from Longjing tracksite, Sichuan Province, China.

Number.	ML	MW	R	PL	SL	PA	ML /MW
LJ-S1-LP1	42.0	35.0	10°	83.0	139.0	127°	1.2
LJ-S1-RP1	44.0	36.0	15°	72.0	131.0	119°	1.2
LJ-S1-LP2	45.0	38.0	41°	80.0	118.0	104°	1.2
LJ-S1-RP2	44.0	39.0	12°	70.0	108.0	105°	1.1
LJ-S1-LP3	45.0	38.0	39°	66.0	101.0	102°	1.2
LJ-S1-RP3	45.0	40.0	18°	64.0	99.0	91°	1.1
LJ-S1-LP4	46.0	38.0	43°	74.0	110.0	87°	1.2
LJ-S1-RP4	45.0	38.0	9°	85.0	127.0	110°	1.2
LJ-S1-LP5	50.0	40.0	40°	70.0	116.0	112°	1.3
LJ-S1-RP5	45.0	40.0	19°	70.0	121.0	123°	1.1
LJ-S1-LP6	48.0	42.0	19°	68.0	117.0	115°	1.1
LJ-S1-RP6	46.0	40.0	19°	71.0	116.0	114°	1.2
LJ-S1-LP7	48.0	39.0	30°	67.0	123.0	126°	1.2
LJ-S1-RP7	45.0	39.0	26°	71.0	104.0	98°	1.2
LJ-S1-LP8	46.0	38.0	22°	67.0	111.0	99°	1.2
LJ-S1-RP8	43.0	39.0	17°	79.0	—	—	1.1
LJ-S1-LP9	48.0	38.0	—	—	105.0	—	1.3
LJ-S1-RP9	—	—	—	—	—	—	—
LJ-S1-LP10	46.0	36.0	—	73.0	—	—	1.3
LJ-S1-RP10	45.0	42.0	—	—	—	—	1.1
Mean	45.6	38.7	24°	72.4	115.4	109°	1.2
LJ-S2-LP1	49.5	35.6		—	—	—	1.4
LJ-S1-LM1	33.4	32.3		—	—	—	1.0

Abbreviations: **ML**, maximum length; **MW**, maximum; **R**, rotation; **PL**, pace length; **SL**, stride length; **PA**, pace angulation; and **ML/MW** is dimensionless.

TABLE. 2 Measurements (in cm) of ornithopod tracks from Longjing tracksite, Sichuan Province, China.

Number (LJ-)	ML	MW	II-IV	PL	SL	PA	M	ML /MW
O1-R1	22.0	19.5	47°	52.0	98.0	157°	0.34	1.1
O1-L2	23.0	23.0	—	48.0	97.0	157°	—	1.0
O1-R2	23.5	20.0	45°	51.0	99.0	152°	0.30	1.2
O1-L3	22.0	20.5	—	51.0	96.0	147°	—	1.1
O1-R3	23.0	21.0	—	49.0	90.0	146°	—	1.1
O1-L4	22.5	20.5	—	45.0	93.0	138°	—	1.1
O1-R4	23.0	—	—	54.5	98.0	146°	—	—
O1-L5	23.0	—	—	48.0	—	—	—	—
O1-R5	23.0	—	—	—	—	—	—	—
Mean	22.8	20.8	46°	49.8	95.9	149°	0.32	1.1

Abbreviations: **ML**, maximum length; **MW**, maximum width (measured as the distance between the tips of digits II and IV); **II-IV**, angle between digits II and IV; **PL**, pace length; **SL**, stride length; **PA**, pace angulation; and **ML/MW** is dimensionless.

TABLE. 3. The comparison of typical Early Cretaceous Caririchnium

	ML/MW	M	References
Caririchnium magnificum	1.2	0.31	Xing et al., 2014
Caririchnium leonardii	1.0	0.43	Lockley, 1987
Caririchnium lotus	1.2	0.30	Lockley et al., in press: Fig. 2E
Zhaojue *Caririchnium*	1.1	0.37	Xing et al., 2014
Longjing *Caririchnium*	1.1	0.34	This text

Abbreviations: **ML**, maximum length; **MW**, maximum width; and **M**, mesaxony (length/width ratio for the anterior triangle).

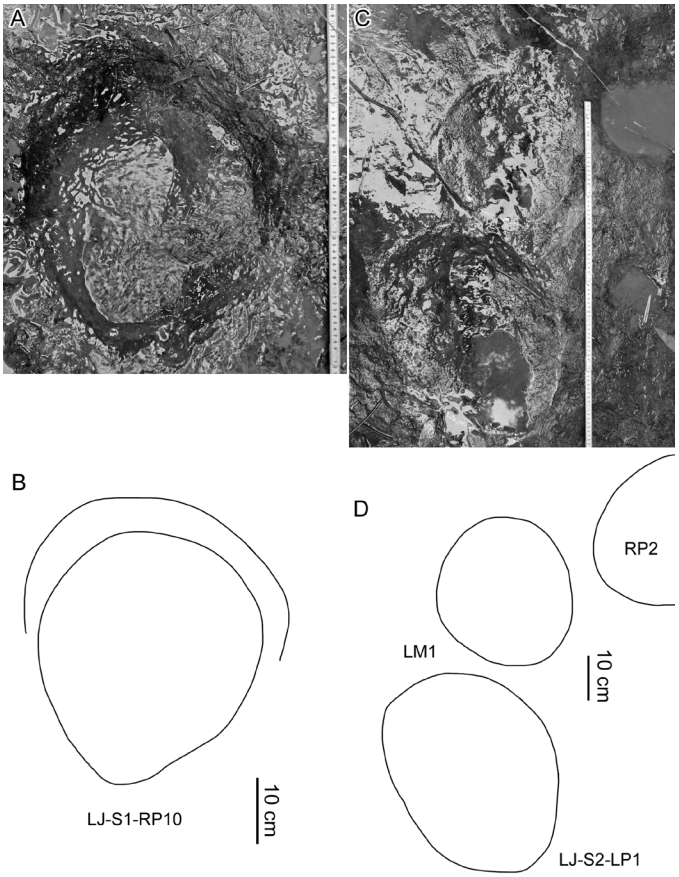

FIGURE 5. Photographs (**A** and **C**) and sketches (**B** and **D**) of the well-preserved sauropod tracks from Longjing tracksite, southeastern Sichuan Province, China.

et al., 2007). Even if differently-sized trackmaker species cannot be completely excluded, the identical morphology of these tracks suggests the presence of ontogenetic stages with juvenile, subadult and adult individuals. This is also supported by the observation that juveniles seldom have manus prints, sub-adult have sporadic cases of manus prints, and all adult specimens show manus prints. Xing et al. (2007) argued that the juvenile trackmakers were bipedal, while the adult trackmakers were quadrupedal, and that the sub-adult trackmakers were facultatively bipedal. A similar suggestion was made by Norman (1980, 1986) and Leonardi (1997). The LJ-O1 tracks have a mean length of 22.8 cm and no associated manus prints are observed. The numerous Zhaojue specimens with a similar length (20–30 cm) only preserve three pairs of associated manus-pes prints. Besides the numerous possible preservational explanations, the absence of manus prints in LJ-O1 may be attributable to the trackmakers being largely bipedal sub-adults similar to *C. lotus*. This hypothesis does not rule out the possibility that they belong to other unnamed *Caririchnium* types.

The comparison of the trackmaker's speed with that of the Zhaojue ornithopod shows that the former progressed slightly slower with 2.48 km/s vs. 3.02–6.01 km/s of the latter.

CONCLUSIONS

The dinosaur footprint assemblage from the Longjing tracksite in southeastern Sichuan Province, China consists of three sauropod trackways and a single determinable ornithopod trackway. A better preserved longer sauropod trackway shows a rather narrow-gauge pattern due to the gait of the trackmaker or, alternatively, to the undertrack nature of the imprints. In this respect they are similar to coeval trackways from nearby Hanxi and Xinyang tracksites that have been assigned to cf. *Brontopodus*.

The ornithopod trackway can be assigned to the characteristic Lower Cretaceous ichnogenus *Caririchnium* based on the imprint morphology and trackway pattern. *Caririchnium* is known from the same unit, the Jiaguan Formation of Chonqing Municipality. The lack of a manus trace can be explained either by preservational factors or the

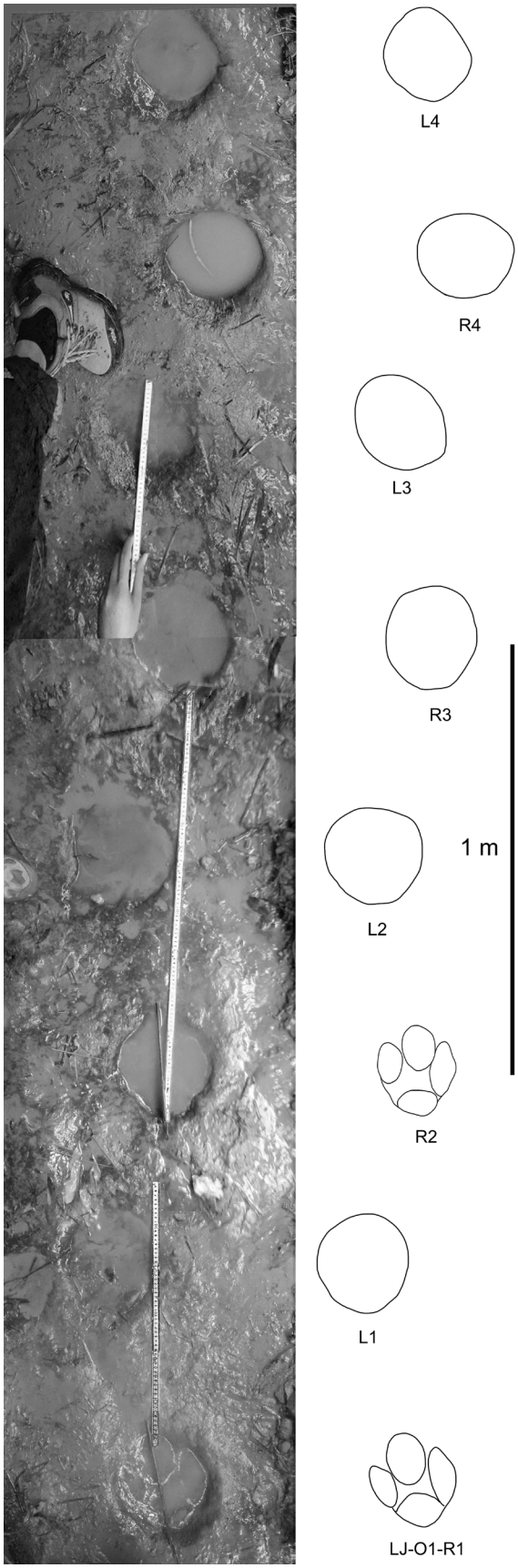

FIGURE 6. Photograph (**A**) and sketch (**B**) of ornithopod trackway LJ-O1 from Longjing tracksite, Southwest China.

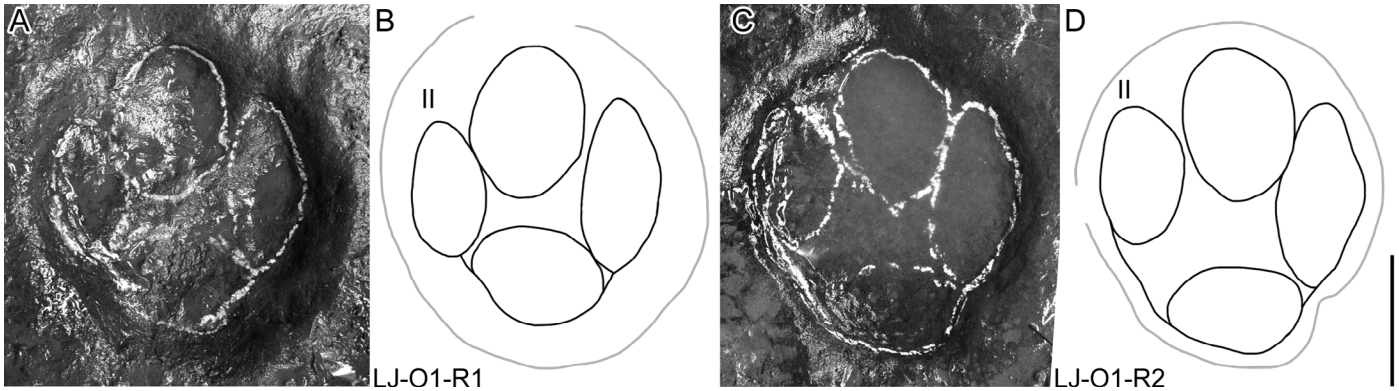

FIGURE 7. Photographs (**A** and **C**) and sketches (**B** and **D**) of the well-preserved ornithopod tracks (*Caririchnium*) from the Longjing tracksite, southeastern Sichuan Province, China. Notice lack of a manus trace.

relatively small size of the imprints suggesting a subadult trackmaker individual with bipedal progression.

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