Cretaceous Research 60 (2016) 176–193

Contents lists available at ScienceDirect

Cretaceous Research

journal homepage: www.elsevier.com/locate/CretRes

A diverse saurischian (theropod–sauropod) dominated footprint assemblage from the Lower Cretaceous Jiaguan Formation in the Sichuan Basin, southwestern China: A new ornithischian ichnotaxon, pterosaur tracks and an unusual sauropod walking pattern

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A R T I C L E I N F O

Article history:
Received 1 September 2015
Received in revised form
29 November 2015
Accepted in revised form 5 December 2015
Available online xxx

Keywords:
Sauropod
Theropod
Ornithopod
Pterosaur
Footprints
Jiaguan Formation
Lower Cretaceous

A B S T R A C T

A sample of fallen blocks of fluvial sandstone from the Lower Cretaceous Jiaguan Formation of Sichuan Province yielded an assemblage of dinosaur and pterosaur tracks preserved as natural impressions and casts. Collectively the assemblage reveals 132 tracks representing at least 30 trackways of tridactyl and didactyl theropods, sauropods, ornithopods and pterosaurs. Ichnotaxonomically, the trackways of small tridactyl theropods (pes lengths 7–18 cm) are indeterminable, whereas the trackway of a small didactyl dromaeosaur (pes length up to 7.5 cm) is tentatively assigned to cf. *Velociraptorichnus*. The sauropod trackways are assigned to cf. *Brontopodus* based on the medium to nearly wide-gauge pattern. Other characteristics are the U-shaped manus and strong heteropody. One sauropod trackway shows a peculiar pattern with a lack of left manus imprints, and an unusual position and rotation of right manus imprints. Different scenarios and explanations for this phenomenon are discussed. Ornithopod trackways are the most abundant in the sample and characterized by pes imprints of a small biped that are assigned here to the new ichnospecies *Caririchnium liucixini*. It is characterized by an unusual broad shape and weak mesaxony. Bivariate analysis of different *Caririchnium* ichnospecies reveals increasing mesaxony toward the larger forms, a trend that is the reverse of typical theropod ichnotaxa, where large imprints have weak mesaxony. Three isolated, small pterosaur tracks (two manus, one pes) are visible on a single surface. They show strong similarities to the widespread ichnogenus *Pteraichnus*. This is the ninth report of tetrapod tracks from the Jiaguan Formation in recent years and represents one of the most diverse assemblages recorded to date. It is also rare evidence of typical didactyl dromaeosaur tracks and the co-occurrence of sauropod and ornithopod tracks in a fluvial depositional environment representing arid climate conditions.

1. Introduction

Widespread Jurassic lacustrine deposits have made the Sichuan Basin one of the core regions for dinosaur research in China (Peng et al., 2005). In contrast, Cretaceous sedimentary exposures of the Sichuan Basin are restricted to the basin's western and southern

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http://dx.doi.org/10.1016/j.cretres.2015.12.005

edges, and recovered skeletal fossils from these localities are limited to fragmentary small theropod (?dromaeosaur) remains and sauropod limb bones (Wang et al., 2008). Because of the sparse fossil record, the Cretaceous Sichuan Basin has been considered – an area of low dinosaur diversity, possibly because of unfavorable habitat conditions in the region during this period (Wang et al., 2008). However, since 2007, the discovery of a growing number of dinosaur track localities from the Lower Cretaceous Jiaguan Formation has changed this view by documenting a thriving Cretaceous dinosaur fauna (Xing et al., 2007, 2015a).

Dinosaur tracksites from the Jiaguan Formation include the Guanyinchong site reported by Young (1960), the Emei tracksite (Zhen et al., 1994; Matsukawa et al., 2006; Lockley et al., 2008, 2013), the Lotus (Xing et al., 2007, 2013a; Xing et al., 2015c) and Tiger (Xing et al., 2015b) tracksites from Qijiang area (Xing et al., 2007, 2013a; Xing et al., 2015c), the Baoyuan tracksite from the Chishui area (Xing et al., 2011), the Xinyang and Longjing tracksites from the Xuyong area (Xing et al., in press-a), and the Hanxi tracksite from Gulin area (Xing et al., 2015a).

Initially track records from the Jiaguan Formation were rare, and dominated by saurischians, such as *Yangtzepus* (Young, 1960), *Velociraptorichnus* (Zhen et al., 1994), *Minisauripus* (Zhen et al., 1994; Lockley et al., 2008), *Koreanaornis* (Zhen et al., 1994; Lockley and Harris, 2010). Since 2007, abundant ornithopod tracks have been found at the Lotus site (Xing et al., 2007). The Jiaguan Formation tracksites contain footprints of ornithopods, sauropods, non-avian theropods and birds, and in many cases pterosaur tracks are also present (Zhen et al., 1994; Xing et al., 2007, 2013a, 2015a). At the Hanxi tracksite, the longest theropod trackway from East Asia, and a diverse sauropod-, theropod-, and ornithopod-track assemblage was reported (Xing et al., 2015a). The relative abundance of morphotypes at these localities and their significance in characterizing the Jiaguan fauna are discussed below.

The dinosaur tracks reported here come from the Shimiaogou (meaning: stone temple valley) site (GPS: 28°12′57.54″, 105°38′31.49″; Fig. 1) which is located close to the Hanxi site, at a distance of about 3.5 km. This is the eighth tracksite recently discovered, described or otherwise known from the Jiaguan Formation. In November of 2014, one of the authors, Ting Xu, found the first dinosaur tracks at this locality. The major authors of this paper inspected the tracksite in April, 2015. Generally, the assemblage at the Shimiaogou site is similar to that known from the Hanxi site, with the addition of deinonychosaur and pterosaur tracks. Here we discuss the ichnotaxonomy of these footprints and introduce a new ornithischian ichnospecies. Furthermore, we document a sauropod trackway indicating an unusual behavior and walking pattern.

Institutional abbreviations and acronyms

L/R = Left/right; T = Theropod; S = Sauropod; O = Ornithopod; D = Deinonychosaurian; P = Pterosaur; SMG = Shimiaogou tracksite, Gulin, Sichuan Province, China.

2. Geological setting

The Sichuan Basin is part of the Yangtze paraplatform and is known for its large area and super-thick Mesozoic continental red beds (Gu et al., 1997). Continental coal-bearing detrital rocks

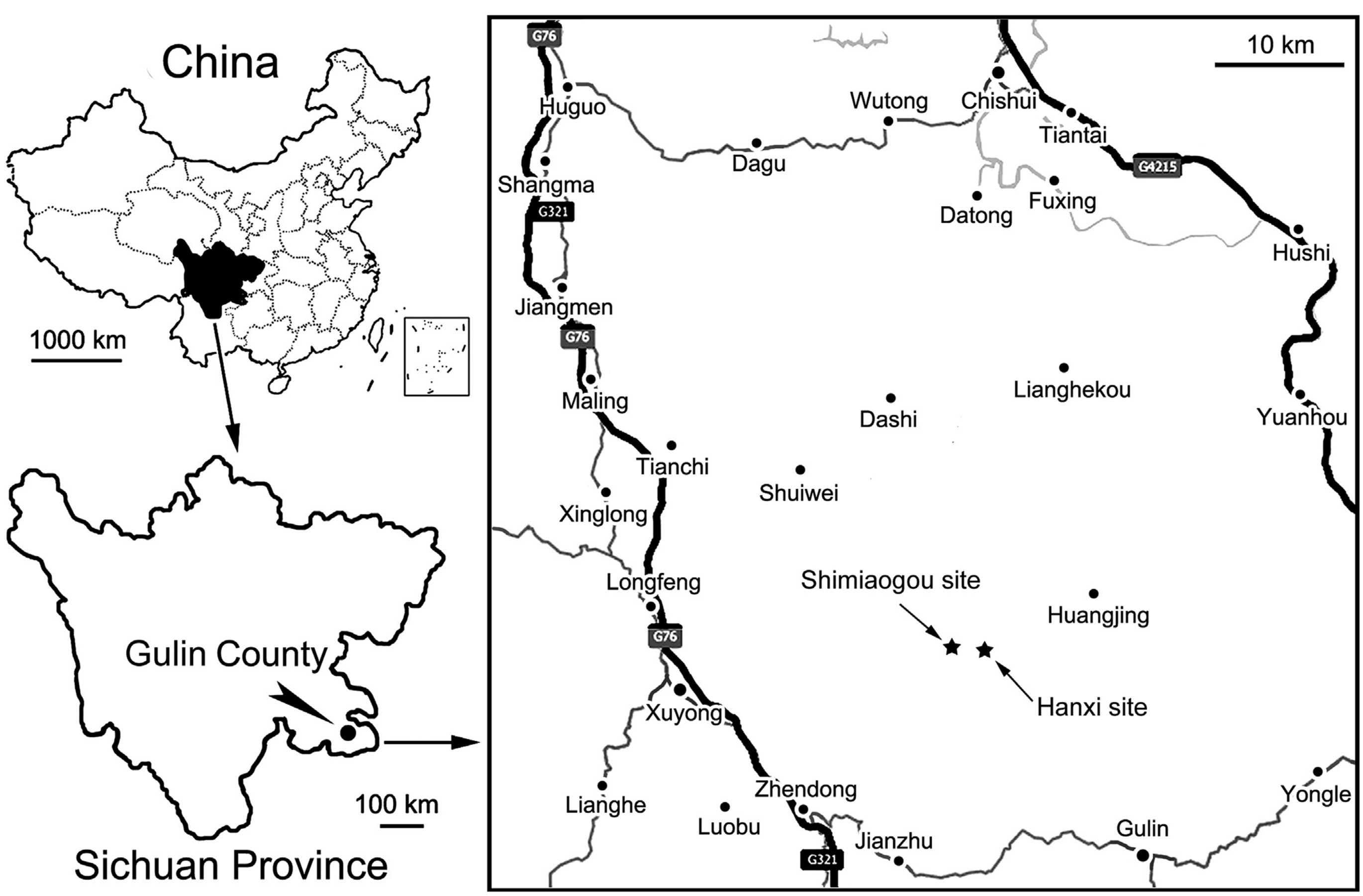

Fig. 1. Map showing the position of the Shimiaogou footprint locality discussed in this paper.

dominate the Upper Triassic strata; Jurassic and Cretaceous strata primarily consist of red continental detrital rocks. The former is largely located in north Sichuan and the latter in the west and south. All three sequences are hundreds of meters to over 3000 m in thickness (Gu et al., 1997).

From bottom to top, the exposed strata include the Middle Jurassic Shangshaximiao and Suining formations, the Upper Jurassic Penglaizhen Formation, the Lower Cretaceous Jiaguan Formation and Quaternary deposits (Xing et al., 2007, 2015c).

The Shimiaogou tracksite is located at the southern margin of the Sichuan Basin. The tracksite consists of several large fallen blocks from an exposure of the upper member of the Jiaguan Formation (Xing et al., 2015a: Fig. 2). The Jiaguan Formation is characterized by a set of thick, brick-red, feldspathic, quartz sandstones (Sichuan Provincial Bureau of Geology Aviation Regional Geological Survey Team, 1976). Well-developed wedge-shaped cross-stratification was observed in the large thick sandstone comprising the track-bearing blocks. The upper member of the Jiaguan Formation comprises primarily meandering river deposits interbedded with occasional anastomosing river deposits, and was formed under semi-arid and semi-humid climatic conditions in a tropical or subtropical climate (Chen, 2009; see also Wang et al., 2008). The surfaces which preserve tracks reveal mud cracks. Recent pollen studies indicate the age of the Jiaguan Formation is Barremian–Albian (Chen, 2009).

3. Materials and methods

At least 15 large fallen blocks occur at the site, spread over a distance of about 105 m. Most tracks are natural molds (concave epireliefs), while some are natural casts (convex hyporeliefs). The tracksite is located in a damp and torrid forest which means the tracks are often filled with water or covered by moss. After cleaning the track surface, the tracks were cataloged, photographed, and measured. Several photos were assembled to form a single image of the complete trackway, using Adobe Photoshop Photomerge.

Maximum length (ML), Maximum width (MW), divarication angle (II–IV), pace length (PL), stride length (SL), pace angulation (PA), and rotation (R) were measured according to the standard procedures of Leonardi (1987) and Lockley and Hunt (1995). Mesaxony (M) of tridactyl tracks (the degree to which the digit III protrudes anteriorly beyond the digits II and IV) was calculated according to the methods of Olsen (1980), Weems (1992), and Lockley (2009). For the trackways of quadrupeds, narrow-, medium- and wide-gauge (trackway width) was quantified for pes tracks using the ratios WAP/P'ML (see Marty, 2008; Marty et al., 2010). From trackways speed (v) was calculated using Alexander's (1976) formula: $v = 0.25g^{0.5} \cdot SL^{1.67} \cdot h^{-1.17}$, where g = gravitational acceleration in m/sec; SL = stride length; and h = hip height [based on methods of Alexander (1976) and Thulborn (1990)]. Also, relative stride length (SL/h) was calculated using the method of Thulborn (1990) in order to determine whether the trackmaker was walking, trotting or running.

Table 1
Numbers of identifiable tracks and trackways recorded on bocks 1–8 (tracks from other blocks were mostly unidentifiable) from the Shimiaogou tracksite, Sichuan Province, China. Abbreviations: TS/TWS: tracks/trackways; Th: non-avian theropod; Dr: dromaeosaurian; Sa: sauropod; Or: ornithopod; Pt: pterosaurian

Block no.	TS/TWS	TWS				
		Th	Dr	Sa	Or	Pt
1	53/9	6	–	1	2	–
2	6/1	–	–	1	–	–
3	8/2	–	–	1	1	–
4	20/6	–	1	1	3	2
5	21/4	–	–	2	2	–
6	14/2	–	1	1	–	–
7	6/3	1	–	–	2	–
8	4/3	1	–	–	2	–
Totals	**132/30**	**8**	**2**	**7**	**12**	**2**

Eight of the well-preserved track-bearing blocks were discovered to reveal identifiable tracks suitable for documentation. They are here referred to as “blocks” 1–8 in the order they are described.

Trackways are numbered with the prefix SMG (for Shimiaogou) as part of the whole sample, regardless of the blocks on which they occur. This avoids the potential confusion of additional numbers and letter designations. Trackways have the designations T1, T2, D1, S1, S2, O1, O2, P1 etc., for theropod (T), dromaeosaurid (D), sauropod (S), ornithopod (O), and pterosaur (P), respectively. We also follow the convention of describing the track types in the following order: saurischian, ornithischian, pterosaurian, in conformity with standard archosaur classifications.

Each block in the series 1–8 reveals a variable number of tracks comprising well-defined trackways and/or isolated footprints. A brief summary list (Table 1) is useful as a basis for an overall census (discussed below). In all cases we only count the minimum number of clearly identifiable tracks and trackways.

Block 1 reveals the largest number of identifiable tracks and trackways (53 and 9, respectively) representing three morphotypes. Block 4 reveals four morphotypes and the other six blocks one or two morphotypes each. Collectively the blocks reveal a total of at least 132 tracks comprising 30 trackways representing five distinct morphotypes (Table 1).

4. Tetrapod footprints

4.1. Theropod tracks

4.1.1. Small tridactyl tracks

The small tridactyl tracks (7–18 cm pes length) from the SMG site include at least seven trackways which are cataloged as T1–T7 and contain 31 tracks (Fig. 2, Table 2). Additionally, four isolated tracks were found. Most tracks are natural molds (concave epireliefs), and only trackways T7 and TI4 (Figs. 3, 4) are natural casts (convex hyporeliefs). Because of original preservation factors and severe weathering, all molds are poorly preserved without identifiable digital pads.

T2-L1 (Fig. 4) is the best-preserved example of a typical theropod track. It has a length/width ratio of 1.1. Digit III is the longest, and the two outer digits are nearly equal in length. A trace of the metatarsophalangeal region of digit IV is located on the long axis of digit III. The divarication of digits II–IV (76°) is wide. In contrast to the molds, all casts are well-preserved with principal features being similar to those in T2-L1. TI4 and T7-L1 have more developed metatarsophalangeal regions. T7-L1 has a strong indentation behind digit II, which is a major characteristic of theropod tracks (Lockley, 1991). Pace angulations of most trackways are between 144° and 177°.

According to Olsen (1980), Weems (1992), and Lockley (2009), theropod tracks can be differentiated on the basis of mesaxony. Tracks T2-L1, TI4, and T7-L1 are characterized by weak to moderate mesaxony (0.64, 0.45, and 0.49), which is typical for footprints of the ichno- or morphofamily Eubrontidae Lull 1904, and some Early Cretaceous theropod tracks from China, such as *Jialingpus* (0.56–0.68, Xing et al., 2014a). Due to their poor preservation, the tracks cannot be referred to a specific ichnogenus, and they are here referred to as indeterminate theropod footprints.

Based on Alexander's (1976) formula, we estimate the speed of T1, T2, T4, and T6 at 3.96 km/h–6.66 km/h, with T5 showing the highest value. The relative stride length of T1, T2, T4, and T6 is

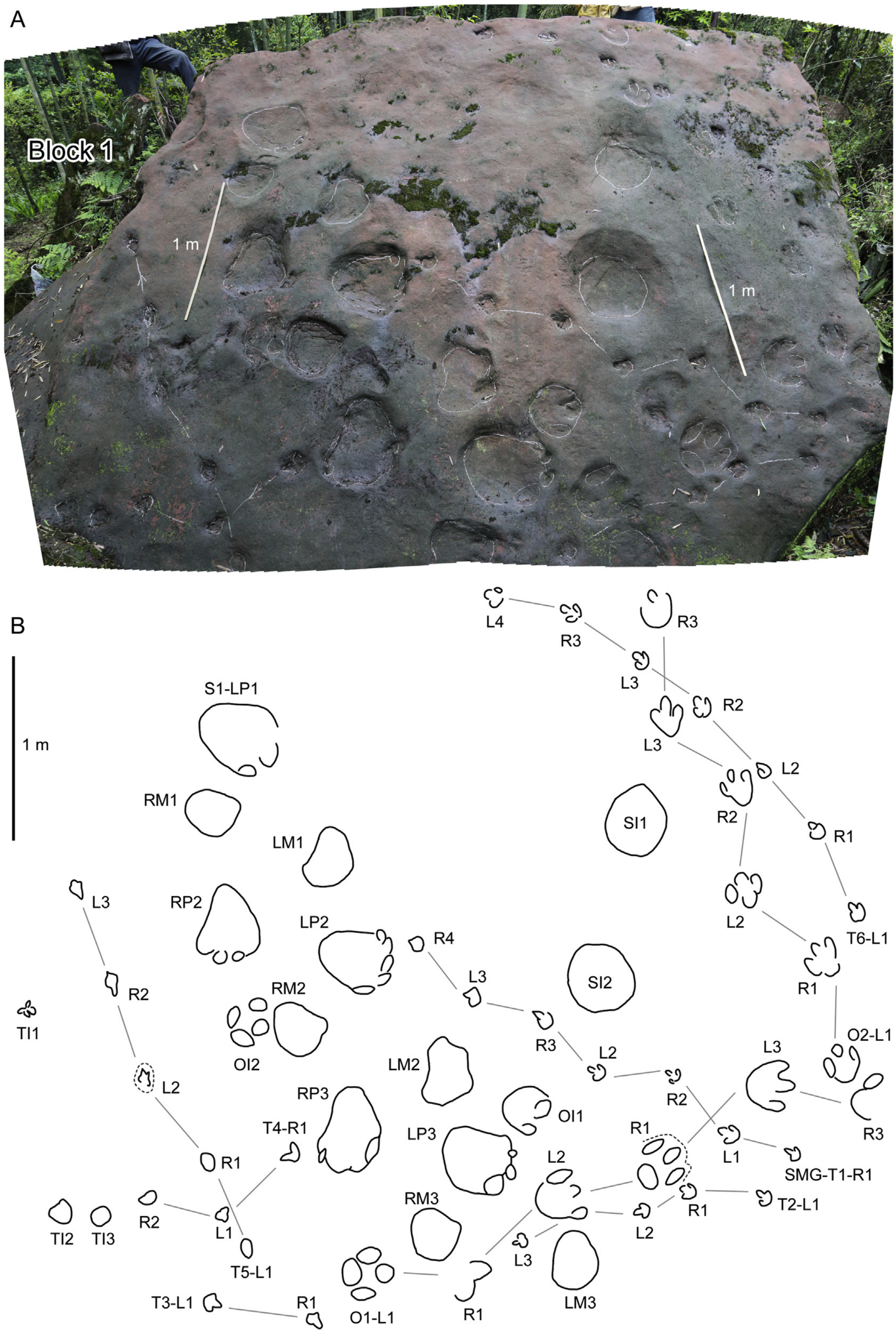

Fig. 2. Photograph (A) and map (B) of large track-rich block 1 from the Shimiaogou footprint locality showing a diverse assemblage of trackways preserved as natural impressions (concave epireliefs). The trackways are attributable to at least three distinct trackmaking groups: compare with Fig. 3 and Table 1.

Table 2
Measurements (in cm and degrees) of tridactyl and ornithopod tracks from the Shimiaogou tracksite, Sichuan Province, China. 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; ML/MW is dimensionless.

Number	ML	MW	II–IV	PL	SL	PA	ML/MW
SMG-T1-R1	11.0	8.0	73°	39.0	80.0	152°	1.4
SMG-T1-L1	13.5	10.5	65°	43.5	80.0	134°	1.3
SMG-T1-R2	9.0	8.9	77°	43.5	82.0	139°	1.0
SMG-T1-L2	10.5	9.0	77°	44.0	82.5	150°	1.2
SMG-T1-R3	14.5	10.5	–	41.5	82.5	145°	1.4
SMG-T1-L3	12.0	10.8	–	45.0	–	–	1.1
SMG-T1-R4	10.5	9.5	–	–	–	–	1.1
Mean	11.6	9.6	73°	42.8	81.4	144°	1.2
SMG-T2-L1	11.0	9.8	76°	43.5	72.0	156°	1.1
SMG-T2-R1	11.0	10.0	65°	30.0	–	–	1.1
SMG-T2-L2	10.5	9.0	71°	–	72.0	–	1.2
SMG-T2-R2	–	–	–	–	–	–	–
SMG-T2-L3	9.0	9.0	–	–	–	–	1.0
Mean	10.4	9.5	71°	36.8	72.0	156°	1.1
SMG-T3-L1	11.5	11.0	77°	60.0	–	–	1.0
SMG-T3-R1	11.0	9.0	–	–	–	–	1.2
Mean	11.3	10.0	77°	60.0	–	–	1.1
SMG-T4-R1	12.5	13.0	–	48.5	82.5	125°	1.0
SMG-T4-L1	9.5	9.0	–	44.5	–	–	1.1
SMG-T4-R2	11.0	9.0	–	–	–	–	1.2
Mean	11.0	10.3	–	46.5	82.5	125°	1.1
SMG-T5-L1	11.5	–	–	53.0	111.0	165°	–
SMG-T5-R1	11.5	–	–	59.0	114.0	159°	–
SMG-T5-L2	11.5	7.5	–	57.0	110.0	165°	1.5
SMG-T5-R2	16.0	9.0	–	54.0	–	–	1.8
SMG-T5-L3	12.0	8.0	–	–	–	–	1.5
Mean	12.5	8.2	–	55.8	111.7	163°	1.6
SMG-T6-L1	12.0	9.0	47°	49.0	93.0	180°	1.3
SMG-T6-R1	12.0	9.6	–	44.0	95.5	180°	1.3
SMG-T6-L2	9.2	7.5	–	51.5	93.0	168°	1.2
SMG-T6-R2	13.5	11.6	58°	42.0	90.0	180°	1.2
SMG-T6-L3	11.5	10.0	58°	48.0	–	–	1.2
SMG-T6-R3	13.0	11.0	74°	–	–	–	1.2
SMG-T6-L4	11.5	12.0	–	–	–	–	1.0
Mean	11.8	10.1	59°	46.9	92.9	177°	1.2
SMG-T7-L1	13.5	9.3	56°	42.0	–	–	–
SMG-T7-R1	18.0	12.0	56°	–	–	–	–
Mean	15.8	10.7	56°	42.0	–	–	–
SMG-D1-R1	7.5	4.5	39°	33.0	–	–	1.7
SMG-D1-L1	7.5	4.5	27°	–	48.5	–	1.7
SMG-D1-R2	–	–	–	–	–	–	–
SMG-D1-L2	6.5	5.0	45°	17.0	38.0	161°	1.3
SMG-D1-R3	7.0	4.0	45°	21.5	–	–	1.8
SMG-D1-L3	7.0	4.0	37°	–	–	–	1.8
Mean	7.1	4.4	39°	23.8	43.3	161°	1.7
SMG-TI1	11.0	8.0	–	–	–	–	1.4
SMG-TI2	14.5	12.0	–	–	–	–	1.2
SMG-TI3	12.0	9.5	–	–	–	–	1.3
SMG-TI4	13	10	63°	–	–	–	–
SMG-O1-L1	30.5	30.0	60°	56.0	116.0	140°	1.0
SMG-O1-R1	–	–	–	67.5	127.5	160°	–
SMG-O1-L2	27.0	30.0	53°	62.0	135.5	170°	0.9
SMG-O1-R2	32.5	31.0	47°	74.0	127.5	157°	1.0
SMG-O1-L3	29.5	28.5	57°	56.0	–	–	1.0
SMG-O1-R3	–	–	–	–	–	–	–
Mean	29.9	29.9	54°	63.1	126.6	157°	1.0
SMG-O2-L1	22.5	21.0	49°	57.0	109.5	149°	1.1
SMG-O2-R1	22.0	22.5	52°	56.5	105.0	135°	1.0
SMG-O2-L2	21.0	22.0	51°	57.0	106.5	146°	1.0
SMG-O2-R2	22.5	20.0	47°	54.5	106.5	149°	1.1
SMG-O2-L3	23.0	19.5	51°	56.0	–	–	1.2
SMG-O2-R3	20.5	19.0	51°	–	–	–	1.1
Mean	21.9	20.7	50°	56.2	106.9	145°	1.1
SMG-O3-R1*	21.0	24.0	76°	70.5	124.5	142°	0.9
SMG-O3-L1	24.0	27.0	80°	61.0	121.5	149°	0.9
SMG-O3-R2	22.5	29.0	73°	65.0	117.0	135°	0.8
SMG-O3-L2	22.0	26.5	79°	61.5	122.0	140°	0.8
SMG-O3-R3	22.5	28.0	71°	68.5	–	–	0.8
SMG-O3-L3	22.0	25.0	73°	–	–	–	0.9
Mean	22.3	26.6	75°	65.3	121.3	142°	0.9
SMG-O4-L1	23.5	23.0	55°	61.0	101.5	–	1.0
SMG-O4-R1	23.0	21.0	–	–	107.0	–	1.1
SMG-O4-L2	–	–	–	56.0	104.0	127°	–
SMG-O4-R2	23.0	22.5	48°	60.0	–	–	1.0
SMG-O4-L3	19.0	22.5	62°	–	–	–	0.8
Mean	22.1	22.3	55°	59.0	104.2	127°	1.0
SMG-O5-R1	20.5	23.0	58°	56.0	111.0	158°	0.9
SMG-O5-L1	23.5	20.5	52°	57.0	114.0	156°	1.1
SMG-O5-R2	20.5	23.0	65°	59.5	114.0	156°	0.9
SMG-O5-L2	22.0	21.5	57°	57.0	107.5	151°	1.0
SMG-O5-R3	25.5	23.0	64°	54.0	–	–	1.1
SMG-O5-L3	18.0	–	–	–	–	–	–
Mean	21.7	22.2	59°	56.7	111.6	155°	1.0
SMG-O6-R1	28.0	32.0	70°	63.0	–	–	0.9
SMG-O6-L1	28.0	26.5	58°	–	–	–	1.1
Mean	28.0	29.3	64°	63.0	–	–	1.0
SMG-O7-R1	23.0	25.5	–	110.0	–	–	0.9
SMG-O7-L1	25.0	26.0	58°	–	–	–	1.0
Mean	24.0	25.8	58°	110.0	–	–	1.0
SMG-O8-R1	28.0	29.5	50°	60.5	–	–	0.9
SMG-O8-L1	26.0	25.0	51°	–	–	–	1.0
Mean	27.0	27.3	51°	60.5	–	–	1.0
SMG-O9-R1	29.8	30.0	–	59.0	–	–	1.0
SMG-O9-L1	29.5	30.0	46°	–	–	–	1.0
Mean	29.7	30.0	46°	59.0	–	–	1.0
SMG-O10-L1	22	23.5	59°	58.5	–	–	0.9
SMG-O10-R1	21	21.5	67°	–	–	–	1.0
Mean	21.5	22.5	63°	58.5	–	–	1.0
SMG-O11-L1	24.3	26.3	60°	60.0	–	–	0.9
SMG-OI1	29.0	27.0	53°	–	–	–	1.1
SMG-OI2	26.0	29.5	63°	–	–	–	0.9
SMG-OI3	22.0	23.0	55°	–	–	–	1.0

1.54–1.75, implying that the animal was walking, whereas the stride length of T5 is 1.99, being close to a trotting movement.

4.1.2. Deinonychosaurian tracks

A trackway consisting of five footprints, numbered SMG-D1-R1–L3 (Figs. 4, 5), appear continuous except for missing track R2. One isolated track is numbered as SMG-DI1 (Fig. 6). SMG-D1 is a poorly-preserved didactyl trackway, with tracks having a mean length of 7.1 cm and an L/W ratio of 1.7. The pace angulation is 161°. Most of the imprints lack discernable claw marks and phalangeal pads, which is probably the result of weathering.

D1-L3 is the best preserved track. Digit II is a short, round impression, located proximo-medially to digit III. Digit IV is longer than digit III (excluding the claw). The metatarsophalangeal region of digit IV is smoothly curved, and separated from the other digits by a distinct border. The divarication angle is 37° between digits III and IV. Other tracks are basically the same as D1-L3, but do not have digit II traces. L1 has a small divarication angle (27°), while the divarication angles of the other tracks are bigger (39°–45°). The pace length (33 cm) of D1-R1–L1 is significantly longer than that of R3–L3 (21.5 cm), indicating that the trackmaker was slowing (from 3.2 km/h to 2.12 km/h, based on the formula of Alexander, 1976).

The didactyl tracks of deinonychosaurian dinosaurs are among the most distinctive theropod tracks known (Fig. 7). Deinonychosaurian ichnotaxa comprise four ichnogenera

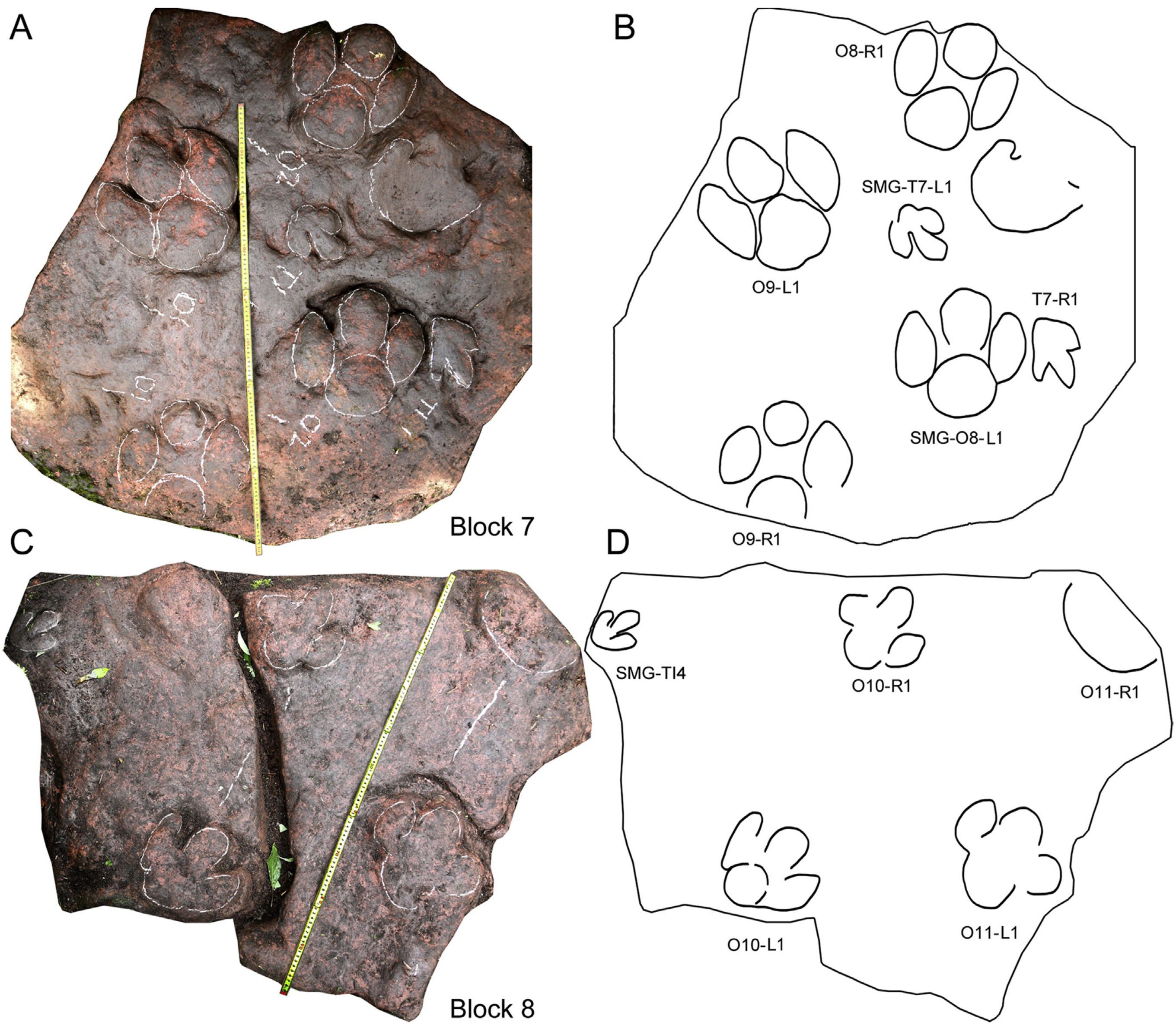

Fig. 3. Photographs (A and C) and maps (B and D) of track casts preserved on blocks 7 and 8 (top and bottom, respectively). Block 7 contains the holotype trackway of *Caririchnium liucixini* ichnosp. nov. SMG-O9-R1-L1.

(*Velociraptorichnus*, *Dromaeopodus*, *Dromaeosauripus* and *Menglongipus*) (Xing et al., 2013b; Lockley et al., in press). Xing et al. (2013b) divided deinonychosaurian tracks into three classes according to their sizes. SMG specimens belong to small sized-tracks (mean pes length 10 cm) that include the ichnotaxa *Velociraptorichnus sichuanensis* (Zhen et al., 1994; Xing et al., 2009), *Velociraptorichnus* isp. (Li et al., 2007), *Velociraptorichnus zhangi* (Xing et al., 2015d), *Menglongipus sinensis* (Xing et al., 2009), and *Dromaeosauripus jinjuensis* (Kim et al., 2012).

Based on morphology, SMG-D1 is substantially different from *D. jinjuensis* which lacks a developed metatarsophalangeal region (Kim et al., 2012), from *V. zhangi* in not having large digit II claw traces (Xing et al., 2015d), and from *M. sinensis* in having longer digit IV impressions (Xing et al., 2009). SMG-D1 is similar to *V. sichuanensis*. Both share subequal digit III and IV lengths, indistinct or missing digital pad traces, digit II being partially embedded within the impression of digit III at its proximomedial edge, and similar length:width ratios (1.8 vs. 1.7 of SMG-D1). But digit III of SMG-D1 projects relatively farther anteriorly, and the claws are not developed. Because of the indifferent preservation quality and small sample size, we tentatively refer SMG-D1 to cf. *Velociraptorichnus*.

4.2. Sauropod tracks

4.2.1. Common trackways

The SMG tracksite preserves at least three well-preserved and diagnostic sauropod trackways (SMG-S1–S3), which are composed of 11, 6, and 9 manus/pes traces (Figs. 2, 5, 8–10, Table 3).

Most sauropod trackways in China are wide- (or medium-) gauge and are therefore referred to the ichnogenus *Brontopodus* (Lockley et al., 2002). The SMG-S1 and SMG-S2 tracks are consistent with the characteristics of *Brontopodus* type tracks from the Lower Cretaceous of North America (Farlow et al., 1989; Lockley et al., 1994a); these features include: medium-gauge or nearly wide-gauge (the WAP/P'ML ratio of SMG-S1 and S2 is 1.3 and 1.2,

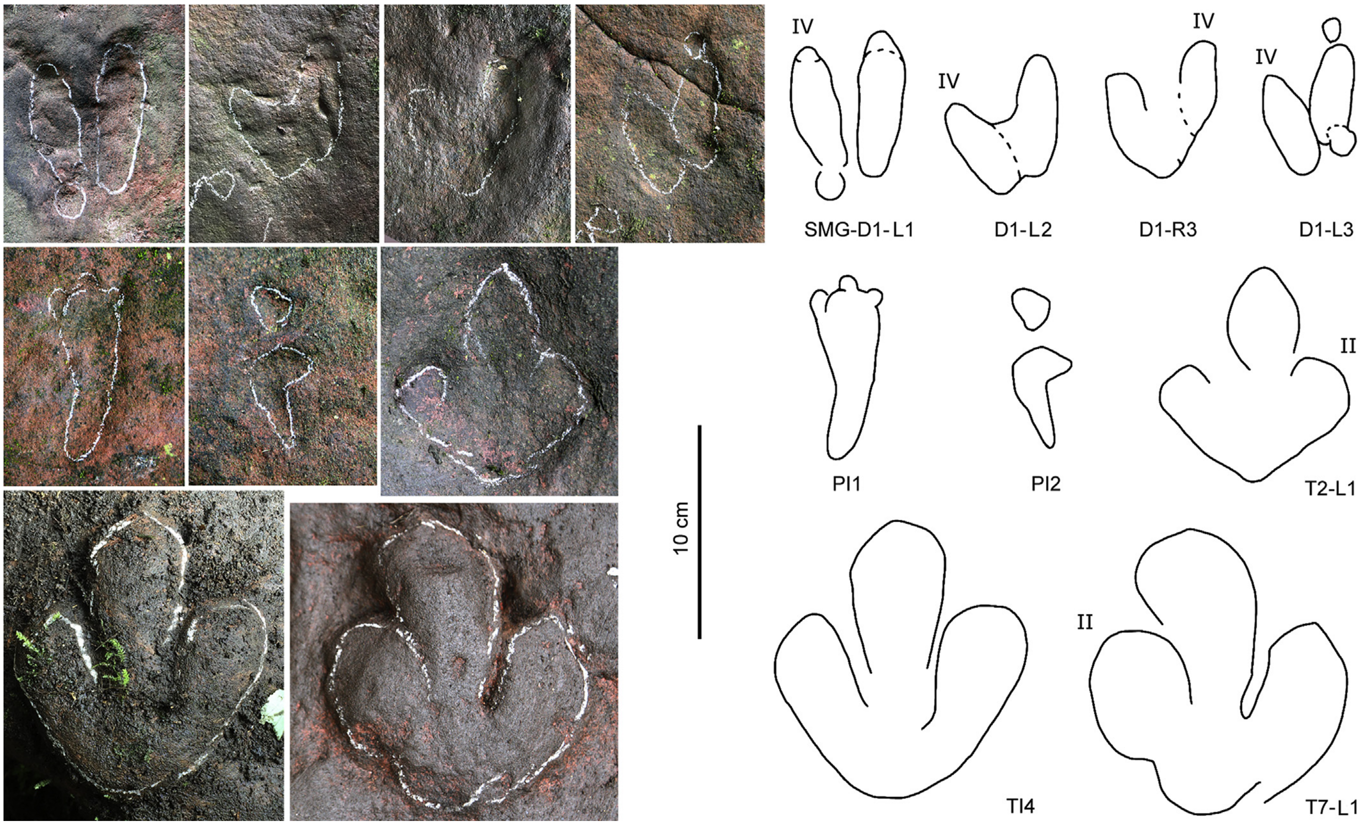

Fig. 4. Photos and corresponding line drawings of small theropod and pterosaur tracks from the Shimiaogou site.

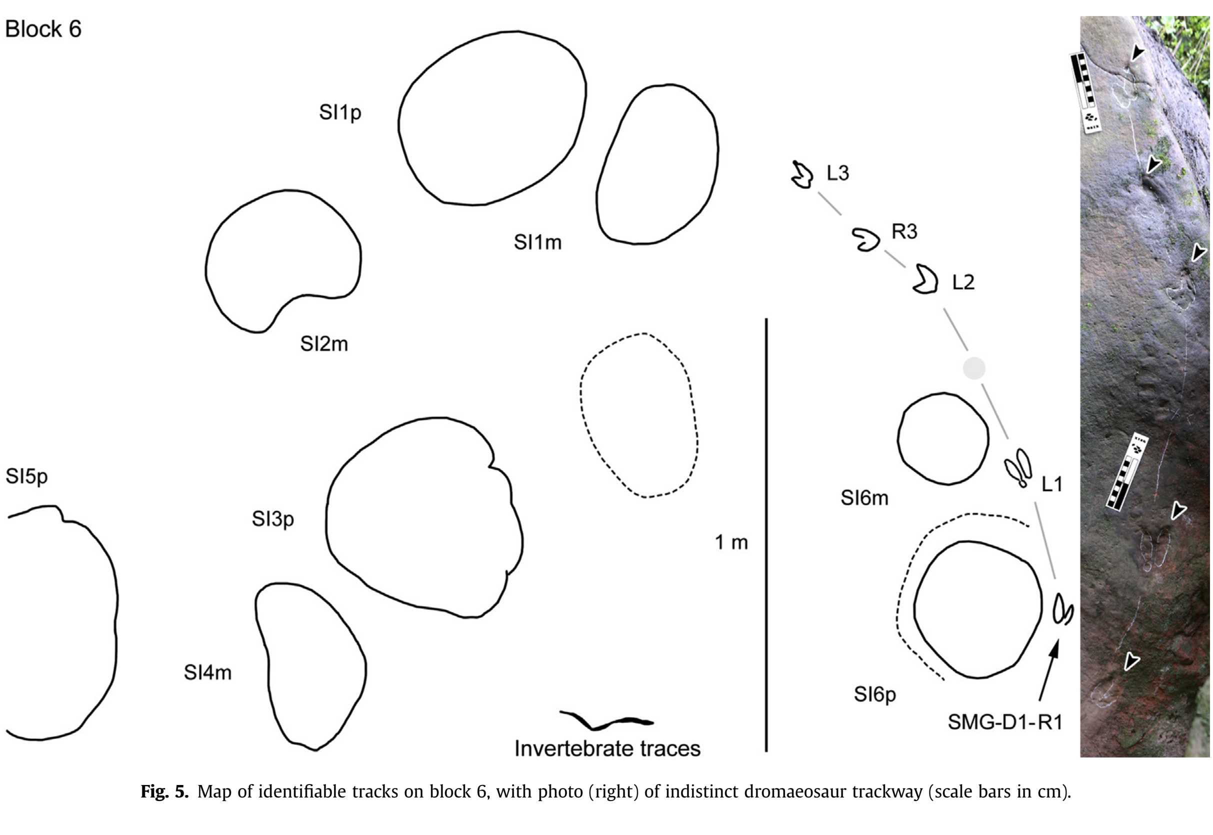

Fig. 5. Map of identifiable tracks on block 6, with photo (right) of indistinct dromaeosaur trackway (scale bars in cm).

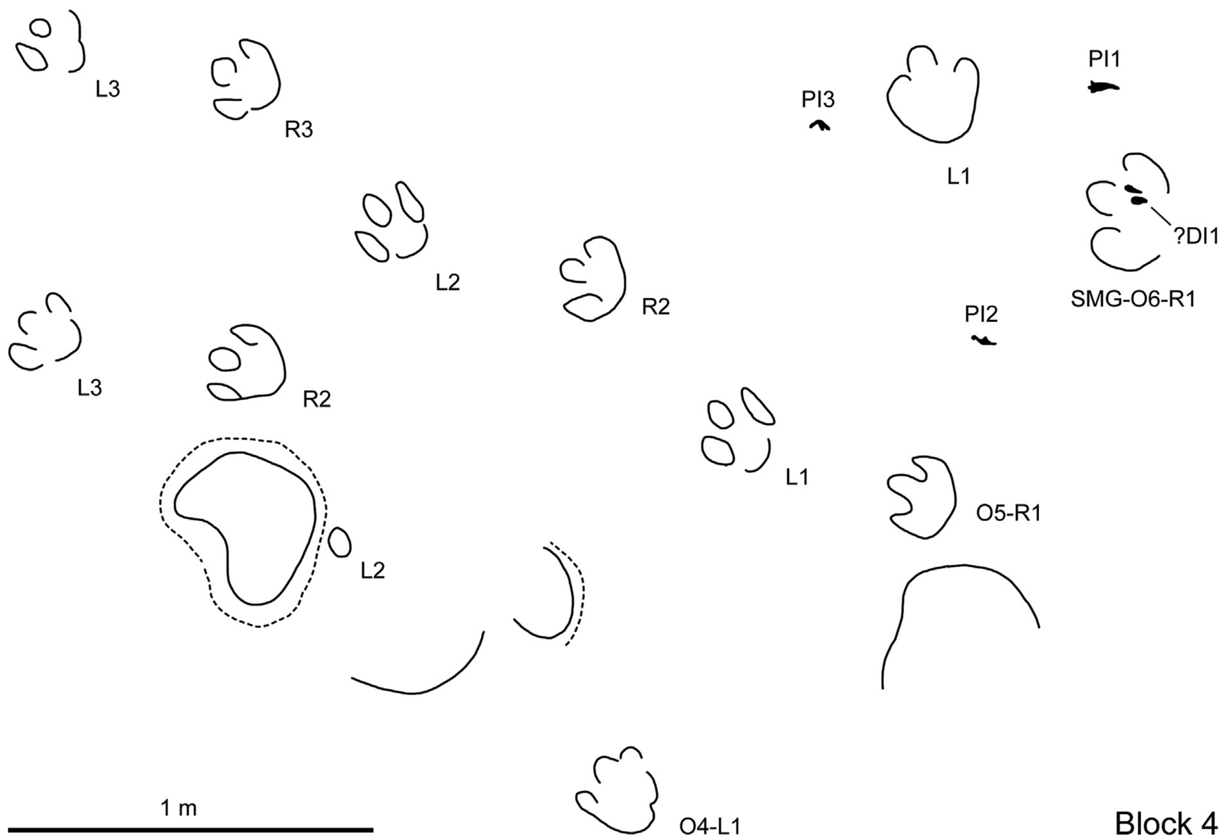

Fig. 6. Map of identifiable tracks on block 4.

respectively), pes tracks that are longer than wide (a length/width ratio of 1.3 for the pes of SMG-S1), large and outwardly-directed semicircular manus prints, and a high degree of heteropody (ratio of manus to pes size) (1:1.5–2.3 of SMG-S1, 1:1.7–2.1 of SMG-S2). In SMG-S1, the manus impressions are rotated approximately 46° outward from the trackway axis, which is larger than the outward rotation of the pes impressions (approximately 35°). The average manus PA is 96°, while the average pes PA is 103°. These sauropod

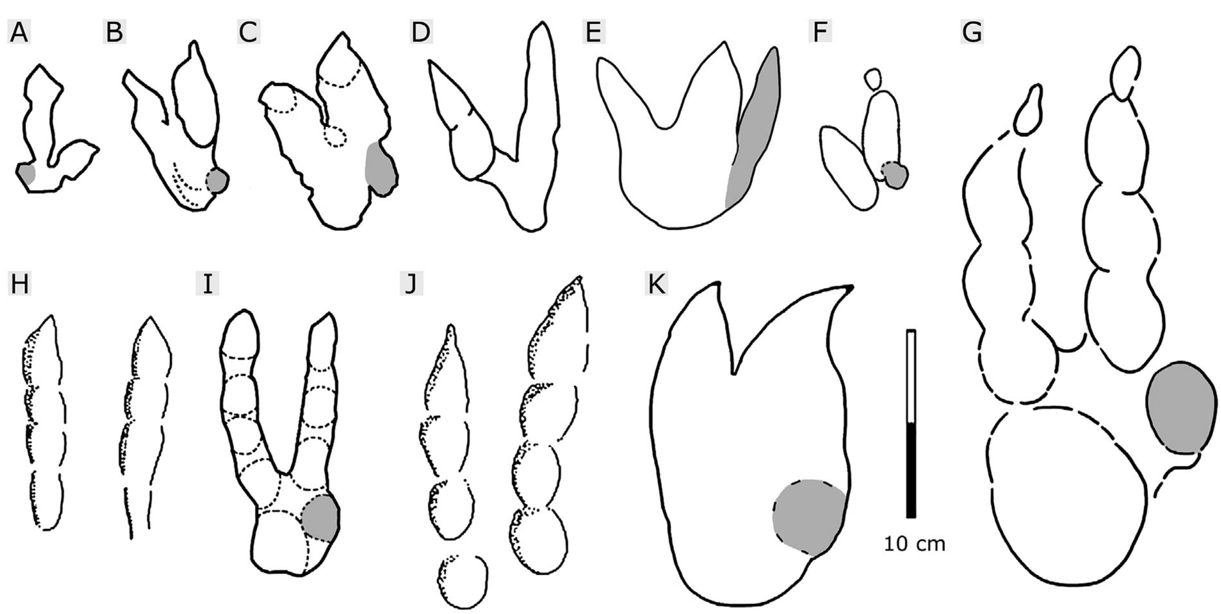

Fig. 7. Interpretative outline drawings of dromaeopodid ichnotaxa drawn to the same scale. (A) *Menglongipus* (Xing et al., 2009); (B) *Velociraptorichnus* from Shandong (Li et al., 2007); (C) *Velociraptorichnus* from Emei (Xing et al., 2009); (D) *Velociraptorichnus* from Mujiaowu (Xing et al., 2015d); (E) *Velociraptorichnus wangi* (Xing et al., 2015d); (F) SMG *Velociraptorichnus* (this paper); (G) *Dromaeopodus shandongensis* (Li et al., 2007); (H) *Dromaeosauripus jinjuensis* (Kim et al., 2012); (I) *Dromaeosauripus yongjingensis* (Xing et al., 2013b); (J) *Dromaeosauripus hamanensis* (Kim et al., 2008); (K) Jishan *Dromaeosauripus* isp. (Xing et al., 2013b).

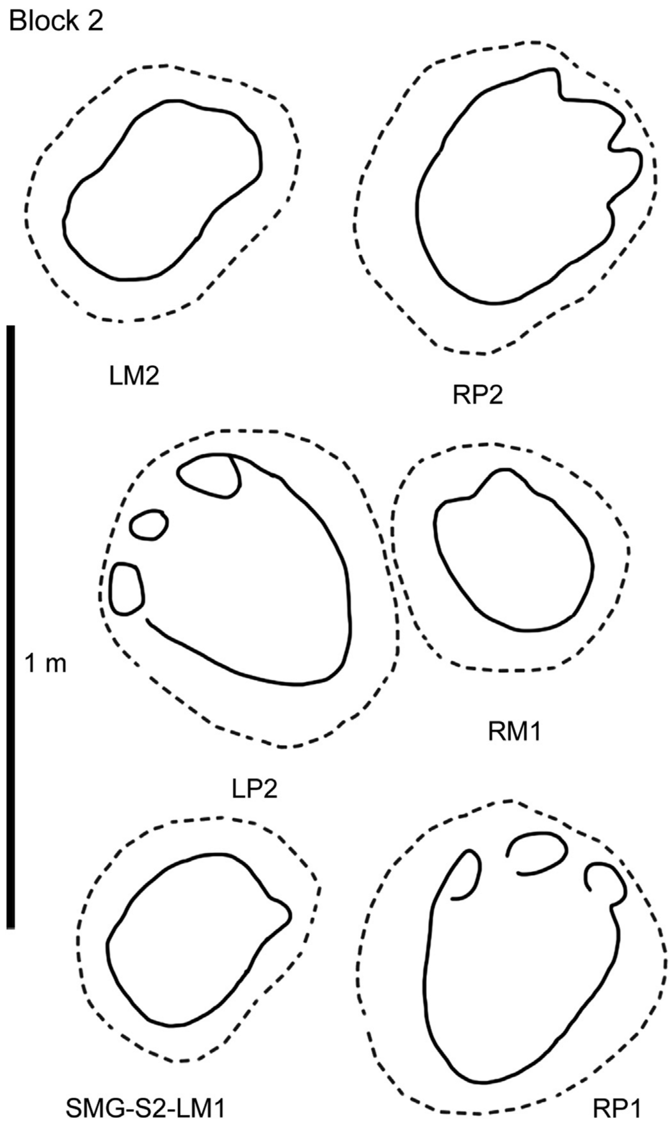

Fig. 8. Line drawing of sauropod trackway segment showing well defined pes claw traces from block 2.

trackways are tentatively assigned here to cf. *Brontopodus*. Pes digit traces are visible in some better preserved imprints (Figs. 8–10). Characteristically, they decrease in size from digit I to digit V. Mostly four digit traces are preserved, whereas in one specimen (Fig. 10) five digit traces were observed.

4.2.2. Sauropod trackway with unusual walking pattern

The SMG-S3 is well-preserved with at least six pes impressions and three manus impressions, three tracks of which have additional corresponding casts (Figs. 9, 10). RP4 is the best preserved and shows distinct traces of digits I–V in addition to the above-mentioned characteristics of *Brontopodus*. The ratio of manus to pes size is 1:2.2–2.3, which is similar to that of SMG-S1 and S2 and to *Brontopodus* tracks described from (1:2.3) from the Lower Cretaceous Feitianshan Formation of the Zhaojue tracksite (1:2.3) and the type specimen of *Brontopodus birdi* (1:3) (Lockley et al., 1994a).

However, SMG-S3 shows an unusual walking pattern. It only preserves right manus impressions. These manus prints are rotated approximately 21° outward from the trackway axis, which is smaller than the outward rotation of the pes impressions (approximately 33°). The right manus tracks are located on the inner side of the trackway, almost between the left and right pes tracks. Moreover, the distal edge of RM2 and proximal edge of RM3 are slightly deformed due to the subsequently formed RP3 and LP3 (see arrows in Fig. 10B). SMG-S3 is different from other sauropod trackways with unusual walking patterns currently known from the Lower Cretaceous of China (Fig. 11).

Optimal substrate conditions with imprints being only about 7 cm at their deepest part, allowed for the preservation of distinct details. This excludes the possibility that these are undertracks. The following causes may explain the absence of the left manus impressions:

1. The left manus prints are not preserved, or are overlapped by other tracks. Because the track preserving surface is limited in extent, the sauropod manus and pes set designated as SI7m and SI7p (Fig. 10A) and considered here as an isolated couple, might alternatively belong to the trackway SMG-S3 and partly represent a left manus trace. However, this is difficult to interpret since it is well preserved, but there are no other impressions nearby that might indicate a different trackway. It is also possible that the trackmaker of SI7 left a true trackway on a higher level surface, and the deeper tracks of SI7 were formed due to the softer local sediment. This is the case in an extraordinary manus print of the YSI-S3 trackway from Yanguoxia No.1 tracksite, Gansu Province (Xing et al., 2015e).
2. The left manus prints are overlapped by the right pes prints. This situation is sometimes seen in turning trackways, such as that from Tangdigezhuang tracksite, Shandong Province (Fig. 11D) (Xing et al., 2015f). However, the well-preserved pes impressions show no sign of overlap. The decreasing pace lengths of SMG-S3 suggest that the walking speed of the trackmaker was slowing, and such a change in speed is sometimes correlated with a turn of the trackmaker (sensu Ishigaki and Matsumoto, 2009; Castanera et al., 2012; Xing et al., 2014b, 2015f, 2015g, in press-b; Torcida Fernández-Baldor et al., 2015).
3. Left and right manus impressions are overlapped. However, the detailed examination of the trackway provided no indication of this pattern.
4. Pathological causes. Tetrapod ichnopathology describes abnormities in the gait and pes/ manus morphology that can be deduced from trackways McCrea et al. (2015). For example, injuries of the limbs and disease can be reflected in unusual trackway and imprint patterns. However, sometimes this is difficult to distinguish from extramorphological influences or variation of the normal gait due to substrate-related factors. Abnormal gaits or morphologies reflecting dinosaur pathology (ichnopathology) are rare. McCrea et al. (2015) reported a variety of Cretaceous theropod tracks with abnormal morphologies from western North America and demonstrated the evidence for ichnopathology. These abnormalities include swelling, extreme curvature, dislocation or fracture, and amputation. The left fore limb of the trackmaker of SMG-S3 might have been injured or even amputated to some degree so that it did not touch the ground, forcing the right fore limb to register along the midline of the trackway in order to maintain a kind of tripedal balance. This scenario is difficult to imagine, and it is speculative to reconstruct the trackway that might result for tripedal progression. It is clear however that the configuration of pes tracks (RP1–RP4) is more or less normal.

After limb loss or limb incapacitation, a reorganization of the locomotor system would be required. Simulation by a quadrupedal robot walking tripedally shows that tripedal gait means slower speed and lower efficiency (Smith and Jivraj, 2010). Gross and

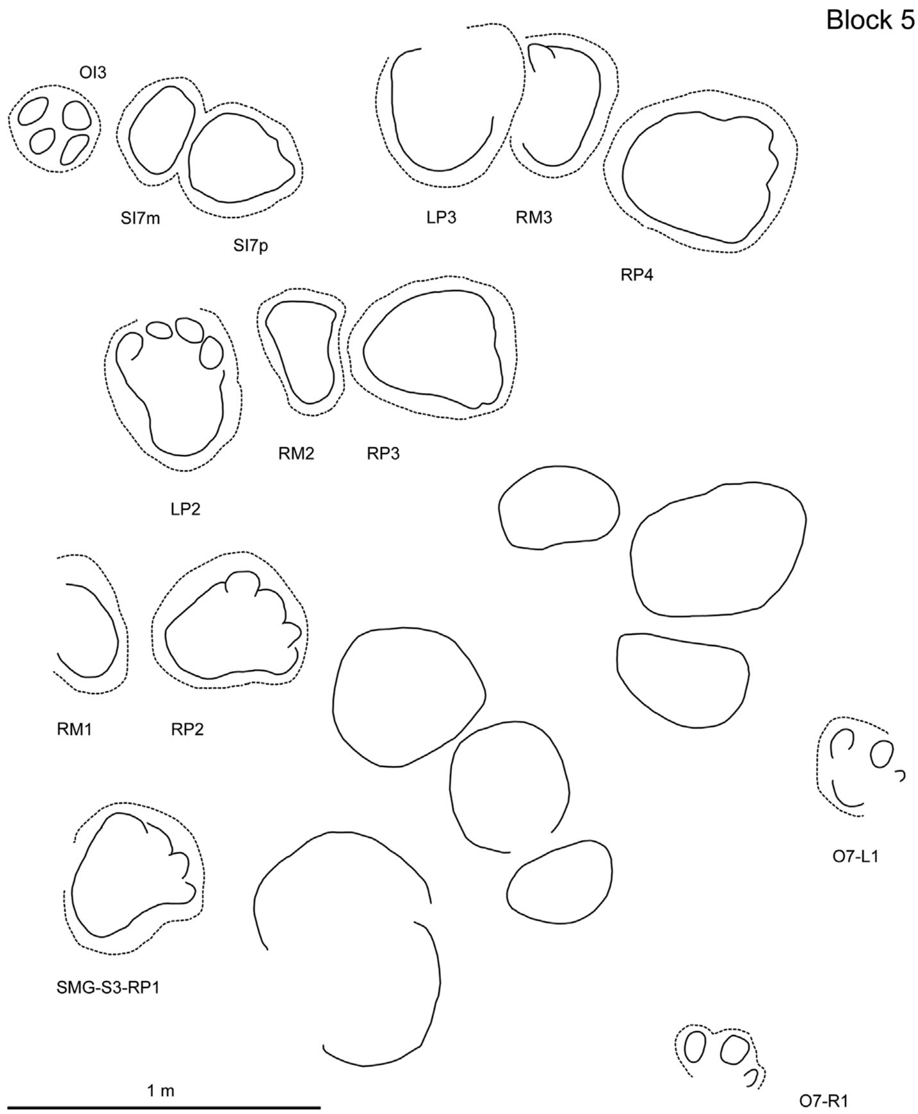

Fig. 9. Map of identifiable tracks on block 5.

Seyfarth (2010) suggest that dogs with fore limb amputation run with a higher duty factor and step frequency in the remaining fore limb.

For sauropods, Alexander (1976) first suggested that hip height was equal to 4 × foot length, whereas, later, Thulborn (1990) estimated hip height to be 5.9 × foot length. The SL/h ratios calculated for SMG-S3 are between 0.43 and 0.5 and accordingly suggest walking. Using the equation to estimate speed from trackways (Alexander, 1976), the mean locomotion speed of the trackmaker is between 1.08 and 1.44 km/h. These speed estimations are basically the same as those of typical sauropod trackways: for example, SMG-S1 and S2 (SL/h ratios of 0.5–0.51 give speed estimates of 1.44–1.48 km/h). In conclusion, a possible tripedal gait would not necessarily significantly influence locomotion if this interpretation is applied to SMG-S3.

4.3. *Ornithopod tracks*

Ornithopod trackways are the most common in the Shimiaogou samples, occurring on all described blocks except for block 6 (Table 2). All have a characteristic quadripartite morphology typical of *Caririchnium*, and all appear to represent bipedal progression. They are preserved as both natural impressions and molds, with preservation of tracks as natural casts on blocks 7 and 8 being particularly clear.

4.3.1. *Systematic paleoichnology*

Iguanodontopodidae Vialov, 1988 *sensu* Lockley, Xing, Lockwood and Pond, 2014

Diagnosis. Large, subsymmetric tridactyl pes tracks lacking digital phalangeal pad traces but sometimes divided by inter-digital creases into a quadripartite configuration, indicating three, fleshy, sub-oval digits and a heel pad, and sometimes with broad ungual traces. Heel may be rounded or posteriorly bilobed. Manus small, rounded, oval to semi-circular or crescentic, when present, and typically situated anterior to anterolateral. Trackway typically with short step and inwardly rotated pes (Lockley et al., 2014).

Ichnogenus *Caririchnium* Leonardi, 1984

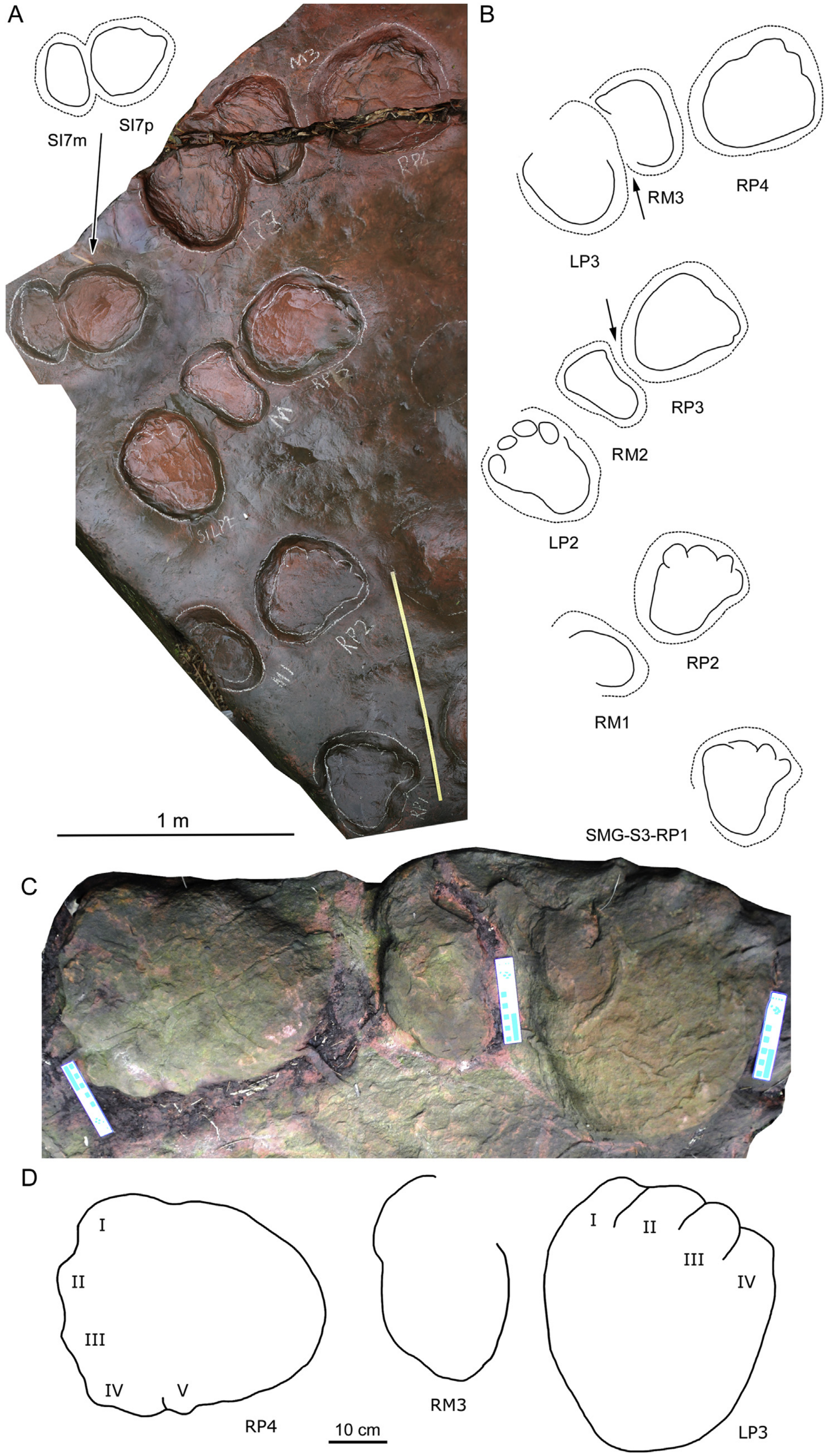

Fig. 10. Photograph (A and C) and corresponding map (B and D) of sauropod track casts on block 5, with details of sauropod pes track casts. Note clearly preserved pes toe traces.

Table 3
Measurements (in cm and degrees) of sauropod trackways from the Shimiaogou tracksite, Sichuan Province, China. Abbreviations: ML: Maximum length; MW: Maximum width; 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 are dimensionless.

Number.	ML	MW	R	PL	SL	PA	ML/MW	WAP	WAP/P'ML	WAM	WAM/M'MW
SMG-S1-LP1	48.5	39.0	39°	–	138.0	–	1.2	–	–	–	–
SMG-S1-LM1	26.0	32.0	29°	96.0	134.0	–	0.8	–	–	52	1.6
SMG-S1-RP1	–	–	–	–	–	–	–	–	–	–	–
SMG-S1-RM1	25.5	32.0	42°	74.0	129.0	103°	0.8	–	–	–	–
SMG-S1-LP2	44.5	35.0	41°	95.0	132.0	103°	1.3	58	1.3	–	–
SMG-S1-LM2	26.0	34.0	51°	90.0	126.0	89°	0.8	–	–	57	1.7
SMG-S1-RP2	45.0	37.0	25°	73.0	133.0	–	1.2	59	1.3	–	–
SMG-S1-RM2	26.0	31.0	63°	90.0	138.0	–	0.8	–	–	62.5	2.0
SMG-S1-LP3	44.0	35.0	–	–	–	–	1.3	–	–	–	–
SMG-S1-LM3	26.0	30.0	–	83.0	–	–	0.9	–	–	–	–
SMG-S1-RP3	47.0	36.0	–	74.0	–	–	1.3	61.5	1.3	–	–
SMG-S1-RM3	27.0	29.0	–	–	–	–	0.9	–	–	56.5	1.9
Mean (M)	26.1	31.3	46°	86.6	131.8	96°	0.8	–	–	57.0	1.8
Mean (P)	45.8	36.4	35°	80.7	134.3	103°	1.3	59.5	1.3	–	–
SMG-S2-LM1	22.0	30.5	44°	85.0	130.0	97°	0.7	–	–	–	–
SMG-S2-RP1	44.0	32.5	18°	80.0	131.0	105°	1.4	–	–	–	–
SMG-S2-RM1	25.5	27.0	–	89.0	–	–	0.9	–	–	56.5	2.1
SMG-S2-LP2	44.0	33.0	–	85.0	–	–	1.3	51	1.2	–	–
SMG-S2-LM2	20.0	36.0	–	–	–	–	0.6	–	–	–	–
SMG-S2-RP2	42.0	23.5	–	–	–	–	1.8	–	–	–	–
Mean (M)	22.5	31.2	44°	87.0	130.0	97°	0.7	–	–	56.5	2.1
Mean (P)	43.3	29.7	18°	82.5	131.0	105°	1.5	51.0	1.2	–	–
SMG-S3-RP1	40.0	38.0	22°	90.0	119.0	–	1.1	–	–	–	–
SMG-S3-RM1	20.0	32.5	15°	–	–	–	0.6	–	–	–	–
SMG-S3-LP1	–	–	–	–	–	–	–	–	–	–	–
SMG-S3-LM1	–	–	–	–	–	–	–	–	–	–	–
SMG-S3-RP2	40.0	37.0	32°	85.0	117.0	–	1.1	–	–	–	–
SMG-S3-RM2	19.0	35.0	27°	–	116.0	–	0.5	–	–	–	–
SMG-S3-LP2	46.0	33.0	52°	85.0	134.0	105°	1.4	68.5	1.5	–	–
SMG-S3-LM2	–	–	–	–	–	–	–	–	–	–	–
SMG-S3-RP3	42.0	39.0	26°	84.0	106.0	78°	1.1	61.5	1.5	–	–
SMG-S3-RM3	23.0	39.0	–	–	–	–	0.6	–	–	–	–
SMG-S3-LP3	42.0	33.0	–	84.0	–	–	1.3	73.7	1.8	–	–
SMG-S3-LM3	–	–	–	–	–	–	–	–	–	–	–
SMG-S3-RP4	48.0	41.0	–	–	–	–	1.2	–	–	–	–
Mean (M)	20.7	35.5	21°	–	116.0	–	0.6	–	–	–	–
Mean (P)	42.0	36.0	33°	85.6	119.0	92°	1.2	67.9	1.6	–	–
SMG-SI1m	26.0	38.5	–	–	–	–	0.7	–	–	–	–
SMG-SI1p	38.0	45.5	–	–	–	–	0.8	–	–	–	–
SMG-SI2m	29.0	28.0	–	–	–	–	1.0	–	–	–	–
SMG-SI3p	45.5	44.0	–	–	–	–	1.0	–	–	–	–
SMG-SI4m	22.5	33.5	–	–	–	–	0.7	–	–	–	–
SMG-SI5p	–	53.0	–	–	–	–	–	–	–	–	–
SMG-SI6m	21.0	21.0	–	–	–	–	1.0	–	–	–	–
SMG-SI6p	34.0	30.0	–	–	–	–	1.1	–	–	–	–
SMG-SI7m	17.5	28.0	–	–	–	–	0.6	–	–	–	–
SMG-SI7p	34.0	28.5	–	–	–	–	1.2	–	–	–	–

Diagnosis. Pes tracks belonging to Iguanodontipodidae, with a large heel impression that is rounded, centred and wide (wider than the width of the proximal part of the digit III impression); short, wide digit impressions (Díaz-Martínez et al., 2015).

Type ichnospecies *C. magnificum*, Leonardi, 1984

Caririchnium liucixini ichnosp. nov.

Etymology. The specific name is in honor of Mr. LIU Cixin (born 1963), a famous science fiction writer from China. Liu's *Three-Body Problem* (2007) won the 2015 Hugo Award for Best Novel.

Holotype. One natural cast track on Block 7 that forms part of a small trackway segment (Fig. 3A–B, Table 2) and catalogued as SMG-O9-L1 from the SMG tracksite. The original specimens remain in the field. Replicas are stored in the Gulin County Bureau of Land Resources under GCBLR-SMG-O9-L1. SMG-O9-R1 natural cast track and preceding imprint of the same partial trackway.

Paratypes. Ten ornithopod trackways, catalogued as SMG-O1–O8, O10–O11; and at least three isolated ornithopod tracks, catalogued as SMG-OI1–OI3 (Blocks 1, 3–5, 8; Figs. 2, 3, 6, 9, 12); all in all 41 imprints. O8 and O10–O11 are natural casts (convex hyporeliefs), all others are natural molds (concave hyporeliefs). All tracks remain *in situ*.

Locality and horizon. Shimiaogou tracksite, Gulin, Sichuan Province, Lower Cretaceous (Barremian–Albian), Jiaguan Formation, China.

Diagnosis. Medium-sized, pes-only *Caririchnium* tracks with lengths almost equal to widths (1.0), quadripartite morphology including three digits with blunt claw or ungual marks, and triangular heels. Differ from other *Caririchnium* tracks in having weak mesaxony (0.23 and 0.28 for type). Interdigital divarication II–IV = 46°. Short steps with pace length being 2.0 × footprint length.

Description. None of the SMG ornithopod trackways have manus impressions. Their pes impressions are 21.5–30 cm in length. This is smaller than the lengths of the types of other *Caririchnium* ichnospecies (~35–40 cm).

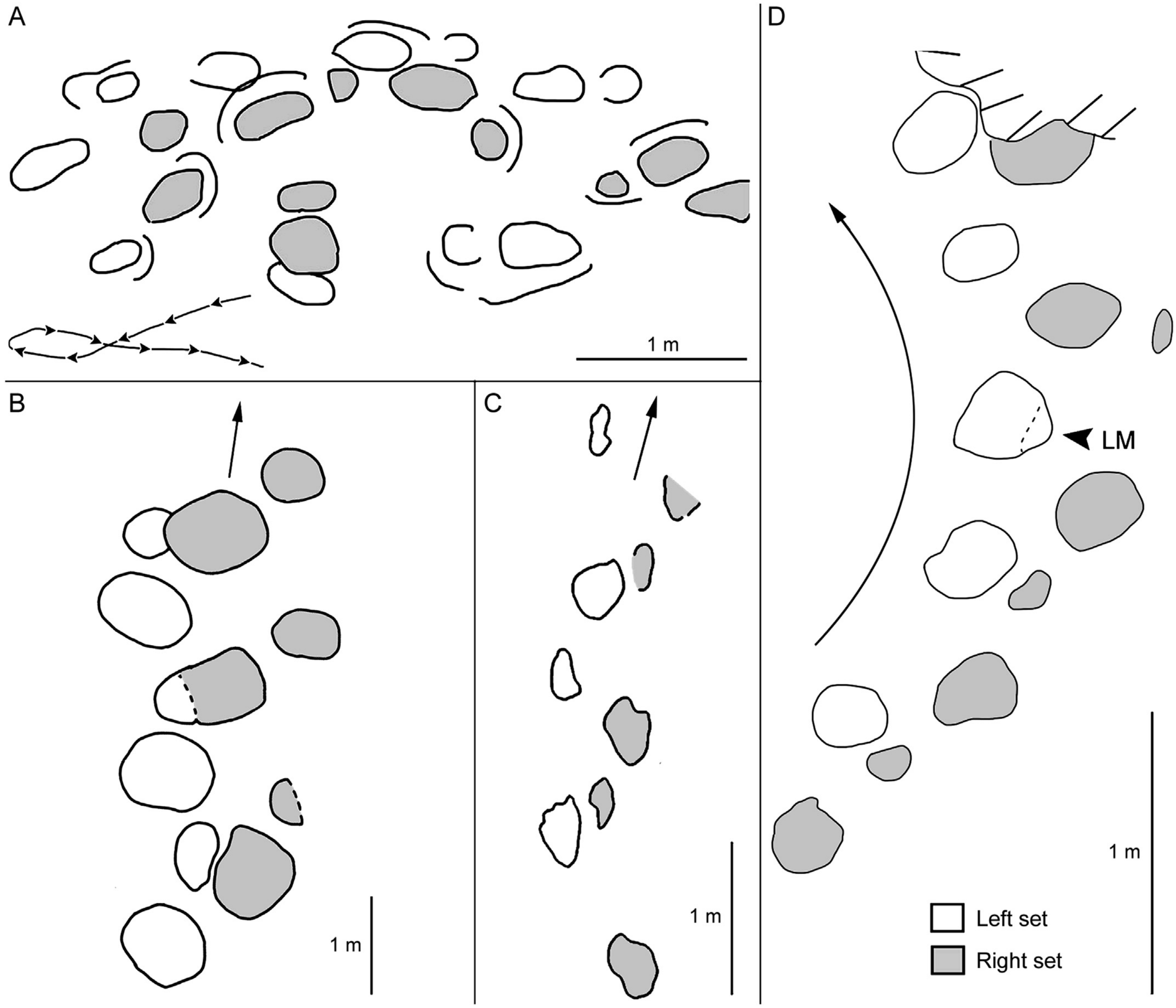

Fig. 11. Trackways of turning sauropods for comparison. A, from Zhaojue original site from Sichuan Province (Xing et al., 2015g); B, from Qingquanshi site of Shandong Province (Xing et al., in press-b); C, from Zhaojue IIN site of Sichuan Province (Xing et al., 2014b); D, from Tangdigezhuang site of Shandong Province (Xing et al., 2015f). Notice overstepped left manus (LM).

SMG-O9-L1 (Fig. 3A–B) is the best-preserved example among the SMG ornithopod tracks. The holotype pes trace of O9-L1 is mesaxonic, functionally tridactyl and digitigrade–semidigitigrade with a length of 29.5 cm. It is preceded in the trackway sequence by SMG-O9-R1. The average and median ML/MW ratio is 1.0. Both pes traces show a quadripartite morphology, consisting of impressions of three digits and a heel pad separated by pronounced grooves (as would appear in the trackmaker's foot), but which appear as ridges in natural impressions. The anterior triangle L/W ratio (degree of mesaxony) is 0.23. Digit III trace is the shortest, while traces of digits II and IV are almost equal in length. Each digit trace has a strong and blunt claw or ungual mark. The heel pad is subrounded to triangular in shape. There is a distinct border between the heel and the three digits. The interdigital divarication angle II–IV is 46°. In the trackway SMG-O9, pace length is 2× length of the pes.

Other ornithopod trackways from the SMG tracksite are basically consistent with the morphology of O9-L1, with an ML/MW ratio of 0.8–1 (median = 0.9, mean = 0.9), and mesaxony values of 0.22–0.3 (median = 0.27, mean = 0.26, based on the well-preserved O3, O8, and O9 trackways). The average pace angulation of these trackways ranges between 127° and 157°. Based on trackways SMG-O3, the pes traces show consistent inward rotation: 12°–14° (right pes) and 4°–8° (left pes).

Comparisons and discussion. Although it is agreed that many large ornithopod dinosaur tracks are difficult to differentiate, researchers started to review this idea in recent years, such as Lucas et al., 2011; Lockley et al., 2014; Díaz-Martínez et al., 2015. We emphasize that all ichnotaxonomy has to be based on a detailed study of the holotypes. Here we adopt ichnotaxonomy criteria proposed by Lockley et al., 2014.

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*, *Caririchnium*, *Iguanodontipus*, and *Ornithopodichnus*

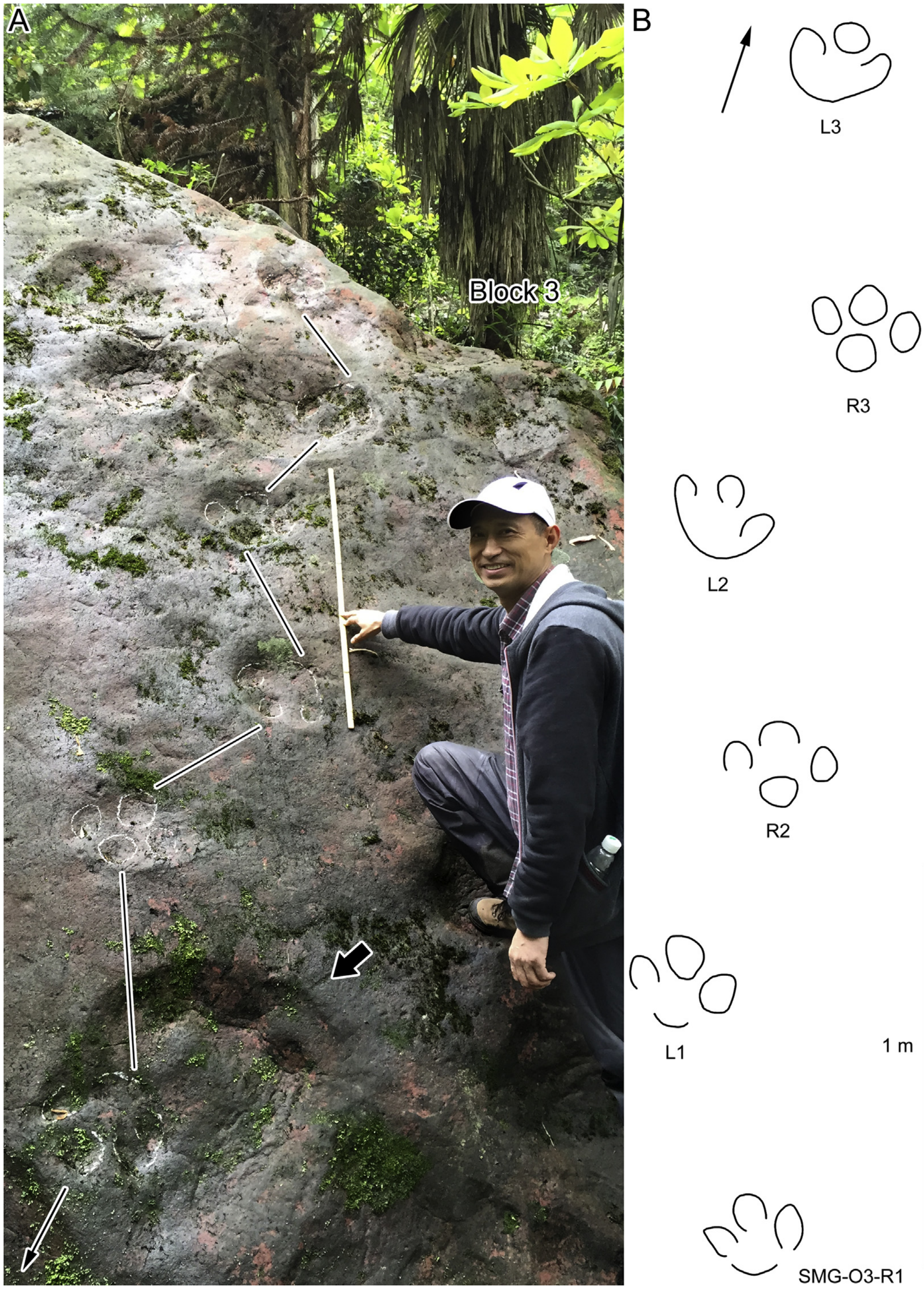

Fig. 12. Photograph of block 3 showing trackway of a bipedal ornithopod with one track overlapping a sauropod pes footprint (arrow).

(Lockley et al., 2014). SMG ornithopod tracks resemble *Caririchnium* (Fig. 14), an ichnogenus originally described from the Antenor Navarro Formation, Brazil (Leonardi, 1984). Currently, *Caririchnium* includes *C. magnificum* (Leonardi, 1984), *C. leonardii* (Lockley, 1987), *C. protohadrosaurichnos* (Lee, 1997), *C. lotus* (Xing et al., 2007), and *C. kyoungsookimi* (Lim et al., 2012): see Diaz-Martinez et al. (2015) for comments on the validity of three ichnotaxa. Lockley et al. (2014) reviewed and 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. In life, these ridges would have represented concave-up creases separated by convex-down pads. Most formally named *Caririchnium* ichnospecies, discussed below, are based on trackways made during quadrupedal progression. Thus, the evidence that the Shimiaogou tracks were made by bipeds indicates a behavioral difference expressed in the trackway configuration. It is a matter of debate as to whether the presence or absence of the manus has ichnotaxonomic significance (Currie, 1995; Lockley

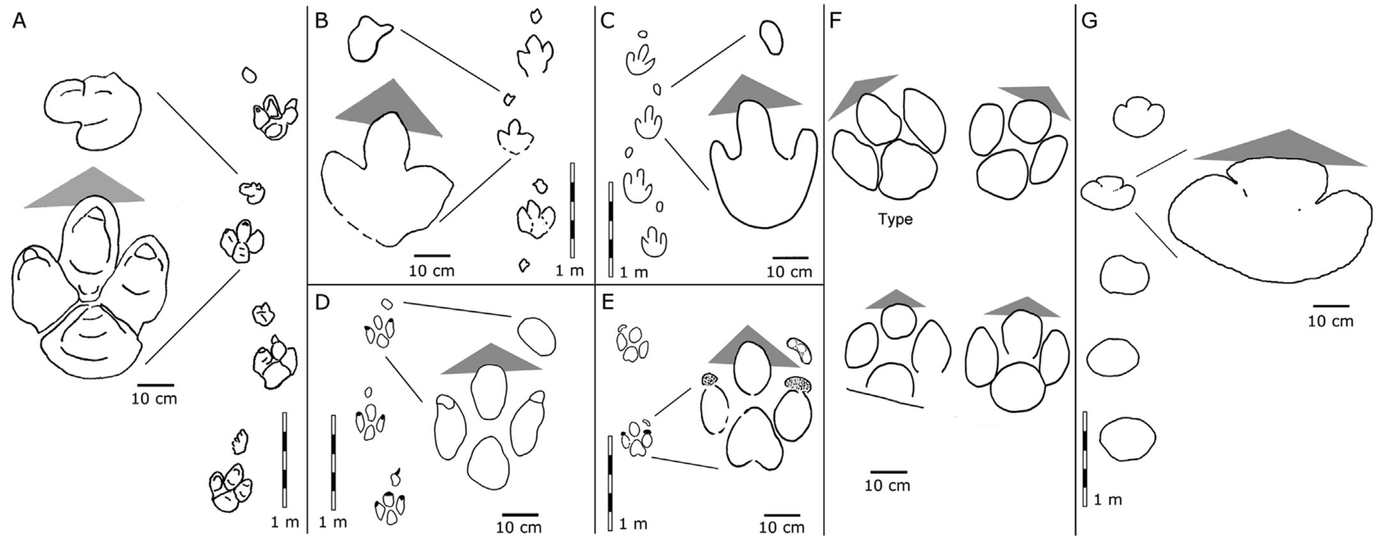

Fig. 13. Interpretative outline drawings of *Caririchnium* drawn to the same scale (modified after Lockley et al., 2014). A, *Carirchnium magnificum* (Leonardi, 1984); B, *Caririchnium leonardii* (Lockley, 1987); C, *Caririchnium protohadrosaurichnos* (Lee, 1997); D, *Caririchnium lotus* (Xing et al., 2007); E, *Caririchnium kyoungsookimi* (Lim et al., 2012), F, Shimiaogou *Caririchnium* from this paper, and G, *Ornithopodichnus masanensis* (Kim et al., 2009).

et al., 2014; Díaz-Martinez et al., 2015), especially when the pes tracks are similar. This is because it is known that large Cretaceous ornithopods included many facultative quadrupeds. For example, the Lotus site which also belongs to the Jiaguan Formation also has abundant ornithopod tracks. All of the ornithopod tracks Type A (>30 cm in length, range mostly 33–37 cm) represent quadrupeds. Only 17% (N = 18) of the ornithopod tracks of Type B (<30 cm in length, range mostly 20– 24 cm) no manus prints (Xing et al., 2015c). Even the well-preserved blocks of the Shimiaogou ornithopod tracks (e.g. blocks 1, 7 and 8) do not have any manus prints. Therefore, we are certain that the possibility of removal of manus tracks by weathering, dinoturbation or overprinting can be ruled out (cf. Castanera et al., 2013).

We subjected the Shimiaogou sample to bivariate analysis (Fig. 13). It is shown that the tracks are wider with a shorter anterior triangle than is the case in larger *Caririchnium* tracks. This is the reverse of the typical trend in tridactyl forms, for example, theropod tracks such as those of the *Grallator–Eubrontes* plexus, where smaller imprints tend to be relatively longer with stronger mesaxony than large imprints (Lockley, 2009). This implies that the differences are inherent in the track (and trackmaker) morphology and not attributable to unusual preservation. We also rule out the possibility that the tracks are significantly distorted by flattening (sensu Lockley and Xing, 2015) as none of the characteristic features of flattening, especially the rhomb shaped outline of digit III casts are present. Lockley et al. (2012) placed Cretaceous ornithopod tracks from Korea, with low length/width ratios, in *Ornithopodichnus*. However, these tracks lack the strong quadripartite morphology seen in *Caririchnium*.

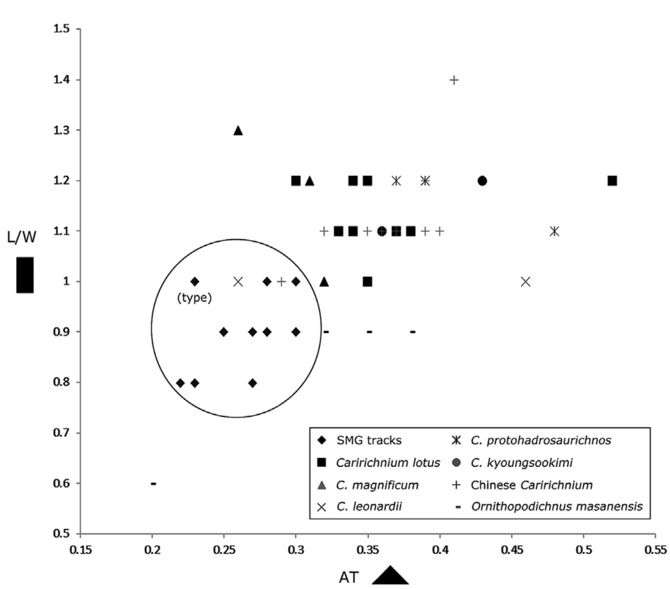

Fig. 14. Bivariate analysis plotting the length/width ratio vs. AT (anterior triangle length-width ratio) of Shimiaogou ornithopod tracks and other ornithopod ichnotaxa.

Besides the lack of manus traces, SMG specimens are morphologically different from other ichnospecies in having a mean pace length of 3.0 × footprint length, whereas in *C. magnificum* (Leonardi, 1984) and *C. leonardii* (Lockley, 1987), both larger than SMG specimens, this value is 2.0 × footprint length. Heels of SMG specimens are especially large components of the quadripartite morphology, unlike *C. lotus* (Xing et al., 2007) which is also from the Jiaguan Formation. Digit traces of SMG specimens are evidently more developed than in *C. protohadrosaurichnos* (Lee, 1997). SMG specimens also lack the bilobed heel trace seen in *C. kyoungsookimi* (Lim et al., 2012).

Bivariate analysis (based on footprint length/width ratio vs. anterior triangle length–width ratio) of the SMG ornithopod tracks and other *Caririchnium* ichnotaxa (Lockley et al., 2014; Xing et al., 2015c) and the unnamed Chinese species of *Caririchnium* (Xing et al., 2015c) finds that SMG ornithopod tracks differ from all *Caririchnium* tracks, as their widths are relatively larger than lengths (ML/MW ratio) and have weaker mesaxony, despite being smaller (Fig. 13). As noted above this is the reverse of the expected allometric trend in ornithopod pes tracks and tridactyl tracks in general (Lockley, 2009; Lockley et al., 2012).

Kim et al. (2009) named the ichnogenus *Ornithopodichnus* based on large footprints from the Lower Cretaceous of Korea, which exhibit distinctively weak mesaxonic and broad, transverse pes imprints that are wider than long. SMG ornithopod tracks are similar to *Ornithopodichnus* in possessing weak mesaxony, but

Table 4
Numbers of identifiable trackmakers records from the Jiaguan Formation, Sichuan Province, China. Abbreviations: Nu = the number of trackmakers (the total number of trackways and isolated tracks, Xing et al., 2015a); Or = ornithopod; Th = non-avian theropod; Bi = bird; Sa = sauropod; Pt = pterosaur.

Tracksite	Nu	Th	Bi	Sa	Or	Pt	Ref
Guanyingchong	3	100%	–	–	–	–	Young, 1960 Xing et al., 2009
Emei	22	90%	5%	–	5%	–	Zhen et al., 1994
Lotus	165	<1%	18%	10%	68%	3%	Xing et al., 2007
Tiger	2	–	–	100%	–	–	Xing et al., 2015b
Baoyuan	9	100%	–	–	–	–	Xing et al., 2011
Xinyang	5	80%	–	20%	–	–	Lockley and Xing, 2015 and unpublished date
Longjing	4	–	–	75%	25%	–	Xing et al., in press-a
Hanxi	20	35%	–	40%	25%	–	Xing et al., 2015a
Shimiaogou	38	32%	–	26%	37%	5%	This text

evident quadripartite morphology and triangular heel endow them greater affinity with *Caririchnium*. Several small ornithopod trackways from Korea and China have been attributed to *Ornithopodichnus*, based on low ML/MW ratio and mesaxony (Lockley et al., 2012; Xing and Lockley, 2014; Xing et al., 2015a). Only a small sample of small sized *Ornithopodichnus* from several different sites have elementary quadripartite morphology and are not definitive examples of *Caririchnium*. Therefore, length–width ratio cannot be considered a valid diagnostic characteristic at the ichnogenus level.

In general, SMG ornithopod tracks are morphologically closer to other *Caririchnium* tracks, justifying recognition of the difference at the ichnospecies level. These objective differences are sufficient to warrant erecting a new ichnospecies: *Caririchnium liucixini* ichnosp. nov.

Thulborn (1990) suggests that h = 5.9*P'ML for small ornithopods (P'ML < 25 cm). 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). The SL/h ratios of the SMG ornithopod trackways range from 0.72 to 0.92 and accordingly suggest a walking gait. Using the formula of Alexander (1976), the speed of these trackways ranges between an estimated 2.16 and 2.81 km/h. These results are consistent with speed of most Chinese *Caririchnium* trackways from China, such as those from the Lotus site (Xing et al., 2007) and the Zhaojue site (Xing et al., 2014b).

4.4. *Pterosaur tracks*

Only three isolated tracks, including one pes trace and two manus traces, numbered SMG-PI1–3 (Figs. 4, 6) are interpreted as pterosaurian. All tracks remain *in situ*. Although the pterosaur tracks have been affected by weathering, their main morphological features remain identifiable. The plantigrade pes print SMG-PI1 (8.5 cm in length) is narrow and has a U-shaped heel. Three indentations at the distal ends of SMG-PI1 may represent the proximal ends of digits I–III. All tracks lack a trace of digit IV. For example, in PI2 (7.5 cm in length), which is an asymmetrical and digitigrade manus print, only three digits are preserved. These radiate from a central depression, and digit III is the deepest. All pad and claw impressions of manual digits are indistinct. The divarication angle between digits I and III is very high (131°).

Pterosaur tracks are not abundant in China: about seven pterosaur tracksites have been discovered thus far, all from Cretaceous rock units. These are the Yanguoxia area (2 sites) in Gansu (Zhang et al., 2006; Li et al., 2015) and Qijiang in Chongqing (Xing et al., 2013a) which yielded the largest number of tracks. Pterosaur tracks were also found in Xinjiang, as well as in some southwestern, northern and northeastern parts of China (Xing et al., 2013a).

Morphologically, all of these Chinese pterosaur tracks are extremely similar to the ichnogenus *Pteraichnus* and are attributed to that ichnotaxon (Xing et al., 2013a). *Pteraichnus* was initially erected for a quadrupedal pterosaur trackway from the Upper Jurassic Morrison Formation of Apache County, Arizona (Stokes, 1957). Subsequently, *Pteraichnus* has become by far the most prevalent and best preserved pterosaur ichnotaxon (Lockley and Harris, in press).

The SMG pterosaur tracks may also be referred to *Pteraichnus* type tracks based on their elongate, subtriangular, plantigrade and tetradactyl pes print; clawed elongate, asymmetrical, digitigrade and tridactyl manus print; digit III print posterior; and digit prints increasing respectively in length (Lockley et al., 1995; Billon-Bruyat and Mazin, 2003). According to their position, tracks PI2 and PI3 may belong to the same trackway. Therefore, the tracks may reflect at least two different trackmakers, and further pterosaur tracks may be overlapped by surrounding ornithopod tracks.

5. Ichnofauna and palaeoenvironment

Nine tracksites have been found in the Jiaguan Formation (Table 4). If one trackway or one isolated track is regarded as reflecting an individual trackmaker, the abundance of trackmakers and proportions of different groups from the Jiaguan Formation can be estimated. Here estimates are based on a more conservative method suggesting one individual per trackway, and excluding isolated tracks (Table 1). Based on track types, saurischian (theropod and sauropod) tracks dominate seven sites, while the remaining two, the SMG and Lotus tracksites, are dominated by ornithopod tracks.

Deinonychosaurian tracks remain rare in the Jiaguan Formation. The SMG tracksite adds another deinonychosaurian record to that of the Emei tracksite. Similarly, pterosaur tracks at the SMG tracksite represent the second record in the Jiaguan Formation, but are less abundant there compared with the Lotus tracksite (Xing et al., 2013a). Vertebrate trackmakers at the SMG tracksite are diverse, including small theropods, deinonychosaurians, sauropods, ornithopods and pterosaurs. Generally, sauropod tracks commonly co-occur with theropod tracks but rarely with ornithopod tracks. Regionally this is the third record showing a co-occurrence of sauropods and ornithopods after the many assemblages documented from Korea (Lim et al., 1994) and from the Yanguoxia site, China (Zhang et al., 2006). Interestingly, the known skeletal record from the Jiaguan Formation consists of fragmentary theropod (?dromaeosaur) skeletal remains and sauropod limb bones (Wang et al., 2008).

Sauropod tracks are usually preserved in coastal sediments and lake shore sediments in low latitude arid regions or in river and lake sediments in semi-arid areas, while ornithopod tracks are usually preserved in humid environments frequently associated with coal beds (Lockley et al., 1994b; Mannion and Upchurch, 2010). During the Jurassic, a set of super-thick red beds formed in the Sichuan Basin. At the time, the environment was a river-flood basin with a tendency towards drought. Sauropods were thriving, but records of ornithopods are rare (Peng et al., 2005). In the middle–late Early Cretaceous, sediments of the Sichuan Basin mainly developed in the Ya'an-Chengdu subregion, in the west and in the Yibin-Xishui subregion in the southwest (Wang et al., 2008), that is the main area with exposures of the Jiaguan Formation. These areas are characterized by red sandstone sequences representing arid paleoenvironments, with intermittent river deposits such as sandstone–conglomerate–mudstone facies sediments with layers displaying large scale cross bedding (Cao, 2007). Dinosaurs at that time lived in a dry hot climate, with intermittent river environments and a few oases (Wang et al., 2008). The Jiaguan Formation was positioned at a paleolatitude of 25.5° N (Jiang et al., 2000), and low-latitude sauropod and higher latitude ornithopod ichnofaunas might be mixed in this area.

6. Conclusions

The SMG tracksite reveals more than 132 tracks representing at least 30 individual trackmakers belonging to at least five distinct trackmaking groups: tridactyl theropods, didactyl deinonychosaurian theropods, sauropods, ornithopods and pterosaurs.

The site represents the ninth discovery in a rapidly growing series of tracksite reports from the red beds of the Jiaguan Formation.

Most Jiaguan Formation tracksites are saurischian (theropod + sauropod) dominated. However, the Shimiaogou site is one of only two with ornithopod tracks, and reveals the largest proportion of this type so far recorded in this formation.

The ornithopod trackways are assigned to the ichnogenus *Caririchnium*, but unlike most other occurrences they represent bipedal, rather than quadrupedal progression. They are also morphologically distinct from other ichnospecies of this ichnogenus in being smaller, proportionally wider with weaker mesaxony. For this reason they are assigned to the new ichnospecies *Caririchnium liucixini*.

We also record an unusual sauropod trackway showing a distinctive walking (possibly pathological causes or turning) pattern and lacking traces of the left manus.

Acknowledgments

The authors thank Ignacio Díaz-Martínez and Diego Castanera for their constructive reviews. This research was supported by the Gulin People's Government, the Zigong Dinosaur Museum, and the 2013 and 2015 support fund for graduate students' science and technology innovation from China University of Geosciences (Beijing), China.

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