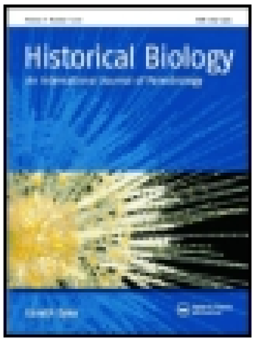

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Saurischian (theropod–sauropod) track assemblages from the Jiaguan Formation in the Sichuan Basin, Southwest China: ichnology and indications to differential track preservation

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ABSTRACT
Saurischian (theropod and sauropod) tracks and trackways from the Jiaguan Formation (Lower Cretaceous) of the Sichuan Basin are exposed as natural casts with associated undertrack or transmitted print casts. The theropod tracks (cf. *Eubrontes* and *Grallator*) were left by differently sized trackmakers. This is a further example for the occurrence of characteristic Lower Jurassic ichnotaxa in the Cretaceous that obviously had a more extended stratigraphic range in East Asia. The sauropod trackway is tentatively assigned to cf. *Brontopodus* based on imprint morphology and (nearly wide) gauge. The tracks, however, allow a detailed study of their formation and the taphonomic processes under different substrate conditions. Differential preservation and erosion of primary sedimentary structures, and post-burial deformation structures, give insight into a complex preservational history during a low energy phase interrupting the deposition of a sequence of thick high energy sandstones. This is the sixth report of dinosaur tracks from the Jiaguan Formation and the fifteenth report from the Lower Cretaceous of Sichuan Province. Thus, the tetrapod ichnological record in this region is rapidly becoming of major importance for our knowledge of dinosaur faunas in south-western China.

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Sauropod; theropod; footprints; transmitted prints; Jiaguan Formation; Lower Cretaceous

1. Introduction

At present, documented medium- to large-sized, functionally tridactyl, theropod tracks from the Cretaceous of China include *Asianopodus*, *Eubrontes*, *Irenesauripus*, *Kayentapus* and *Therangospodus* (Lockley et al. 2013; Xing, Lockley, Zhang, et al. 2013; Xing, Niedźwiedzki, et al. 2014). Using the criteria of Thulborn (1990), which categorises non-avian theropod (hereafter simply 'theropod') tracks as 'small' if they are 25 cm or less in length, we exclude ichnogenera such as *Grallator* (and *Paragrallator)* and *Corpulentapus* (Li, Lockley, et al. 2011; Lockley et al. 2013) from the medium- to large-sized theropod track category. Due to the lack of well preserved specimens, most *Irenesauripus* type tracks can be classified as cf. *Irenesauripus–Kayentapus* (Xing, Harris, et al. 2011; Xing, Lockley, Zhang, et al. 2013). Based on a re-evaluation of *Therangospodus oncalensis* materials from the Iberian Range (Spain), Castanera et al. (2013) suggested that *Therangospodus* tracks from the Spanish localities represent an ornithopod, while the North American type material of *Therangospodus pandemicus* (Lockley et al. 1998) is clearly of theropod origin. Such reinterpretations call into question the taxonomic affinity of all Chinese ichnites classified as *Therangospodus*. The East Asia-specific ichnogenus *Asianopodus* is similar to *Eubrontes*, but with a large more rounded heel pad trace, which may reflect true morphological distinctiveness in the feet and the pes evolution of Early Cretaceous Asian theropods (Matsukawa et al. 2005, 2006; Xing, Niedźwiedzki, et al. 2014).

Most of the Cretaceous vertebrate tracks found in the Sichuan Basin are from the Lower Cretaceous, including those from the Jiaguan Formation in the Emei (Zhen et al. 1994; Lockley et al. 2013) and Qijiang areas (Xing et al. 2007; Xing, Lockley, Piñuela, et al. 2013), the Jiaguan Formation (formerly known as Wotoushan Formation) in the Chishui area (Xing, Harris, et al. 2011) and the Feitianshan Formation in the Zhaojue area (Xing, Lockley, Zhang, et al. 2013; Xing, Lockley, Zhang, Klein, Persons, et al. 2014; Xing et al. 2015). The track assemblages of the Feitianshan Formation include footprints of ornithopod, sauropod and theropod dinosaurs, as well as pterosaurs (Xing et al. 2015). Those of the Jiaguan Formation also include ornithopods, sauropods, theropods and pterosaurs, as well as birds (Zhen et al. 1994; Xing et al. 2007; Xing, Lockley, Piñuela, et al. 2013; Xing et al. in review). Compared with the theropod tracks of the Feitianshan Formation, those of the Jiaguan Formation are inferior both in terms of the quantity and the state of preservation.

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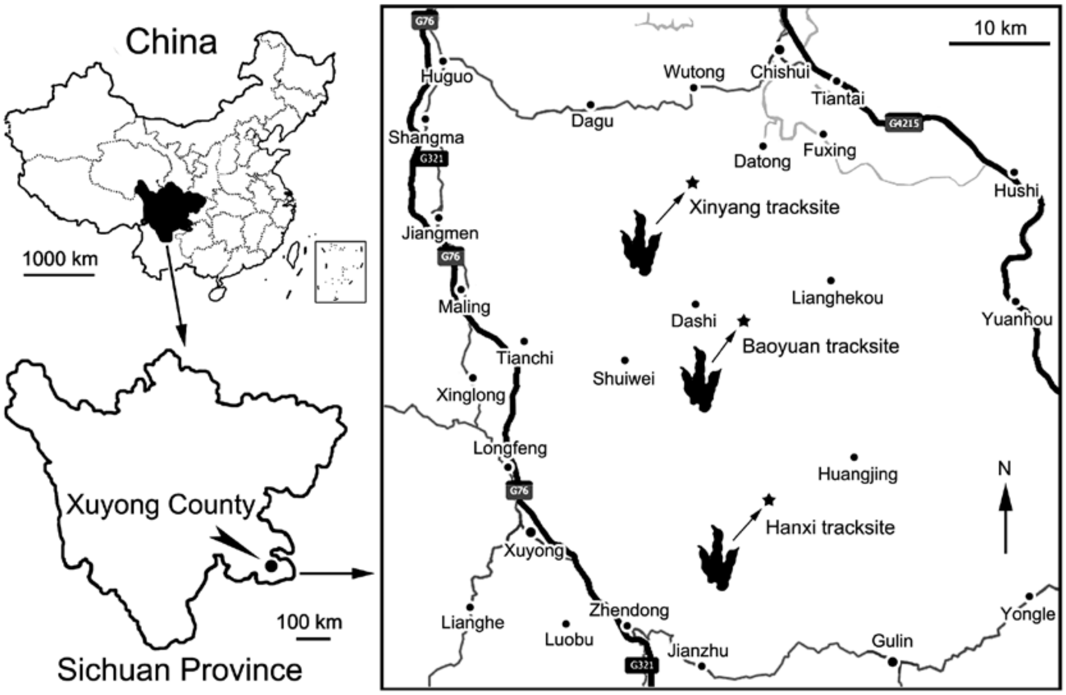

Figure 1. Map showing the position of footprint localities in the Lower Cretaceous of Sichuan Province, south-western China (footprint icon): Xiyang (this text), Baoyuan (Xing, Harris, et al. 34) and Hanxi tracksites

Figure 2. Photographs of the Xiyang tracksite. (A) possible original layer and resource of the Xiyang tracks; arrow indicates wedge-shaped cross-stratification. (B) tracks preserved on the large fallen block.

The theropod tracks reported here are from the roadsides of the Ancient Tea Route (a connecting roadway between Xuyong and Chishui, originally constructed during the Qing Dynasty, A.D. 1644–1912) near Xinyang Village, Xuyong County, Luzhou City, Sichuan Province (Figure 1). A portion of one of the tracksites was exposed during the Qing Dynasty (A.D. 1840). At that time, local villagers thought, the tracks were left by 'strange heavenly ducks'. This is another example of fossil tracks influencing Chinese folklore and legends (Xing, Mayor, et al. 2011). In June 2013, a villager named Chaogui Zhang began to expose more tracks at this site. The major authors of this paper (XL, PG and YY) inspected the tracksite in July and September, 2014. In the following, we present a comprehensive documentation of footprint material discovered on the lower surface of a large fallen block. Besides the discussion of ichnotaxonomy, we focus on the taphonomy and preservation of these tracks.

2. Geological setting

The Xingyuan tracksite (GPS: 28°26′21.2′′N, 105°35′5.3′′E) is located at the southern margin of the Sichuan Basin. 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 characterised by a set of thick, brick-red, feldspathic, quartz sandstones (Sichuan Provincial Bureau of Geology aviation regional Geological Survey

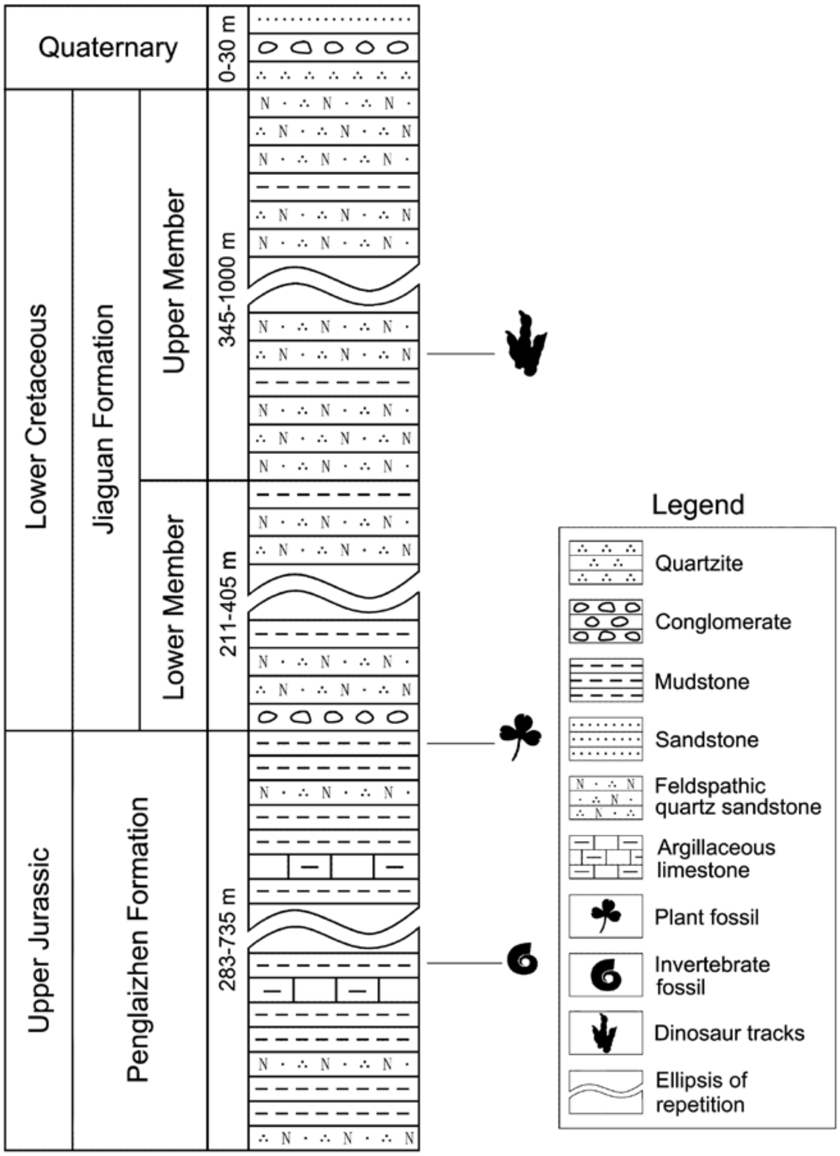

Figure 3. Stratigraphic section of the Jurassic–Cretaceous in the study area with position of footprints, invertebrates and plant fossil remains.

team 1976). The Jiaguan Formation consists of upper and lower members. The lower member is 211–405 m thick, with a 0- to 10-m-thick conglomerate layer at the base and a 2- to 10-m-thick mudstone layer at the top. The upper member is a 345- to 1000-m-thick feldspathic quartz sandstone succession, with thin or lenticular mudstone interlayers. Within the upper member, there are large cross-bedded units and typical sedimentological features such as mud cracks, raindrop impressions and ripple marks (Sichuan Provincial Bureau of Geology aviation regional Geological Survey team 1976; Chen 2009). The tracksite is a large fallen block from an exposure of the upper member of the Jiaguan Formation (Figures 2 and 3), which displays current ripples and abundant mud cracks. Well developed wedge-shaped cross-stratification was observed on the large thick sandstone comprising the tracksite block.

The age of the Jiaguan Formation has been estimated to be between 117 and 85 Ma (Aptian–Santonian) by Li (1995) and between 140 and 85 Ma (Berriasian–Santonian) by Gou and Zhao (2001). Recent pollen studies indicate a Barremian–Albian age (Chen 2009).

3. Materials and methods

All tracks are natural casts (convex hyporeliefs), occurring on the underside of a large fallen block. After cleaning the track surface, the tracks were catalogued, photographed and measured. Several photos were assembled to form a single image of the complete trackway, using Adobe Photoshop Photomerge. Numerous images of individual tracks and trackway segments were also obtained (Figures 2 and 4–7).

Photogrammetric images were produced from multiple digital photographs (Canon EOS 5D Mark III) which were converted into scaled, highly accurate 3D textured mesh models using Agisoft Photoscan Professional. The mesh models were then imported into Cloud Compare where the models were rendered with accurately scaled colour topographic profiles (Falkingham 2012).

The degree of mesaxony was calculated according to the methods used by Olsen (1980), Weems (1992) and Lockley (2009). After these authors, tridactyl tracks can be differentiated on the basis of mesaxony: i.e. the degree to which the distal

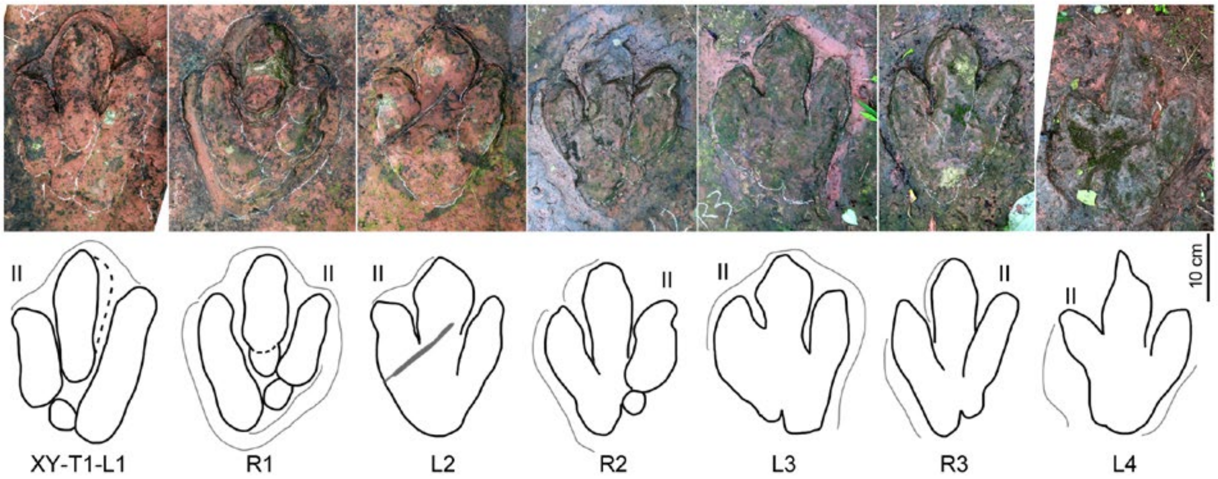

Figure 4. Photographs and sketches of specimens XY-T1-L1 and L4 from the Xiyang tracksite, Sichuan Province, China

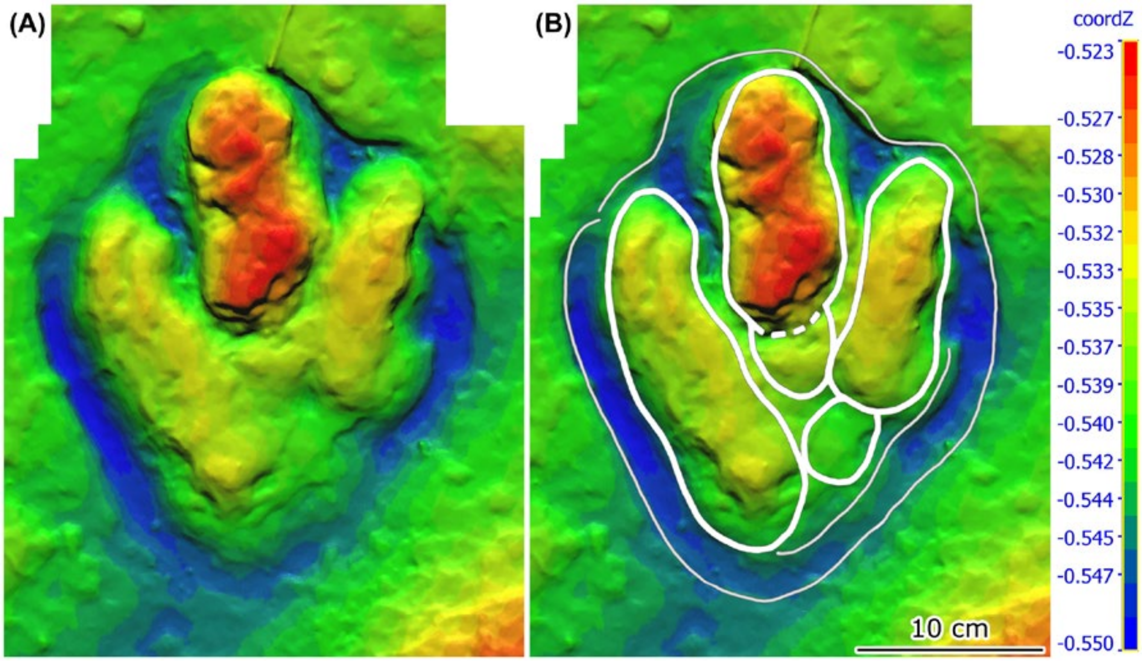

Figure 5. 3D height map of XY-T1-R1 (A), and combined with superimposed sketch (B). Deepest parts are coloured in red. Topographic profile scale is in metres.

end of the central digit (III) protrudes anteriorly beyond the distal end of the medial (II) and lateral (IV) digits to define an anterior triangle.

For theropod trackways, we calculated speed (v) using Alexander's (1976) formula: $v = 0.25\ g^{0.5}\ SL^{1.67}\ h^{-1.17}$, where g = gravitational acceleration in m/s; SL = stride length; and h = hip height, estimated as 4.5 times foot length, using the ratio for large theropods proposed by Thulborn (1990).

For the quadrupedal sauropod trackway, gauge (trackway width) was quantified for pes and manus tracks using the ratio between the width of the angulation pattern of the pes (WAP) and the pes length (L) (Marty 2008; Marty et al. 2010). If the ratio is smaller than 1.0, tracks intersect the trackway midline, which corresponds to the definition of narrow-gauge (Farlow 1992). Accordingly, a value of 1.0 separates narrow-gauge from medium-gauge trackways, whereas the value 1.2 was chosen by Marty et al. (2010) to differentiate between medium-gauge and wide-gauge trackways.

Institutional abbreviations: L/R = Left/right; T = Theropod; XY = Xinyang tracksite, Xuyong, Sichuan Province, China.

4. Results

4.1. Theropod tracks

The theropod trackway XY-T1 is roughly 5 m in length and consists of seven tridactyl footprints preserved as natural casts (convex hyporeliefs), labelled XY-T1-L1–XY-T1-L4 (Figures 2, 4–6) (Table 1). The footprints have an average length and width of 26.4 cm and 17.6 cm, respectively, and a depth of 2–4 cm. The average length: width ratio of the imprints is 1.5, the pace angulation 164° and the average divarication angle between digits II and IV 48°. The divarication angle between digits II and III is larger

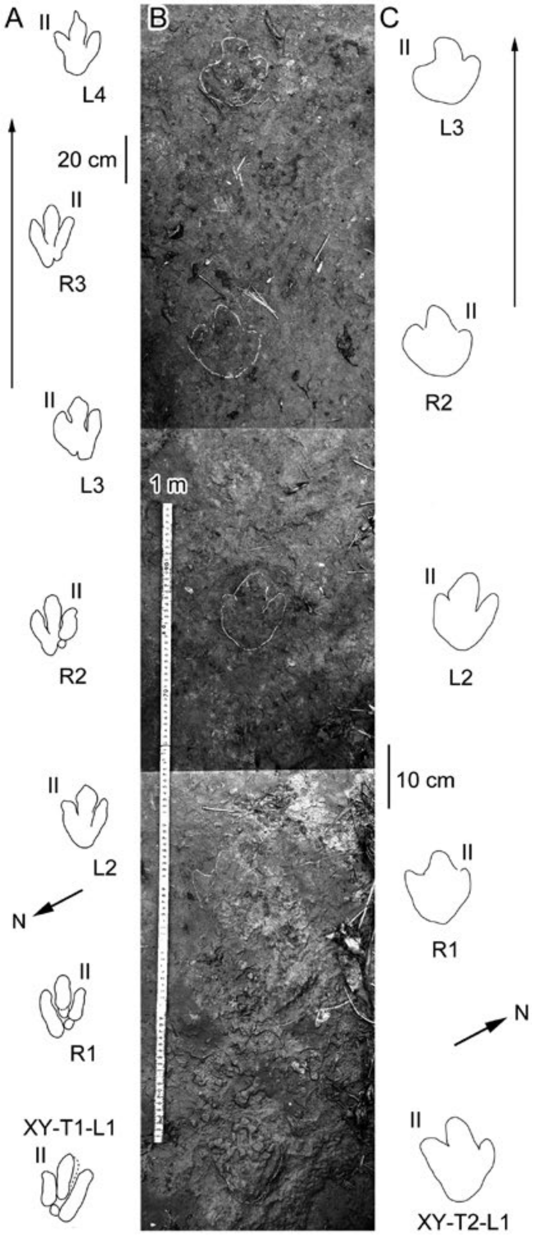

Figure 6. Theropod trackways from the Xiyang tracksite. XY-T1 cf. *Eubrontes*. (A) sketch indeterminate theropod trackway XY-T2. (B) photograph, (C) sketch.

than that of digits III and IV (25° vs. 23°). One step (78.6 cm) is about 3 times the length of a single footprint.

XY-T1-L1 is the best-preserved track in the XY-T1-L1–XY-T1-L4 sequence, although the differences in preservation of all seven imprints are quite small. In XY-T1-L1, digit II is the shortest, and digit III is slightly shorter than digit IV (Figure 4). Digit II has two digital pads, while the count of the digital pads in digits III and IV is unclear due to poor preservation. Clawmarks are mostly absent or indistinct. Two distinct metatarsophalangeal pad traces can be seen: a smaller one posterior to digit II and another larger one posterior to digit IV. The former is oval in shape and adjacent to, but distinctly offset from, the trace of the first proximal pad of digit II. The latter is round, blunt and faintly defined, positioned in line with the axis of digit IV and closely amalgamated with the latter. The two metatarsophalangeal pad traces contact each other close to the axis of digit III. All three toes of XY-T1-L1 are deep, well defined and have a 'fleshy' appearance. Around this footprint cast and others in the trackway sequence, there is evidence of a broken layer about 5 mm in depth, which previously underlay the footprints continuously before it was depressed into shallow concavities (concave epireliefs) on the upper surface [and corresponding convex hyporeliefs, or casts of undertracks (sensu Marty 2008), on the lower surface]. The broken areas where this layer has eroded away are between about 5 and 20 mm wide (Figure 5). The mechanism responsible for deforming the sediments during the preservation of the tracks is discussed below and by Lockley and Xing (2015).

The morphology of the other XY-T1 tracks is basically similar to that of XY-T1-L1. There is no margin outlining the two metatarsophalangeal pad cast traces of XY-T1-L2, R3 and L4, instead they fuse into single large heel traces. This may be due to a difference in substrate moister, which has great impacts on preserved details.

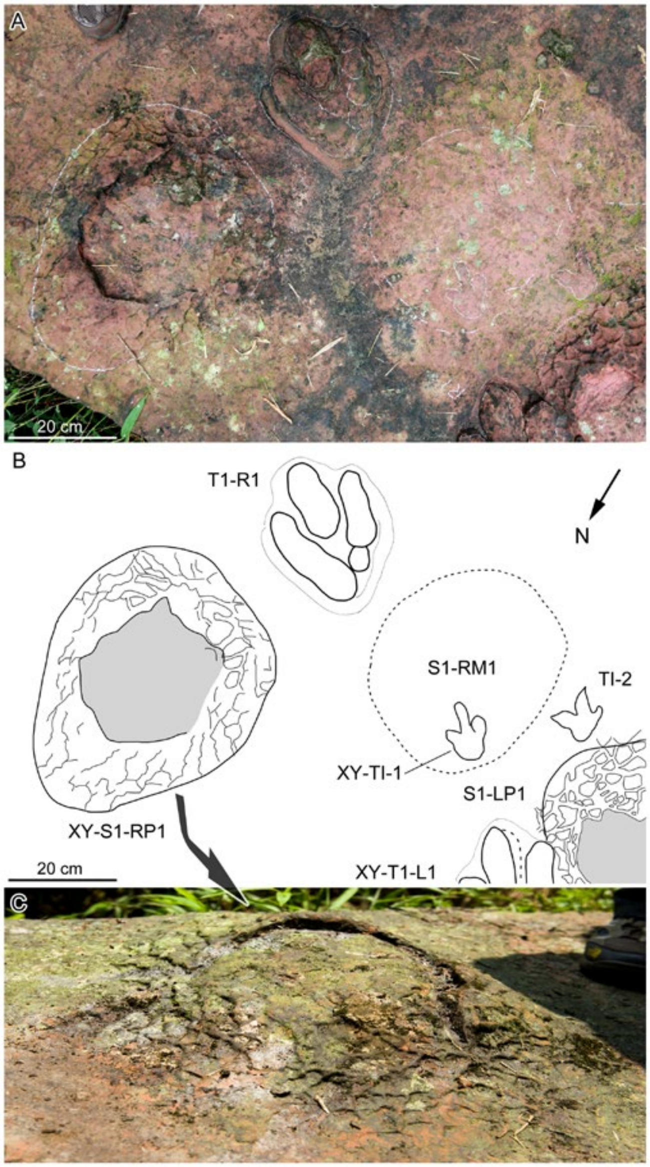

Figure 7. Details of sauropod and theropod natural casts from the Xiyang tracksite. (A) photograph, (B) sketches, (C) low-angle light photograph of sauropod track XY-S1-RP1.

XY-T1 constitutes a single trackway. Based on the length of the step, we estimated a speed of ~1.3 m/s or ~4.8 km/h (Alexander 1976; Thulborn 1990). The relative stride length (SL/*h*) is 1.3, implying that the animal was walking, not trotting or running.

A trackway consisting of five footprints, numbered XY-T2-L1–L3 (Figure 6) and two isolated tracks numbered as XY-T-1 and 2 belong to a smaller trackmaker. XY-T2 is a poorly preserved trackway, with tracks having a mean length of 12.1 cm and a L/W ratio of 1.2. It shows weak to moderate mesaxony (average 0.39, ranging between 0.34 and 0.44, *N* = 5). The imprints lack discernable claw marks and phalangeal pads, which is probably the result of weathering. The pace angulation is 169°, which is close to the angulation of XY-T1. Adopting the formula of Alexander (1976), the speed of XY-T2 is ~1.2 m/s or ~4.4 km/h. The relative stride length (SL/*h*) is 1.55, implying that the animal was walking. XY-TI-1 and II are poorly preserved tracks (Figure 7). The possibility of undertracks should not be excluded. TI-1 is 'overlapped' by a sauropod manus track (S1-RM1) and exhibits relatively strong mesaxony (0.62), differing from other XY tridactyl tracks. TI-2 possesses strong extramorphological characters, such as the unusually thin right outer digit.

4.2. *Sauropod tracks*

The XY tracksite preserves one large trackway of a quadruped (XY-S1), which includes four pairs of manus-pes traces (Figures 7 and 8), exposed as casts of undertracks. The thin (~5 mm) layer of sandstone exposed on the surface of the block represents the layer beneath the sauropod trackway, where it was depressed to produce downward bulges (natural casts or convex hyporeliefs of undertracks) as noted for theropod trackway XY-T1. In the case of some sauropod tracks, however, this layer was not broken, or in some cases, broken only where the tracks are deepest. In none of the tracks (undertracks), the layer is eroded up to the edge of the track, therefore the outline of the 'true track is never exposed'. The manus impressions of XY-S1 lie anteromedially to the pes

Table 1. Measurements (in cm) of saurischian (theropod–sauropod) tracks from the Xinyang tracksites, Xuyong, Sichuan Province, China.

Number	L	W	II-III	III-IV	II-IV	PL	SL	PA	M	L/W
XY-T1-L1	26.0	18.0	25°	19°	44°	77.5	155.0	171°	0.39	1.4
XY-T1-R1	26.5	15.0	26°	23°	49°	78.0	153.0	162°	0.37	1.8
XY-T1-L2	26.5	18.5	26°	22°	48°	77.0	155.0	158°	0.38	1.4
XY-T1-R2	26.5	19.0	23°	25°	48°	81.0	156.0	162°	0.39	1.4
XY-T1-L3	26.5	15.8	24°	21°	45°	77.0	157.0	167°	0.37	1.7
XY-T1-R3	26.5	17.5	26°	23°	49°	81.0	–	–	0.36	1.5
XY-T1-L4	26.5	18.5	26°	28°	54°	–	–	–	0.38	1.4
Mean	26.4	17.5	25°	23°	48°	78.6	155.2	164°	0.38	1.5
XY-T2-L1	13.0	10.0	26°	29°	55°	41.5	85.0	171°	0.36	1.3
XY-T2-R1	11.5	9.5	26°	32°	58°	44.0	85.2	165°	0.34	1.2
XY-T2-L2	13.0	10.5	29°	26°	55°	42.0	83.7	170°	0.39	1.2
XY-T2-R2	11.5	9.5	37°	22°	59°	43.0	–	–	0.41	1.2
XY-T2-L3	11.5	11.0	43°	35°	78°	–	–	–	0.44	1.0
Mean	12.1	10.1	32°	29°	61°	42.6	84.6	169°	0.39	1.2
XY-TI-1	11.3	7.5	–	–	47°	–	–	–	0.62	1.5
XY-TI-2	10.5	10.0	–	–	82°	–	–	–	0.40	1.1
XY-S1-LP1	53.0	40.0	–	–	–	123.0	163.0	80°	–	1.3
XY-S1-LM1	35.0	33.0	–	–	–	97.0	173.0	98°	–	1.1
XY-S1-RP1	51.0	45.0	–	–	–	130.0	192.0	94°	–	1.1
XY-S1-RM1	26.0	32.0	–	–	–	130.0	185.0	98°	–	0.8
XY-S1-LP2	56.0	40.0	–	–	–	133.0	–	–	–	1.4
XY-S1-LM2	28.0	34.0	–	–	–	114.0	–	–	–	0.8
XY-S1-RP2	49.0	42.0	–	–	–	–	–	–	–	1.2
XY-S1-RM2	26.0	28.0	–	–	–	–	–	–	–	0.9
Mean-P	52.3	41.8	–	–	–	128.7	177.5	87°	–	1.3
Mean-M	28.8	31.8	–	–	–	113.7	179.0	98°	–	0.9

Abbreviations: L: length; W: 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; M: mesaxony; L/W: length/width.

impressions. The average length/width ratios of the manus and pes impressions are 0.9 and 1.3, respectively. LP1–LM1 is the best-preserved manus-pes association and shows U-shaped manus imprints with rounded marks of digits I and V. The pes impression is oval, while the digit traces are too indistinct to be identified with confidence, and the metatarso-phalangeal region is smoothly curved. The manus impressions, best seen on the left side, are rotated approximately 57° outward from the trackway axis, which is larger than the outward rotation of the pes impressions (approximately 44°). The average manus PA is 87°, while the average pes PA is 98°.

The WAP/L ratio of XY-S1 is 1.4, which is nearly wide-gauge; however, as noted above, the exposed underside of the trackway represents an undertrackway. This makes the determination of trackway gauge slightly imprecise.

5. Discussion

5.1. Ichnotaxonomy

By their size (>25 cm pes length) and by the degree of mesaxony, the large tridactyl tracks from Xinyang can be assigned to the ichnogenus *Eubrontes* (see Olsen et al. 1998). They are characterised by weak to moderate mesaxony (average 0.38, range 0.36–0.39, *N* = 7), which is close to that of typical footprints of the ichno- or morpho-family Eubrontidae, Lull 1904 (0.37–0.58 in *Eubrontes* type; Lockley 2009). The most striking character of the Xinyang tracks is the presence of a distinct metatarsophalangeal pad trace posterior to digit II. This character is common in *Eubrontes* tracks, such as the type specimens of *Eubrontes* AC 151 (Olsen et al. 1998). This characteristic also makes the Xinyang tracks different from those of cf. *Irenesauripus* isp., from the Jiaguan Formation in the Chishui area, Guizhou Province (Xing, Harris, et al. 2011), and *Asianopodus* from the Cretaceous Hekou Group at the Huazhuang tracksite, Gansu Province (Xing, Niedźwiedzki, et al. 2014), which show hallux impressions. *Irenesauripus* tracks, from the Lower Cretaceous Feitianshan Formation in the Zhaojue area, Sichuan, also display weak to moderate mesaxony (0.37), but a wider interdigital divarication II–IV (71°) (Xing, Lockley, Zhang, et al. 2013; Xing, Lockley, Zhang, Klein, Persons, et al. 2014).

In terms of size, presence of metatarsophalangeal pad traces, the interdigital divarication of digits II–IV and pace angulation, the Xinyang tracks are similar to typical *Eubrontes giganteus* and are here compared with this ichnospecies, however, tentatively assigned to cf. *Eubrontes* because of the limited and moderately preserved sample. The fact that this is an ichnotaxon best known from the Lower Jurassic is discussed below.

The size of the small imprints in XY-T2 matches the range of typical Grallator (<15 cm; Olsen et al. 1998). However, the weak to moderate mesaxony (average 0.39, ranging between 0.34 and 0.44, *N* = 5), is typical for footprints of the ichno- or morpho-family Eubrontidae, Lull 1904 (Lockley 2009). In consideration of the preservation conditions, further analysis is difficult for XY-T2. However, considering the mesaxony and pace angulation, XY-T2 could be a juvenile individual of the same adult track-making taxon represented by XY-T1 (cf. *Eubrontes*, see above).

The overlap of TI-1 by a sauropod manus track (SM1-RM1) is not uncommon as in the case of bird tracks (*Koreanaornis hamanensis*) recorded in a sauropod pes track (*Brontopodus pentadactylus*) (Kim and Lockley 2012). TI-1 exhibits relatively

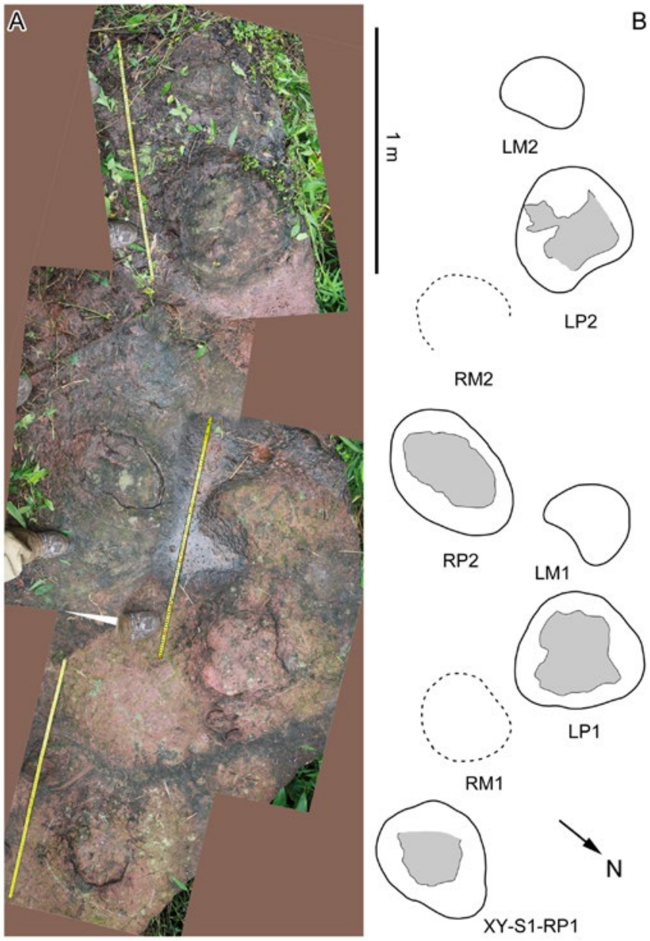

Figure 8. Photograph (A) and sketch (B) of sauropod trackway XY-S1.

strong mesaxony (0.62), differing from other XY tridactyl tracks, while resembling Early Cretaceous *Grallator* from China (Xing, Lockley, Klein, et al. 2014).

In a review of Chinese ichnotaxonomy, Lockley et al. (2013) considered the abundance of *Grallator* in the Cretaceous of China to be particularly striking and perhaps characteristic of an indigenous East Asian ichnofauna. This inference is in part because *Grallator* is an ichnogenus traditionally recognised as part of the widely distributed Lower Jurassic biochron (Lucas 2007). Presently, the Cretaceous distribution of *Grallator* affects our ability to differentiate Cretaceous and Jurassic grallatorid tracks and reduces the apparent global ichnodiversity among Cretaceous theropod tracks. This conclusion was based on the observation that while *Grallator* type tracks are common in North America and Europe only during the Jurassic, *Grallator* type tracks remain abundant in Cretaceous deposits of China, such as *Grallator ssatoi* from the Upper Jurassic–Lower Cretaceous Tuchengzi Formation in Yanshan area, Liaoning Province (Yabe et al. 1940); *Grallator emeiensis* from the Lower Cretaceous Jiaguan Formation in Emei region of Sichuan Province (Zhen et al. 1994); the grallatorid track *Paragrallator yangi* (Li and Zhang 2000; Li, Lockley, et al. 2011) from the Lower Cretaceous Yangjiazhuang Formation in Zucheng area, Shandong Province and *Jialingpus* (another grallatorid track morphotype) from the Lower Cretaceous Luohe Formation of the Ordos Basin, Shaanxi Province (Xing, Lockley, Klein, et al. 2014).

Other classically Jurassic theropod ichnotaxa may also be present in Cretaceous deposits of China, such as *Eubrontes* type tracks from the Jurassic-Cretaceous Boundary Tuchengzi Formation in Beijing, China (Xing et al. 2015); *Chapus* and *Asianopodus* (generalised *Eubrontes* type tracks, Xing, Niedźwiedzki, et al. 2014) from the Lower Cretaceous of the Chabu area in Inner Mongolia (Li et al. 2006; Li, Bai, et al. 2011); *Asianopodus* from the Cretaceous Hekou Group at the Huazhuang tracksite, Gansu Province (Xing, Niedźwiedzki, et al. 2014) and *Eubrontes* type tracks from the Upper Cretaceous Xiaoyan Formation in Anhui Province (Xing, Lockley, Zhang, Klein, Kim, et al. 2014). The Xinyang *Eubrontes* type tracks provide us with another example. Though it must be noted that the Chinese Cretaceous theropod track record from China also includes highly distinctive and well preserved forms, such as *Corpulentapus* (Li, Lockley, et al. 2011), *Velociraptorichnus* (Zhen et al. 1994), *Minisauripus* (Zhen et al. 1994), *Dromaeopodus* (Li et al. 2007) and *Paracorpulentapus* (Xing, Lockley, Zhang, Klein, Kim, et al. 2014). Cretaceous theropod track assemblages from China are characterised not only by the late occurrence of typical Jurassic ichnofaunal components such as *Grallator*–*Eubrontes*, but include other novel and diverse morphotypes.

The footprints cf. *Eubrontes* from Xinyang contribute to the known diversity of theropod tracks from the Jiaguan Formation, which also includes *Grallator*, *Velociraptorichnus* and *Minisauripus* from Emei area (Zhen et al. 1994) and cf. *Irenesauripus* isp. from Chishui (Xing, Harris, et al. 2011).

The sauropod tracks of trackway XY-S1 are consistent with characteristics of *Brontopodus*-type tracks from the Lower Cretaceous of North America (Farlow et al. 1989; Lockley et al. 1994). Most sauropod trackways in China are wide (or medium) gauge and are therefore referred to the ichnogenus *Brontopodus* (Lockley et al. 2002). Features linking XY-S1to *Brontopodus* are (1) pes tracks longer than wide, (2) large and outwardly directed U-shaped manus prints, and (3) high degree of heteropody (ratio of manus-to-pes size) (1:2.5 of XY-S1). This is close to *Brontopodus birdi* (1:3), as is the nearly wide-gauged trackway pattern of XY-S1. Similar, but narrow-gauged trackways were also discovered in the Jiaguan Formation at the Hanxi tracksite (Xing et al. in review). The factors affecting gauge may include the speed of the trackmaker (Xing et al. 2010; Castanera et al. 2012) and the quality of preservation. In reference to this, latter factor is important, as noted in the following section, to differentiate between true tracks with well-defined outlines, steep walls and undertracks with very low-angle margins, which may reduce the inner trackway width and estimation of gauge. Unfortunately, effective statistical evaluation is difficult due to the single sample of XY-S1. Therefore, these sauropod trackways are tentatively assigned here to cf. *Brontopodus*.

5.2. Taphonomy and track preservation

Well developed mud cracks were recorded in all S1 pes traces, but are not evident on the surfaces between the tracks. This raises the question of whether the tracks acted as traps for wet mud and silt that was susceptible to drying, desiccation and cracking. The cracked surface is missing from the centre of the track casts, showing that the layer is quite thin (~0.5–1.0 cm), and probably was removed by erosion after the large block fell down and was overturned. The following sequence of events can be inferred (Figure 9):

1. The sauropod trackmaker left shallow manus and pes 'tracks' probably undertracks on a surface that is no longer preserved. This surface was probably the uppermost layer of sandstone from which the fallen block separated.
2. A thin layer of silty sandstone overlain by fine silt and mud was deposited as part of a fining upwards, lowering energy, depositional sequence. Tracks were then made on the fine-grained substrate during the depositional hiatus.
3. The tracked areas were probably deeper and wetter as a result of track impact.
4. Desiccation cracks developed within some of the tracks as the area dried out.
5. The desiccation tracks would have penetrated to the thin silty sandstone layer.
6. After fossilisation/lithification and recent exhumation of the outcrop at the mud-cracked level (of less resistant, fine-grained silty sandstone), the block fell, was overturned and began further weathering.
7. The thin layer of mud-cracked sediment, originally forming shallow convex-down (convex hyporelief), undertrack features was now oriented to create convex-up features that weathered most at the highest points. This produced the features seen today in which the centre of the mud-cracked areas below the tracks became most eroded. No well developed desiccation cracks are observed on the sandstone under (that is stratigraphically above) the damaged layer: i.e. in the sediment that fills in above the desiccation cracked layer.

This interpretation is compatible with the suggestion that the sauropod tracks are so shallow because they are undertracks. Thus, the sauropod tracks, like the theropod tracks, appear to have been made in muddy sediment that was deposited as part of the fining upwards sequence, of which the thin (~1.0 cm) silty sandstone layer is the lowest exposed on the block. Assuming the thin layer was indented to create undertracks, the large sauropod tracks in the overlying mud/silt could fill preferentially with more water than would have filled the smaller theropod tracks. Thus, the areas within the circumference of the large sauropod tracks would have been subject to desiccation cracking that penetrated the thin silty layer. This scenario requires only one episode of trackmaking during the depositional hiatus which followed the deposition of a fining up, low energy, fine silty sandstone, silt and mud.

We now turn to the theropod tracks which also protrude as overturned convex epirelief features from the upside down block. This allows us to make further observations about preservation as follows:

1. The track casts are quite well preserved showing the diagnostic tridactyl features of *Eubrontes* group tracks described above, and so were probably made in a near-optimum substrate for track registration (neither too wet or too dry).
2. The track casts appear to have rather wide or 'fleshy' digit traces.
3. The track casts also show that they originally protruded downward to deform the thin silty sand layer into shallow concave-down indentations (now appearing convex-up). Thus, they created undertracks.
4. These originally convex hyporeliefs, although mostly eroded away do not show the desiccation cracks associated with the sauropod tracks.
5. Tracks casts are surrounded by eroded areas, where softer sediment is inferred to have been removed.

As noted above, the phenomenon of the flattening of theropod tracks casts, by overburden pressures, has been described in detail elsewhere (Lockley and Xing in review). Here, we need only to note that such widening of digit traces is fairly subtle and results in post-registration extramorphological distortion of tracks that were probably true tracks with well-defined morphology at the time of registration.

Given the sequence of events inferred above for the sauropod track registration and infilling, we may draw a few conclusions about the relationship of these tracks to the theropod tracks that occur on the same surface.

1. Because desiccation cracks appear in the thin layer preserved within the sauropod tracks circumference, but not in the theropod tracks, it appears that the cracks were the result of infilling by wet sediment after the former were left. This would imply that the theropod tracks were made somewhat later on a firmer sediment.
2. This inference is supported by the clear outlines of the theropod track casts and the evidence that they were filled by sand and unaffected by desiccation tracks.

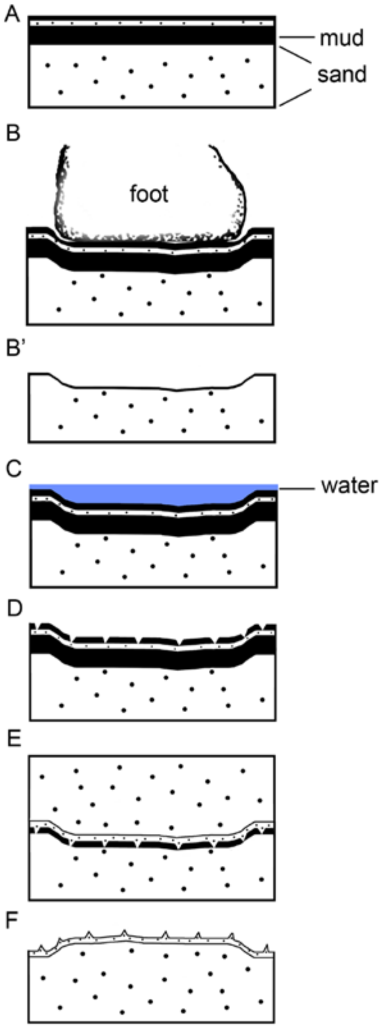

Figure 9. Schematic diagram showing how sauropod casts were preserved. (A) sandstone deposition cycle ends with mud deposition; (B) tracks made at hiatus level where thin mud units deposited; (B′) undertracks also registered at this time; (C) tracks act as traps for water; (D) after drying mud cracks are centred on tracks; (E) compaction squeezes out mud; (F) block separates and is overturned.

(3) The lack of well preserved sauropod track digit traces, demonstrating that they are not as well preserved as the theropod tracks, also supports the idea that the tracks were not made at exactly the same time and under the same substrate conditions. However, the time lapse between the registration of the theropod and sauropod tracks is difficult to estimate (see point 5 below).

(4) The combination of desiccation cracks and poor preservation of the sauropod tracks is consistent with the inference that the sauropod tracks were likely subject to extramorphological modification by wetting, saturation and dissolution.

(5) However, in reference to the previous points (3 and 4), if the sauropods exerted more pressure per unit area in track registration, it is possible that they changed the properties of the sediment more than the theropods, perhaps by liquefaction. If this was the case, the theropod and sauropod tracks could have been made at about the same time, without the need to postulate a time gap to allow changes in the condition of the substrate.

6. Conclusions

The Xinyang tracksite shows the trackways of four theropods and one sauropod on a surface covering about 11 m^2. Sedimentological evidence suggests that the tracks were made in a period that represents a hiatus between the deposition of thick high energy sandstone units. This hiatus is evidenced by the remnants of a fining upwards sequence followed by trackmaking on a fine-grained silt mud substrate. It is inferred that the trackmakers produced both well preserved theropod tracks that later were filled by sand forming well-defined casts, and sauropod tracks that formed traps for water that finally dried out and left desiccation cracks within the sauropod track circumferences.

With the addition of the Guanyingchong tracksite (Young 1960), Emei tracksite (Zhen et al. 1994), Lotus tracksite (Xing et al. 2007), Baoyuan tracksite (Xing, Harris, et al. 2011) (see Lockley et al. 2014 for report of 4 tracksites: No.23, 24, 95, 96), and the Hanxi tracksite (Xing et al. in review), it is clear that the dinosaur track record from the Jiaguan Formation is larger than was previously suspected. To date, we know of six documented dinosaur tracksites from the Jiaguan Formation and at least fifteen (see Lockley et al. 2014: No.89–91, and 6 new tracksites) from the Lower Cretaceous of Sichuan. Generally most, like the Xinyang tracksite, are saurischian dominated.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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