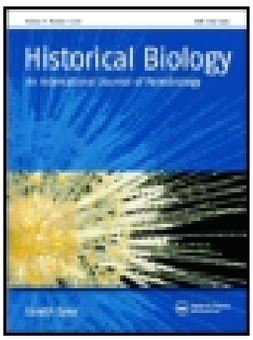

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Two new dinosaur tracksites from the Lower Cretaceous Jiaguan Formation of Sichuan Basin, China: specific preservation and ichnotaxonomy

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ABSTRACT

Two new dinosaur tracksites are reported from the Lower Cretaceous Jiaguan Formation in the Sichuan Basin, Qijiang District of Chongqing. These are the Gaoqing-Yongsheng and the Huibu tracksites, which represent the 13th and 14th reports from this formation. The Gaoqing-Yongsheng tracksite reveals the trackway of a large biped (ornithopod) in association with isolated sauropod tracks and large indeterminate undertracks with radial cracks. These features are preserved as natural casts with pebble infillings in a coarse, cross bedded and very thick bedded sandstone sequence. The Huibu tracksite reveals isolated theropod tracks and ornithopod tracks, the latter having a quadripartite, *Caririchnium*-like morphology, preserved in a thin bedded sandstone sequence with intercalated mudstone.

Abbreviations: GY: Gaoqing-Yongsheng site; Qijiang District; Chongqing Municipality; China; HB: Huibu site; Mabian Yi Autonomous County; Leshan City; Sichuan Province; China

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Dinosaur tracks; Theropod; Sauropod; Ornithopod; Jiaguan Formation; Lower Cretaceous

Introduction

Outcrops of the Lower Cretaceous Jiaguan Formation afford one of the most important dinosaur track records in southwest China. The first of these were found in 1960 (Young 1960). After a hiatus of close to five decades, finally new discoveries had been made (Xing et al. 2007). According to Xing and Lockley (2016), the Jiaguan Formation hosts 12 tracksites, most of these dominated by saurischian (theropod and sauropod) tracks, and provides a database of over three hundred potential trackmaking individuals. In the current study, we report on two new tracksites and offer an interpretation of their ichnotaxonomy and mode of preservation.

In October 2016, following reports from local backpackers, the Land and Resources Bureau of Qijiang District, Chongqing, found dinosaur tracks at Luanshigang (GPS: 28°48'29.34" N, 106°29'41.22"E), the Sixth Group Area of Gaoqing-Yongsheng Village, Guofu Town. These tracks had been known to the local people and were regarded with superstition to be footprints left by Mountain-Gods, thus providing another example of dinosaur tracks influencing Chinese folklore (e.g. Xing et al. 2011, 2015a). In the following month of November, a geophysical prospecting team from Sichuan Geology and Mineral Exploration and Development Bureau found dinosaur tracks along a path in the Second Group Area of Huibu Village (GPS: 28°49'42.61"N, 103°43'45.52"E), Qiaoba Township, Mabian Yi Autonomous County, Sichuan Province. The Huibu tracksite resides ~270 km west from the Gaoqing-Yongsheng site.

Geological setting

The Sichuan Basin contains a 2400–3200 m thick Jurassic-Cretaceous flood-plain deposit, consisting of organic poor, red, arenaceous pelitic sediments, is disconformably overlain by Quaternary surface soil, loose sand, and gravel layers (Dai 2016). The Cretaceous sedimentary sequences are composed of the Jiaguan Formation (Lower Cretaceous) and the Guankou Formation (Upper Cretaceous; Gu & Liu 1997). The majority of the Cretaceous tracks are known from the Jiaguan Formation (Xing & Lockley 2016) and are characterised by thick, brick-red, feldspathic, quartz sandstones (Sichuan Provincial Bureau of Geology aviation regional Geological Survey team 1976). The Jiaguan Formation represents the depositional environment of primarily meandering rivers formed during semi-arid and semi-humid conditions in a tropical/subtropical climate (Wang et al. 2008; Chen 2009; Xing et al. 2016a).

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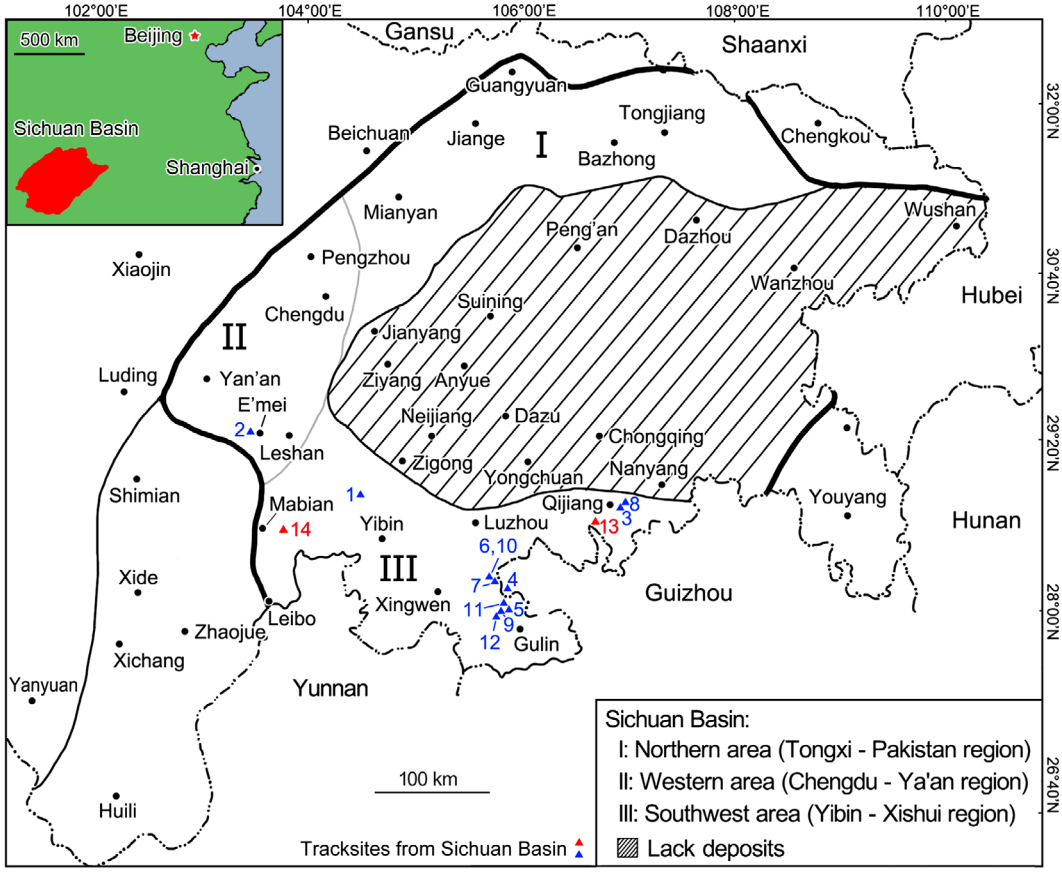

Figure 1. Cretaceous sections and dinosaur footprint site distribution in the Jiaguan Formation of the Sichuan Basin: 1, Guanyuanchong; 2, Emei (Chuanzhu); 3, Lotus; 4, Baoyuan; 5, Hanxi; 6, Xinyang; 7, Longjing; 8, Tiger; 9, Shimiaogou; 10, Xinyang II; 11, Leibei; 12, Shihuawan; 13, Gaoqing-Yongsheng (this paper); 14, Huibu (this paper).

The Gaoqing-Yongsheng tracksite lies near the Gaoqing Town of Qijiang District (Figure 1) and is roughly 35 km southwest from the Lotus tracksite, the latter representing arguably the most important ichnological site currently known from the Jiaguan Formation in terms of the abundance of well-preserved tracks and locality of holotype ichnotaxa (Xing et al. 2007, 2015b) (Figure 2). Dinosaur tracks from Gaoqing-Yongsheng occur in the same sedimentary sequence as the Lotus site (i.e. lower member of the Jiaguan Formation) but are preserved as natural casts on a large ex situ sandstone boulder (Figures 3 and 4). The boulder on which the tracks are preserved has light yellowish-brown sandstone layers which contain occasional sub-round to round pebble conglomerates (Figure 3(C)). The sandstone layers are sequences from meandering river facies with medium-sized wedge-shaped cross bedding. The top surfaces of the layers show a number of invertebrate trace fossils, although these are severely eroded, which prevents ichnotaxonomic assignment (Figure 3(B)).

The Huibu tracksite is located near the Huibu Village of Mabian County (Figure 1) and geologically is spatially positioned at the southwest margin of the Sichuan Basin, the intersection of Leshan, Yibin and Lianshang cities, within the area of distribution of the Jiaguan Formation. The section from Dianlanba–Qiaoba of Mabian County to Zhongdu in Muchuan County just runs along the Mabian–Muchuan arc structure (Han et al. 2009), in which the core of the Dianlanba–Zhonghezhuang syncline is constituted of the Danxia landform. The Danxia landform in Mabian County primarily comprises Jurassic and Cretaceous sediments. In the latter there has been deposited a red bed which is several thousand meters thick and dominated by brick-red sandstone of the Jiaguan Formation interbedded with purple red mudstone. The palaeoenvironment of the Jiaguan Formation is suggested to be a continental river sedimentary environment which was exposed to frequent drought and periodic flooding (Hu et al. 1991; Dai et al. 2015). In the outcrop of the Huibu tracksite, the upper part is corroded and the lower part is a road, so it is difficult to compare it with the Jiaguan Formation sequences at the Gaoqing-Yongsheng site, the Lotus site at Qijiang and other areas. The sedimentary sequence consists of brick-red fine-grained feldspathic quartz sandstone inter-bedded with siltstone and sandy mudstone of the same colour. A total of three tracks are preserved, two *in situ* on track horizons separated by 57 cm.

Material and methods

During November 2016 the lead author visited the Gaoqing-Yongsheng and Huibu tracksites.

The documented material consists of a trackway with 5 consecutive pes imprints, as well as isolated tracks, all in all 10 tracks preserved as natural casts. These were photographed under natural lighting conditions using a Canon EOS 5D Mark III camera with a 58 mm lense. Track parameters measured onsite included length/width ratio, anterior triangle, pace angulation, stride length and divarication angle (as per Lockley 2009),

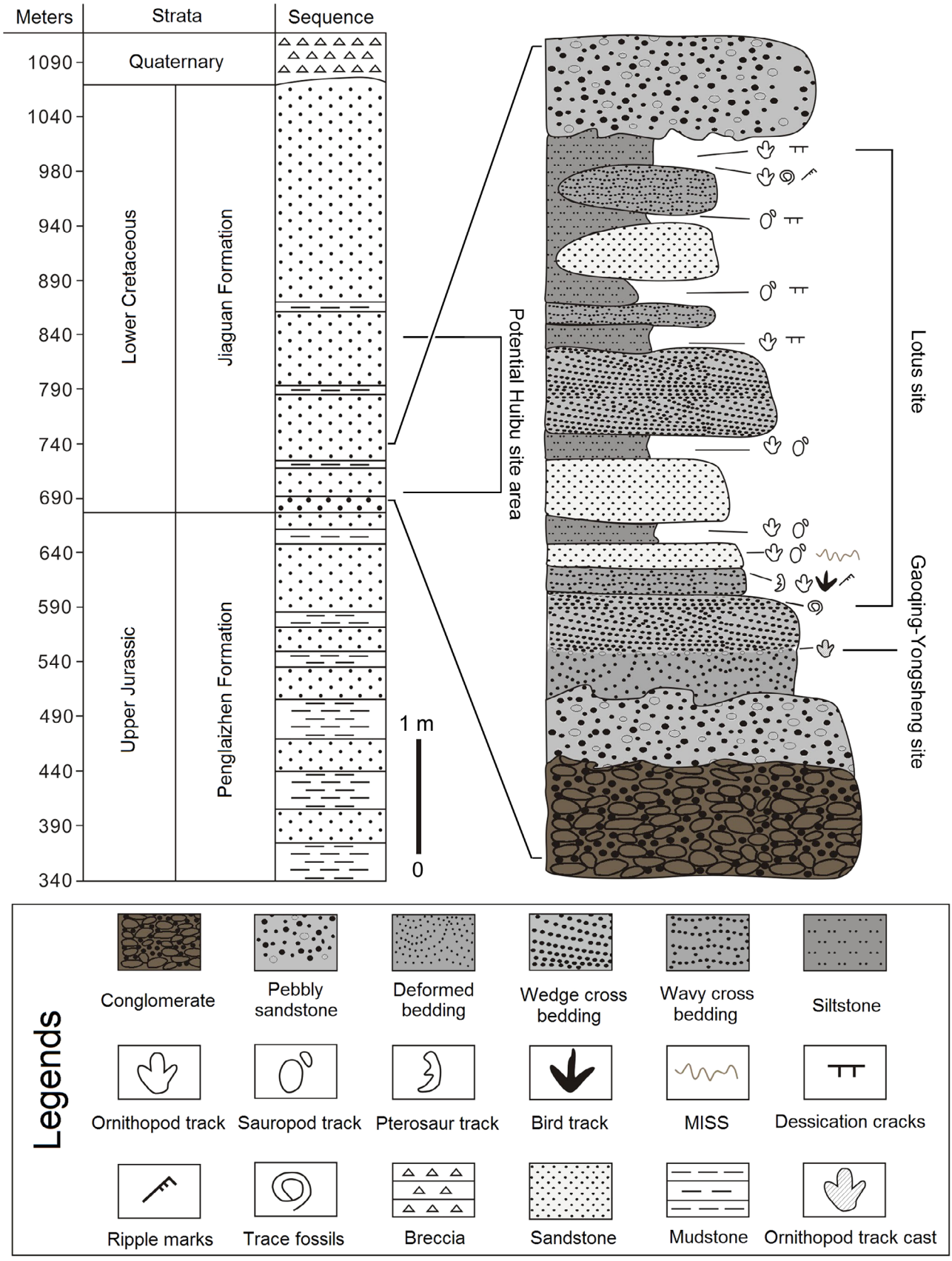

Figure 2. Stratigraphic sections of the Gaoqing-Yongsheng, Huibu, Lotustracksites from Qijiang area.
Note: Based on regional geological mapping, Huibu site may be located in the lower part of the Jiaguan Formaiton.

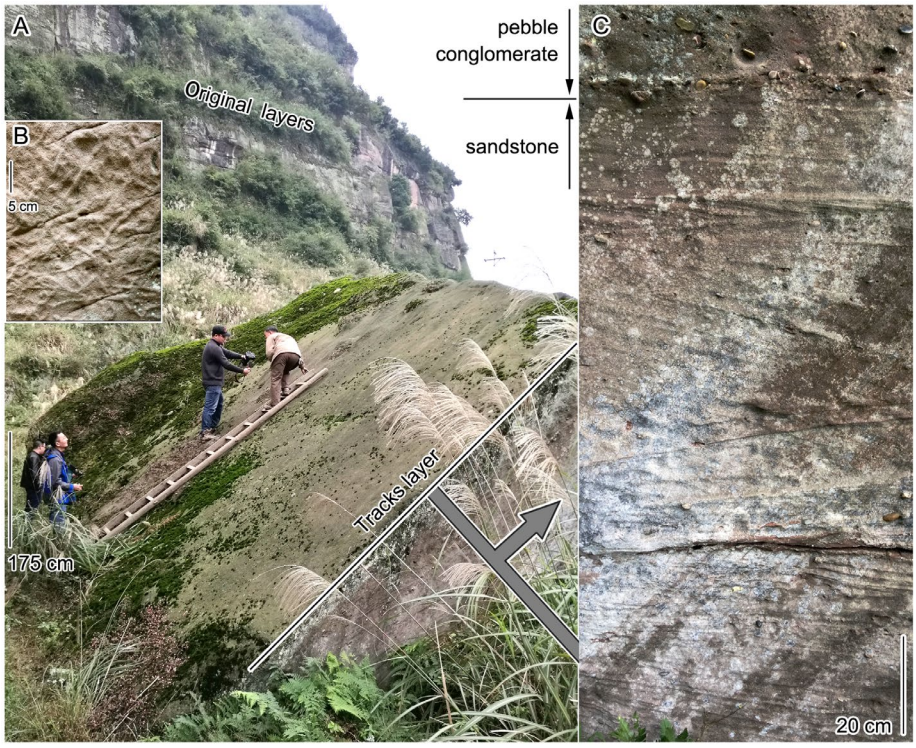

Figure 3. The Gaoqing-Yongsheng tracksite, Jiaguan Formation (Lower Cretaceous) of Qijiang.
Notes: A, Photograph of the ex situ boulder (foreground) in context with likely stratigraphic horizon (background); B, invertebrate trace fossils from top surface of the layers; C, medium-sized wedge-shaped cross bedding from the vertical section.

with track positions recorded using acetate sheeting as per (Xing et al. 2013).

A three dimensional digital surface model of the removed theropod track from the Huibu tracksite (HB-TI1) was made using photogrammetric methods adapted from Romilio and Salisbury (2014). This specimen was digitally photographed (total of 15 photographs) in a series of overlapping images from varying viewpoints under natural light conditions. Photographic jpg image files were added to Agisoft Photoscan Professional Edition (version 1.2.6 build 2038 64 bit) to generate scale-corrected models that were exported as .ply files and orthophotographic mosaics (.png files). The track models were applied with a false-color elevation map and contour lines using Paraview (version 5.0.0 64 bit) to illustrate surface elevation. The preservation of tracks was classified using the criteria of Belvedere and Farlow (2016).

Gaoqing-Yongsheng site

Specific preservation

The Gaoqing-Yongsheng site preserves ornithopod and sauropod tracks (GY-O1 and GY-SI, respectively). The tracks were registered on a sandy layer and filled by sandy conglomerate, and are preserved as natural casts. The convex-up, convex hyporelief, cast surfaces are made of a layer of very thin sandy sediment, the weathering of which led to exposure of gravels which were prone to further weathering and erosion. Therefore, the tracks were vulnerable to morphological damage and are poorly preserved, corresponding to grade 1 after the classification of Belvedere and Farlow (2016).

The ex situ boulder contains five consecutive ornithopod pedal tracks from a single trackway. Digit traces are visible in the ornithopod track casts, but are very poorly preserved in the heavily weathered first track GY-O1-RP1 (Figure 4). A notable feature of these track casts is that there is a concentration of pebbles in the rear of the casts, most clearly in GY-O1-LP1, RP2, and LP2 (Figure 5). A minimum of four probable sauropod tracks is also present at the site but a distinct trackway pattern cannot be seen. Sauropod tracks GY-SI1p and GY-SI2p are better preserved compared to other sauropod tracks from this locality. However, they do not reach a grade higher than 1 (Belvedere & Farlow 2016). Sauropod and ornithopod tracks also co-occur at the Lotus site. Another notable preservation feature is a convex-up cast feature with very distinct radial cracks, typical of undercasts (Lockley et al. 1989).

The counterpart of the fallen block that could have revealed the corresponding track molds was not found. Therefore the detailed lithology of the bed in which the tracks were registered is not known. However, it has been possible to measure the stratigraphy of the 2 meter-thick track-bearing fallen block. The lower and middle part shows medium-sized, wedge-shaped cross bedding. Gravel, pebble conglomerate layer occurs in the upper part.

Ornithopod tracks

GY-O1 is a tridactyl trackway with distinct pattern, consisting of five pedal traces lacking an associated manual print. All the tracks are tridactyl, are longer than wide (proximodistal average length of 59 cm, mediolateral width of 41 cm), show medium–strong mesaxony (average length/width of anterior triangle 0.35, 0.31,

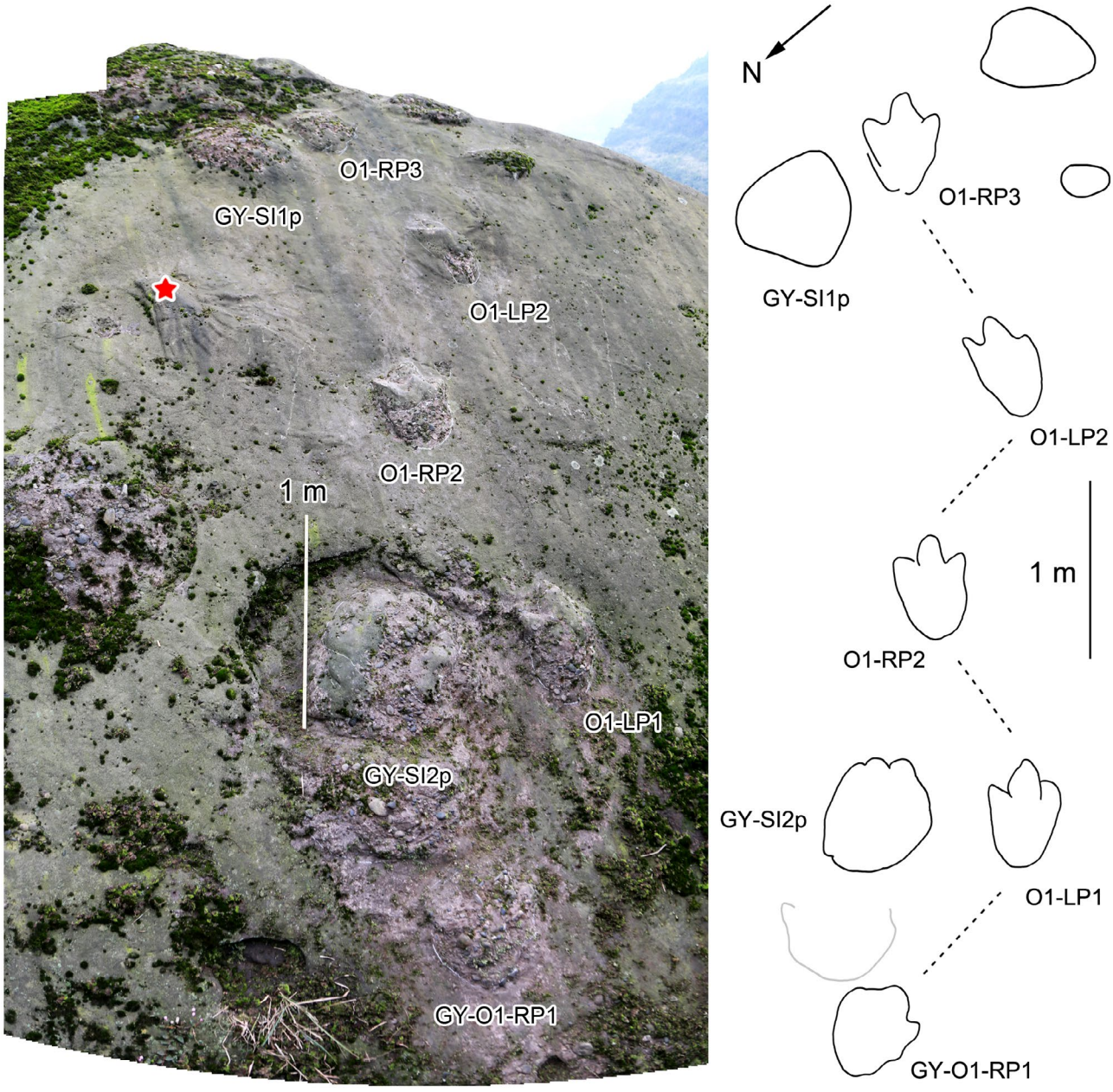

Figure 4. The Gaoqing-Yongsheng tracksite, Jiaguan Formation (Lower Cretaceous) of Qijiang.
Notes: A, photograph (oblique view); B, interpretative outline drawing of the ornithopod and sauropod tracks from over-head perspective. The star indicates a notable preservation feature, a convex-up cast with very distinct radial cracks, typical of undercasts.

0.39, n = 3). The distal portion of the digital impressions have blunt claw marks while the proximal track margin is smoothly curved. The average divarication angle between digital impressions II and IV for all the tracks is 44°. Track vary in their orientation relative to the trackway axis: O1-RP1 and LP2 are inwardly rotated (each ~30°); LP1 and RP2 are outwardly rotated (i.e. 4° and 10°, respectively). Mean pace and stride lengths are 1.43 and 2.52 meters (respectively). Outer trackway width 0.83–1.11 meters, while there is no distance (i.e. zero meters) in the inner trackway width. Mean pace angulation is consistently about 110° (Figure 4). Track depth (average ~15 cm) decreases sharply in the middle to posterior part, perhaps due to foot dragging and/or erosion, and is a feature not uncommon in deep track casts, such as GGM-1 from Zhongpu area, Gansu Province (Xing et al. 2015c).

GY-O1 can be referred to ornithopod tracks as its tracks have relatively large pace angulation and blunt digit trace terminations (Lockley et al. 2014). Despite tracks being longer than wide, these other track features are diagnostic of ornithopods not theropods. The better preserved ornithopod tracks in Qijiang District are from Lotus tracksite, and Xing et al. (2007) named them *Caririchnium lotus*. In *C. lotus*, the length/width ratio is 1.1 and mean value of mesaxony is 0.37 (Xing et al. 2015b). GY-O1 has a mesaxony (0.35) similar to that of *C. lotus*. The major differences between *C. lotus* and the GY-01 specimen are the lack of distinct quadripartite morphology and a higher length/width ratio in GY-O1 (1.3–1.6 vs. 0.9–1.5 in *C. lotus*; Table 1). The former may be attributed to poor preservation, and the latter may reflect lengthening from foot dragging, as previously noted. Though similar to *C. lotus* in some respects, the poor track preservation

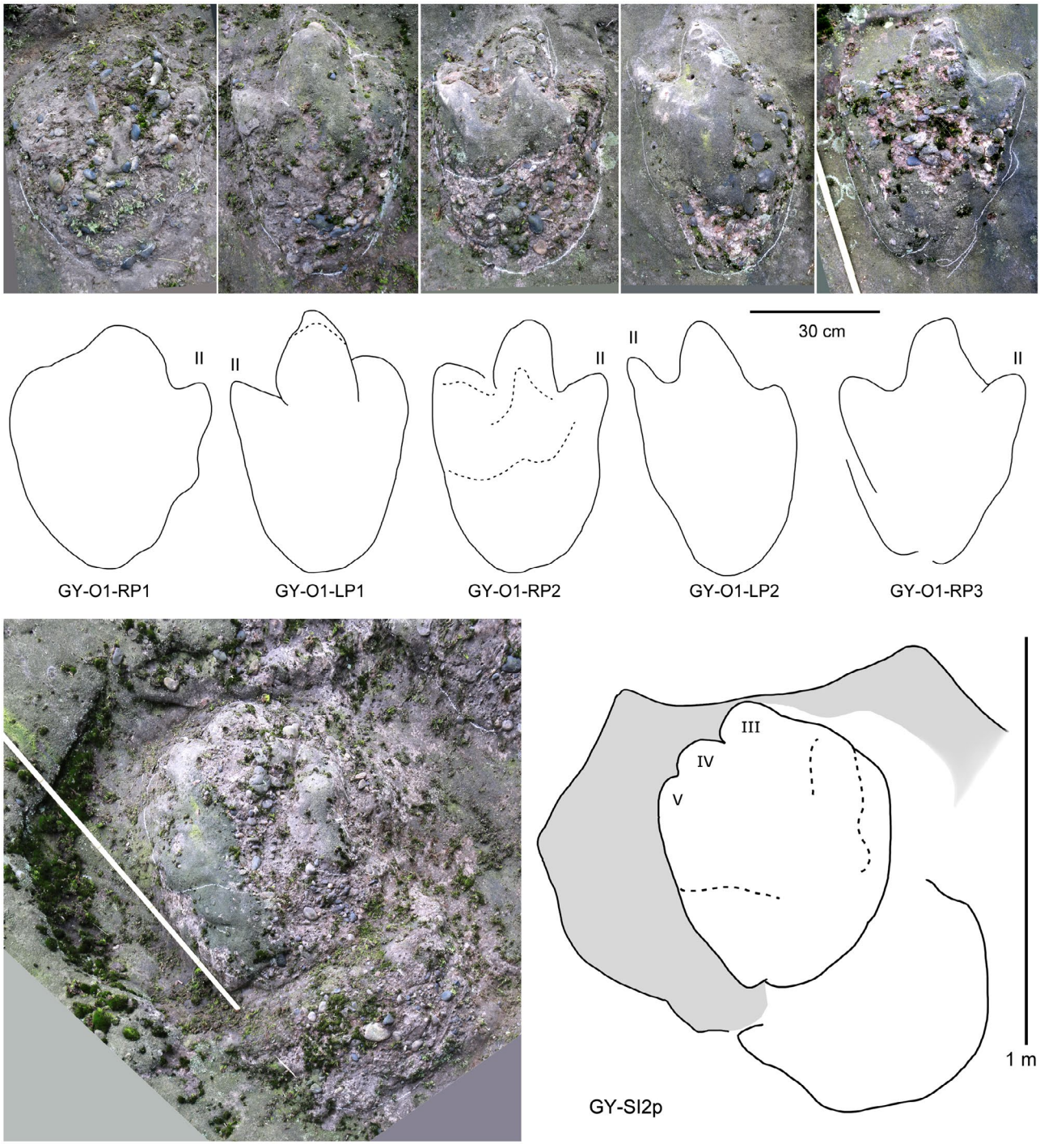

Figure 5. Ornithopod- (top row) and sauropod- (bottom row) tracks from the Gaoqing-Yongsheng tracksite, Jiaguan Formation (Lower Cretaceous) of Qijiang, represented by photographs, and interpretative outline drawings.

currently does not permit GY-O1 to be assigned more specifically than ornithopod track indet.

Sauropod tracks

All sauropod traces are poorly preserved. GY-SI1p and GY-SI2p, large (mean length of 73 cm), oval in shape, with a length/width ratio of 1.1. GY-SI2p is the best preserved, with clear digital impressions of III, IV and V, whereas digit impressions I and II are indistinct due to weathering. No claw marks are observed. The proximal track margin is smoothly curved. The posterior end of the track has a linguiform drag mark. The pedal track lacks an associated manus print.

Most Chinese sauropod tracks are referred to the ichnogenus *Brontopodus* (Lockley et al. 2002; Xing et al. 2013). GY-SI2p is an isolated pedal impression, thus it is difficult to make further comparison. However, the digits pattern, and length/width ratio of GY-SI2p is 1.1, all these characteristics are coincident with

Table 1. Measurements (in cm) of dinosaur tracks from Gaoqing-Yongsheng to Huibu sites, Sichuan Basin, China.

Number	ML	MW	II-IV	PL	SL	PA	ML/MW
GY-O1-RP1	53.0	42.0	50°	152.0	256.0	129°	1.3
GY-O1-LP1	64.0	39.0	40°	132.0	247.0	135°	1.6
GY-O1-RP2	59.0	40.5	45°	135.0	253.0	123°	1.5
GY-O1-LP2	64.0	40.0	41°	153.0	–	–	1.6
GY-O1-RP3	56.0	44.0	–	–	–	–	1.3
Mean	59.2	41.1	44°	143.0	252.0	129°	1.4
GY-SI1p	74.0	65.0	–	–	–	–	1.1
GY-SI2p	72.0	61.0	–	–	–	–	1.2
HB-OI1	25.0	24.5	42°	–	–	–	1.0
HB-OI2	–	–	–	–	–	–	–
HB-TI1	25.0	18.0	53°	–	–	–	1.4

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.

that of typical sauropod tracks such as *Brontopodus* (Farlow et al. 1989; Xing et al. 2015d). Because GY-SI1p and GY-SI2p are only isolated tracks and *Brontopodus* is essentially based on wide-gauge trackways, they are tentatively referred to cf. *Brontopodus*.

Huibu tracksite

The Huibu tracksite has yielded two tridactyl ornithopod pedal tracks and one tridactyl theropod track preserved as natural casts (Figures 6–7) (Table 1). Representatives of the ornithopod (HB-OI1) and theropod (HB-TI1) tracks were collected and housed at Mabian County Land and Resources Bureau. The second ornithopod track (HB-OI2) remains *in situ*.

Ornithopod tracks

HB-OI1 is a tridactyl track with relatively weak mesaxony (length /width of anterior triangle 0.23 sensu Lockley 2009), a length /width ratio of 1.0, and a typical quadripartite track morphology (three digital and one metatarsophalangeal pad impressions). All three digital impressions have blunt distal ends. Though it is somewhat worn on the sides of the heel pad, the overall shape indicates a subtriangular form. HB-OI1 points towards the inside of the layer without trace of a manus. 55 cm from HB-OI1 on the same layer, there is another track preserved

Figure 6. The Huibu tracksite Jiaguan Formation (Lower Cretaceous) of Mabian, showing the *in situ* positions of the ornithopod- (HB-OI1 and HB-OI2) and theropod- (HB-TI1) tracks.

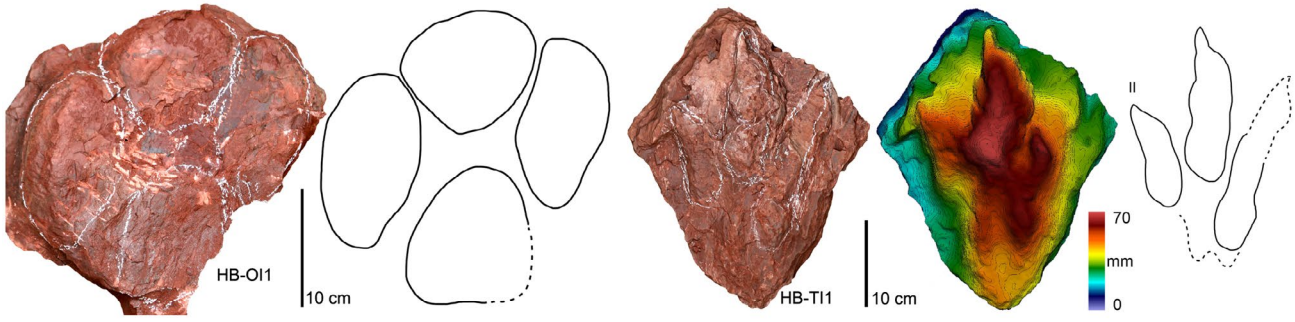

Figure 7. Ornithopod (HB-OI1) and theropod (HB-TI1) tracks from the Huibu tracksite Jiaguan Formation (Lower Cretaceous).
Notes: Photographs, interpretative outline drawings, and 3D height maps (cool–warm colours represent low–high elevation of 70 mm, with contour lines every 1 mm).

in the same manner and cataloged as HB-OI2. Its anterior end with the digits was still covered by layers, and only the posterior end and heel was exposed. By preservation, we classify all ornithopod tracks from the Huibu tracksite as grade 1 (Belvedere & Farlow 2016).

The quadripartite track morphology of HB-OI1 is typical of ornithopod pes tracks. Ornithopod tracks from Jiaguan Formation include *Caririchnium lotus* (Xing et al. 2007), *Caririchnium liucixini* (Xing et al. 2016b) and *Ornithopodichnus* isp. (Xing & Lockley 2014). The pes-only *C. liucixini* has a quadripartite morphology, lengths almost equal to widths (1.0), and differs from other *Caririchnium* tracks in having weak mesaxony (0.23 and 0.28 for type), which is similar to *Ornithopodichnus.* HB-OI1 consists of only one specimen and is consistent with *Caririchnium* isp.

Theropod track

HB-TI1 is a medium-sized (25 cm long) tridactyl theropod track with a length/width ratio of 1.4 and a mesaxony value (length /width ratio of anterior triangle) of 0.36. Digit III is directed anteriorly and is the longest, whereas digit II is short. Digit IV is incomplete distally, but seems to have been longer than digit II. Digit II has two phalangeal pad traces, and digit III presents three phalangeal pad traces. Acuminate claw marks are distinct in digits II and III, with that of digit III being most developed. The trace of the metatarsophalangeal region is sub-symmetrically bilobed and lies nearly in line with the long axis of the digit III impression. Especially in the proximal part of digit IV an oval metatarsophalangeal pad is markedly preserved. The divarication angles between the impressions of digits II–III and III–IV are subequal (II 28° III 25° IV). This track is the best preserved in the assemblage and can be classified as grade 2, considering the distinct claw marks and observable pad traces (Belvedere & Farlow 2016).

The Lower Cretaceous Jiaguan Formation has yielded a considerable record of theropod tracks of the *Grallator-Eubrontes* plexus type, which are typical in Jurassic formations of North America and China (Lockley et al. 2013), extending the stratigraphic and palaeobiogeographic range of these trackmakers into Cretaceous East Asia (Xing et al. 2015d). Based on the size (25 cm pes length) and degree of mesaxony, the HB-TI1 track can be tentatively assigned to the ichnogenus *Eubrontes sensu lato* (see Olsen et al. 1998). The weak to moderate mesaxony (0.36) is close to the typical footprints of the ichno- or morpho-family Eubrontidae, Lull 1904 (0.37–0.58 in *Eubrontes* type; Lockley 2009). Other Jurassic-Cretaceous theropod ichnotaxa such as *Jialingpus* are morphologically different. *Jialingpus* has a large rounded metatarsophalangeal pad positioned in line with digit III and a small metatarsophalangeal pad belonging to digit II. The latter is separated from the former by a crease only (Xing et al. 2014). Contrary, HB-TI1 shows a clearly bilobed metatarsophalangeal area and a metatarsophalangeal pad IV that is laterally positioned relative to the digit III long axis, similar to typical *Eubrontes*. There is also some similarity with the ichnogenus *Therangospodus* (Lockley et al. 1998a). However *Therangospodus* has a larger mesaxony value (0.55; Lockley et al. 1998) and lacks well-separated phalangeal pads. Another Jurassic-Cretaceous theropod ichnogenus *Megalosauripus* (Lockley et al. 1998b) has a more extensive metatarsophalangeal area when compared with HB-TI1.

Conclusions

The Gaoqing-Yongsheng site is the third dinosaur tracksite discovered in the Qijiang area and it is stratigraphically lower (and temporally older) than the Lotus site. The Huibu tracksite located near Mabian, represents the first to be discovered in the immediate area. These locations extend the spatial and temporal distribution of dinosaur tracks in the Jiaguan Formation of the Qijiang area, effectively increasing the number of tracksites currently known in this unit to fourteen. The composition of the new Jiaguan locations is different from that of the famous Lotus tracksite by (1) the lack of avian theropod and pterosaur tracks, and (2) by the presence of non-avian theropod tracks, suggesting different ecological conditions. Further discoveries are highly likely, since the Huibu tracks were found *in situ*, and although the Gaoqing-Yongsheng tracks lay ex situ, the stratigraphical position may not be difficult to determine in future investigations.

Disclosure statement

No potential conflict of interest was reported by the authors.

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