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New Middle Jurassic dinosaur track record from northeastern Sichuan Province, China

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Abstract Two relatively small tridactyl tracks from the Middle Jurassic Xintiangou Formation of northeastern Sichuan are assigned to cf. *Anomoepus* based on low length/width and anterior triangle ratios, and a relatively short step and inward rotation of the footprint axes. *Anomoepus* is typical of many Middle Jurassic dinosaur-dominated ichnofaunas from central and southern China and appears to be allied to the globally widespread Lower Jurassic tetrapod track biochron.

Keywords Dinosaur tracks · Middle Jurassic · Xintiangou Formation

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Abbreviation
QL Qili site, Xuanhan County, Sichuan Province, China

Introduction

Dinosaur track records are abundant in the Sichuan Basin, especially in Jurassic and Early Cretaceous outcrops (Xing et al. 2007, 2014a; Lockley et al. 2013). Jurassic tracks were mainly left by theropods and sauropods with relatively few made by small ornithopods (Xing et al. 2013a, 2014a; Xing and Lockley 2014), consistent with the general profile of contemporaneous dinosaur tracks around the world (Lucas 2007). These tracks correlate well with body fossil records, although the latter also commonly includes stegosaurs (Peng et al. 2005). However, to date, tracks have only been reported in the southern and eastern areas of the Sichuan Basin.

With support of the National Natural Science Foundation project and the State Key Basic Research Program of the Ministry of Science and Technology, China, M.S. Pole, Y.D. Wang and their colleagues found dinosaur tracks in July 2015 in Xuanhan County, located on the south side of Daba Mountain, northeastern Sichuan Province (Fig. 1). Xuanhan County connects Sichuan, Chongqing, Hubei and Shaanxi Provinces. Significantly, this represents the first dinosaur tracks discovered in northeastern Sichuan Province.

Geological setting

The tracksite is located beside the Xuanhan-Kaixian highway, in Qili town, Xuanhan County. The tracks are preserved on a collapsed siltstone slab that cannot be traced

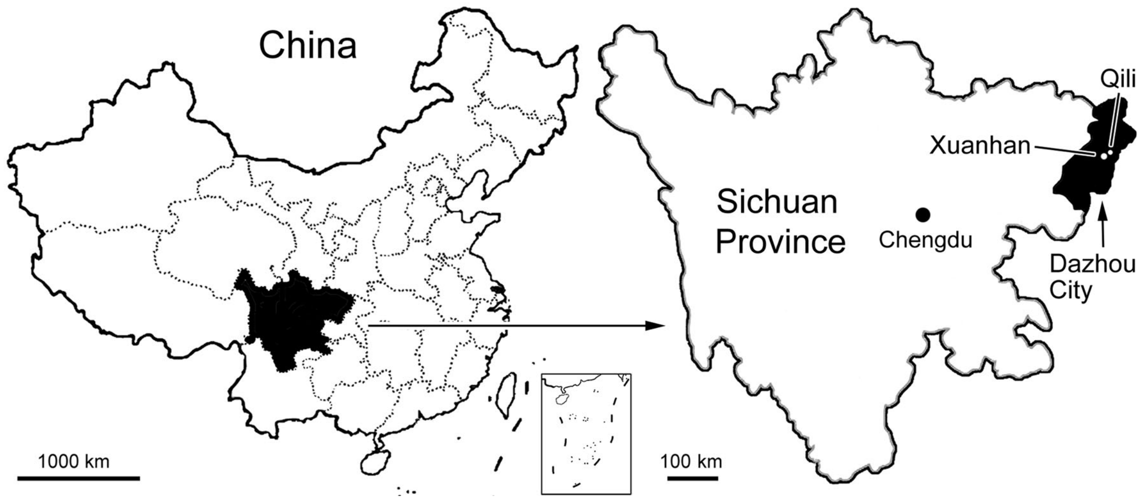

Fig. 1 Maps showing position of study area and Qili track locality in Sichuan Province, China

to the original stratum; however, according to the location and lithology, this siltstone slab probably came from an abandoned quarry 10 m away. The quarry is about 8 m wide and is now filled with waste soil, making it difficult to trace specific track-bearing beds (Fig. 2).

Peng et al. (2005) established a biostratigraphic sequence based on vertebrate fossil records from Sichuan Basin, especially the dinosaur fauna from the Zigong area: Middle Jurassic (Bathonian–Callovian), Sauropod—*Shunosaurus* fauna and Late Jurassic, Sauropod—*Mamenchisaurus* fauna (Dong 1992). This biostratigraphic sequence identifies two formations (Zhenzhuchong and Ziliujing) as Lower Jurassic, two (Xintiangou and Xiashaximiao) as Middle Jurassic and three (Shangshaximiao, Suining and Penglaizhen) as Upper Jurassic (Xing et al. 2014b–d).

In this area, the Lower and Middle Jurassic sequences are well-exposed and comprise the Zhenzhuchong, Ziliujing, Xintiangou and Xiashaximiao formations from bottom to top (Wang et al. 2010). Tracks are found from the siltstone layer in the lower part of the Middle Jurassic Xintiangou Formation (GPS: 31°12′6.68″N, 107°43′59.66″E). This formation overlies the Lower Jurassic Zhenzhuchong and Ziliujing formations and is covered by the Middle Jurassic Xiashaximiao Formation. The Xintiangou Formation is divided into three informal formation-level units: the upper and lower units are dominated by variegated mudstones and the middle unit is composed of black shale, containing bivalve, conchostracans, ostracods, sporo-pollen and vertebrate remains (Wang et al. 2010). Abundant bivalve fossils have also been found in association with the tracks. Furthermore, ripple marks cover some bed surfaces at the tracksites.

Description of tracks

QL-T1-L1 and R1 are tridactyl natural casts forming a single step without manus tracks or tail traces (Fig. 3; Table 1). The average length of the pes imprints is 9.5 cm, *L*/*W* ratio is 1.2, average divarication angle is 67°, and average anterior triangle length–width ratio is 0.39.

QL-T1-L1 is the best preserved track. The impression of digit III is directed anteriorly and is the longest, whereas that of digit II is shorter than digit IV. Digit II possesses two digit pad traces. Digits III and IV have three phalangeal pad traces, but although the margins of the first (proximal) pad are clear, the borders between pads 2 and 3 are more difficult to distinguish. Claw marks are sharp. The metatarsophalangeal area is visible and oval, and, where preserved, is positioned in line with the long axis of digit III.

QL-T1-L1 and R1 constitute a step, 28.5 cm long (three times footprint length). This is a relatively short step. It is notable that the axis of QL-T1-R1 is rotated inwardly at about 24° relative to the axis of QL-T1-L1. With only two tracks preserved in sequence it is possible that both tracks were rotated an average of 12° relative to the trackway mid-line. Such rotation is characteristic of *Anomoepus*-like ornithischian tracks rather than theropod tracks, although in this case the sample is too small to draw definitive conclusions.

In the absence of a complete trackway with more than two pes imprints, we estimated possible stride length equal to two pace lengths, and calculated trackmaker speed (v) using the formula of Alexander (1976): $v = 0.25g^{0.5} \times \mathrm{SL}^{1.67} \times h^{-1.17}$, where g = gravitational acceleration in m/s; SL = stride length; and h = hip height, estimated as 4.5 times foot length, using the ratio

Fig. 2 Photograph of quarry: *A* opencast pit filled with waste soil (8 m), *B* stone walls. *Arrows* indicate the ripple marks

for small theropods (the length less than 0.25 m) proposed by Thulborn (1990). We calculated a relative stride length (SL/h) of 1.33, indicating that the animal was travelling at 0.83 m/s or ~2.99 km/h, suggesting a slow run. However, given the aforementioned *Anomoepus*-like track characteristics we also calculated the speed using the small ornithopod foot length–hip height ratio of 4.8 ratio proposed by Thulborn (1990). Using these values we estimated a speed of ~0.77 m/s (≅2.77 km/hr), with a relative stride length (SL/h) of 1.25, implying a walking trackmaker.

Discussion

In general, the Middle Jurassic Xintiangou Formation, which lacks fossil bones, is dominated by assemblages of the theropod tracks *Grallator*, *Eubrontes*, *Kayentapus*, and, to a lesser extent, some small ornithischian tracks referred to *Anomoepus*. A number of tracksites have been reported from the Xintiangou Formation in the Sichuan Basin, including the Wu Ma Cun sites A and B in Zizhong County (Matsukawa et al. 2006). The two localities were formerly described by Yang and Yang (1987). These authors named "*Zizhongpus wumanensis*", "*Tuojiangpus shuinanensis*", "*Chonglongpus hei*", and "*Chuanchengpus wuhuangensis*" from Wumacun Site A, and "*Megaichnites jizhaishiensis*" and "*Chongqingpus microiscus*" from Wu Ma Cun Site B. All of these ichnogenera, however, have more recently been considered subjective junior synonyms of *Grallator*, *Eubrontes* and *Kayentapus* (Lockley and Matsukawa 2009; Lockley et al. 2013). Moreover, there is growing evidence that such tracksites yield assemblages with *Grallator*, *Eubrontes* and *Anomoepus*, an ichnofauna typical of the Lower Jurassic tetrapod footprint biochron (sensu Lucas 2007). The dating resolution of Middle Jurassic tracksites from China is not precise enough to definitively demonstrate that they are significantly younger than the forementioned *Grallator*–*Eubrontes*–*Anomoepus* Lower Jurassic ichnofaunas from other regions. Here we simply note the similarities between the global Lower Jurassic biochron and similar Lower Jurassic as well as Middle Jurassic ichnofaunas from China. It is possible that typical Lower Jurassic ichnofaunas persisted in China for

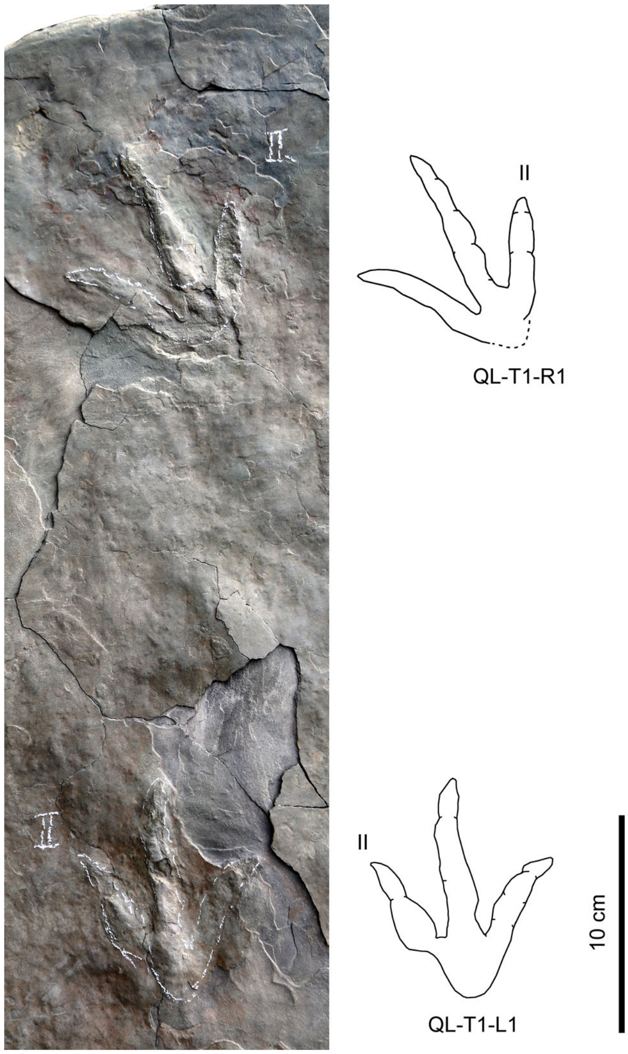

Fig. 3 Two consecutive tracks (QL-T1-L1 and R1) of a small tridactyl trackmaker tentatively assigned to *Anomoepus*. Note *inward rotation* of tracks, and low degree of mesaxony

Table 1 Measurements (in cm) of the dinosaur tracks from Qili tracksite, Sichuan Province, China

Number	ML	MW	II–IV	*L/W*	AT
QL-T1-L1	9.8	8.3	68°	1.2	0.40
QL-T1-R1	9.1	8.0	66°	1.1	0.38
Mean	9.5	8.2	67°	1.2	0.39

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, *L/W* is dimensionless, *AT* anterior triangle length–width ratio

longer than they persisted in other regions. However, such inferences need to be verified with reliable high-resolution dating before they can be used for generalizations about the global ichnofaunal spatio-temporal distribution patterns.

From the Xiashaximiao Formation Nianpanshan dinosaur tracksite in Zizhong County, first studied in the 1980s, Yang and Yang (1987) suggested that one large track and two medium-sized tracks were left by different individuals of the *Jinlijingpus nianpanshanensis* trackmaker, and that another smaller footprint was similar to the theropod track *Chuanchengpus* Lockley and Matsukawa (2009), the small "*Chuanchengpus*" trackway is referable to *Anomoepus*. Lockley et al. (2013) assigned the *J. nianpanshanensis* to *Eubrontes nianpanshanensis*. Moreover, recent restudy of tracks from the Middle Jurassic of Yanan, Shaanxi County, including revaluation of the illustrations of the lost holotype of *Shensipus tungchuanensis* (Young 1966) indicates that it is best synonymized with *Anomoepus* as *Anomoepus tungchuanensis* (Xing et al. 2015). This identification is consistent with other reports of *Anomoepus* from the Middle Jurassic of this region (Lockley and Matsukawa 2009; Xing et al. 2013a).

QL-T1-L1 and R1 have a low *L/W* ratio and mesaxony (1.2 and 0.39, respectively). This is less than in *Grallator* (2.6 and 1.22, respectively, or 2.1 and 1.0, respectively; Lockley 2009) referring to footprints of similar size. Instead, the QL-T1 ratios are more similar to *Anomoepus* from Shaanxi (1.0–1.2, 0.45), (Xing et al. 2015) or those of larger theropod tracks such as *Changpeipus* from Shanshan of Xinjiang (1.6, 0.48, Xing et al. 2014a) and cf. *Kayentapus* sp. (= "*Zizhongpus wumanensis*") from Sichuan (1.2, 0.5), which have lower length width and anterior triangle (AT) values than those of small theropods (Lockley 2009; Lockley et al. 2003, 2013). However, a comparison with *Changpeipus* is difficult, because small specimens of this ichnogenus and their values are unknown. Possibly the latter would differ from those of larger imprints. *Kayentapus* is different from the footprints described here by the more separated digit traces (Lockley et al. 2011; Xing et al. 2013b). The QL-T1 specimens are also different from the *Grallator* tracks ("*Chongqingpus microiscus*" and "*Chuanchengpus wuhuangensis*") found in the Xintiangou Formation (Lockley 2009; Lockley et al. 2013) which are more elongate in shape, showing correspondingly high AT values.

The grallatorid *Jialingpus* appeared in China during the Late Jurassic–Early Cretaceous. Length/width ratios and mesaxony values are high in the Late Jurassic *Jialingpus* (1.5–1.9 and 0.70–0.93, respectively) but low in Early Cretaceous specimens of this ichnogenus (1.1–1.5 and 0.54–0.68, respectively; Xing et al. 2014b). QL-T1 displays an *L/W* ratio and mesaxony lower than Late Jurassic *Jialingpus* and closer to Early Cretaceous specimens. However, typical *Jialingpus*, both from the Jurassic and the Cretaceous, is morphologically different from the Xuanhan footprints, for example by the presence of a large metatarsophalangeal area divided into a small metatarsophalangeal pad behind digit II and a large metatarsophalangeal pad behind digit IV. QL-T1 is referred here tentatively to cf. *Anomoepus* isp., based on the relatively low mesaxony and length/width ratio values, features characteristic for this ichnogenus. *Anomoepus* from the type horizon in the Newark Supergroup of North America, typically reflects gait variation of a facultative biped with the occasional impression of a pedal digit I (hallux), a pentadactyl manus and, in sitting posture, a metatarsal trace (Olsen and Rainforth 2003). Numerous *Anomoepus* trackways are known that were left from bipedal movement only and might sometimes be confused with those of theropods, showing similar (functionally tridactyl) pes imprints. This variation is probably preserved in the Xintiangou tracks.

Conclusions

Discovery of tracks attributable to cf. *Anomoepus* in northeastern Sichuan Province corresponds to what is generally known of the Lower–Middle Jurassic dinosaur track assemblages from this region.

Together with former discoveries in the Xintiangou Formation, the new record matches the composition of typical Lower Jurassic dinosaur ichnofaunas in North America, Europe and southern Africa, that are the basis for a distinct biochron. Lower Jurassic ichnofaunas are characterized by co-occurrence of the theropod ichnogenera *Grallator* and *Eubrontes* with *Anomoepus*, which is considered as an ornithischian track. Possibly, in China this assemblage has a longer stratigraphic range; however, this has to be examined in the future by more exact dating of the track-bearing strata.

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