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First report of sauropod tracks from the Upper Jurassic Tianchihe Formation of Guxian County, Shanxi Province, China

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ABSTRACT

This paper presents the first report of sauropod tracks from the Upper Jurassic of Shanxi Province, China. Dinosaur tracks appear concentrated in five trackways, in different stratigraphic levels of the Late Jurassic Tianchihe Formation. Tracks are dominantly small and medium-size sauropod tracks and are tentatively assigned to *Brontopodus* based on preserved track morphology, trackway pattern and statistical analysis. The Tianchihe Formation in which the tracks appear shows a gradual change from meandering fluvial to sandy braided fluvial depositional systems developed in a seasonally arid environment. Comparisons of the evaluated speed of bipedal to quadruped trackways indicate that the slower walk more easily produces pes-dominated overprints. Trackways in the Guxian tracksite appear following different orientations, suggesting that these trackways were produced by different sauropods at different times. An unusual trackway following a curved pattern has been identified in the site and could represent a special locomotion character or a social behavior. The presence of eolian deposits in central Shanxi Province could have acted as a paleogeographic and paleoenvironmental barrier for the dispersion of the Yanliao Biota that survived in northern Hebei-western Liaoning and northestern Shanxi Province to the Ordos Basin during the Late Jurassic.

1. Introduction

In recent years, abundant new discoveries of dinosaur footprints have been made in China, such as the Early-Middle Jurassic tracksites in Yunnan Province (Xing et al., 2013a, 2014a, 2016a), Sichuan Province (Xing et al., 2015a, 2016b), the Early Cretaceous tracksites in Shandong Province (Li et al., 2011; Chen et al., 2013; Kuang et al., 2013; Peng et al., 2013; Wang et al., 2013; Xing et al., 2013b; Xu et al., 2013), Gansu Province (Xing et al., 2013c, 2014b), and the Late Cretaceous tracksites in Guangdong Province (Xing et al., 2016c). However, the Late Jurassic dinosaur tracks have rarely been reported from literature, except for the theropod-sauropod track assemblage from the Shuangbai tracksite, Yunnan Province (Xing et al., 2016d). Although many theropod, ornithopod and possible sauropod tracks have been discovered in the Jurassic-Cretaceous transition red beds in northern North China, most of them are concentrated in the early Early Cretaceous (Xu et al., 2016a,b).

Shanxi Province, located at the center of North China, is known as a coal area. It contains thick Mesozoic terrestrial stratigraphic successions, which yielded the Middle Triassic tetrapods of the *Sinokannemeyeria-Shansisuchus* assemblage (Young, 1957; Sun, 1960, 1980; Li and Cheng, 1995; Liu, 2015; Liu and Fernando, 2015), and the Late Cretaceous dinosaur fauna (Cheng and Pang, 1996). The dinosaur fauna includes the hadrosauroid dinosaur *Shantungosaurus* (Pang and Cheng, 2001), *Datonglong tianzhenensis* (Xu et al., 2016a,b), the ankylosaur *Tianzhenosaurus youngi* (Pang and Cheng, 1998), *Sanxia tianzhenensis* (Barrett et al., 1998), the sauropod *Huabeisaurus allcotus* (Pang and Cheng, 2000), and the theropod *Szechuanosaurus campi* (Pang et al., 1996). In contrast, the Jurassic dinosaur bones and footprints are scarce. The Jurassic sauropod bones have been only sporadically reported from the Early Jurassic sandstones in the center of Shanxi Province (Pan, 2001).

During the field investigation in May 2015, the authors found sauropod tracks preserved in the Late Jurassic Tianchihe Formation in Guxian County, Linfen City, Shanxi Province, which was the first discovery of dinosaur tracks in Shanxi Province. In May 2016, the team

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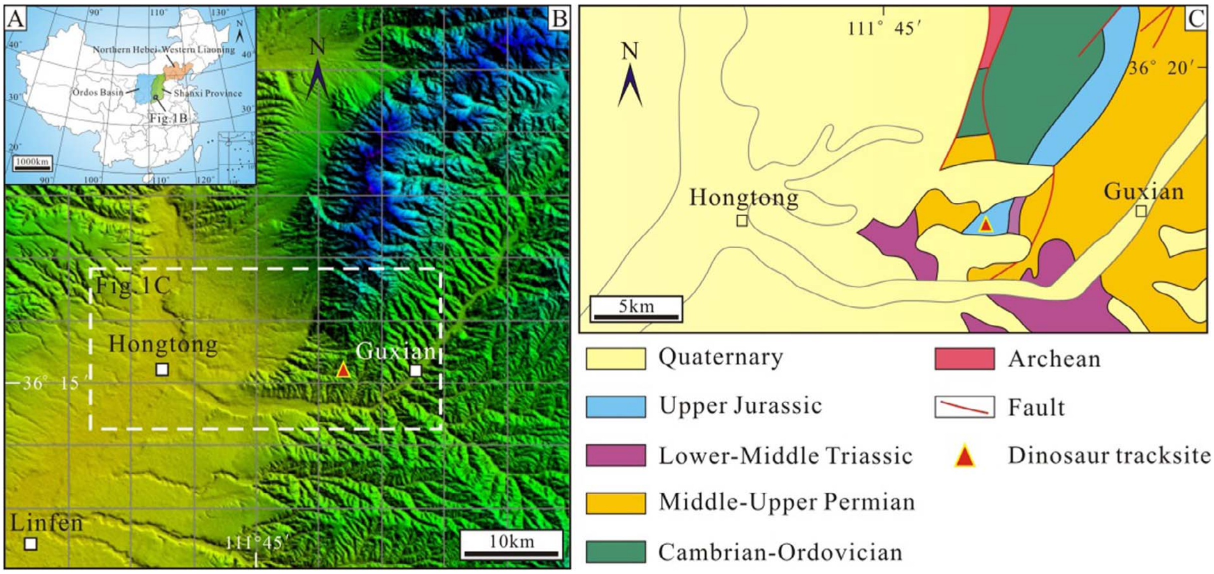

Fig. 1. Geological location of the study area. (A) Location of the Shanxi Province. Note its connection with northern Hebei-western Liaoning and the Ordos Basin; (B) Topographic map of the study area; (C) Geological map of the tracksite.

went to the tracksite and conducted a detailed study of tracks and also paid particular attention to the sedimentary features of the track-bearing levels. The aims of this paper are: (1) to describe the morphology of sauropod tracks and trackways; (2) to analyze the sedimentary environment of the tracksite, (3) to analyze the possible track makers and their behavior; (4) to reconstruct the paleoenvironments and (5) discuss the effect of arid environments on the paleogeographical dispersions of the Late Jurassic dinosaur fauna in North China. The new discovery of the Late Jurassic sauropod tracks in Shanxi Province increases our knowledge of the distribution and evolution of the dinosaur fauna in China during the Late Jurassic.

2. Geological setting

Shanxi Province, bordered by the Taihang Mountain to the east and Lüliang Mountain to the west, is located in the eastern part of the Ordos Basin, and connected with northern Hebei Province in its northeastern part (Fig. 1A). The tracksite (GPS: N 36°15′48.59″, E 111°49′35.77″) is situated at the Ruqu village, 10 km west of Guxian county, southern Shanxi Province. Tracks appear in different stratigraphic levels of the Tianchihe Formation (Fig. 1B and C), which is well exposed in central and southern Shanxi Province.

The Tianchihe Formation is a clastic unit 350–500 m thick, dominated by large scale cross-bedded eolian sandstones, in the center of the Shanxi Province, pinching out into fluvial facies to the southern part of the province (Fig. 2). It conformably overlies the Yungang Formation and is unconformably covered by Cenozoic conglomerates. Previous studies based on stratigraphic correlations inferred that the most probable age for the Tianchihe Formation was Middle Jurassic. However, recent geochronological studies conducted by Li et al. (2014a,b) on tuff layers from the top of the underlying Yungang Formation gave an age of 160.6 ± 0.55 Ma. Although this age could not precisely constrain the age of the Tianchihe Formation, it suggests that the overlying Tianchihe Formation is younger than 160 Ma and may be correlated with the Tiaojishan Formation in northern Hebei-western Liaoning (Fig. 2). Isotopic dating has constrained the age of the Tiaojishan Formation to 165–152 Ma (Chen et al., 2004; He et al., 2004; Davis, 2005; Liu et al., 2006, 2012a; Chang et al., 2009, 2014). Due to a lack of latest Jurassic-Early Cretaceous strata widely distributed in northeastern Shanxi Province and nothern Hebei-western Liaoning, the age of the upper part of the Tianchihe Formation is uncertain, as well as its correlation with the Jurassic-Cretaceous transition red beds represented by the Tuchengzi Formation of 154–137 Ma (Xu et al., 2012).

At present, track fossils have not been reported from the Tianchihe Formation in Shanxi Province. In contrast, numerous Jurassic vertebrate tracks are known from sedimentary units in the Ordos Basin. The Hailiutu tracksite from the north of the basin contains 119 vertebrate tracks, including the theropod tracks *Eubrontes glenrosensis*, *Kayentapus hailiutuensis*, ornithopod tracks *Anomoepus intermedius*, and crocodile tracks (Li et al., 2010). These tracks are preserved in the upper part of the Shiguaizi Group, which is correlative with the Late Jurassic Changhangou Formation or Tiaojishan Formation or Anding Formation (Xu et al., 2016a,b), The Shenmu tracksite and the Tongchuan tracksite from the west of the basin include theropod tracks and ornithopod tracks, respectively. The former is attributed to coelurosaurid *Shensipus tungchuanensis* from the Middle Jurassic Zhiluo Formation (Young, 1966), and the latter is iguanodontid *Sinoichnites youngi* from the Late Jurassic Anding Formation (Kuhn, 1958; Fig. 2).

Moreover, large numbers of mammals, feathered dinosaurs, pterosaurs, salamanders, insects, fishes and plants known as the Yanliao Biota have been found in the Jiulongshan and Tiaojishan formations in northern Hebei-western Liaoning (Gao and Shubin, 2003; Meng et al., 2006; Hu et al., 2009; Lü et al., 2010; Luo et al., 2015; Meng et al., 2015). Abundant dinosaur tracks, consisting of small-sized theropod tracks dominated by *Grallator*, possible sauropod tracks and ornithopod tracks, are mostly preserved in the upper part of the Tuchengzi Formation in northern Hebei-western Liaoning (Zhang et al., 2004, 2012; Fujita et al., 2007; Sullivan et al., 2009; Xing et al., 2011a; Liu et al., 2012a,b). Sparse dinosaur bones represented by *Chaoyangsaurus youngi* and *Xuanhuasaurus niei* were discovered in the lower-middle part of the Tuchengzi Formation (Zhao et al., 2006). The bird tracks attributed to *Pullornipes aureus* are present in the middle-upper part of the Tuchengzi Formation in Beipiao City, western Liaoning Province (Lockley et al., 2006a; Fig. 2).

3. Materials and methods

The tracksite appears in a 35° dipping section of the Tianchihe Formation (Fig. 3). Tracks can be followed laterally for 20 m in an area of 120 m^2. The five main recognized trackways of this site that include 37 tracks, have been identified and described in detail (Fig. 3). In order to make more accurate measurement and mapping, tracks were outlined in chalk and photographed. All the trackways and tracks have

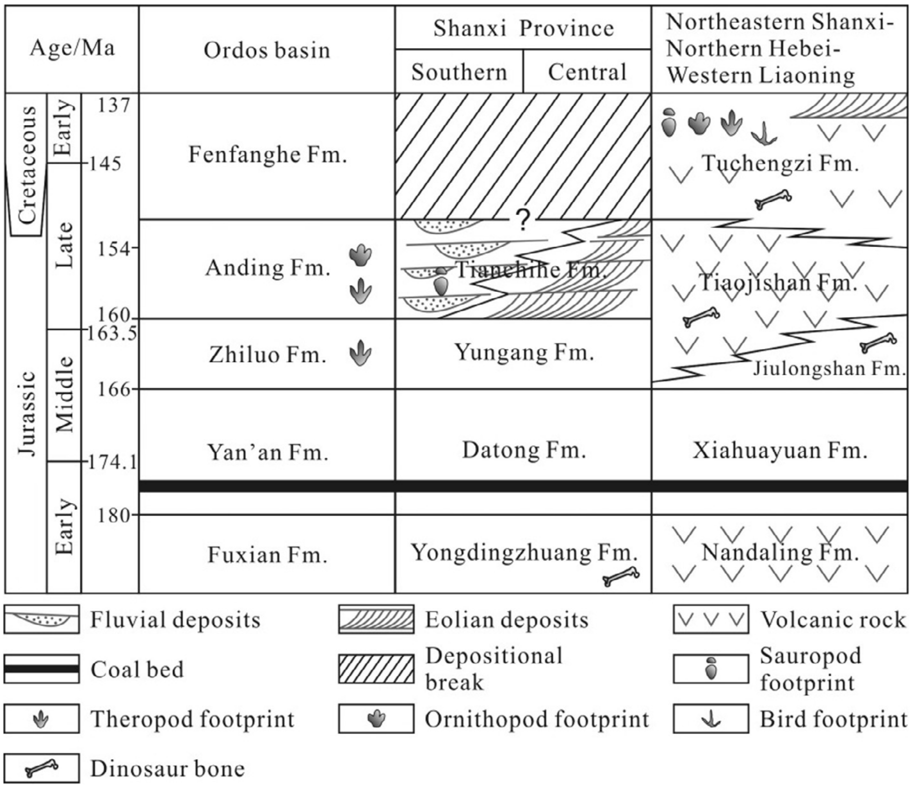

Fig. 2. Jurassic-Early Cretaceous stratigraphic sequences and regional correlations in central-northern North China.

been serially numbered with the prefix "S" for sauropod trackway (Fig. 4). For all trackways, tracks and trackways parameters have been systematically measured in detail, including pes length, pes width, manus length, manus width, pace length, stride length, pace angulation, trackway direction and the width of the angulation pattern of manus and pes. Tracks with a clear outline, morphology and ridge are defined as true tracks or surface prints. Tracks with relative clear outline, unclear morphology and no ridge are defined as transmitted prints. The terminology for trackway patterns is based on Leonardi (1987), Thulborn (1990), and Romano and Whyte (2003). Measured parameters are included in Appendix A.

The trackway width/trackway gauge, firstly introduced by Farlow (1992), is an essential parameter for the classification of sauropod trackways and the identification of their trackmakers (Marty et al., 2010). Farlow (1992) and Lockley et al. (1994) classified the trackway gauge as two kinds: wide gauge and narrow gauge. The wide gauge trackway is characterized by tracks relatively far away from the trackway midline, while the narrow gauge trackway is defined as tracks closer or overlapping the trackway midline. Romano et al. (2007) and Marty (2008) proposed two different trackway ratios to define trackway gauge, and divided it into three kinds: wide gauge, medium gauge and narrow gauge. Romano et al. (2007) used the ratio between the width of the angulation pattern defined as the ratio between the track width and overall trackway width. In contrast, Marty (2008) was using the ratio between the width of the angulation pattern (WAP, WAM) and the corresponding track length (PL) or width (MW). Marty (2008) suggested the following limits: narrow gauge (< 1.0), medium gauge (1.0–1.2) and wide gauge (> 1.2). Due to the limitations when measuring the trackway width of a turning trackway present in the tracksite, we chose Marty's method for studying sauropod trackway gauge in this study. The sauropod track size classes presented in this paper are also based on Marty (2008): tiny (< 25 cm), small (25–50 cm), medium (50–75 cm) and large (> 70 cm).

Locomotion speed for sauropod trackways of the tracksite was evaluated based on the formula of Alexander (1976): $v = 0.25g^{0.5}S^{1.67}h^{-1.17}$, with hip height $(h) = 5.9 * \text{foot length}$

Fig. 3. Photograph of the Guxian tracksite, Shanxi Province, China. Note the trackways.

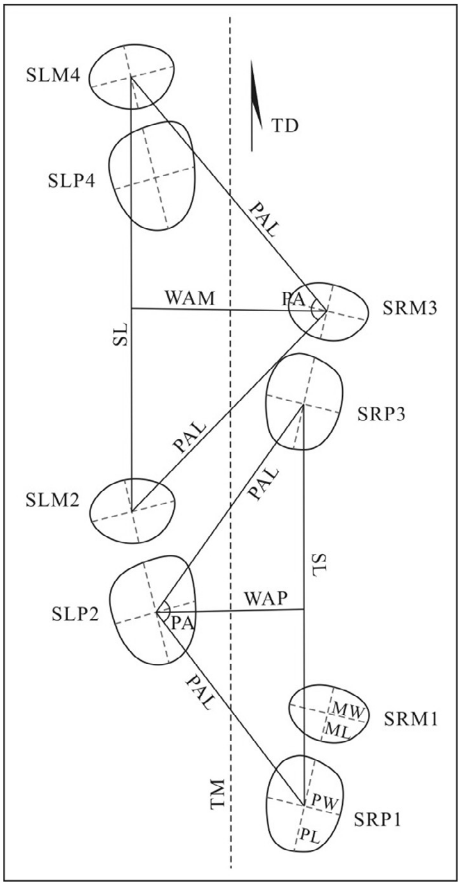

Fig. 4. Schematic sauropod trackway showing the essential features measured. ML: Manus Length; MW: Manus Width; PL: Pes Length; PW: Pes Width; SLP: Sauropod Left Pes; SRP: Sauropod Right Pes; SLM: Sauropod Left Manus; SRM: Sauropod Right Manus; PAL: Pes Pace Length; MAL: Manus Pace Length; PSL: Pes Stride Length; MSL: Manus Stride Length; WAM: Width of the Manus Angulation Pattern; WAP: Width of the Pes Angulation Pattern; TM: Trackway middleline; TD: Trackway direction.

(Thulborn, 1990). The locomotion status was based on the relative stride length (SL/H): walking (< 2.0), trotting (2.0–2.9), and running (> 2.9) (Alexander, 1976; Thulborn, 1990). Not all the trackways are suitable for calculating the trackway gauge and locomotion speed because of incomplete trackway data. Results are shown in Appendix A.

4. Sedimentary environment of the tracksite

The Tianchihe Formation in the tracksite is well exposed. A complete stratigraphic and sedimentological analysis was carried out.

The section is 32 m long and 11 m thick (Figs. 5 and 6A). It can be divided into three parts based on the vertical lithological succession. The lower part mainly consists of red thick–medium-bedded, coarse–-medium-grained sandstone interbedded with red, thin-bedded muddy siltstone, constituting three fining upward cycles (Fig. 5). The sandstones are organized in fining upwards sequences with planar or scoured bases and gravel lags, internally showing parallel bedding and planar cross-bedding, The sand grains are well sorted, subrounded to subangular (Fig. 6B and C). Asymmetric ripple marks with sinuous ridge and small scale desiccation cracks are present in the muddy siltstones (Fig. 6D). The middle part is an interval of red, thick–medium-bedded mudstones with interbedded red, medium–thin-bedded fine-grained sandstone layers in the lower part and medium-bedded siltstone layers in the upper part (Figs. 5 and 6E). The mudstones are structureless. The fine- grained sandstones display a lenticular shape, are normally graded and contain ripple cross-bedding (Fig. 6F). The siltstones are horizontal bedded with climbing ripple cross-bedding. The upper part consists dominantly of red, medium-thick-bedded coarse–medium- grained sandstones interbedded with red, medium-bedded or lenticular siltstones and mudstones (Fig. 5). The sandstones with planar cross-bedding is normally graded with mud clasts and scoured base resting on the underlying red mudstone (Fig. 6G–I). The tracks are present in the middle part of the sandstone (Figs. 3 and 5).

The gravel lags with scoured base present in the lower part of the cross-beds are interpreted as channel lag formed in a high-energy regime (McLaurin and Steel, 2007). The channelized coarse-grained sandstone with cross-beds, lag deposits and scoured base represents channel fill. The planar-cross bedded coarse-medium sandstone with planar or scour base is consistent with longitudinal bar, representing avalanche-slope progradation (Miall, 1977; Walker and Cant, 1984). Lenticular siltstone and mudstone interbedded within cross-bedded sandstone is indicative of lateral creation during the shallow water level period (Allen, 1970; Miall, 1977). Medium–thin-bedded fine grained sandstone and siltstone with climbing ripple cross-beds interbedded within medium bedded mudstone could represent levee deposits (Brierley et al., 1997). Asymmetric ripple marks with sinuous ridges are interpreted as current ripples on the flood plain. Desiccation cracks occur on the rippled muddy siltstones and indicate seasonal aridity or at least exposure and desiccation. Structureless, medium–thick- bedded mudstones interbedded with siltstone and sandstones represent flood plain facies. Fining upward sequences, consisting of sandstones, siltstones and finally mudstones, represent the vertical trend of the channel fills through time. The assembly of channel lag conglomerate, channel fill sandstone, levee siltstones and flood plain siltstones and mudstones could correspond to facies associations of a meandering fluvial system (Walker and Cant, 1984; Ghazi and Mountney, 2009). In contrast, the facies association of longitudinal bar sandstones and minor flood plain siltstones and mudstones are interpreted as belonging to a sandy braided fluvial system (Smith et al., 2006).

5. Description of trackways

The tracksite shows five trackways cataloged as S1, S2, S3, S4 and S5 (Figs. 3 and 7). These tracks fall in two different size categories: small and medium-sized tracks (Marty, 2008). The average pes length of the three small tracksways (S1, S2, S3) ranges from 40.5 cm to 46.1 cm. The average pes length of the two medium-sized tracksways (S4, S5) is 55 cm and 65.5 cm, respectively. S1-S4 consists mainly of pes prints, with some manus prints overlapped by pes prints, while S5 are composed of pes and manus prints, suggesting quadruped characteristics. Almost all of the tracks are ovoid and semi-round in shape, and some pes tracks exhibit well-defined round, swollen rims (Fig. 8). An isolated pes mold is well preserved in morphology and exhibits possible four forwardly directed digits (Fig. 9). All these identified features suggest that the track maker was a sauropod dinosaur (Thulborn, 1990; Marty et al., 2010).

Trackway S1 is moderately preserved, with nine pes prints, three incomplete pes prints and one overprinted manus print. The mean length and width of pes prints is 43.4 cm and 38 cm, respectively. The average length/width ratio of pes impressions is 1.17. The average pace and stride length of pes prints are 64.2 cm and 72.7 cm, respectively. WAP/PL = 1.13, indicating a medium gauge trackway (Marty, 2008). The pace angulation is 71.3°. The direction of the trackway changes from 90° to 50°, exhibiting a turning trackway. The evaluated speed of the trackway is 0.55 km/h, which corresponds to a small-sized sauropod walking slowly.

Trackway S2 is poorly preserved in short length, and only consists of two manus and pes prints. The manus prints in semicircle shape are overlapped by pes prints. Around the pes prints, a swollen rim is visible (Fig. 8A). The mean length and width of pes prints is 40.5 cm and 38.5 cm, respectively. The average length/width ratio of pes impressions is 1.05. No data are available for the evaluation of trackway gauge and speed. The direction of trackway is 92°.

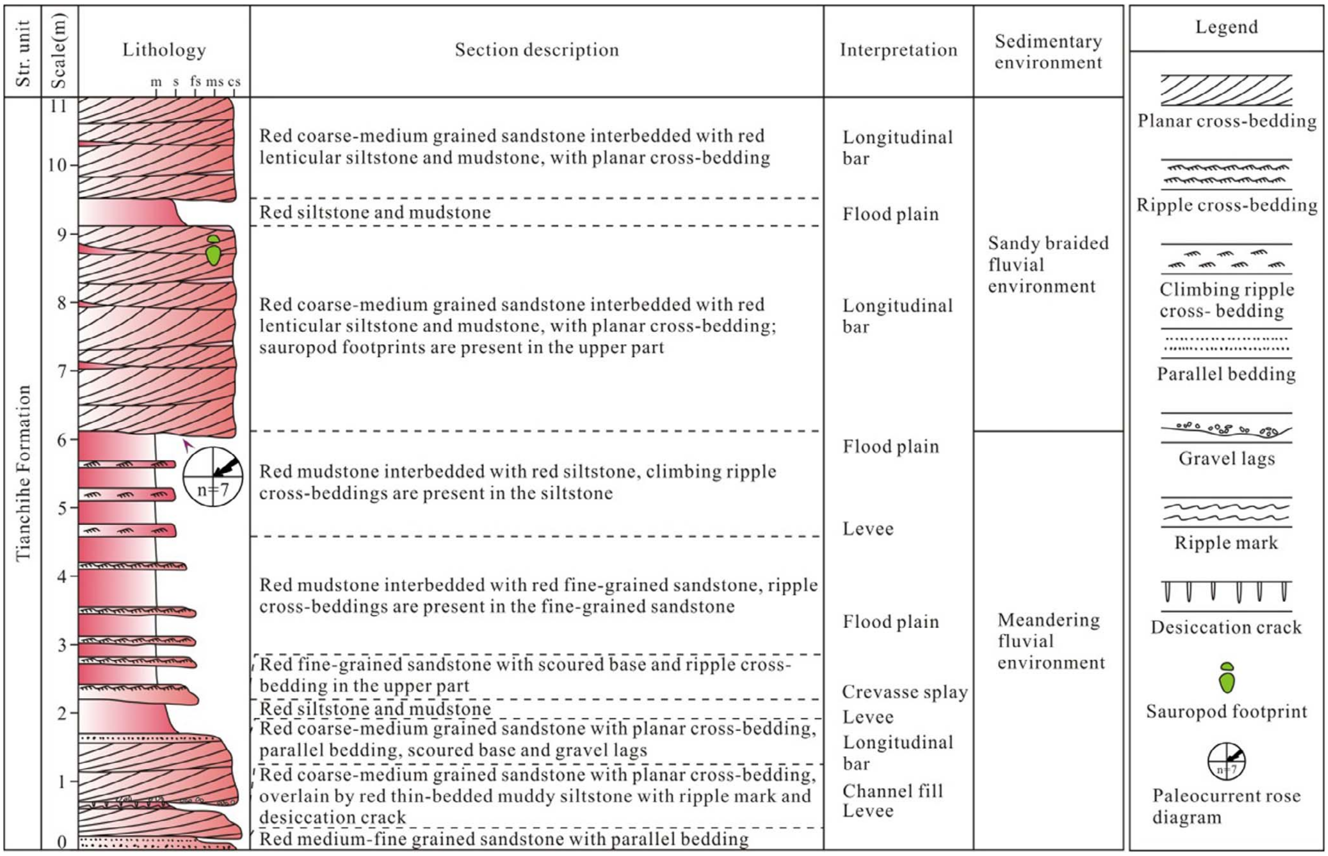

Fig. 5. Stratigraphic section of the Guxian tracksite, Shanxi Province, China.

Trackway S3 is moderately preserved, with eight pes impressions. Two tracks are missing because the bedding plane was damaged by differential weathering. The pes impressions show a circular shape without morphological features, except clear marginal ridges (Fig. 8B–D). The corresponding manus impressions are absent, maybe overprinted by pes impressions. The mean length and width of pes prints is 46.1 cm and 41.9 cm, respectively. The average length/width ratio of pes impressions is 1.17. The average pace and stride length of pes prints are 75 cm and 95.1 cm, respectively. The relationship WAP/PL = 1.35, indicating a wide gauge trackway (Marty, 2008). The pace angulation of the pes is 92°. The direction of the trackway is 325°. The evaluated speed of the trackway is 0.94 km/h, corresponding to a small-sized sauropod with a slow walk.

Trackway S4 is poorly preserved, and comprises four pes impressions. One pes impression is incomplete because of weathering. The pes impressions are relatively circular in shape, without any morphological features. The corresponding manus prints are absent. The mean length and width of pes prints is 55 cm and 45.7 cm, respectively. The average length/width ratio of pes impressions is 1.2. The average pace and stride length of pes prints are 78 cm and 130 cm, respectively. WAP/PL = 1.40, indicating a wide gauge trackway (Marty, 2008). The evaluated speed of the trackway is 1.08 km/h, which corresponds to a medium-sized sauropod walking slowly.

Trackway S5 is poorly preserved, mostly composed of transmitted prints. The bedding plane was damaged by weathering. The identified three pes and four manus impressions just exhibit relatively circular shapes with shallow depth and no morphological features. Because the trackway S5 is only one complete quadruped trackway in the tracksite, we conducted a relatively rough measurement on this trackway. The mean length and width of pes and manus prints is 65.5 cm, 47 cm, and 41 cm, 39 cm, respectively. The average length/width ratio of pes and manus impressions is 1.39 and 1.05. The average pace and stride length of pes and manus prints are 117.5 cm, 206 cm and, 112.7 cm, 182.5 cm, respectively. WAM/MW = 1.92, indicating a wide gauge trackway (Marty, 2008). The pace angulation of pes and manus impressions are 130° and 100°. The direction of the trackway is 68°. The evaluated speed of the trackway is 1.62 km/h, which corresponds to a medium-sized sauropod with slow walk.

6. Discussion

6.1. Track makers

Three valid sauropod ichnogerera, including *Breviparopus* (Dutuit and Ouazzou, 1980), *Brontopodus* (Farlow et al., 1989) and *Parabrontopodus* (Lockley et al., 1994), are proposed on the basis of track morphology and trackway gauge. Moreover, Avanzini et al. (2003) and Santos et al. (2009) also subdivided the *Sauropodomorpha* ichno – morphotypes into four-five types based on pes print morphology: *Tetrasauropus* – like, *Otozoum* – like, *Breviparopus/Parabrontapodus* – like, *Brontopodus* – like, and *Polyonyx* – like. Among these ichno-morphotypes, the wide-gauge *Brontopodus* and narrow-gauge *Parabrontopodus* are more widely identified and distributed. In general, the *Brontopodus* were widely distributed in the Cretaceous, and the *Parabrontopodus* were more common in the Jurassic, while they could co-occurred in either Jurassic or Cretaceous (Lockley et al., 1994; Marty et al., 2003, 2010). So far, the Late Jurassic sauropod tracks are known from many places, including narrow-gauge trackways from Purgatoire Valley of southeastern Colorado (Lockley et al., 1986), *Parabrontopodus* from Canton Jura, Northern Switzerland (Marty et al., 2003), *Brontopodus* from Chevenez-Combe Ronde tracksite, NW Switzerland (Marty, 2008), *Brontopodus*, *Parabrontopodus* and *Breviparopus* from Jura Mountain, NW Switzerland and central High Atlas Mountains, Morocco (Marty et al., 2010), *Deltapodus* from Morocco

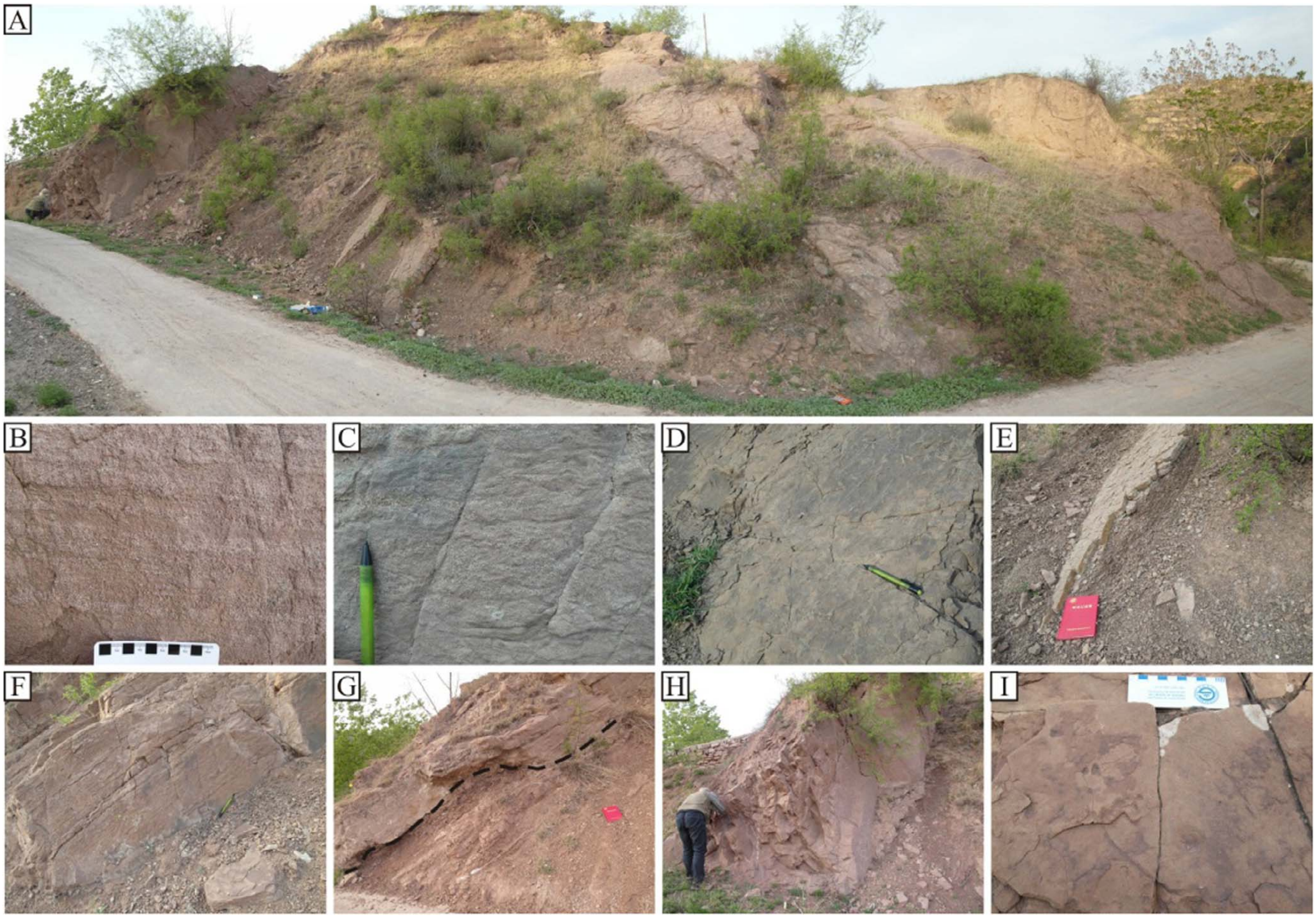

Fig. 6. Photographs showing features of the interpreted fluvial deposits. (A) Overview photograph of the measured section; (B) Purple red thick bedded coarse-medium grained sandstone with parallel bedding and normal graded sequence; (C) Light purple red thick-medium bedded coarse-medium grained sandstone with lenticular lag coarse grained sandstone, scoured base and small-scale wedge shaped cross-bedding; (D) Light purple red fine-grained sandstone with ripple marks; (E) Red thick bedded mudstone interbedded with light purple red medium-thin bedded fine grained sandstone; (F) Light Purple red lenticular fine grained sandstone with ripple cross-bedding interbedded within red thick bedded siltstone and mudstone; (G-H) Purple red channelized coarse-medium grained sandstone with plannar cross-bedding and scoured base resting on the red thick bedded mudstone; (I) Mud clasts on the purple red medium grained sandstone with sauropod tracks. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Belvedere and Mietto, 2010), *Parabrontopodus* and *Brontopodus* from Jura, France (Loeuff et al., 2006; Mazin et al., 2016), *Parabrontopodus* from Istria, Croatia (Mezga et al., 2007), narrow-gauge trackways from Cameros Basin in Spain (Moratalla, 2009), wide- and narrow-gauge trackways from central-west Portugal (Mateus and Milàn, 2010), first giant sauropod footprints similar to *Brachiosaurus* from Zimbabwe (Ahmed et al., 2004), and medium-wide gauge *Iguanodonichnus frenki* from Chile (Moreno and Benton, 2005).

In contrast, sauropod tracks have rarely been reported from the Upper Jurassic of China. Most sauropod tracks were from the Lower Cretaceous and attributed to *Brontopodus* and *Parabrontopodus*, such as the tracksites in Yishu fault zone and Zhucheng in Shandong Province (Xing et al., 2013b, 2015b), the Nanguzhai tracksite in Jiangsu Province (Xing et al., 2010), the Yanguoxia tracksite in Gansu Province (Li et al., 2006; Zhang et al., 2006), the Chabu tracksite in Inner Mongolia (Lockley et al., 2002a), the Zhaojue tracksite, Shimiaogou tracksite, and Bajiu tracksite in Sichuan Province (Xing et al., 2014c, 2016e, 2016f). Moreover, sparse sauropod tracks were also discovered from the Jurassic, including the Early Jurassic *Parabrontopodus/Breviparopus* from Sichuan Province (Xing, 2010), the Early-Middle Jurassic *Brontopodus* from Changdu, Tibet (Xing et al., 2011b) and the Middle-Late Jurassic *Brontopodus* from Yunnan Province (Xing et al., 2016d).

The Guxian tracks are the first sauropod tracks reported from Shanxi Province, China. Trackways are between medium gauge and wide gauge trackways with a WAP/PL or WAM/MW ratio of 1.13–1.92. The average length/width ratio of pes impressions is 1.05–1.39, which suggests that the pes tracks are longer than wide. Trackway 5, as the only one trackway with quadrupedal impressions preserved, shows clear larger and outwardly directed pes prints. These features suggest that the Guxian sauropod trackways are similar to *Brontopodus* from the Upper Jurassic of France, Switzerland and Portugal (Meyer and Pittmann, 1994; Marty, 2008; Marty et al., 2010), although the poor preservation in the tracksite could not provide enough data and detailed configuration.

The wide gauge *Brontopodus* has been previously attributed to brachiosaurids and titanosaurians (Lockley et al., 1994; Day et al., 2002), which were widely distributed in North America and Africa during the Late Mesozoic (Fastovsky and Weishampel, 1996; Upchurch et al., 2004). Santos et al. (2009, 2010) proposed that some basal eusauropods, such as Turiasauria were responsible for *Brontopodus*-like trackways, instead of exclusive to brachosaurid or titanosauriform sauropods. In China, the Late Jurassic dinosaur fauna is dominated by the basal eusauropod *Mamenchisaurus* assemblage, which is widely distributed in southwest and northwest of China (Li and Cai, 1997). Fang et al. (2004) proposed that the Mamenchisauridae probably originated from Yunnan Province, and then it radiated from Sichuan, Gansu to Xinjiang Province. The occurrence of Mamenchisauridae from the Upper Jurassic-Lower Cretaceous in Thailand (Suteethorn et al., 2012) suggests that the distribution of Mamenchisauridae is wider than previously supposed, and it not only radiated northward but also southward in Asia. The Mamenchisauridae represent en endemic fauna from Asia in the Late Jurassic (Upchurch et al., 2002; Suteethorn et al.,

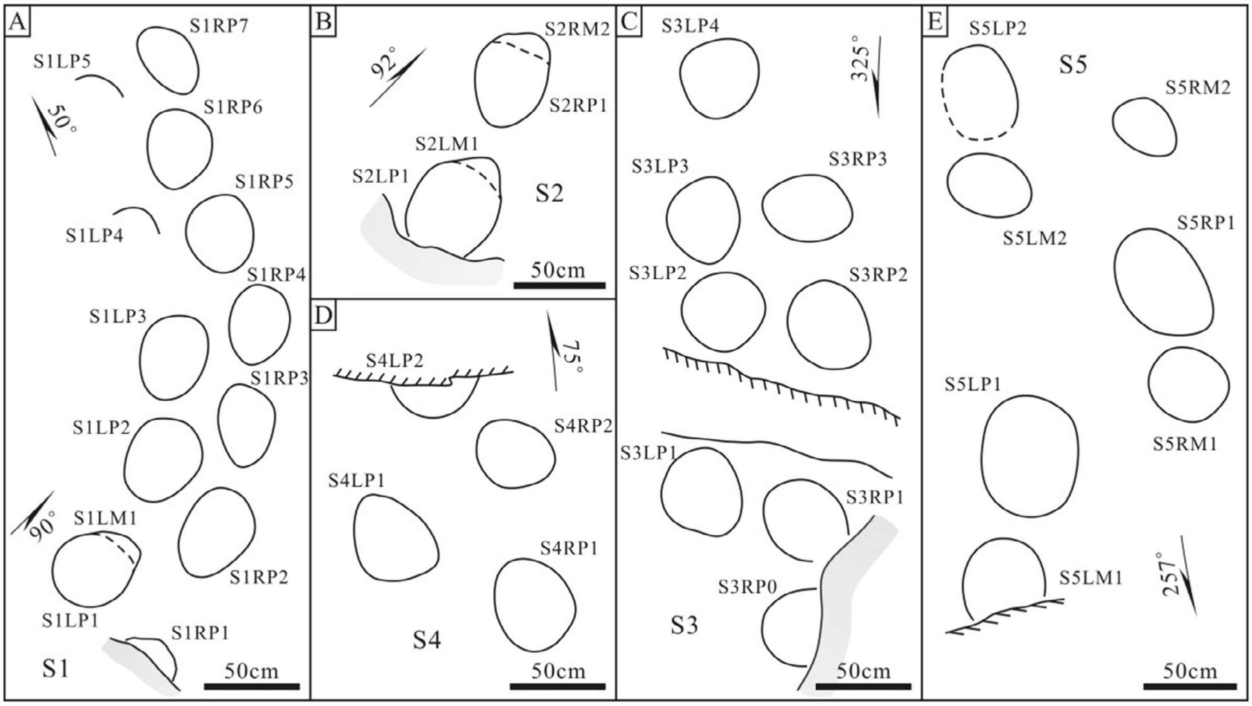

Fig. 7. Interpretative outline drawings of sauropod trackways from Guxian tracksite, Shanxi Province, China.

2012; Xing et al., 2015c). Xing et al. (2016d) reported a typical-wide gauge sauropod trackway (*Brontopodus*) from the Middle-Late Jurassic in the Hemenkou tracksite, Yunnan Province and related it with the basal eusauropods, such as *Mamenchisaurus* and *Omeisaurus*. In contrast to Yunnan Province, where abundant Jurassic body fossils have been discovered, rare dinosaur body fossils have been reported from the Jurassic of the Ordos Basin. Based on the sauropods occurred in China in the Late Jurassic, *Mamenchisaurus* is undoubtedly a candidate for the trackmakers in the Guxian tracksite, Shanxi Province.

6.2. Trackmaker behavior

Trackway patterns and configurations can offer considerable information on dinosaur behavior (Lockley et al., 1986, 2002b; Matsukawa et al., 1997, 1999; Barco et al., 2006). Parallel trackways, that is a common phenomenon observed and interpreted at many sauropod tracksites, are regarded as gregarious behavior (Lockley et al., 1986; Zhang et al., 2006; Kim et al., 2009; Kukihara and Lockley, 2012). By contrast, those sauropod trackways with diversified

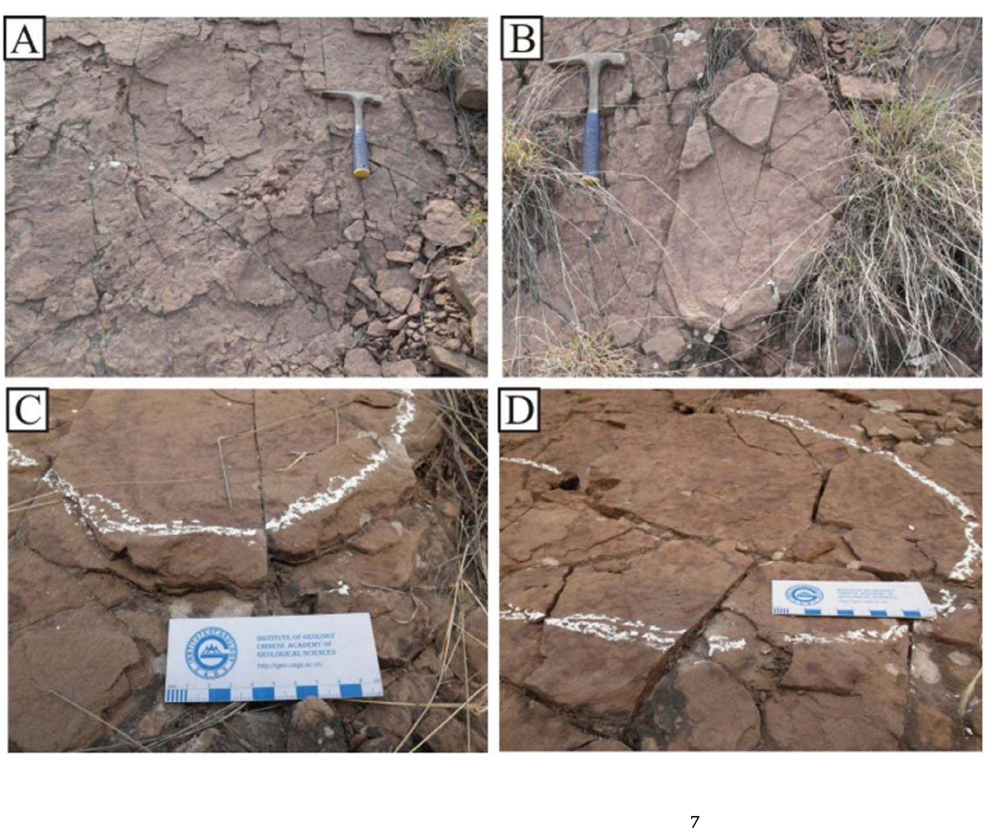

Fig. 8. Photographs showing track morphology and well defined round swollen rims. (A) S2RP1 from S2; (B-D) S3RP1, S3LP3 and S3RP3 from S3.

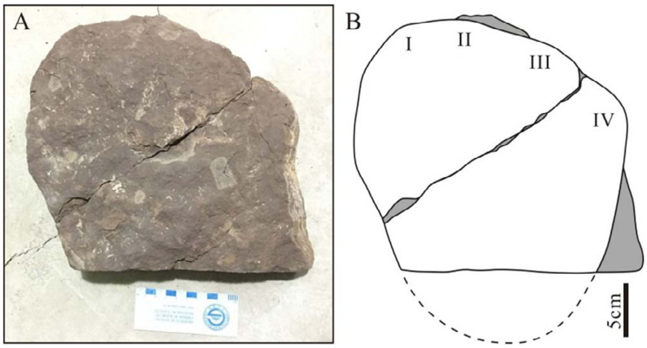

Fig. 9. Isolated sauropod pes mold from Guxian tracksite, Shanxi Province, China. (A) Photograph of pes mold; (B) Interpretative outline drawing from A.

orientations could represent unorganized herds (Mazin et al., 2016). The Guxian sauropod trackways are quite different regarding trackway direction and orientation. The combination of trackways showing different patterns suggests that they were probably formed by different sauropod at different times rather than all together at the same time. This is the case of trackways also reported from Switzerland (Marty et al., 2003), France (Mazin et al., 2016) and Croatia (Mezga and Bajraktarević, 1999).

Sauropod trackways at the Guxian tracksite shows a majority of pes records except for trackway 5. This apparent bipedalism in quadruped sauropods is the result of overprint of the manus by pes (Zhang et al., 2006). The evaluated speed of the trackway 1–4 ranges from 0.55 km/h to 1.08 km/h, while the trackway 5 is 1.62 km/h, suggesting that slower walkers produced pes dominated overprints (Mezga et al., 2007). This phenomenon is common at sauropod tracksites in the Upper Jurassic of Chile (Moreno and Benton, 2005) and Colorado (Lockley et al., 1986), the Lower Cretaceous of South Korea (Lockley et al., 2006b) and Gansu Province, China (Zhang et al., 2006).

Trackway 5 shows an interesting turning trackway in the Guxian tracksite. Such an unusual turn around behavior in sauropods is known from western Europe (Mezga and Bajraktarević, 1999; Meyer et al., 1994; Castanera et al., 2014), North America (Lockley, 1990), North Africa (Ishigaki and Matsumoto, 2009) and China (Lockley and Matsukawa, 2009; Xing et al., 2015b, 2015d). Ishigaki and Matsumoto (2009) defined this kind of pattern as "off-tracking". Sauropod trackways with turns in China are mainly reported from the Lower Cterateous, including the Dazu tracksite in Chongqing City (Lockley and Matsukawa, 2009), Zhaojue tracksite in Sichuan Province (Xing et al., 2015d) and Tandigezhuang tracksite in Shandong Province (Xing et al., 2015b). Up to know, no turning trackways have been reported from the Jurassic. Trackway 5 with medium gauge is pes dominated and produced by a small trackmaker. The directional change of the trackway is 40°, smaller than other well preserved examples of turning sauropod trackways, as the sauropod "turning around" in semicircle turn from the Tangdigezhuang tracksite, Shandong Province (Xing et al., 2015b). The occurrence of a turning trackway in the Guxian tracksite could be related to many factors, such as an obstacle in the path or just suggest that the common "off-tracking" phenomenon in sauropods represent a special locomotion character or social behavior. More work on this special behavior is required in the future.

6.3. Paleoenvironment and paleogeography

In the Early-Middle Jurassic, great expansion and subsidence took place in the Ordos Basin. The sedimentary area of the basin expanded eastward to the eastern Shanxi Province, where fluvial, deltaic and lacustrine deposits were present (Cheng et al., 1997; Zhao et al., 2010). The occurrence of abundant coal and plant fossils indicate a warm and humid environment, which is common in the north of China (Li et al., 2014a,b). In the late Middle Jurassic, an extensive intracontinental orogeny, known as the Yanshan movement, took place in North China, resulting in the formation of the Yanshan orogenic belt and the uplift of eastern North China, as well as the westward subsidence of the Ordos Basin (Davis et al., 1998; Yang et al., 2006; Dong et al., 2008; Liu et al., 2013, 2015). Shanxi Province was dominated by deltaic and lacustrine deposits present in the Early-Middle Jurassic and by fluvial-eolian deposits in the Late Jurassic, suggesting a transition from humid to arid environments (Zhang et al., 2008).

The measured section at the Guxian tracksite shows the sedimentary facies change from meandering fluvial to sandy braided fluvial depositional systems. The occurrence of desiccation cracks present in the meandering fluvial deposits suggests seasonally arid environment. The successive sedimentation in short time indicates that the seasonal aridity was common in the Late Jurassic and played an important role in the development of fluvial depositional system in the Ordos Basin (Cheng et al., 1997). Body and track fossil evidence indicates that the sauropods were more adapted to a seasonally arid environment (Retallack, 1997; Lockley et al., 2002a), although some sauropods were present in humid environments (Farlow, 1992). The paleocurrent orientation reconstructed from the sandy longitudinal bar of braided river shows northeastward direction, implying that the source area of the fluvial systems was probably located in a southern paleogeographic location with higher altitude. This inference is consistent with the Late Jurassic paleogeographic reconstructions of the Ordos Basin by other workers (Cheng et al., 1997; Liu et al., 2013, 2015). Moreover, provenance studies indicate that the Qingling orogenic belt, located in the south of the Ordos Basin, was a main source area of the Ordos Basin in the Late Jurassic (Li et al., 2015). It experienced large scale N-S compression in the Late Jurassic-Early Cretaceous (Dong and Santosh, 2015). Therefore, the Qingling orogenic belt constituted a paleogeographic highland in southern Ordos Basin during the Late Jurassic-Early Cretaceous.

Remarkably, although Shanxi Province was located in the east of the Ordos Basin in the Late Jurassic, its paleogeograghy was quite different from north to south. In the northeast of Shanxi Province, a series of intramontane basins filled with intermediate volcanic rocks interbedded with clastic rocks of the Tiaojishan Formation. The early Late Jurassic volcanic activities were extensive and frequent in nothern Hebei-western Liaoning, where large numbers of mammals, feathered dinosaurs, pterosaurs, insects known as the Yanliao Biota were survived (Zhang, 2002). In contrast, the middle part of Shanxi province was dominated by eolian sandstone characterized by large-scale cross-beds. At present, no vertebrate and invertebrate fossils originated from the Yanliao Biota have been found in the eolian deposits and sedimentary rocks of the Ordos Basin. The desertic environment probably acted as a paleogeographic barrier for the migration of the Yanliao Biota to the Ordos basin. In the south of Shanxi Province, the eolian sandstone was gradually replaced by fluvial deposits, which created more appropriate conditions for the survival of sauropod dinosaurs.

7. Conclusions

The Guxian tracksite, consisting of five sauropod trackways, constitute the first report of sauropod tracks from the Upper Jurassic Tianchihe Formation from Shanxi Province. The studied section indicates that the tracks are present in sandy braided fluvial environments showing seasonal aridity. Based on morphological and statistical analysis, the sauropod trackways are assigned to wide gauge *Brontopodus*. Different trackway orientations and trackway patterns present in the tracksite suggest that these trackways were produced by different sauropod at different times rather than contemporaneously. Most of the trackways are pes dominated. The analysis of evaluated speed of trackways indicates that the slower walk more easily produces pes dominated overprints. A turning trackway is observed in the tracksite, which may be a common phenomenon in sauropods and represents a special locomotion character or social behavior. The occurrence of eolian deposits in central Shanxi Province could have acted as a paleogeographic and paleoenvironmental barrier for the migration of the Yanliao Biota to the Ordos Basin.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jseaes.2017.10.042.

References

Ahmed, A.A.-K., Lingham-Soliar, T., Broderick, T.J., 2004. Giant sauropod tracks from the Middle-Late Jurassic of Zimbabwe in close association with theropod tracks. Lethaia 37, 467–470.

Alexander, R.M., 1976. Estimates of speeds of dinosaurs. Nature 26, 129–130.

Allen, J.R.L., 1970. Studies in fluviatile sedimentation: a comparison of fining-upwards cyclothems, with special reference to coarse-member composition and interpretation. J. Sediment. Res. 40, 298–323.

Avanzini, M., Leonardi, G., Mietto, P., 2003. *Lavinipes cheminii* ichnogen., ichnosp. nov., a possible sauropodomorph track from the Lower Jurassic of the Italian Alps. Ichnos 10, 179–193.

Barco, J.L., Canudo, J.I., Ruiz-Omenaca, J.I., 2006. Gregarious behaviour in theropods. Ichnos 13, 237–248.

Barrett, P.M., You, H.L., Upchurch, P., Burton, A.C., 1998. A new ankylosaurian dinosaur (Ornithischia: Ankylosauria) from the Upper Cretaceous of Shanxi Province, People's Republic of China. J. Vertebr. Paleontol. 18, 376–384.

Brierley, G.J., Ferguson, R.J., Woolfe, K.J., 1997. What is a fluvial levee? Sed. Geol. 114, 1–9.

Castanera, D., Vila, B., Razzollini, N.L., Santos, V.F., Pascual, C., Canudo, J.I., 2014. Sauropod trackways of the Iberian Peninsula: palaeoetological and palaeoenvironmental implications. J. Iberian Geol. 40, 49–59.

Chang, S.C., Zhang, H., Renne, P.R., Fang, Y., 2009. High-precision ^{40}Ar/^{39}Ar age constraints on the basal Lanqi Formation and its implications for the origin of angiosperm plants. Earth Planet. Sci. Lett. 279, 212–221.

Chang, S.C., Zhang, H., Hemming, S., Meso, G., Fang, Y., 2014. ^{40}Ar/^{39}Ar age constraints on the Haifanggou and Lanqi Formations: when did the first flowers bloom? Geol. Soc. Lond. Spec. Publ. 378, 277–284.

Chen, J., Kuang, H.W., Liu, Y.Q., Wu, Q.Z., Cheng, G.S., Xu, K.M., Peng, N., Xu, H., Liu, H., Xu, J.L., Wang, M.W., Wang, B.H., Zhang, P., 2013. Characteristics of dinosaur footprints of the late Early Cretaceous in Linshu area, Shandong Province. J. Palaeogeogr. 15, 505–516 (in Chinese with English abstract).

Chen, W., Ji, Q., Liu, D.Y., Zhang, Y., Song, B., Liu, X.Y., 2004. Isotope geochronology of the fossil-bearing beds in the Daohugou area, Ningcheng, Inner Mongolia. Geol. Bull. Chin. 23, 1165–1169 (in Chinese with English abstract).

Cheng, S.T., Huang, Y.Q., Fu, X.H., 1997. Paleogeography reconstruction of the Early-Middle Jurassic large Ordos Basin and development and evolution of continental downwarping. Acta Sedimentol. Sin. 15, 43–49 (in Chinese with English abstract).

Cheng, Z.W., Pang, Q.Q., 1996. A new dinosaurian fauna from Tianzhen Shanxi Province with its stratigraphical significance. Acta Geosci. Sin. 17 (Suppl.), 135–139 (in Chinese with English abstract).

Davis, G.A., 2005. The Late Jurassic "Tuchengzi/Houcheng" Formation of the Yanshan fold-thrust belt: an analysis. Earth Sci. Front. 12, 331–345.

Davis, G.A., Cong, W., Zheng, Y.D., Zhang, J.J., Zhang, C.H., Gehrels, G.E., 1998. The enigmatic Yinshan fold-and-thrust belt of northern China: new views on its intraplate contractional styles. Geology 26, 43–46.

Day, J.J., Upchurch, P., Norman, D.B., Gale, A.S., Powell, H.P., 2002. Sauropod trackways, evolution, and behavior. Science 296 1659-1659.

Dong, S.W., Zhang, Y.Q., Long, C.X., Yang, Z.Y., Ji, Q., Wang, T., Hu, J.M., Chen, X.H., 2008. Jurassic tectonic revolution in China and new interpretation of the "Yanshan Movement". Acta Geol. Sin. 82, 334–347.

Dong, Y., Santosh, M., 2015. Tectonic architecture and multiple orogeny of the Qinling orogenic belt, central China. Gondwana Res. http://dx.doi.org/10.1016/j.gr.2015.06.009.

Dutuit, J.M., Ouazzou, A., 1980. Découverte d'une piste de dinosaur sauropode sur le site d'empreintes de Demnat (Haut – Atlas Marocain). Mémoire de la Société Géologique de France, New Series 139, 95–102.

Fang, X.S., Zhao, X.J., Lu, L.W., Cheng, Z.W., 2004. Discovery of Late Jurassic Mamenchisaurus in Yunnan, southwestern China. Geol. Bull. Chin. 23, 1005–1009.

Fastovsky, D.E., Weishampel, D.B., 1996. The Evolution and Extinction of the Dinosaurs. Cambridge University Press, Cambridge.

Farlow, J.O., 1992. Sauropod tracks and trackmakers: integrating the ichnological and skeletal records. Zubia 10, 89–138.

Farlow, J.O., Pittman, J.G., Hawthorne, J.M., 1989. *Brontopodus birdi*, Lower Cretaceous sauropod footprints from the U. S. Gulf coastal plain. In: Gillette, D.D., Lockley, M.G. (Eds.), Dinosaur Tracks and Traces. Cambridge University Press, Cambridge, pp. 371–394.

Fujita, M., Azuma, Y., Lee, Y.N., Lü, J.C., Dong, Z.M., Noda, Y., Urano, K., 2007. New theropod track site from the Upper Jurassic Tuchengzi Formation of Liaoning Province, northeastern China. Memoir Fukui Prefectural Dinosaur Mus. 6, 17–25.

Gao, K.Q., Shubin, N.H., 2003. Earliest known crown-group salamanders. Nature 422, 424–428.

Ghazi, S., Mountney, N.P., 2009. Facies and architectural element analysis of a meandering fluvial succession: the Permian Warchha Sandstone, Salt Range, Pakistan. Sed. Geol. 221, 99–126.

He, H.Y., Wang, X.L., Zhou, Z.H., Zhu, R.X., Jin, F., Wang, F., Ding, X., Boven, A., 2004. ^{40}Ar/^{39}Ar dating of ignimbrite from Inner Mongolia, northeastern China, indicates a post-Middle Jurassic age for the overlying Daohugou Bed. Geophys. Res. Lett. 31. http://dx.doi.org/10.1029/2004GL020792.

Hu, D.Y., Hou, L.H., Zhang, L.J., Xu, X., 2009. A pre-Archaeopteryx troodontid theropod from China with long feathers on the metatarsus. Nature 461, 640–643.

Pan, Y.S., 2001. The confirmation of the Early Jurassic Yongdingzhuang Formation and the discovery of dinosaur body fossils in the Ningwu-Jingle Basin in Shanxi Province. Chin. Geol. 28, 36–37 (in Chinese).

Ishigaki, S., Matsumoto, Y., 2009. "Off-tracking"-like phenomenon observed in the turning sauropod trackway from the Upper Jurassic of Morocco. Memoir Fukui Prefectural Dinosaur Mus. 8, 1–10.

Kim, J.Y., Lockley, M.G., Kim, H.M., Lim, J.D., Kim, K.S., 2009. New dinosaur tracks from Korea, Ornithopodichnus *Masanensis ichnogen.* et *ichnosp.* nov. (Jindong Formation, Lower Cretaceous): implications for polarities in ornithopod foot morphology. Cretac. Res. 30, 1387–1397.

Kuang, H.W., Liu, Y.Q., Wu, Q.Z., Cheng, G.S., Xu, K.M., Liu, H., Peng, N., Xu, H., Chen, J., Wang, B.H., Xu, J.L., Wang, M.W., Zhang, P., 2013. Dinosaur track sites and palaeogeography of the late Early Cretaceous in Shuhe Rifting Zone of Shandong Province. J. Palaeogeogr. 15, 435–453 (in Chinese with English abstract).

Kuhn, O., 1958. Die Fährten der vorzeitichen Amphibien und Reptilien. Ver-lagshaus Meisenbach KG, Bamberg, pp. 64.

Kukihara, R., Lockley, M.G., 2012. Fossil footprints from the Dakota Group (Cretaceous) John Martin Reservoir, Bent County, Colorado: new insights into the paleoecology of the dinosaur freeway. Cretac. Res. 33, 165–182.

Leonardi, G., 1987. Glossary and Manual of Tetrapod Footprint Palaeoichnology. Publicacão do Departemento Nacional da Producão Mineral Brasil, Brasília (Brasil), pp. 75.

Li, D.Q., Azuma, Y., Fujita, M., Lee, Y.N., Arakawa, Y., 2006. A preliminary report on two new vertebrate track sites including dinosaurs from the Early Cretaceous Hekou Group, Gansu Province, China. J. Paleont. Soc. Korea 22, 29–49.

Li, J.L., Cheng, Z.W., 1995. A new Late Permian vertebrate fauna from Dashankou, Gansu, with comments on Permian and Triassic vertebrate assemblage zones of China. In: Sun, A.L., Wang, Y.Q. (Eds.), Sixth Symposium on Mesozoic Terrestrial Ecosystems and Biota, Short Papers. China Ocean Press, Beijing, pp. 33–37.

Li, J.J., Bai, Z.Q., Lockley, M.G., Zhou, B., Liu, J., Song, Y., 2010. Dinosaur tracks in Wulatezhongqi, Inner Mongolia. Acta Geol. Sin. 84, 723–742 (in Chinese with English abstract).

Li, K., Cai, K.J., 1997. Classification and evolution of *Mamenchisaurus*. J. Chengdu Univ. Technol. 24, 102–107 (in Chinese with English abstract).

Li, S.L., Yu, X.H., Tan, C.P., Stell, R., 2014a. Jurassic sedimentary evolution of southern Junggar Basin: implication for palaeoclimate changes in northern Xinjiang Uygur Autonomous Region, China. J. Palaeogeogr. 3, 145–161.

Li, R.H., Lockley, M.G., Matsukawa, M., Wang, K.B., Liu, M.W., 2011. An unusual theropod track assemblage from the Cretaceous of the Chucheng area, Shandong Province, China. Cretac. Res. 32, 422–432.

Li, Z.H., Dong, S.W., Qu, H.J., 2014b. Timing of the initiation of the Jurassic Yanshan movement on the North China Craton: evidence from sedimentary cycles, heavy minerals, geochemistry, and zircon U-Pb geochronology. Int. Geol. Rev. 56, 288–312.

Li, Z.H., Dong, S.W., Feng, S.B., Qu, H.J., 2015. Sedimentary response to Middle-Late Jurassic tectonic events in the ordos basin. Acta Geosci. Sin. 36, 22–30 (in Chinese with English abstract).

Liu, J., 2015. New discoveries from the *Sinokannemeyeria-Shansisuchus* Assemblage Zone: 1. Kannemeyeriiformes from Shanxi, China. Vertebr. PalAsiatica 53, 16–28.

Liu, J., Fernando, A., 2015. New discoveries from the *Sinokannemeyeria-Shansisuchus* Assemblage Zone: 2. A new species of *Nothogomphodon* (Therapsida: Therocephalia) from the Ermaying Formation of Shanxi, China. Vertebr. PalAsiatica 53, 123–132.

Liu, S.F., Su, S., Zhang, G.W., 2013. Early Mesozoic basin development in North China: indications of cratonic deformation. J. Asian Earth Sci. 62, 221–236.

Liu, Y.Q., Liu, Y.X., Ji, S.A., Yang, Z.Y., 2006. U-Pb zircon age for the Daohugou Biota at Ningcheng of Inner Mongolia and comments on related issues. Chin. Sci. Bull. 51, 2634–2644.

Liu, Y.Q., Kuang, H.W., Jiang, X.J., Peng, N., Xu, H., Sun, H.Y., 2012a. Timing of the earliest known feathered dinosaurs and transitional pterosaurs olderthan the Jehol Biota. Palaeogeogr. Palaeoclimatol. Palaeoecol. 323–325, 1–12.

Liu, Y.Q., Kuang, H.W., Peng, N., Xu, H., Chen, J., Xu, J.L., Liu, H., Zhang, P., 2012b. New discovery of dinosaur footprints in the UpperJurassic–Lower Cretaceous Houcheng Formation at Shangyi, northwestern Hebei Province and its biogeographical implications. J. Palaeogeogr. 14, 617–627 (in Chinese with English abstract).

Liu, Y.Q., Kuang, H.W., Peng, N., Xu, H., Zhang, P., Wang, N.S., An, W., 2015. Mesozoic basins and associated palaeogeographic evolution in North China. J. Palaeogeogr. 4, 189–202.
Lockley, M., Matsukawa, M., Ohira, H., Li, J.J., Wright, J., White, D., Chen, P.J., 2006a. Bird tracks from Liaoning Province, China: new insights into avian evolution during the Jurassic-Cretaceous transition. Cretac. Res. 27, 33–43.
Lockley, M.G., Farlow, J.O., Meyer, C.A., 1994. *Brontopodus* and *Parabrontopodus ichnogen*. nov. and the significance of wide- and narrow-gauge sauropod trackways. Gaia 10, 135–145.
Lockley, M.G., Wright, J., White, D., Matsukawa, M., Li, J.L., Feng, L., Li, H., 2002a. The first sauropod trackways from China. Cretac. Res. 23, 363–381.
Lockley, M.G., Houck, K.J., Prince, N.K., 1986. North America's largest dinosaur trackway site: implications for morrison formation paleoecology. Geol. Soc. Am. Bull. 97, 1163–1176.
Lockley, M., Schulp, A.S., Meyer, C.A., Leonardi, G., Mamani, D.K., 2002b. Titanosaurid trackways from the upper cretaceous of bolivia: evidence for large manus, wide-gauge locomotion and gregarious behaviour. Cretac. Res. 23, 383–400.
Lockley, M.G., Houck, K., Yang, S.Y., Matsukawa, M., Lim, S.K., 2006b. Dinosaur-dominated footprint assemblages from the Cretaceous Jindong Formation, Hallyo Haesang National Park area, Goseong County, South Korea: evidence and implications. Cretac. Res. 27, 70–101.
Lockley, M.G., 1990. Tracking the rise of dinosaurs in Eastern Utah. Canyon Legacy 2, 2–8.
Lockley, M.G., Matsukawa, M., 2009. A review of vertebrate track distributions in East and Southeast Asia. J. Paleont. Soc. Korea 25, 17–42.
Loeuff, J.L., Gourrat, C., Landry, P., Hautier, L., Liard, R., Souillat, C., Buffetaut, E., Enay, R., 2006. A Late Jurassic sauropod tracksite from southern Jura (France). C. R. Palevol. 5, 705–709.
Luo, Z.X., Meng, Q.J., Ji, Q., Liu, D., Zhang, Y.G., Neander, A.I., 2015. Mammalian evolution. evolutionary development in basal mammaliaforms as revealed by a docodontan. Science 347, 760–764.
Lü, J.C., Fucha, X.H., Chen, J.M., 2010. A new scaphognathine pterosaur from the Middle Jurassic of Western Liaoning, China. Acta Geosci. Sin. 31, 263–266.
Marty, D., Belvedere, M., Meyer, C.A., Mietto, P., Paratte, G., Lovis, C., Thüring, B., 2010. Comparative analysis of Late Jurassic sauropod trackways from the Jura Mountains (NW Switzerland) and the central High Atlas Mountains (Morocco): implications for sauropod ichnotaxonomy. Hist. Biol. 22, 109–133.
Marty, D., 2008. Sedimentology, taphonomy, and ichnology of Late Jurassic dinosaur tracks from the Jura carbonate platform (Chevenez—Combe Ronde tracksite, NW Switzerland): insights into the tidal–flat palaeoenvironment and dinosaur diversity, locomotion, and palaeoecology. GeoFocus 21, 1–275.
Marty, D., Hug, W.A., Iberg, A., Cavin, L., Meyer, C.A., Lockley, M.G., 2003. Preliminary report on the courtedoux dinosaur tracksite from the Kimmeridgian of Switzerland. Ichnos 10, 209–219.
Mateus, O., Milàn, J., 2010. A diverse Upper Jurassic dinosaur ichnofauna from central-west Portugal. Lethaia 43, 245–257.
Matsukawa, M., Hamuro, T., Mizukami, T., Fujii, S., 1997. First trackway evidence of gregarious dinosaurs from the Lower Cretaceous Tetori Group of eastern Toyama prefecture, central Japan. Cretac. Res. 18, 603–619.
Matsukawa, M., Lockley, M.G., Hunt, A.P., 1999. Three age groups of ornithopods inferred from footprints in the mid-Cretaceous Dakota Group, eastern Colorado, North America. Palaeogeogr. Palaeoclimatol. Palaeoecol. 147, 39–51.
Mazin, J.-M., Hantzpergue, P., Pouech, J., 2016. The dinosaur tracksite of Loulle (Early Kimmeridgian; Jura, France). Geobios. http://dx.doi.org/10.1016/j.geobios.2016.01.018.
Mclaurin, B.T., Steel, R.J., 2007. Architecture and origin of an amalgamated fluvial sheet sand, lower Castlegate Formation, Book Cliffs, Utah. Sed. Geol. 197, 291–311.
Meng, J., Hu, Y.M., Wang, Y.Q., Wang, X.L., Li, C.K., 2006. A Mesozoic gliding mammal from northeastern China. Nature 444, 889–893.
Meng, Q.J., Ji, Q., Zhang, Y.G., Liu, D., Grossnickle, D.M., Luo, Z.X., 2015. Mammalian evolution: an arboreal docodont from the Jurassic and mammaliaform ecological diversification. Science 347, 764–768.
Meyer, C.A., Pittmann, J.G., 1994. A comparison between the *Brontopodus* ichnofacies of Portugal, Switzerland and Texas. Gaia 10, 125–133.
Meyer, C.A., Lockley, M.G., Robinson, J.W., dos Santos, V.F., 1994. A comparison of well-preserved sauropod tracks from the Late Jurassic of Portugal and the western United States: evidence and implications. Gaia 10, 57–64.
Mezga, A., Bajraktarević, Z., 1999. Cenomanian dinosaur tracks on the islet of Fenoliga in southern Istria, Croatia. Cretac. Res. 20, 735–746.
Mezga, A., Tešović, B.C., Bajraktarevi, Z., 2007. First record of dinosaurs in the Late Jurassic of the Adriatic-Dinaridic carbonate platform (Croatia). Palaios 22, 188–199.
Miall, A.D., 1977. A review of the braided-river depositional environment. Earth Sci. Rev. 13, 1–62.
Moratalla, J.J., 2009. Sauropod tracks of the Cameros Basin (Spain): Identification, trackway patterns and changes over the Jurassic-Cretaceous. Geobios 42, 797–811.
Moreno, K., Benton, M.J., 2005. Occurrence of sauropod dinosaur tracks in the Upper Jurassic of Chile (redescription of *Iguanodonichnus frenki*). J. S. Am. Earth Sci. 20, 253–257.
Pang, Q.Q., Cheng, Z.W., 2001. The Late Cretaceous dinosaur fauna and strata from Tianzhen, Shanxi and Yangyuan, Hebei, China. In: Deng, T., Wang, Y.Q. (Eds.), Proceedings of the Eighth Annual Meeting of the Chinese Society of Vertebrate Paleontology. China Ocean Press, Beijing, pp. 75–82 (in Chinese).
Pang, Q.Q., Cheng, Z.W., 2000. A new sauropod dinosaur from the Late Cretaceous of Tianzhen, Shanxi Province, China. Acta Geol. Sin. 74, 1–9 (in Chinese with English abstract).
Pang, Q.Q., Cheng, Z.W., Yang, J.P., Xie, M.Z., Zhu, C.F., Luo, J.L., 1996. The preliminary report on Late Cretaceous dinosaur fauna expeditions in Tianzhen, Shanxi. J. Hebei College Geol. 19, 227–235 (in Chinese).
Peng, N., Liu, Y.Q., Kuang, H.W., Wu, Q.Z., Liu, H., Chen, J., Xu, H., Xu, J.L., Wang, M.W., Wang, B.H., Wang, K.B., Chen, S.Q., Zhang, Y.X., 2013. Difference in characteristics of dinosaur footprints in the late Early Cretaceous, Yishu Rifting Zone, Shandong Province. J. Palaeogeogr. 15, 517–528 (in Chinese with English abstract).
Pang, Q.Q., Cheng, Z.W., 1998. A new ankylosaur of Late Cretaceous from Tianzhen, Shanxi. Prog. Nat. Sci. 8, 326–334 (in Chinese) Washington DC, 345–359.
Retallack, G., 1997. Dinosaurs and dirt. In: Wolberg, D.L., Stump, E., Rosenberg, G.D. (Eds.), Dinofest International. The National Academy of Natural Sciences, Washington DC, pp. 345–359.
Romano, M., Whyte, M.A., 2003. Jurassic dinosaur tracks and trackways of the Cleveland Basin, Yorkshire: preservation, diversity and distribution. Proc.-Yorkshire Geol. Soc. 54, 185–215.
Romano, M., Whyte, M.A., Jackson, S.J., 2007. Trackway ratio: a new look at trackway gauge in the analysis of quadrupedal dinosaur trackways and its implications for ichnotaxonomy. Ichnos 14, 257–270.
Santos, V., Moratalla, J., Royo-Torres, R., 2009. New sauropod trackways from the Middle Jurassic of Portugal. Acta Palaeontol. Pol. 54, 409–422.
Santos, V., Moratalla, J., Royo-Torres, R., 2010. New sauropod trackways from the Middle Jurassic of Portugal. Acta Palaeontol. Pol. 54, 409–422.
Smith, G.H.S., Ashworth, P.J., Best, J.L., Woodward, J., Simpson, C.J., 2006. The sedimentology and alluvial architecture of the sandy braided South Saskatchewan River, Canada. Sedimentology 53, 413–434.
Sullivan, C., Hone, D.W.E., Cope, T.D., Liu, Y., Liu, J., 2009. A new occurrence of small theropod tracks in the Houcheng (Tuchengzi) Formation of Hebei Province, China. Vertebr. PalAsiatica 47, 35–52.
Sun, A.L., 1960. On a new genus of kannemeyerids from Ningwu, Shanxi. Paleovertebr. Paleoanthropol. 4, 67–80 (in Chinese).
Sun, A.L., 1980. Late Permian and Triassic terrestrial tetrapods of North China. Vertebr. PalAsiatica 18, 100–111 (in Chinese with English abstract).
Suteethorn, S., Loeuff, J.L., Buffetaut, E., Suteethorn, V., Wongko, K., 2012. First evidence of a mamenchisaurid dinosaur from the Upper Jurassic-Lower Cretaceous Phu Kradung Formation of Thailand. Acta Palaeontol. Pol. 58, 459–469.
Thulborn, T., 1990. Dinosaur Tracks. Chapman and Hall, London, pp. 410.
Upchurch, P., Barrett, P.M., Dodson, P., 2004. Sauropoda. In: Weishampel, D.B., Dodson, P., Osmólska, H. (Eds.), The Dinosauria, second ed. University of California Press, Berkeley, pp. 259–322.
Upchurch, P., Hunn, C.A., Norman, D.B., 2002. An analysis of dinosaurian biogeography: evidence for the existence of vicariance and dispersal patterns caused by geological events. Proc. R. Soc. Lond. B 269, 613–621.
Walker, R.G., Cant, D.J., 1984. Sandy fluvial systems. Facies Models 1, 71–89.
Wang, B.H., Liu, Y.Q., Kuang, H.W., Wang, K.B., Chen, S.Q., Zhang, Y.X., Peng, N., Xu, H., Chen, J., Liu, H., Xu, J.L., Wang, M.W., 2013. New discovery and its significance of dinosaur footprint fossils in the late Early Cretaceous at Tangdigezhuang village of Zhucheng County, Shandong Province. J. Palaeogeogr. 15, 454–466 (in Chinese with English abstract).
Xing, L.D., Lockley, M.G., Li, Z.D., Klein, H., Zhang, J.P., Gierliński, G.D., Ye, Y., Person Iv, W.S.P., Zhou, L., 2013a. Middle Jurassic theropod trackways from the Panxi region, southwest China and a consideration of their geologic age. Palaeoworld 22, 36–41.
Xing, L.D., Lockley, M.G., Miyashita, T., Klein, H., Wang, T., Person Iv, W.S.P., Pan, S.G., Zhang, J.P., Dong, Z.M., 2014a. Large sauropod and theropod tracks from the middle Jurassic Chuanjie formation of Lufeng County, Yunnan Province and palaeobiogeography of the Middle Jurassic sauropod tracks from southwestern China. Palaeoworld 23, 294–303.
Xing, L.D., Lockley, M.G., Klein, H., Falkingham, P.L., Kim, J.Y., Mccrea, R.T., Zhang, J.P., Person Iv, W.S.P., Wang, T., Wang, Z.Z., 2016a. First Early Jurassic small ornithischian tracks from Yunnan Province, southwestern China. Palaios 31, 516–524.
Xing, L.D., Lockley, M.G., Zhang, J.P., Klein, H., Kümmell, S.B., Person Iv, W.S.P., 2015a. Theropod tracks from the Lower Jurassic of Gulin area, Sichuan Province, China. Palaeoworld. http://dx.doi.org/10.1016/j.palwor.2015.11.003.
Xing, L.D., Lockley, M.G., You, H.L., Peng, G.Z., Tang, X., Ran, H., Wang, T., Peng, J., Person Iv, W.S.P., 2016b. Early Jurassic sauropod tracks from the Yimen Formation of Panxi region, Southwest China: ichnotaxonomy and potential trackmaker. Geol. Bull. Chin. 35, 851–855.
Xing, L.D., Lockley, M.G., Marty, D., Klein, H., Buckley, L.G., Mccrea, R.T., Zhang, J.P., Gierliński, G.D., Divay, J.D., Wu, Q.Z., 2013b. Diverse dinosaur ichnoassemblages from the Lower Cretaceous Dasheng Group in the Yishu fault zone, Shandong Province, China. Cretac. Res. 45, 114–134.
Xing, L.D., Li, D.Q., Harris, J.D., Bell, P.R., Azuma, Y., Fujita, M., Lee, Y.N., Currie, P.J., 2013c. A new deinonychosaurian track from the Lower Cretaceous Hekou Group, Gansu Province, China. Acta Palaeontol. Pol. 58, 723–730.
Xing, L.D., Niedźwiedzki, G., Lockley, M.G., Zhang, J.P., Cai, X.F., Person Iv, W.S.P., Ye, Y., 2014b. Asianopodus-type footprints from the Hekou group of Honggu district, Lanzhou city, Gansu, China and the "heel" of large theropod tracks. Palaeoworld 23, 304–313.
Xing, L.D., Lockley, M.G., Li, D.L., Klein, H., Ye, Y., Iv, W.S.P., Ran, H., 2016c. Late Cretaceous ornithopod-dominated, theropod, and pterosaur track assemblages from the Nanxiong Basin, China: New discoveries, ichnotaxonomy, and paleoecology. Palaeogeogr. Palaeoclimatol. Palaeoecol. http://dx.doi.org/10.1016/j.palaeo.2016.11.035.
Xing, L.D., Lockley, M.G., Zhang, J.P., Klein, H., Wang, T., Kümmell, S.B., Burns, M.E., 2016d. A theropod-sauropod track assemblage from the? Middle–Upper Jurassic Shedian Formation at Shuangbai, Yunnan Province, China, reflecting different sizes of trackmakers: review and new observations. Palaeoworld 25, 84–94.

Xing, L.D., Harris, J.D., Gierlínski, G.D., 2011a. Therangospodus and Mega-losauripus track assemblage from the Upper Jurassic-Lower Cretaceous Tuchengzi Formation of Chicheng County, Hebei Province, China and their paleoecological implications. Vertebr. PalAsiatica 49, 423–434.
Xing, L.D., Marty, D., Wang, K.B., Lockley, M.G., Chen, S.Q., Xu, X., Liu, Y.Q., Kuang, H.W., Zhang, J.P., Ran, H., Person Iv, W.S.P., 2015b. An unusual sauropod turning trackway from the Early Cretaceous of Shandong Province, China. Palaeogeogr. Palaeoclimatol. Palaeoecol. 437, 74–84.
Xing, L.D., Harris, J.D., Jia, C.K., 2010. Dinosaur tracks from the Lower Cretaceous Mengtuan Formation in Jiangsu, China and morphological diversity of local sauropod tracks. Acta Palaeontol. Sin. 49, 448–460.
Xing, L.D., Lockley, M.G., Zhang, J., Klein, H., Person Iv, W.S.P., Dai, H., 2014c. Diverse sauropod-, theropod-, and ornithopod-track assemblages and a new ichnotaxon *Siamopodus xui*, ichnosp. nov. from the Feitianshan Formation, Lower Cretaceous of Sichuan Province, southwest China. Palaeogeogr. Palaeoclimatol. Palaeoecol. 414, 79–97.
Xing, L.D., Lockley, M.G., Marty, D., Klein, H., Yang, G., Zhang, J.P., Peng, G.Z., Ye, Y., Person Iv, W.S.P., Yin, X.Y., Xu, T., 2016e. 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. Cretac. Res. 60, 176–193.
Xing, L.D., Lockley, M.G., Yang, G., Cao, J., Mccrea, R.T., Klein, H., Zhang, J.P., Person Iv, W.S.P., Dai, H., 2016f. A diversified vertebrate ichnite fauna from the Feitianshan Formation (Lower Cretaceous) of southwestern Sichuan, China. Cretac. Res. 57, 79–89.
Xing, L.D., 2010. Report on dinosaur trackways from Lower Jurassic Ziliujing Formation of Gulin area, Sichuan, China. Geol. Bull. Chin. 29, 1730–1732 (in Chinese).
Xing, L.D., Harris, J.D., Currie, P.J., 2011b. First record of dinosaur trackway from Tibet, China. Geol. Bull. Chin. 30, 173–178.
Xing, L.D., Miyashita, T., Zhang, J., Li, D., Ye, Y., Sekiya, T., Wang, F.P., Currie, P.J., 2015c. A new sauropod dinosaur from the Late Jurassic of China and the diversity, distribution, and relationships of Mamenchisaurids. J. Vertebr. Paleontol. 35, e889701.
Xing, L.D., Lockley, M.G., Marty, D., Piñuela, L., Klein, H., Zhang, J.P., Persons, W.S.I.V., 2015d. Re-description of the partially collapsed Early Cretaceous Zhaojue dinosaur tracksite (Sichuan Province, China) by using previously registered video coverage. Cretac. Res. 52, 138–152.
Xu, H., Liu, Y.Q., Kuang, H.W., Wang, K.B., Chen, S.Q., Zhang, Y.X., Peng, N., Chen, J., Wang, M.W., Wang, B.H., 2013a. Middle Early Cretaceous super-large scale dinosaur tracks in Zhucheng area, Shandong Province, and their palaeogeography and palaeoecology. J. Palaeogeogr. 15, 467–488 (in Chinese with English abstract).
Xu, H., Liu, Y.Q., Kuang, H.W., Liu, Y.X., Peng, N., 2016a. Jurassic-Cretaceous terrestrial transition red beds in northern North China and their implication on regional paleogeography, paleoecology, and tectonic evolution. Palaeoworld. http://dx.doi.org/10.1016/j.palwor.2016.05.007.
Xu, H., Liu, Y.Q., Kuang, H.W., Jiang, X.J., Peng, N., 2012. U-Pb SHRIMP age for the Tuchengzi Formation, northern China, and its implications for biotic evolution during the Jurassic-Cretaceous transition. Palaeoworld 21, 222–234.
Xu, S.C., You, H.L., Wang, J.W., Wang, S.Z., Yi, J., Jia, L., 2016b. A new hadrosauroid dinosaur from the Late Cretaceous of Tianzhen, Shanxi Province, China. Vertebr. PalAsiatica 54, 67–78.
Yang, J.H., Wu, F.Y., Shao, J.A., Wilde, S.A., Xie, L.W., Liu, X.M., 2006. Constraints on the timing of uplift of the Yanshan Fold and Thrust Belt, North China. Earth Planet. Sci. Lett. 246, 336–352.
Young, C.C., 1957. The significance of the Lower Triassic reptilian fauna from Wuhsiang of Shansi. Sci. Rec. 1, 71–76.
Young, C.C., 1966. Two footprints from the Jiaoping coal mine of Tungchuan, Shensi. Vertebr. PalAsiatica 10, 68–71.
Zhang, H., Jin, X.L., Li, G.H., Yang, Z.Y., Zhang, H., Jia, J.C., 2008. Original features and palaeogeographic evolution during the Jurassic-Cretaceous in the Ordos Basin. J. Palaeogeogr. 10, 1–11 (in Chinese with English abstract).
Zhang, J.F., 2002. Discovery of Daohugou Biota (pre-Jehol Biota) with a discussion on its geological age. J. Stratigr. 26, 173–177 (in Chinese with English abstract).
Zhang, J.P., Xing, L.D., Gierlínski, G.D., Wu, F.D., Tian, M.Z., Currie, P., 2012. First record of dinosaur tracks in Beijing, China. Chin. Sci. Bull. 57, 144–152.
Zhang, J.P., Li, D.Q., Li, M.L., Lockley, M.G., Bai, Z., 2006. Diverse dinosaur-, pterosaur-, and bird-track assemblages from the Hakou Formation, Lower Cretaceous of Gansu Province, northwest China. Cretac. Res. 27, 44–55.
Zhang, Y.Z., Zhang, J.P., Wu, P., Zhang, X.B., Bai, S., 2004. Discovery of dinosaur track fossils from the Middle-Late Jurassic Tuchengzi Formation in the Chaoyang area, Liaoning Province. Geol. Rev. 50, 561–566 (in Chinese with English abstract).
Zhao, J.F., Liu, C.Y., Liang, J.W., Wang, X.M., Yu, L., Huang, L., Liu, Y.T., 2010. Restoration of the original sedimentary boundary of the Middle Jurassic Zhiluo Formation-Anding Formation in the Ordos Basin. Acta Geol. Sin. 84, 553–569 (in Chinese with English abstract).
Zhao, X.J., Cheng, Z.W., Xu, X., Makovicky, P.J., 2006. A new ceratopsian from the Upper Jurassic Houcheng Formation of Hebei, China. Acta Geol. Sin. 80, 467–473.