Geoscience Frontiers 12 (2021) 737–745

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Contents lists available at ScienceDirect

Geoscience Frontiers

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

Research Paper

Unusual dinosaur trackway preservation as clues to paleo-landscape and behavior from the Lower Cretaceous Luohe Formation, Shaanxi Province, China

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ARTICLE INFO

Article history:
Received 4 April 2020
Received in revised form 30 June 2020
Accepted 18 September 2020
Available online 14 October 2020

Handling Editor: X.Q. Wan

Keywords:
Theropod tracks
Ornithischian tracks
Deinonychosaurian
Dunes sediments

ABSTRACT

Poorly preserved tracks have limited ichnotaxonomic or biotaxon utility, but may reveal useful information about the paleoenvironment, behavior and track taphonomy. Eight mostly parallel to sub parallel trackway segments (T1–T8) were registered on a truncation surface in the Lower Cretaceous Luohe Formation of Shaanxi Province. These attest to the passage of several bipeds, probably all theropods, in a paleo-contour-parallel, south-north direction in an arid setting. Quality of preservation in these trackways is poor, but notably superior in two additional trackways (T9–T10) on a foreset surface. Trackway T9 indicates a didactyl trackmaker, probably a deinonychosaurian, heading north to south. This is the 13th report of deinonychosaurian tracks from the Lower Cretaceous of China. If any or all the eight south-north oriented trackway segments represent continuations of other segments in the same trackways, the total number of individual trackmakers heading in this direction may have been as low as three. Although the trackway pattern and sedimentological evidence could indicate a physically controlled pathway influencing the direction taken by these trackmakers, the possibility that the trackways also represented small social or gregarious group cannot be ruled out.

1. Introduction

Ordos Basin is a landlocked depression basin, located on the western margin of the North China Platform, crossing Shaanxi, Gansu, Ningxia, Inner Mongolia and Shanxi Provinces. With an area of roughly 300,000 km^2, and a stratigraphic thickness of 4000–6000 m, it is the second largest basin in China. The Ordos Basin is famous for its abundant coal, oil and gas resources, primarily concentrated in the Carboniferous–Jurassic strata (Yao et al., 1999).

An important vertebrate fossil assemblage, known as the *Psittacosaurus* Fauna, occurs in the Lower Cretaceous Jingchuan and Luohandong formations of the Ordos Basin (Russell and Zhao, 1996). Xing et al. (2018) listed the components of the *Psittacosaurus* Fauna, which includes chelonians, choristoderes, crocodyliformes, pterosaurs, cerapodans, stegosaurs, ankylosaurs, sauropods, non-avian theropods, avians and primitive mammals. However, known vertebrate material from the *Psittacosaurus* Fauna of the Ordos Basin is rarely articulated or complete. Trace fossils are abundant and play an important role in our understanding of the fauna. There are currently at least 17 significant tracksites documented from the Jingchuan and Luohandong formations with over 1000 tracks reported. Among these are non-avian theropod tracks identified as *Chapus*, *Asianopodus*, and *Ordexallopus*, the avian ichnogenus *Tatarornipes* and the sauropod ichnogenus *Brontopodus* (Lockley et al., 2002; Li et al., 2009, 2011; Lockley et al., 2011; Lockley et al., 2014a, 2018). In addition, the non-avian theropod track *Jialingpus*, has been reported from the Lower Cretaceous Luohe Formation in Xunyi County at the southern margin of the Ordos Basin (Xing et al., 2014a; Xing et al., 2014b). The ichnofaunas are heavily saurischian dominated with a notable absence of evidence for ornithischians.

In 2017, the Shaanxi Institute of Geological Survey, conducted a detailed investigation of the Danxia Landform, in Longzhou, Shaanxi Province. One site of landform traces was found 120 km northeast of Zhongji Town, Shenmu City, at the northeastern margin of the Ordos Basin, and five tetrapod tracksites were found in Cretaceous purple–red soft

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https://doi.org/10.1016/j.gsf.2020.09.014
1674-9871/

sandstone (commonly referred to as “arsenic sandstone”, in China) (Tang et al., 2020). The tracks included the mammaliomorph *Brasilichnium* isp., the deinonychosaurian *Sarmientichnus* isp., and tridactyl theropod tracks of uncertain taxonomy (Xing et al., 2018). This assemblage represents the first Asian example of an ichnofauna typical of the *Chelichnus* Ichnofacies (*Brasilichnium* sub-ichnofacies) of desert habitats (Xing et al., 2018). This Chinese Cretaceous desert ichnofauna is consistent with global ichnofacies predictions (Xing et al., 2018).

In June–Sep 2019, the same team discovered dinosaur tracks at the Baituping site (GPS: 37°29′56.61”N, 109°1′37.52″E), in Longzhou Town, Yulin City, Shaanxi Province (Fig. 1). These tracks are poorly preserved, but record a special preservation pattern that is distinct from that of the Cretaceous dinosaur tracks of Zhongji Town.

Abbreviations: BTP = Baituping site, Longzhou Town, Jingbian County, Yulin City, Shaanxi Province, China.

2. Geological setting

As a relatively stable block, the Jingbian region is located in the south-central part of the Ordos Basin. The strata of the Jingbian area are well developed with an average sedimentary thickness of 5000 m. The Mesozoic strata (Triassic–Cretaceous) are composed of inland lake, swamp and fluvial facies, with a total thickness of 2500–3000 m. During the Jurassic–Cretaceous the Yanshan Movement (Orogeny), the Yinchuan, Hetao, Fenwei and other small fault basins were formed along the border of the Ordos Basin. The Cretaceous strata are dominated by sediments of desert facies. Desert–alluvial fan deposits are exposed along the Ordos–Yulin line, which is a north–south alignment of the Ordos–Yulin fault (Tang et al., 2020).

The Luohe Formation of the Cretaceous Zhidan Group is a series of purple–red and grayish purple–red, coarse to medium–fine grained, arkose, quartz sandstone and lithic feldspathic quartz sandstone, partly sandstone mixed with mudstone. The Luohe Formation generally exhibits a succession of eolian desert deposition, partly with fore-dune depression deposition (Xie et al., 2005).

The Lower Cretaceous Luohe Formation mainly consists of three lithologic members: the lower member is a dark purple–red and purple–gray massive mudstone with dark purple micro-thin bedded argillaceous siltstone, and gray–yellow thick-bedded “conglomeratic” sandstone with horizontal bedding and low-angle oblique bedding developed. The middle member consists of purple–red thin-bedded quartz–fine sandstone and fine–medium grained feldspathic quartz sandstone, generally with large tabular oblique bedding, cross-bedding and parallel bedding, partly with shallow water ripple marks, rain prints, hail marks, scolites and crawling traces on exposed bedding surfaces. The upper member consists of purple–red and gray–yellow massive mudstone, silty mudstone and thin-bedded argillaceous siltstone, with parallel bedding and low-angle oblique bedding developed. The Luohe Formation in the Jingbian area is generally 71–348 m thick (Tang et al., 2020). Only a less than 200 m thick portion of the upper member of the Luohe Formation is exposed in our study area (Tang et al., 2020).

Large-scale tabular cross-bedding and medium–large scale trough cross-bedding are developed in the sandstone of the Luohe Formation. The layers of tabular cross-bedding are generally 1.5–16 m thick, with in some cases extending up to 38 m (Tang et al., 2020). According to the lithological features, large-scale cross bedding, the Luohe formation mainly exhibits a set of dune subfacies formed in a desert environment, and interdune subfacies that formed in semi-arid climate (Qi et al., 1993; Xie et al., 2005). The desert depocenter in this area is located in Zhidan and Wuqi areas, of Shaanxi province, with a sedimentary thickness of 200–380 m. In this section, multiple dunes are superimposed, cross-bedding and tabular bedding are extremely developed, and the strata are loose, porous, and dominated by quartzose arkose.

The dinosaur tracks at the Baituping site, were recognized on the surface of the purple–red thin-bedded medium-grained feldspathic quartz sandstone. There are three granulometric characters of the section: (1) grain size fines from the base to the top; (2) the single-layer sandstone changes upwards from thick (10–20 cm) to thin (5–8 cm) as do the layer series (1.10 m thick to 0.20 m thin); and (3) fine-grained sediments or argillaceous sediments increase relatively between the dunes. The bedding types vary from large and medium-sized cross bedding to small-scale cross bedding and horizontal bedding, which result from small changes in wind direction in a field of small to and medium eolian dunes. The desert lake deposits of the upper section reflect the features of a shallow lake paleoenvironment, and are dominated by argillaceous sediments and silts with fine particle size and light color. The single-layer sandstone deposits are thin, with horizontal bedding, wavy cross-stratification and mud cracks (Tang et al., 2020).

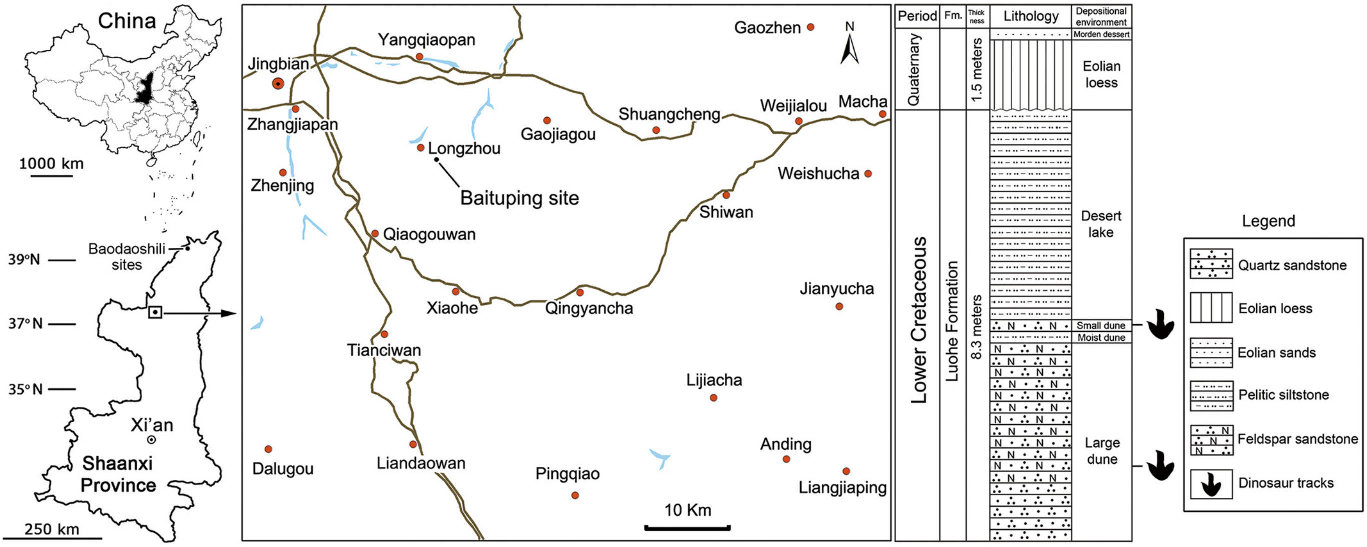

Fig. 1. Geographical setting showing the location of the Baituping and Baodaoshili sites in northernmost Shaanxi Province, China, and lithostratigraphic section showing sediment characteristics and position of track-bearing levels at the Baituping Site.

Overall, at the Baituping site, it can be inferred that the dinosaur tracks were formed in zones in or between low sand dunes and a shallow-water desert lake in a warm dry climate. In this area, small dunes, wet dunes and shallow-water desert lakes inter-fingered as continuous aeolation and short-term fluviation in rainy seasons occurred (Tang et al., 2020).

3. Materials and methods

Dinosaur tracks were found near the shore of the Huiqiao reservoir in Baituping, Longzhou Town, Yulin, Jingbian city, Shaanxi province. Within the red Danxia landscape region in an exposure of about 2000 m^2, 10 dinosaur trackways were found. These trackways are exposed on the steep eroded surface of a monolithic outcrop (Figs. 2 and 3) consisting of purplish–red thin-bedded medium-grained feldspathite quartz sandstone, capped unconformably by Quaternary loess. All the trackways are preserved as concave epireliefs. Only two (T9 and T10) show recognizable digit traces, while the others consist of oval concavities only.

A drone was used to obtain information on the distribution of the tracks and tracksites (Fig. 2A). The whole exposed surface was photographically recorded using a remote controlled four-axis quadcopter (DJI Inspire 1: weight: 3400 g; max. Service ceiling above sea level: 4500 m; max. Flight time: 15 min; max. Wind speed resistance: 10 m/s and with DJI GO App, iOS 8.0 or later) with a 12 M-pixel camera (model X5, with a 15 mm lens). After taking off from the ground, the DJI Inspire 1 was controlled remotely, using real-time HD video through a mobile APP (DJI GO version 3.1.23). Outline drawings of the trackways were made from drone images (Fig. 4).

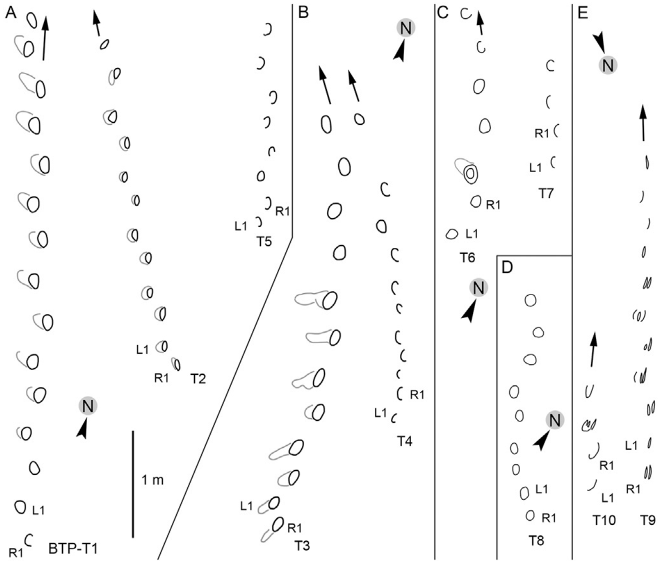

Fig. 3. Interpretive outline drawings of ten trackways from the Baituping site. The position of trackway groupings T1, T2, and T5, T3 and T4, T6 and T7, T8 and T9 and T10 are shown in Fig. 2A. 1 m scale for all trackway sketches.

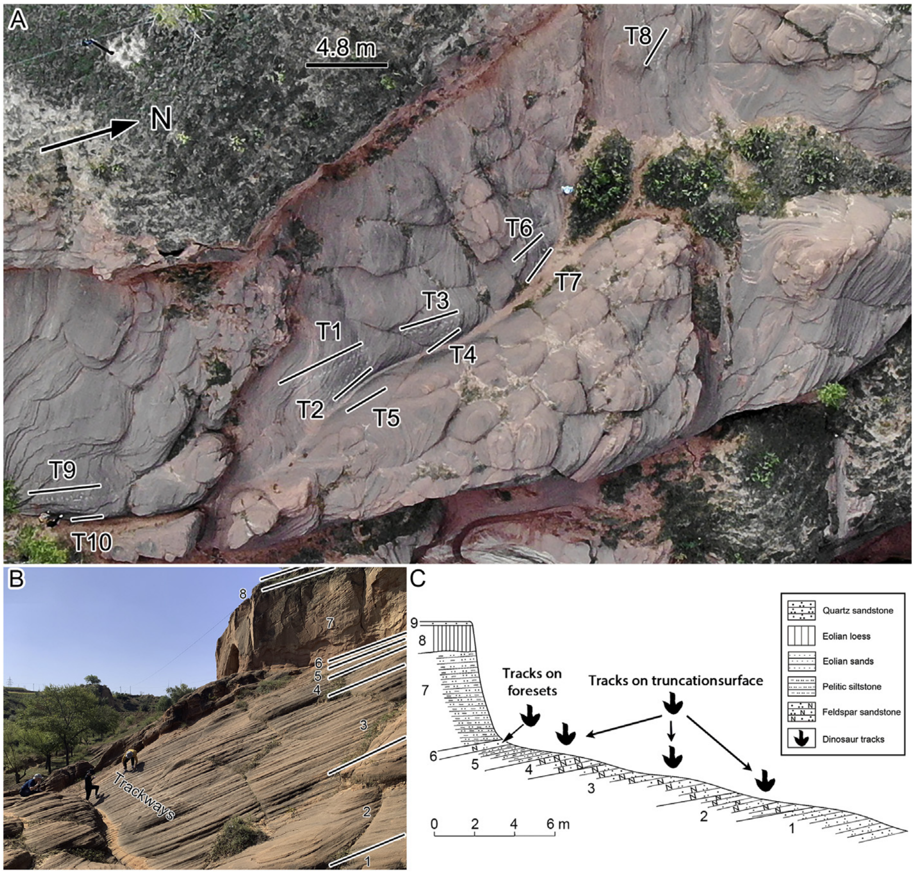

Fig. 2. (A) Aerial drone photograph of Baituping site with solid lines indicating ten trackways registered on large dune sets. (B) Stratigraphic section showing position of track-bearing levels from the Baituping Site. (C) Detailed correlation between local Baituping outcrop and measured section. Note that trackways T9 and T10 occur on a foreset surface in unit 6. Compare with Fig. 6.

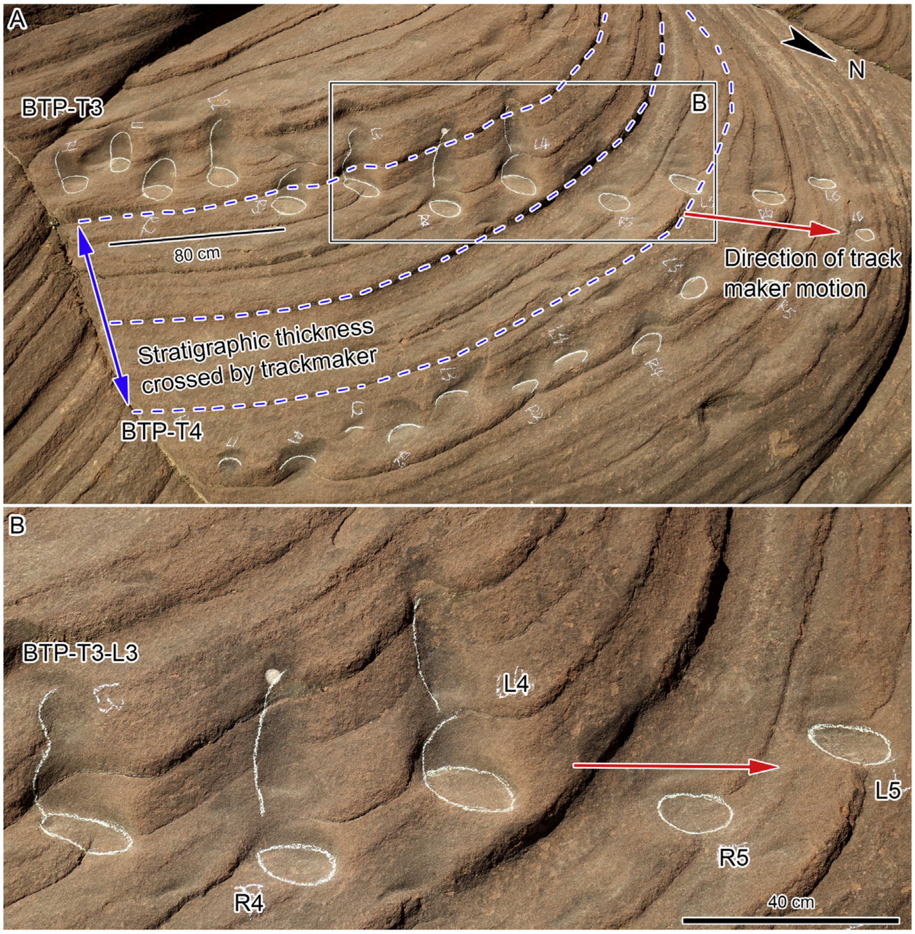

Fig. 4. Photographs of BTP-T3 and T4 trackways from the Baituping site. (A) trackway alignments showing progression of the trackways across a considerable stratigraphic thickness (~1.0 m) of foresets. (B) Detail of trackway 3 showing track bounding or wall features on upslope site of tracks. See text for details.

Based on the standard procedures introduced by Leonardi (1987) and Lockley and Hunt (1995), maximum length (ML), maximum width (MW), and pace length (PL), were determined. The rotation of tracks (R) was measured according to the standard procedures of Lockley and Hunt (1995) and Marty (2008).

Hip heights and speed estimations of inferred theropod and ornithopod trackmakers were derived from the trackways following the methods of Alexander (1976) and Thulborn (1990).

Lockley (1991) and Lockley et al. (1994) classified formations and facies according to the relative abundance (proportions) of traces (tracks) and body fossils. They defined Type 1 deposits as containing only tracks, Type 2 as track dominated, Type 3 as having tracks and bones in more or less equal abundance, Type 4 as bone-dominated, and Type 5 as containing only bones. Deposits of Types 2, 3 and 4 may be divided into subcategory "a" where the track and bone evidence is consistent with regard to faunal elements or subcategory "b" where the evidence is inconsistent.

4. Ichnology

4.1. Trackways of small bipeds

4.1.1. Description

The Baituping trackways are designated: BTP-T1–T8 and contain 15, 12, 12, 11, 8, 7, 4 and 9 tracks respectively. All tracks remain in situ but are poorly-preserved, as oval impressions. However, in many cases the outline of the flat floor of the track is clearly recognizable and with a low amplitude sandstone rim also visible (e.g., BTP-T3-R5). The steep walls of the tracks are also visible on the upslope side of the outcrop. Based on the asymmetrical oval shape with the posterior heel trace narrower than the anterior region, most indicate a direction of travel from south to north (T1, T2, T3 and T4), and two (T6 ad T8) are oriented somewhat more from southwest to northeast. The orientation of trackway registration for T5 and T7 is uncertain, although probably to the north and northeast respectively in the same direction as the other six in the T1–T8 series. The track lengths vary from an average length of 11.3 cm in BTP-T7 to 14.5 cm in BTP-T1. Based on the size and direction of the trackways, BTP-T1 and BTP-T3 may represent the same type of trackmaker.

BTP-T3 (Figs. 3B and 4) is the most representative and characterizes the typical pattern and track shape from this surface. Most tracks in the BTP-T3 trackway are oval impressions with no distinct digital traces, and the tracks are 13.9 cm long on average, with an average length/width ratio of 1.6. The pace angulation is 143° and pace lengths are regular (mean = 32.5 cm). In all trackways, both left and right pes tracks are slightly rotated to the axis of the trackway. Mean track rotations are relatively small with an angle of ~15°. A total of 8 footprints, BTP-T3-R1–L4, were preserved with vertical bounding marks, apparently in the position of the track wall (Figs. 3 and 4). These are 13.0, 12.7, 13.7, 26.4, 28.2, 33.1, 36.5 and 39.8 cm high respectively. The width of the marks is roughly the same as the length of the footprint.

The other seven trackways, BTP-T1–T2 and BTP-T4–T8, are similar to BTP-T3, and most of the tracks in BTP-T1 and T2 have vertical bounding traces. BTP-T1, T2 and T5 are three adjacent, sub-parallel trackways, which vary in separation distance from the beginning to the end of each trackway. From south to north the distance between BTP-T1 and

T2 decreases from 120 cm to 52 cm, while the distance between BTP-T2 and T5 increases from 101 cm to 134 cm. The distances between BTP-T3 and T4 decreases from 65 cm to 19 cm. The distances between BTP-T6 and T7 decreases from 65 cm to 55 cm. However, none of the trackway segments cross, see Figs. 2 and 3.

4.2. Probable deinonychosaurian tracks

4.2.1. Description

The Baituping BTP-T9 and BTP-10 trackways contain 11 and 4 tracks respectively, registered parallel on the surface of a foreset with separation distances of 42–44 cm. Both indicate a direction of travel along the present strike from north to south, opposite most of the T1–T8 directions. The orientation is inferred to be parallel to the paleo-contour (i.e., paleo-strike). All tracks remain in situ. All tracks are poorly-preserved, however, they are better preserved than tracks in trackways T1–T8. The trackways described here as T1–T8 are very poorly preserved and would fall between 0 and < 1.0 on the four-point (0—1—2—3) scale of Belvedere and Farlow (2016) (see Marchetti et al., 2019 for further refinement). Trackway T9 would rank a little higher on that scale: i.e., at least 1.0.

BTP-T9 is the best-preserved trackway. Most tracks of BTP-T9 have didactyl impressions, but some tracks consist of only one recognizable digit trace. Some tracks show a faint rim. The tracks are 13.5 cm long on average, with an average length/width ratio of 2.2. The pace angulation is 172°. In all tracks, both left and right pes tracks are slightly inwardly rotated towards the trackway axis. Each of the two digits are roughly parallel, and we tentatively assume that the longest trace is axial digit III, which is the universal pattern for theropods. However, determining which digits are represented in such variable tracks within this trackway is difficult. BTP-T10 contains only four poorly-preserved tracks, and the features are comparable with BTP-T9.

5. Discussion

The Baituping trackways are unusual for a number of reasons. They are an example of poorly preserved individual tracks and trackways that nevertheless, both individually and collectively provide very useful information on organism-substrate relationships and sedimentation-erosion in the paleoenvironment.

The most striking features are: (1) two trackways occur on foresets and eight cut across a series of truncation surface bedding planes from higher to lower stratigraphic levels; (2) the tracks registered on the foresets are shallower and better preserved than most of those registered on the truncation surface; (3) eight trackways mostly show similar trends from south to north and may in many cases represent shorter segments of longer trackways; (4) where track depth is visible, it can be inferred that some of the tracks were very deep. Before analyzing the "big picture" provided by the trackway assemblage as a whole, we first discuss features of the individual tracks and trackways.

The Baituping BTP-T1–T8 trackways provide very limited information on trackmaker foot morphology. Various important morphological details, such as distinct digit traces are mostly missing, but we infer trackway direction by the narrower end to be the heel impression. However, based on size of the tracks and length (L) width (W) ratios, the small size (pes traces<15 cm long), absence of manus and tail traces, and bipedal gait of the elongate (L > W) tracks suggest small-sized theropod tracks (cf. *Grallator*), which is a universally common morphotype, also common in the Lower Cretaceous of China (Xing et al., 2016). However, tracks of a bipedal ornithopod (cf. *Anomoepus*) cannot be ruled out, in cases of poor preservation. However, the lack of known anomoepid examples throughout this facies, region and epoch / series is also a factor in inferring the likelihood of the trackmaker identity.

Pace angulation could potentially be helpful, although as noted below it can vary according to substrate conditions. *Grallator* generally has more narrow trackways (pace angulation close to 180°) (Olsen et al., 1998). Ornithischian (?ornithopod) trackways like *Anomoepus* may have lower pace angulations if steps are short (about 141°, based on Olsen and Rainforth, 2003: Fig. 19.5) and on average have comparatively short stride lengths (61 cm on average), given a mean footprint length of 12.8 cm (Olsen and Rainforth, 2003). Tracks of BTP-T3 also have short stride lengths (61.9 cm on average), compared with a footprint length of 13.9 cm, and a pace angulation of 143°. These traits make BTP-T3 appear to have the gait characteristics of some *Anomoepus* trackways, but this inference is very tentative for reasons noted above. Moreover, the L/W ratios of the tracks in the seven measured trackways is quite high (1.57, range 1.3–2.0) and consistent with the elongate grallatorid morphotype (Table 1).

As the BTP-T1–T8 trackways are all similar in morphology there is no basis for inferring that the trackmakers could have been different. This inference of similarity is supported by the fact that at least six if not all eight of the trackways are oriented in similar directions with the aforementioned parallel to subparallel groupings (T1, T2, T5; T3 and T4; T6 and T7) mapped in groups (Figs. 2–4) according to their locations on different cross set bundles. This similarity in orientation could perhaps suggest that the trackmakers exhibited gregarious behavior. Alternatively, this could indicate a shared "physically controlled pathway" constrained by the local topography, which caused each individual dinosaur to independently choose a pathway with a similar direction (Ostrom, 1972), in this case more or less contour parallel across a truncation surface. It is also possible that both interpretations combine to suggest a group following a determined pathway. Another point is the distribution of the trackways across the present day outcrops that suggest that groups defined here as T1, T2 and T5 to the south, T3 and T4 further north and T6 and T7 further north again could represent segments of the same trackways, one of them even having a continuation in the northermost sequence (T8).

In contrast trackways 9 and 10 at the most southerly track-bearing outcrop, are interpreted as being oriented in the opposite direction (north to south). However, as noted above tracks T9 and T10 occur on a foreset surface. Nevertheless, it is noteworthy that all the trackways represent a broadly linear (bimodal) north-south or south north trend with sedimentological indicators suggesting all trackways were registered as nearly horizontal pathways on inclined surfaces. This interpretation is consistent with the inference made above that the northward oriented trackway segments T1–T8 may collectively represent as few as three trackways, spanning a distance of ~31 m.

The BTP-T1–T8 trackways exhibit similar but unusual patterns of preservation, being registered on different stratigraphic levels within the cross bedded sets. There are different possible explanations for this phenomenon.

(1) Each trackway was made on a single bedding surface, where the feet sank to different depths (Fig. 5 A1); however, in a small trackmaker with a foot length of 10–15 cm and a calculated hip height (h) of ~40–60 cm, this difference would probably be less; increased depth of tracks beyond a certain point (e.g. ~50%–100% of trackmaker leg length) would be physically impossible, while retaining a regular step and stride and would otherwise likely register other body parts (e.g. belly, tail) (Fig. 5 A2).

(2) If erosion had cut through a sequence of layers, trackmakers could have traversed the slope made by the erosive incision of the layers (truncation surface) and thereby have left imprints on multiple levels, spanning a stratigraphic sequence much greater than could be penetrated by walking on a single bedding plane (Fig. 5 B1 and B2).

Trackway BYP-T3 is nevertheless instructive regarding local track depth. It contains a series of eight tracks (BTP-T3-R1–L4) with traces of the vertical wall which one would normally infer to have been created while the tracks were registered. This suggests they penetrated the substrate quite deeply, and is a puzzling inference. In the case of

Table 1
Measurements (in cm and °) of the dinosaur trackways from Baituping tracksite, Shaanxi Province, China.

Number	ML	MW	ML/MW	PL	SL	PA
BTP-T1-R1	14.0	–	–	41.0	74.0	139
BTP-T1-L1	16.5	7.5	2.2	38.0	73.0	157
BTP-T1-R2	14.0	9.0	1.6	36.5	68.5	142
BTP-T1-L2	13.0	8.5	1.5	36.0	66.0	149
BTP-T1-R3	14.5	10.0	1.5	32.5	65.5	146
BTP-T1-L3	13.5	9.5	1.4	36.0	72.0	138
BTP-T1-R4	17.0	9.0	1.9	41.0	74.0	143
BTP-T1-L4	13.5	9.5	1.4	37.0	72.0	167
BTP-T1-R5	15.0	9.0	1.7	35.5	63.0	124
BTP-T1-L5	13.5	9.5	1.4	36.0	66.0	137
BTP-T1-R6	14.0	9.0	1.6	35.0	58.0	120
BTP-T1-L6	14.0	10.0	1.4	32.0	64.0	136
BTP-T1-R7	15.5	8.5	1.8	37.0	61.0	139
BTP-T1-L7	15.0	9.5	1.6	28.0	–	–
BTP-T1-R8	14.0	8.5	1.6	–	–	–
Mean	14.5	9.1	1.6	35.8	67.5	141
BTP-T2-R1	11.0	8.0	1.4	30.0	58.0	130
BTP-T2-L1	10.5	5.5	1.9	34.0	60.5	142
BTP-T2-R2	13.0	6.5	2.0	30.0	60.0	133
BTP-T2-L2	10.5	6.0	1.8	35.5	61.0	123
BTP-T2-R3	12.5	5.5	2.3	34.0	60.5	123
BTP-T2-L3	12.5	6.5	1.9	35.0	58.0	138
BTP-T2-R4	10.5	5.0	2.1	27.0	55.5	140
BTP-T2-L4	10.0	5.0	2.0	32.0	56.0	121
BTP-T2-R5	11.5	5.0	2.3	32.5	64.0	118
BTP-T2-L5	12.5	8.5	1.5	42.0	66.0	132
BTP-T2-R6	10.0	6.0	1.7	30.0	–	–
BTP-T2-L6	12.0	4.5	2.7	–	–	–
Mean	11.4	6.0	2.0	32.9	60.0	130
BTP-T3-R1	13.0	9.0	1.4	23.0	43.0	127
BTP-T3-L1	11.0	8.5	1.3	25.0	53.0	149
BTP-T3-R2	14.0	8.5	1.6	30.0	62.0	145
BTP-T3-L2	15.0	9.5	1.6	35.0	62.0	140
BTP-T3-R3	14.0	9.5	1.5	31.0	65.0	152
BTP-T3-L3	16.0	6.5	2.5	36.0	64.0	140
BTP-T3-R4	13.0	8.0	1.6	32.0	68.0	141
BTP-T3-L4	15.0	9.5	1.6	40.0	70.0	153
BTP-T3-R5	13.0	9.0	1.4	32.0	65.0	146
BTP-T3-L5	14.0	10.0	1.4	36.0	67.0	133
BTP-T3-R6	14.5	9.5	1.5	37.0	–	–
Mean	13.9	8.9	1.6	32.5	61.9	143
BTP-T4-L1	10.5	–	–	28.5	50.5	152
BTP-T4-R1	13.0	–	–	23.5	40.5	144
BTP-T4-L2	7.0	–	–	19.0	38.0	144
BTP-T4-R2	12.0	–	–	21.0	48.0	151
BTP-T4-L3	13.0	–	–	28.5	47.0	147
BTP-T4-R3	–	5.0	–	20.5	49.0	151
BTP-T4-L4	13.0	–	–	30.0	56.0	133
BTP-T4-R4	13.0	–	–	31.0	56.0	125
BTP-T4-L5	12.0	8.0	1.5	32.0	–	–
BTP-T4-R5	12.0	–	–	–	–	–
Mean	11.7	6.5	1.5	26.0	48.1	143
BTP-T5-L1	10.0	11.0	0.9	40.0	62.0	141
BTP-T5-R1	11.0	9.0	1.2	25.5	66.0	155
BTP-T5-L2	9.0	6.0	1.5	42.0	75.0	148
BTP-T5-R2	12.5	10.0	1.3	36.0	69.0	161
BTP-T5-L3	14.0	9.0	1.6	34.0	63.0	140
BTP-T5-R4	12.5	–	–	33.0	–	–
BTP-T5-L4	11.5	–	–	–	–	–
Mean	11.5	9.0	1.3	35.1	67.0	149
BTP-T6-L1	12.0	–	–	33.0	62.0	140
BTP-T6-R1	13.0	–	–	33.0	66.0	146
BTP-T6-L2	12.5	–	–	36.0	–	–
BTP-T6-R3	11.0	–	–	–	–	–
Mean	12.1	–	–	34.0	64.0	143
BTP-T7-L1	10.5	–	–	24.0	49.0	148
BTP-T7-R1	13.0	–	–	27.0	53.0	149
BTP-T7-L2	10.0	7.0	1.4	28.0	54.0	137
BTP-T7-R2	–	6.5	–	30.0	53.5	149
BTP-T7-L3	11.0	6.0	1.8	25.5	57.0	135
BTP-T7-R3	11.5	8.0	1.4	36.0	65.0	141
BTP-T7-L4	11.5	–	–	33.0	–	–
BTP-T7-R4	11.5	–	–	–	–	–
Mean	11.3	6.9	1.6	29.1	55.3	143
BTP-T8-L1	12.0	8.0	1.5	29.0	58.5	165
BTP-T8-R1	15.0	9.0	1.7	30.0	54.0	164
BTP-T8-L2	12.0	7.5	1.6	24.5	57.5	150
BTP-T8-R2	12.5	7.0	1.8	35.0	59.0	144
BTP-T8-L3	12.0	7.5	1.6	27.0	58.0	138
BTP-T8-R3	12.5	9.0	1.4	35.0	60.5	159
BTP-T8-L4	11.0	12.0	0.9	26.5	54.0	164
BTP-T8-R4	9.0	10.0	0.9	28.0	–	–
BTP-T8-L5	11.0	10.0	1.1	–	–	–
Mean	11.9	8.9	1.4	29.4	57.4	155
		max				
BTP-T9-R1	15.0	6.0	2.5	25.0	62.0	180
BTP-T9-L1	10.0	–	–	37.0	69.0	180
BTP-T9-R2	16.5	7.5	2.2	32.0	60.5	180
BTP-T9-L2	17.5	6.0	2.9	28.5	55.5	165
BTP-T9-R3	12.5	7.0	1.8	27.5	62.0	159
BTP-T9-L3	12.0	8.0	1.5	35.5	67.0	180
BTP-T9-R4	13.5	6.5	2.1	31.5	60.0	180
BTP-T9-L4	10.5	–	–	28.5	60.0	159
BTP-T9-R5	11.0	–	–	32.5	71.5	166
BTP-T9-L5	13.0	–	–	39.5	–	–
BTP-T9-R6	16.5	–	–	–	–	–
Mean	13.5	6.8	2.2	31.8	63.1	172

Abbreviations: ML: Maximum length; MW: Maximum; PL: Pace length; SL: Stride length; PA: Pace angulation; ML/MW is dimensionless.

BTP-T3-L4 the wall appears to be up to ~40 cm deep (Fig. 4). This is very deep considering that the trackmaker footprint length averaged only 14.5 cm long. Using the footprint length–hip height (h) ratio of 4.5 proposed by Thulborn (1990) for small theropods, the estimated hip height would be only ~65 cm, and the estimate of h for small ornithopods using a ratio of 5 would be only 72.5 cm. This suggest that the apparent depths of the walls of the "deeper" tracks, as preserved in the present outcrop, are somehow exaggerated, or not actually track walls, if we are not to infer a trackmaker sinking into the substrate for a depth in excess of half its estimated leg length. There are various other possibilities for why these tracks appear so deep in proportion to their size. First, the trackmaker may have created some sort of steep, near vertical trace when walking close to the upslope side of the slope. Second, the apparent wall does not represent the depth of the shaft of foot penetration, because part of the trace, the lower portion of the shaft, represents a transmitted print. Certainly, given the lack of morphological detail on the floor of the ovoid prints, they could be transmitted prints, and it is impossible to infer the level to which the foot penetrated above these traces. This explanation, which infers shallower rather than deeper tracks would more readily explain the regular trackway patterns. Third, we might infer some sort of erosion above the tracks either pre- or post-burial and lithification.

Given the above inference that the tracks must have been made on a surface that incised preexisting cross beds, i.e., on a truncation surface, we are then able to interpret the whole T1–T8 assemblage coherently, as the passage of animals along a horizontal or sub-horizontal contour of a sloping truncation surface that apparently dipped to the east in a direction similar to the main slope of the present outcrop. In this interpretation the trackmakers were walking contour parallel, or sub-parallel, on an exposed surface. In most cases (T1–T8) the trackmakers traversed southward dipping cross sets as they headed north. However, they were clearly not walking upslope. Rather they appear to have been progressing nearly contour parallel to the inferred truncation surface, which caused them to register trackways across progressively lower units in the cross-bed sets (Fig. 2).

Trackways T9 and T10 are preserved quite differently as shallow impressions with digit traces on a foreset surface. They also have a different orientation from north to south. These trackmakers were also not progressing upslope, but rather moved horizontally in a contour parallel direction across the foreset surface. The tracks appear to have been didactyl with a much narrower footprint (length/width ratio of 2.2) and a longer step (31.8 cm), which averages 2.36 × foot length. BTP-T9 also has a correspondingly narrow straddle (pace angulation 172°). These traits are similar to those of *Sarmientichnus* isp. from the Luohe Formation (Xing et al., 2018), which has a pes length/width ratio of 3.3, a step length of 51.8 cm (3.36 × foot length), and a narrow straddle (pace angulation 177°). *Sarmientichnus* was originally found in Jurassic strata of Argentina by Casamiqiela (1964). Xing et al. (2018) explained the affinity of *Sarmientichnus* and deinonychosaurian tracks in detail.

Thus far, twelve Lower Cretaceous deinonychosaurian tracksites have been found in China (Lockley et al., 2016; Xing et al., 2018). The Baituping site may represent the 13th site, an interpretation consistent with the recently reported occurrence elsewhere in the Luohe Formation. Body fossil fragments of deinonychosaurians are known from the Ordos Basin, for example, troodontids have previously been reported from the area (Russell and Dong, 1993; Currie and Dong, 2001), as have the teeth of a small dromaeosaur (Ji et al., 2017). By using the formula of Alexander (1976), our estimation shows that the BTP-T9 trackmaker was walking (hip height = 4.5 × foot length for small theropods, and relative stride length 1.04 ≤ 2.0) (Thulborn, 1990) with a speed of ~0.65 m/s or ~ 2.34 km/h. To date, the best evidence of gregariousness among deinonychosaurs comes from a set of six parallel trackways of large deinonychosaurs from the Lower Cretaceous Tianjialou Formation of Shandong Province (Li et al., 2008). The limited evidence from the Baituping site suggests two individuals progressing along parallel trends.

The dune set architecture is interesting. The present eastward facing surface of the main monolithic outcrop, is likely a large exposed surface that has suffered weathering since having been uncovered. Indeed, it is easy to see that it is mainly where the larger erosion crevices or gullies that have incised the main outcrop, that the trackways have been eroded away (Fig. 2A). It is also notable that the rocks once situated to the east of the truncation surface, that is above it, have been eroded away completely, a possible sign that the dune beds below were more resistant. Since these overlying units are lost, we cannot speculate on how they differed lithologically from those below and to the west.

It is also easy to see that trackways T9 and T10, registered in Unit 6 of the foreset sequence shown in Fig. 2, were subsequently buried by further uniformly oriented progradation of multiple dune sets after the tracks were registered. This raises the question of whether it is possible to infer when they were made in relation to the registration of tracks T1–T8 on the truncation surface. Without answering this question definitively, we can infer that trackways T9 and T10 occur fairly high in a thick sequence of southward prograding dunes (Fig. 2), and that at some point the east facing flank of this large set was eroded into a truncation surface. The topography of this surface appears to have been somewhat irregular if not completely planar and is in fact defined by the more or less linear trackways registered on this surface.

There is a large amount of literature on tracks in eolian deposits from the Late Paleozoic through Cenozoic (Lockley and Hunt, 1995). It is beyond the scope of this paper to review these in detail but it should be noted that examples from the Navajo Sandstone, from the Lower Jurassic of North America are particularly well known and include examples of tracks from flat lying inter-dune deposits, truncation surfaces and foreset dune slope surfaces. The hallmark of most trackways on truncation surfaces is that they have cross cutting relationships with the truncated strata beneath the surfaces (see Lockley and Hunt, 1995, fig. 4.29; Lockley et al., 2014b, fig. 24A). The only rare exceptions might be where truncation surfaces coincide with uncovered surfaces with the same inclinations, so that no angular unconformity is detected. Tracks in eolian dune sand deposits are generally not very well preserved (Haubold et al., 1995a, 1995b), but can be in inter-dune playas. In the case of the abundant dune ichnofaunas known from the Jurassic of North America (Rainforth and Lockley, 1996a, 1996b; Lockley et al., 2007) the more common dinosaurian trackmakers were small theropods. This is consistent with evidence so far obtained from the dune facies of the Luohe Formation.

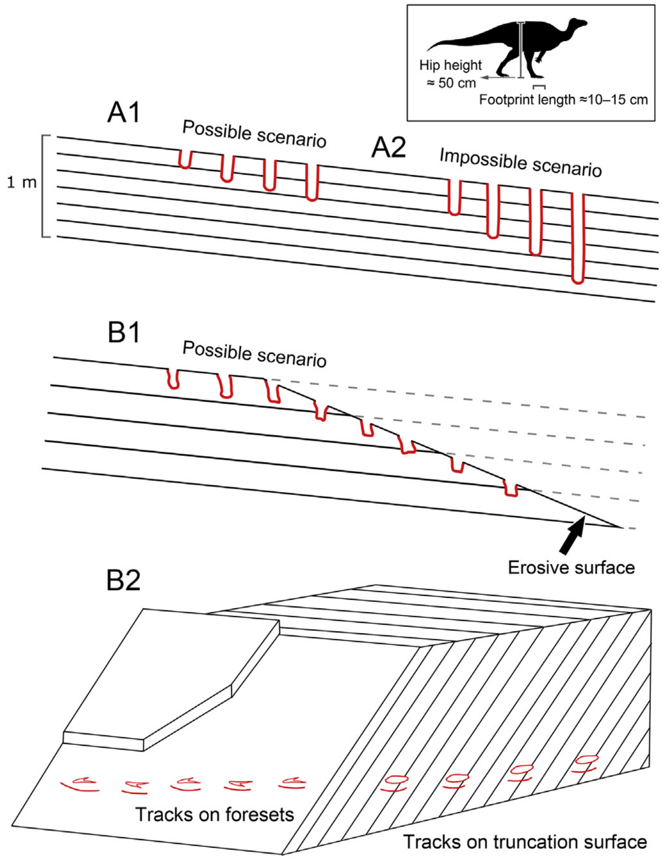

Fig. 5. Scenarios to explain differential preservation of trackways on foresets and truncation surfaces at the Baituping site. A1 and A2 respectively show possible and impossible scenarios to explain the relationship between track depths and different bedding planes. B1 shows how tracks in a single trackway may register on different stratigraphic levels on a truncation surface. B2 shows different preservation of tracks, belonging to the same or similar trackway sequences on foreset v. truncation surfaces.

6. Conclusions

Trackway segments of bipedal dinosaurs that inhabited arid paleoenvironments represented by dune and interdune, fluviatile deposits of the Luohe Formation at the Baituping site are poorly preserved, but can be inferred to represent the activity of a minimum of five individuals. Two trackway segments (T9 and T10) with recognizable toe traces represent didactyl theropods, probably deinonychosaurs (*Sarmientichnus* isp.), previously reported from the Luohe Formation, which progressed contour-parallel from north to south across a southward-dipping dune forest, which was later buried by further southward progradation of the large dune set dunes. Eight others, less well-preserved trackway segments (T1–T8) cross an eastward facing, exhumed truncation surface belonging to this same large dune set. These trackway segments, also oriented more or less contour parallel, can be traced for a distance of ~31 m, and are mostly oriented south to north. If these trackways segments are inferred to be connected in the most parsimonious way, they may represent as few as three northward progressing individuals, either theropods or ornithopods, but based on

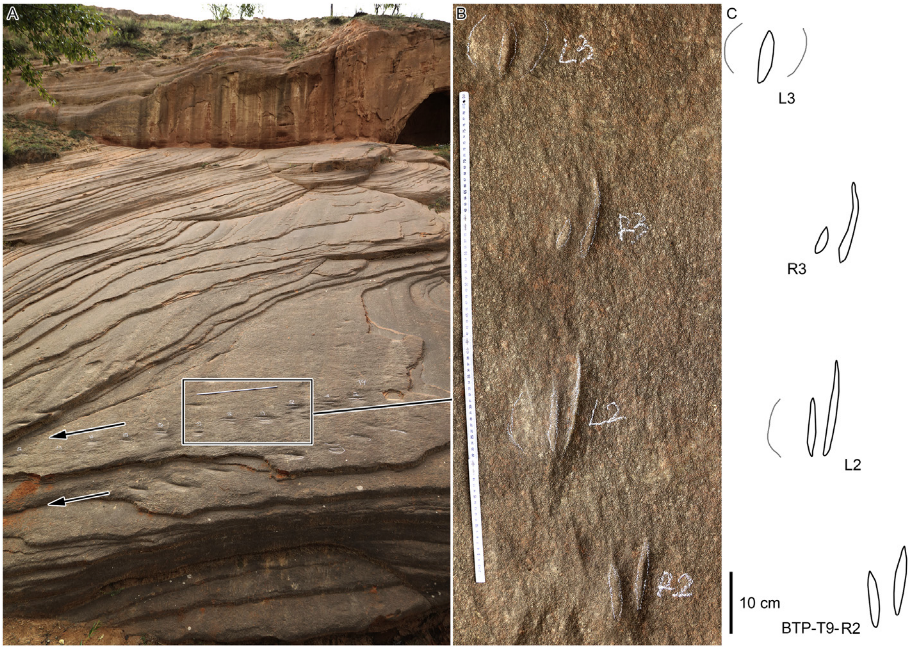

Fig. 6. (A) Overview photograph of T9 and T10 trackways on dune foreset surface. (B) Close up photograph of four-track-segment of inferred deinonychosaur trackway T9 showing toe traces. (C) line drawing of same segment.

the length/width ratio of the imprints rather belong to the former group. Thus, with the two foreset-registered trackways (T9 and T10) the entire assemblages (T1–T10) may represent as few as five trackways. The site is instructive in showing the difference in preservation between tracks registered on foreset surfaces and inclined truncation surfaces. However, across both these different substrates the trackmakers progressed in contour parallel directions: i.e., horizontally rather than steeply up or down slope. This suggests they chose a physically controlled pathway. In the northward oriented trackways, it is possible to infer the passage of at least three individuals moving more or less parallel. The southward oriented ones indicate the parallel passage of two individuals. Thus, it is possible that the small bipedal trackmakers progressed in small groups along the more convenient physically controlled horizontal routes through the dune fields.

The study site demonstrates how poorly preserved and incomplete trackway segments can still be very useful in reconstructing tetrapod activity and its relationship to local paleoenvironments. The study is also consistent with the evidence that deinonychosaur tracks are abundant in the Lower Cretaceous of China.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research was funded by the National Natural Science Foundation of China (No. 41888101, 41790455, 41772008), and the 111 project (B20011).

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