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Diverse sauropod-theropod-dominated track assemblage from the Lower Cretaceous Dasheng Group of Eastern China: Testing the use of drones in footprint documentation

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ABSTRACT

The use of drones in the exploration and documentation of track surfaces in steep terrain, otherwise only accessible by time intensive climbing activity, is tested. Location is the Nanquan site, one of many now known footprint localities from the Lower Cretaceous Dasheng Group that has been recently exposed by local industrial excavation. It reveals an ichnofauna of sauropod, theropod, and ornithopod tracks and trackways occurring at multiple stratigraphic levels (at least 10) in a thin sequence of fine grained purple mudstones with thin sandstone units that are steeply inclined by >45°. It was therefore necessary and most efficient to map the track-bearing surfaces using drone photography. The majority of track-bearing levels reveal sauropod tracks (cf. *Brontopodus*, cf. *Parabrontopodus*), which on some surfaces are very abundant. Large theropod tracks (cf. *Grallator*) and ornithopod tracks (*Caririchnium*) also occur, but only on single horizons. The ichnofauna is evidence of repeated activity by large dinosaurs in a fluvio-lacustrine floodplain setting susceptible to periodic desiccation. The Naquan site forms part of an extensive Dasheng Group outcrop belt with multiple tracks sites, most of these containing multiple track-bearing levels. As a result of the investigation, drone techniques can be recommended as an additional tool for quick documentation, in order to get a general overview and map of the track surface. Details are relatively distinct on the achieved photographs, however, a precise study still needs direct examination and documentation by classical outline drawings or photogrammetry.

1. Introduction

Thus far, drone technology has been sporadically applied in geological exploration of steep terrain. The use in the documentation and mapping of tetrapod footprint surfaces is still less known. Only few ichnological projects included drones in field documentation (Xing et al., 2016; Citton et al., 2017; Romilio et al., 2017). These tests prove that, in case of track sites with difficulties like inaccessibility or unfavourable exposure, aerial survey and digital photogrammetry methods can not only obtain photographic mosaics of the track surface, but also three-dimensional topographical details helpful for describing the track morphology. Here we present results of drone application on a steep surface with dinosaur footprints in Lower Cretaceous deposits of Shandong Province, China. Over the past decade, dinosaur tracks have been found along the Yishu fault zone (mid-segment of the Tanlu fault zone) between the Shandong Province and the northern Jiangsu Province, primarily in the Zhucheng, Junan, Linshu, and Tancheng areas. Xing et al. (2015a) reviewed 13 tracksites in these areas, 12 of which are Lower Cretaceous sites, including 5 sites in the Laiyang Group

Abbreviations: h, hip height; NQ, Nanquan site, Shangdong Province, China.

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and 7 sites in the Dasheng Group. The Houzuoshan and Jishan sites are the most important ichnofossil sites from the Dasheng Group with their diverse and well-preserved dinosaur ichno-assemblages. The former yields non-avian theropod, bird, and ornithopod tracks (Lockley et al., 2007, 2008; Li et al., 2015), and the latter yields small- and large-sized sauropod, theropod, and ornithischian tracks (Xing et al., 2013).

From 2015 to 2017, several of the authors (LX, JZ, YT and XW) found more track sites in Nanguzhai, Houmotuan and Nanquan villages near Tancheng Township. The Nanquan site (GPS: 34°39′47.84″ N, 118°26′7.67″ E) (Fig. 1) is located 6.5 km south of the Nanguzhai sites (Xing et al., 2011. The Nanquan site is adjacent (immediately to the north of) a road, and is about 800 m east of the Nanquan Village. After a local factory excavated a hill for material storage and exposed an anticline, at least 302 dinosaur tracks were found in the strata. In contrast to other tracksites of the Dasheng Group that are theropod-dominated, the Nanquan site is characterized by the high abundance of sauropods. This information is important and suggests being more cautious with conclusions about the Dasheng ichnofauna and their composition.

The layers of Nanquan outcrop are from southwest to northeast, about 170 m long and 4–7 m high (Fig. 2). The steepness of the road cut slope is about 46°. The major surface of the outcrop has weathered with the top lacking adequate supporting points for climbing. This offers an appropriate opportunity to demonstrate the utility of drones for mapping the footprint surface. The images taken by drones can be used for describing and interpreting the tracks.

2. Geological setting

The portion of the Tanlu fault zone in Shandong Province is called the Yishu fault zone. It is about 20–60 km wide and extends to northeast for about 300 km, formed by 4 roughly parallel fault zones: the Changyi-Dadian, Anqiu-Juxian, Yishui-Tangtou and Tangwu-Gegou zones (Xu et al., 1982). They extend along the Yi, Shu and Huai rivers, and taper from south to north (Wang et al., 2000). Within the Yishu fault zone, the Lower Cretaceous strata are made up of fluvial deposits with fine-grained sediments and well-developed fluviatile sedimentary bedding structures (Jiangsu Bureau of Geology and Mineral Resources, 1984; Shandong Provincial Bureau of Geology and Mineral Resources, 1991).

The Laiyang and Dasheng groups form the bulk of the exposed Cretaceous strata in the Yishu fault zone. The Dasheng Group is almost entirely located in the Yishu rift basin (Shi et al., 2003) and represents fluvial and lacustrine facies detrital deposits (Si, 2002). The Dasheng Group primarily comprises clastic rocks formed by purple-gray, purple-red and dark purple conglomerate and fine sandstone occasionally interbedded with yellow green siltstones. Some parts of the Dasheng Group are interbedded with volcanics, mainly andesite and andesitic welded tuff. There are two major cyclothems in the vertical sequence from bottom to top, reflecting alternating transgression and regression (Wang et al., 2013).

The Nanquan tracks are found in purple-grey medium to thick-bedded fine sandstones and siltstones which have developed mud cracks and gypsiferous horizons. In the lower part of the outcrop, there is a 2 m thick layer of purple-red siltstone interbedded with mudstone (Fig. 3). In the upper part of the outcrop, purple-red fine-grained sandstone, about 20–30 cm thick, interbeds with purple-red mudstone about 40–50 cm thick, forming 4 cyclothems. Both

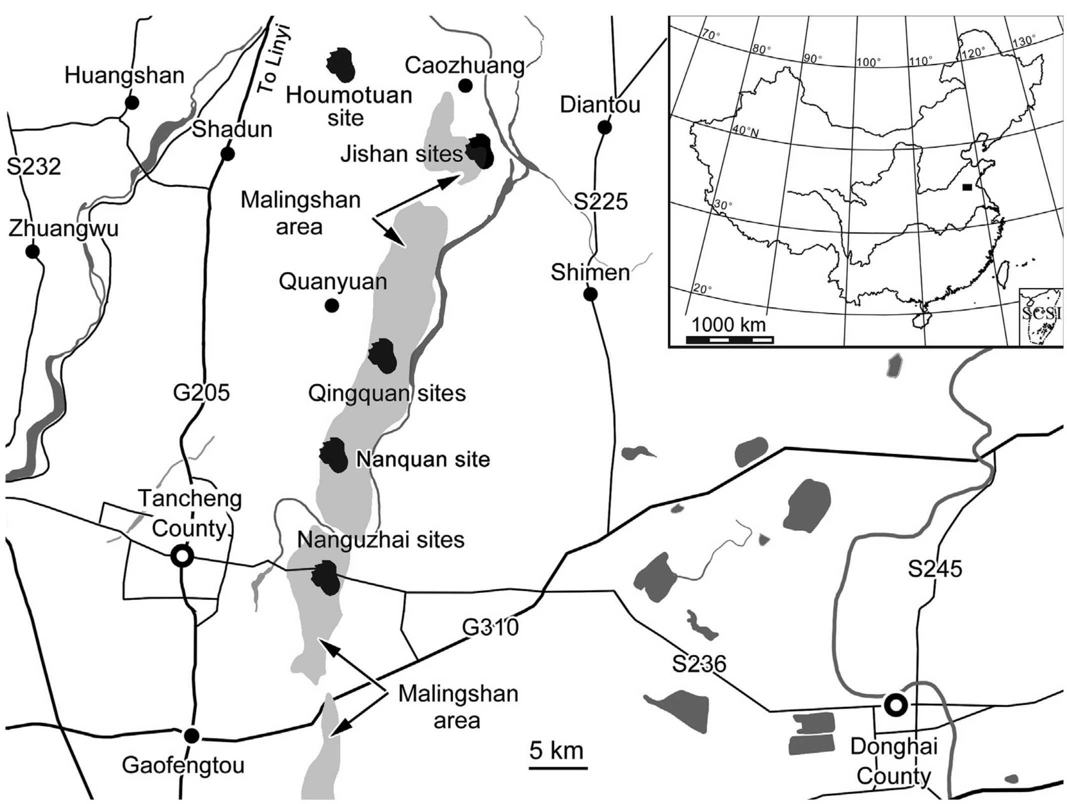

Fig. 1. Geographic location of the Houmotun, Jishan, Qingquan, Nanquan (this study) and Nanguzhai tracksites (indicated by sauropod pes track icons) in Shandong Province, China.

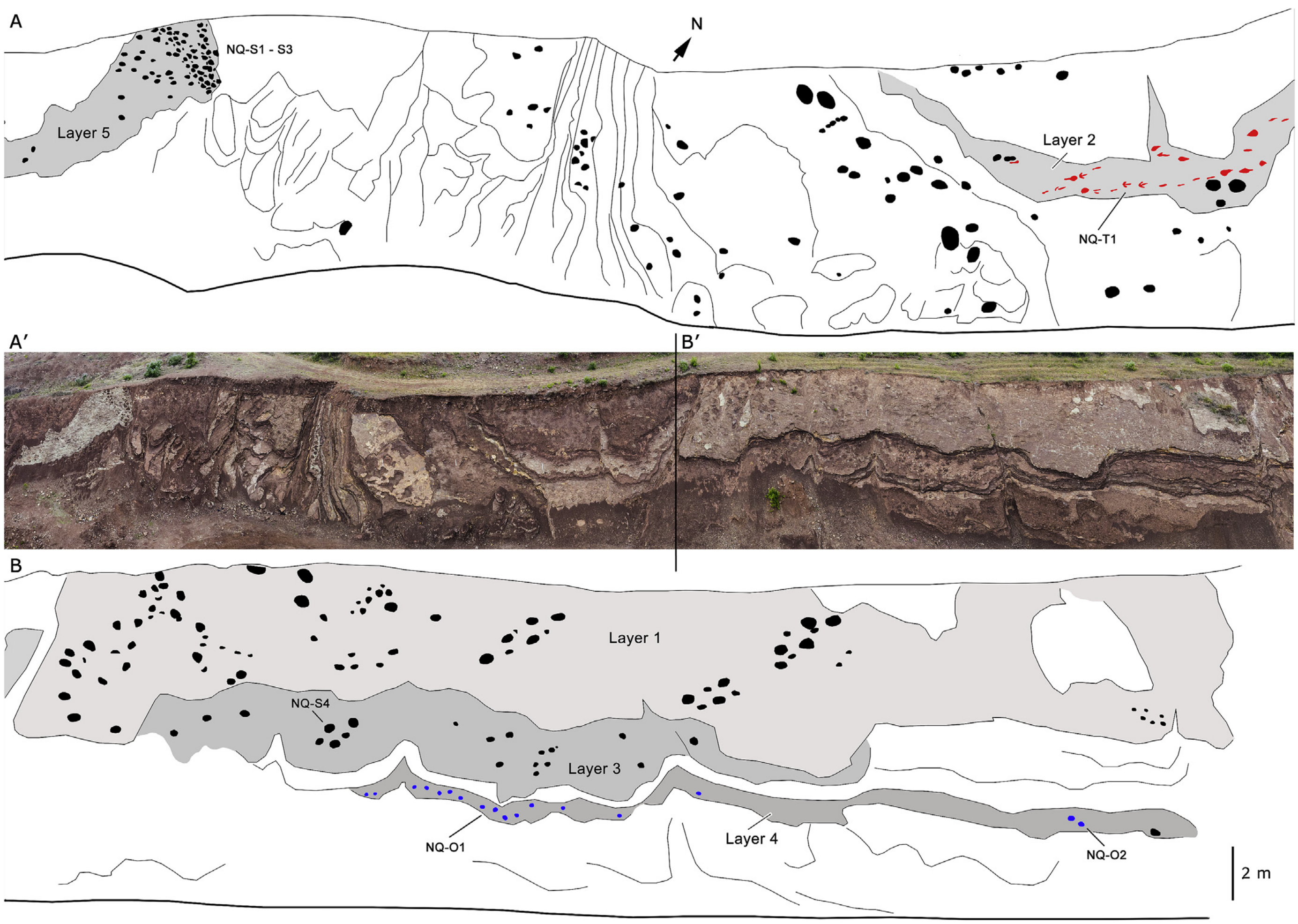

Fig. 2. Photograph and interpretative outline drawing of Nanquan site.

siltstones and mudstones have developed mud cracks. Dinosaur tracks were found in the fine sandstones, siltstones and mudstones surfaces. These characteristics are very similar to those of the nearby Qingquan sites, which belong to the Lower Cretaceous Tianjialou Formation of the Dasheng Group. (Kuang et al., 2013; Xing et al., 2017). Therefore, the Nanquan site is considered here to belong to the Dasheng Group. Being located within the upper part of the Dasheng Group, the Qingquan tracksite can possibly be attributed to the Albian, about 110–100 Ma. (Xing et al., 2017).

3. Materials and methods

A distribution map drawn on plastic film could not cover all tracks at the Nanquan site due to the 46° slope. Instead, the whole 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 mega-pixel camera (model X5, with a 15 mm lens) After taking off from the ground, DJI Inspire 1 can be controlled by a remoter controller during flight and provide real-time HD video through a mobile APP (DJI GO version 3.1.23), so as to finish the photographing and video capture. A photographic mosaic map, consisting of 18 partly overlapped photos, was produced by Adobe Photoshop CS6.

One smaller surface of 5 m^2 with two trackways was covered by a single, large, transparent plastic sheet on which the outlines of the tracks were traced. The plastic sheets are now stored in the collections of Yanqing Global Geopark, in Beijing, China.

The best preserved sauropod track surface in the southwestern corner was digitally photographed (total of 68 photographs: 4600 × 2584 px, 300 dpi) under natural lighting conditions using the quadcopter (DJI Inspire 1; Fig. 4) with GPS metadata recording the spatial position of each image. A topographical model of the track surface followed the procedure adapted from Romilio et al. (2017) where photographic jpg image files were added to Agisoft Photoscan Professional Edition (version 1.2.6 build 2038 64 bit). Several 50 cm long steel rulers (five in total) were suspended onto the surface to verify the scale correction of the model. The resulting model had sub-millimeter resolution (1.49 mm average linear distance between points) and was positioned to the center of the Cartesian coordinate system using MeshLab (64bit_fp v2016.12; Cignoni et al., 2008). Orthophotographic mosaic and ambient occlusion images were obtained using CloudCompare (version 2.8.0). False-color elevation and contoured images were made of the models using Paraview (version 5.0.0 64 bit) to visualize surface height.

For calculation of hip heights and speed estimates, the methods of Alexander (1976) and Thulborn (1990) were adopted. The relative stride length (SL/h) is used to estimate whether the animal was walking (SL/h $\leq$ 2.0), trotting/slow running (SL/h > 2.0 and < 2.9) or running (SL/h $\geq$ 2.9).

According to Olsen (1980), Weems (1992), and Lockley (2009), theropod tracks can be differentiated based on mesaxony (i.e., the

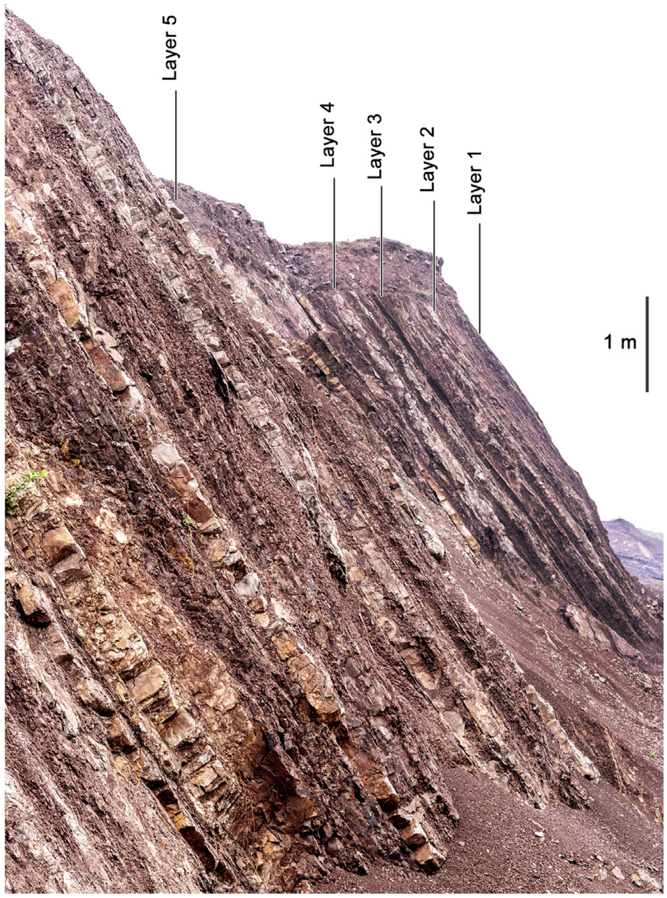

Fig. 3. Photograph of the cross section of Nanquan outcrop. The arrows indicate the main footprint layers.

degree to which the central digit (III) protrudes anteriorly beyond the medial (II) and lateral (IV) digits), there by defining an anterior triangle. There is also, in most cases, a positive correlation between the L (length):W(width) ratio of the anterior triangle (which is used here as an index of mesaxony) and that of the whole track: i.e., elongate tracks generally have stronger mesaxony than transversely broad tracks.

For the trackways of quadrupeds, gauge (trackway internal width) was quantified for pes and manus tracks using the ratios WAP/P'ML (see Marty, 2008; Marty et al., 2010). They were calculated from pace and stride length, assuming that the width of the angulation pattern intersects the stride at a right angle and at the approximate midpoint of the stride (Marty, 2008). If the ratio is smaller than 1.0, tracks intersect the trackway midline, and are considered to be narrow-gauge (see Farlow, 1992). Accordingly, a value of 1.0 separates narrow-gauge from medium-gauge trackways, whereas the value 1.2 is arbitrarily fixed between medium-gauge and wide-gauge trackways, and trackways with a value higher than 2.0 are considered to be very wide-gauge (Marty, 2008).

4. Tracks and trackways

Tracks were registered on about ten different surfaces. These are five main track-bearing layers, which were numbered 1 to 5 from top to bottom. Layer 1 has 85 sauropod tracks; Layer 2 has 25 theropod tracks and 5 sauropod tracks; Layer 3 has 11 sauropod tracks; Layer 4 has 17 ornithopod tracks and one sauropod track; Layer 5 has 84 sauropod tracks. There are at least another 5, 6 track-

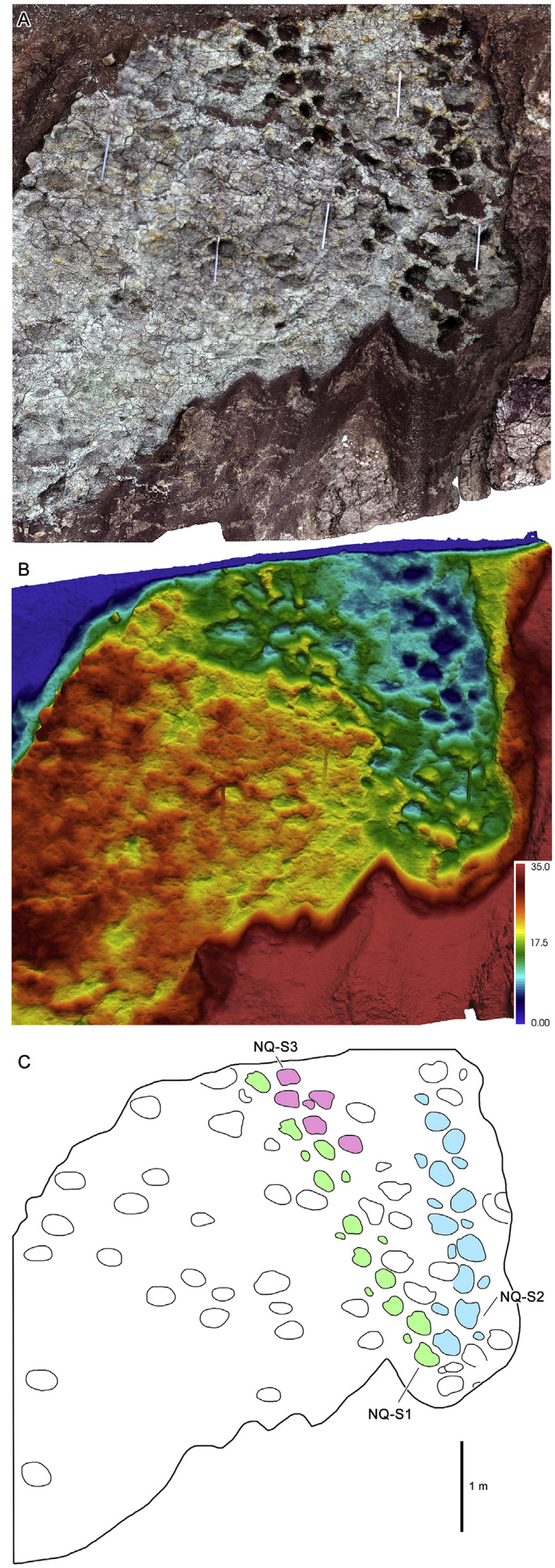

Fig. 4. Photograph (A), coloured depth model (elevation map) (B) and interpretative outline drawing (C) of Nanquan sauropod trackways NQ-S1–S3.

bearing layers, but they are not well exposure. Although 302 individual tracks have been identified, the total number that may have been destroyed due to weathering, industrial excavation, etc. is unknown. These 302 tracks include 260 (86%) sauropod tracks, 25 (8%) theropod tracks and 17 (6%) ornithopod tracks.

4.1. Sauropod tracks

4.1.1. Description

Sauropod tracks are badly weathered, leaving only their outlines. Among the 261 imprints, most are isolated or irregular with at least ten recognizable trackway segments (Figs. 2, 4, and 5, Table 1). Track sizes vary with pes impressions ranging from 25 cm to 85 cm. NQ-S1, S2 and S4 are the best preserved trackways.

NQ-S1 (Fig. 5A) contains 10 pes impressions and 6 corresponding manus impressions. The average length of the manus impressions is 8.2 cm, that of the pes impressions 27.0 cm. The average length/width ratios of the manus and pes impressions are 0.7 and 1.4 respectively. The manus imprints show oval digit impressions, while the claws and the metacarpo-phalangeal region are indistinct. The pes impression is oval, LP5 and LP6 have three clear claw marks indicating digits I – III. The metatarso-phalangeal regions of pes impressions are smoothly curved. The manus traces are strongly rotated outwards relative to the trackway axis by 67° on average, which is larger than the rotation of the pes impressions (approximately 22°). The average manus pace angulation is 79°, while the average pes pace angulation is 142°.The mean heteropody of the well-preserved tracks is 1:5.7 (6.8, and 4.6, n = 2). The WAP/P'ML is 0.4, smaller than 1.0, and clearly suggests narrow-gauge (Marty, 2008).

NQ-S2 shows nine pes impressions and nine corresponding manus impressions. The average length of manus impressions is 10.3 cm and that of pes impressions 31.9 cm. Its key features are similar to those of NQ-S1. The gauge of the trackway is narrow with WAP/P'ML = 0.7. The manus traces are rotated from the trackway axis by 44° on average, which is larger than the rotation of the pes impressions (approximately 35°). The mean heteropody of the well-preserved tracks is 1: 3.5 (3.5, and 3.5, n = 2).

NQ-S4 includes 4 pes impressions and 1 corresponding manus impression. The average length of manus impressions is 26.7 cm, that of the pes impressions is 43.9 cm. The value of WAP/P'ML of NQ-S4 is 1.3, which is between typical medium-gauge and wide-gauge trackways (Marty, 2008). The manus traces are strongly rotated outwards from the trackway axis by 27° on average, which is smaller than the rotation of the pes impressions (approximately 65°). The traces of digits I–IV of the pes and manus are distinct. The heteropody of the LM1and LP1 is 1: 1.7.

4.1.2. Ichnotaxonomy

Occasionally, if not being optimally preserved, sauropod trackways are hard to distinguish from some thyreophoran ichnites. However, stegosaur trackways such as *Deltapodus* or *Stegopodus* mostly have a regular pattern with the manus being position anterior to the pes and with a similar outward rotation as the pes. In sauropod trackways the manus typically has a stronger outward rotation when compared to the pes, and this pattern is seen in the trackways described here. Also, the latter show no distinct manual digit traces, mostly observable in thyreophoran trackways. In *Tetrapodosaurus* another thyreophoran trackway attributed to ankylosaurs, the pes has a nearly parallel orientation relative to the midline, whereas in sauropod trackways it is strongly outward rotated, similar as in the described tracks. Trackways of medium-sized sauropods have been described also from the Dasheng Group of the nearby Jishan site (Xing et al., 2013).

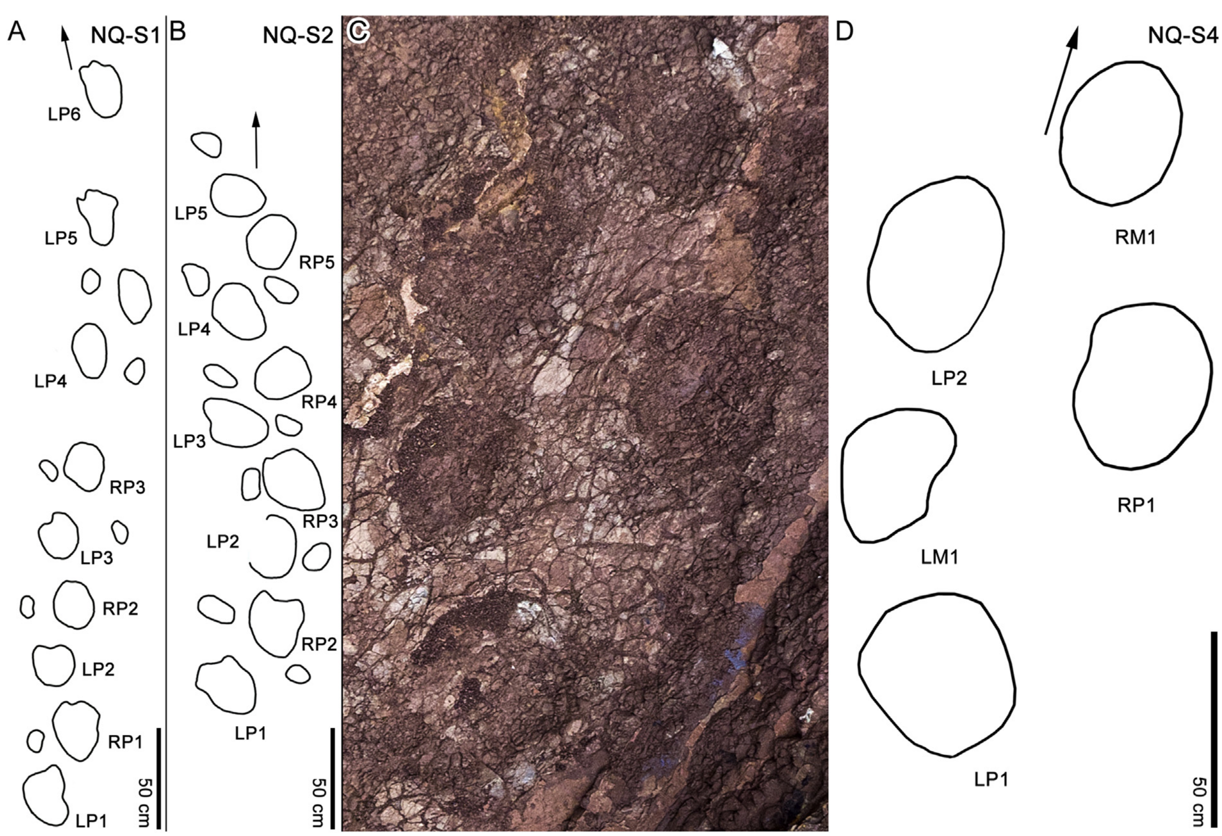

Fig. 5. The outline drawing of sauropod NQ-S1 (A) and S2 (B); photograph (C) and interpretative outline drawing (D) of sauropod NQ-S4.

Table 1
Measurements (in cm) of the sauropod trackways from Nanquan tracksite, Shandong Province, China.

Number	ML	MW	R	PL	SL	PA	ML/MW	WAP	WAP/P'ML
NQ-S1-LP1	28.5	21.8	33°	19.2	31.8	133°	1.3	–	–
NQ-S1-LM1	8.5	11.4	67°	–	34.0	–	0.7	–	–
NQ-S1-RP1	30.8	24.4	6°	15.6	30.1	140°	1.3	14.3	0.5
NQ-S1-RM1	–	–	–	–	–	–	–	–	–
NQ-S1-LP2	21.7	20.6	26°	16.5	32.4	151°	1.1	11.0	0.5
NQ-S1-LM2	6.9	11.3	97°	29.9	34.5	79°	0.6	–	–
NQ-S1-RP2	24.7	18.9	−22°	17.0	35.2	149°	1.3	8.8	0.4
NQ-S1-RM2	7.7	12.2	66°	24.0	40.4	–	0.6	–	–
NQ-S1-LP3	24.1	20.1	33°	19.5	47.8	160°	1.2	9.4	0.4
NQ-S1-LM3	6.8	11.8	−36°	–	–	–	0.6	–	–
NQ-S1-RP3	25.1	21.0	−23°	29.1	44.7	143°	1.2	6.4	0.3
NQ-S1-RM3	9.9	13.5	–	25.1	–	–	0.7	–	–
NQ-S1-LP4	27.8	17.6	18°	17.9	33.5	117°	1.6	13.2	0.5
NQ-S1-LM4	9.7	13.1	–	–	–	–	0.7	–	–
NQ-S1-RP4	27.9	15.8	–	21.3	–	–	1.8	19.5	0.7
NQ-S1-RM4	–	–	–	–	–	–	–	–	–
NQ-S1-LP5	29.1	20.5	14°	–	32.5	–	1.4	–	–
NQ-S1-LP6	30.1	18.0	–	–	–	–	1.7	–	–
Mean-P	27.0	19.9	|22°|	19.5	36.0	142°	1.4	11.8	0.4
Mean-M	8.2	12.2	|67°|	26.3	36.3	79°	0.7	–	–
NQ-S2-RP1	–	–	–	–	–	–	–	–	–
NQ-S2-RM1	9.5	12.9	1°	52.5	59.8	66°	0.7	–	–
NQ-S2-LP1	33.8	23.7	59°	42.6	76.0	135°	1.4	–	–
NQ-S2-LM1	11.4	19.9	−12°	57.7	65.8	75°	0.6	–	–
NQ-S2-RP2	33.9	27.4	6°	39.8	72.9	164°	1.2	15.8	0.5
NQ-S2-RM2	11.4	16.0	−32°	50.3	67.8	105°	0.7	–	–
NQ-S2-LP2	31.8	24.7	−13°	33.9	62.7	116°	1.3	5.6	0.2
NQ-S2-LM2	9.0	16.2	75°	34.2	56.5	92°	0.6	–	–
NQ-S2-RP3	35.9	27.7	−45°	39.7	51.2	80°	1.3	20.1	0.6
NQ-S2-RM3	8.9	14.5	22°	43.7	68.3	89°	0.6	–	–
NQ-S2-LP3	35.0	21.8	82°	39.5	57.9	87°	1.6	31.8	0.9
NQ-S2-LM3	8.9	18.5	−41°	53.0	48.5	60°	0.5	–	–
NQ-S2-RP4	29.2	22.9	62°	44.4	68.8	107°	1.3	30.1	1.0
NQ-S2-RM4	11.2	17.9	−63°	43.0	–	–	0.6	–	–
NQ-S2-LP4	31.3	22.5	42°	41.1	54.2	97°	1.4	24.5	0.8
NQ-S2-LM4	11.2	17.4	–	–	68.1	–	0.6	–	–
NQ-S2-RP5	28.1	21.3	–	30.5	–	–	1.3	21.4	0.8
NQ-S2-LP5	28.3	20.7	–	–	–	–	1.4	–	–
NQ-S2-LM5	10.8	16.4	–	–	–	–	0.7	–	–
Mean-P	31.9	23.6	|44°|	38.9	63.4	112°	1.4	21.3	0.7
Mean-M	10.3	16.6	|35°|	47.8	62.1	81°	0.6	–	–
NQ-S4-LP1	41.1	36.9	33°	102.7	112.9	83°	1.1	55.4	1.3
NQ-S4-LM1	24.3	37.8	65°	–	–	–	0.6	–	–
NQ-S4-RP1	44.1	33.1	20°	61.1	–	–	1.3	–	–
NQ-S4-RM1	29.1	38.0	–	108.3	–	–	0.8	–	–
NQ-S4-LP2	46.5	31.8	–	–	–	83°	1.5	–	–
Mean-P	43.9	33.9	27°	81.9	112.9	83°	1.3	55.4	1.3
Mean-M	26.7	37.9	65°	108.3	–	–	0.7	–	–

Abbreviations: ML: Maximum length; MW: Maximum; R: Rotation; PL: Pace length; SL: Stride length; PA: Pace angulation; WAP: Width of the angulation pattern of the pes (calculated value); ML/MW, WAP/P'ML and are dimensionless.

Most large-sized sauropod trackways in China are wide- (or medium-) gauge and are therefore referred to the ichnogenus *Brontopodus* (Lockley et al., 2002). NQ-S4 is consistent with *Brontopodus* type tracks due to 1) wide-gauge; 2) pes impressions that are longer than wide, large and outwardly directed; 3) U-shaped manus prints (Farlow et al., 1989). However, it has lower heteropody, different from *Brontopodus* from the Upper Jurassic of Portugal and Switzerland (Meyer and Pittman, 1994; Santos et al., 2009) and from the Lower Cretaceous of the USA (Farlow et al., 1989; Lockley et al., 1994a), which is about 1:1.5 in NQ-S4 vs.1:3 in the latter two. The heteropody of NQ-S4 is quite similar with that of *Brontopodus* isp. from Jishan. Both NQ-S4 and Jishan specimens are similar to *Polyonyx gomesi* by their low heteropody of 1:2 (Lockley et al., 1994a; Santos et al., 2009). The NQ specimens and the Jishan *Brontopodus* with lower heteropody indicate that *Brontopodus* from the Dasheng Group may represent a distinguishable morphotype. However the general quality of preservation makes us hesitant to define this based on the present material. Furthermore, the anatomical and ichnotaxonomical significance of features like the manus shape or the gauge, is presently discussed. The former can vary largely with the substrate and imprint depth, the latter can partly be due to variation of the gait within single individuals (Castanera et al., 2012, 2016).

Late Jurassic–Early Cretaceous trackways of small-sized (25–40 cm) sauropods from China have previously been referred to *Parabrontopodus* due to distinguishing features such as strongly outwardly rotated manus traces, narrow to medium gauge (WAP/P'ML 0.8–1.3), high heteropody (1:2.2–1:3.5) (Xing et al., 2015a). The characteristics of NQ-S1 and S2 are nearly exact matches with the strong outward rotation of the manus, the WAP/P'ML ratio being <1.0 (0.4 and 0.7, respectively) and the heteropody being 1:5.7 and 1:3.5, respectively.

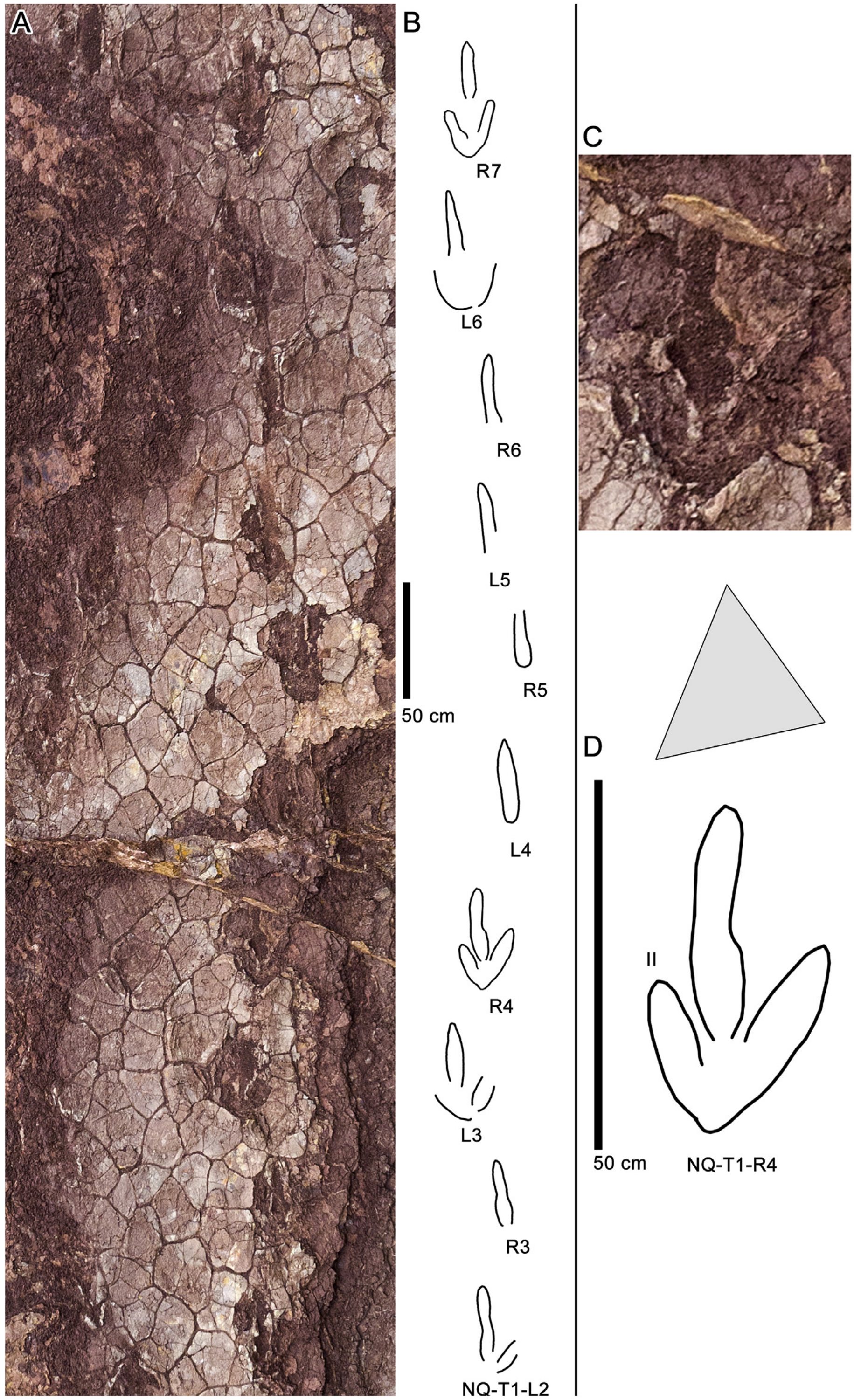

Fig. 6. Photograph (A, C) and interpretative outline drawing (B, D) of Nanquan theropod trackways NQ-T1, and the NQ-T1-R4.

4.2. Theropod tracks

4.2.1. Description

One single trackway, composed of fourteen consecutive pes impressions, catalogued individually as NQ-T1 (Figs. 2, and 6; Table 2). Another ten tracks form two trackways, catalogued as NQ-T2 and NQ-T3 from the same layer.

Ten sequential tracks in the middle part of trackway NQ-T1 (T1-L2–R7) are better preserved, but only two well-preserved tridactyl pes impressions are 47.9 cm in length on average with a L/W ratio of 2.3. All tracks have elongate digit III (mean 31.5, N = 6) depressions. The mean pace angulation of 160° indicates a trackmaker with a narrow stance typical of theropods. NQ-T2, T3 trackways are poorly preserved, but both extend to southwest to northeast as just as T1.

Table 2
Measurements (in cm) of theropod and ornithopod tracks from Nanquan tracksite, Shandong Province, China.

Number	ML	MW	II–IV	PL	SL	PA	L/W
NQ-T1-L2	–	–	–	54.3	112.9	159°	–
NQ-T1-R3	–	–	–	60.6	117.6	150°	–
NQ-T1-L3	43.7	–	–	61.2	126.0	169°	–
NQ-T1-R4	–	–	–	65.4	126.9	169°	–
NQ-T1-L4	44.5	23.6	50°	62.1	112.4	159°	1.9
NQ-T1-R5	–	–	–	52.2	105.6	155°	–
NQ-T1-L5	–	–	–	55.9	128.6	160°	–
NQ-T1-R6	–	–	–	74.5	137.6	158°	–
NQ-T1-L6	52.8	26.8	–	65.7	–	–	2.0
NQ-T1-R7	50.6	21.0	48°	–	–	–	2.4
Mean	47.9	23.8	49°	61.3	120.9	160°	2.1
NQ-O1-RP1	18.8	14.3	35°	46.7	89.0	144°	1.3
NQ-O1-LP1	20.6	16.6	42°	46.9	98.3	157°	1.2
NQ-O1-RP2	19.6	16.3	37°	53.4	–	–	1.2
NQ-O1-LP2	18.9	15.2	48°	–	–	–	1.2
Mean	19.5	15.6	41°	49.0	93.7	151°	1.2
NQ-O2-LP1	27.6	22.2	34°	–	–	–	1.2

Abbreviations: ML: Maximum length; MW: Maximum width (measured as the distance between the tips of digits II and IV); II–IV: angle between digits II and IV; PL: Pace length; SL: Stride length; PA: Pace angulation.; L/W is dimensionless of ML/MW.

Of these, NQ-T1-R4 is the best preserved with partial pad impressions. Digit III is the longest, followed by digits IV and II. Sharp claw impressions are visible, and those on digit II and IV are quite robust. Digit II and digit III have 2 and 3 digital pad impressions, respectively. The metatarsophalangeal region is located in line with the axis of digit III. The digits have a lower divarication angle (49°) with the mean divarication angle between digits II and III being higher than between digits III and IV.

4.2.2. Ichnotaxonomy

NQ-T1 tracks are characterized by strong mesaxony (average L/W ratio for the anterior triangle: 1.06, range 0.9–1.22, N = 2), which is close to the value typical for footprints of the ichno- or morphofamily Grallatoridae (Lull, 1904) (1.0–1.22, *Grallator* type, Lockley, 2009).

In classic *Grallator–Anchisauripus–Eubrontes* plexus, *Grallator* is smaller (<15 cm in length) but has higher L/W ratio (2.64) and strong mesaxony (1.22); *Eubrontes* is the largest (>25 cm in length) but has lower L/W ratio (1.70) and weak mesaxony (0.58). Apart from the size, NQ-T1 tracks are identical in morphology with typical *Grallator*, with the slender overall-shape, the strong mesaxony and the presence of a metatarsophalangeal pad IV and lack of a metatarsophalangeal pad II. However, the preservation of most of the imprints in the trackway is incomplete. Therefore we assign NQ-T1 tentatively to cf. *Grallator*.

Typical Jurassic ichnofaunal components such as *Grallator–Eubrontes* are frequently present in Cretaceous theropod track assemblages from China (Lockley et al., 2013; Xing and Lockley, 2016). They occur for example in Lower Cretaceous strata of the Laiyang Group in Shandong Province with *Grallator yangi* (Lockley et al., 2015) and in the Dasheng Group of the Houzuoshan site that has small grallatorids (Li et al., 2015).

NQ-T1 tracks are likely the largest Early Cretaceous theropod tracks found in Shandong Province. Previous largest theropod track in Shandong is morphotype AT-1 (36 cm) from the Huanglonggou site. Though the 58.2 cm long *Chapus* occurs in the Lower Cretaceous (Li et al., 2006) of Inner Mongolia and the 57.5 cm long *Megalosauripus* isp. is known from the Lower Cretaceous of Shaanxi (Hu et al., 2011), both being *Eubrontes* type tracks with weak mesaxony.

4.2.3. Trackmaker

China's Early Cretaceous *Grallator* type trackmakers are thought to be potentially related to Oviraptorosauria (Sullivan et al., 2009; Xing et al., 2009). Most oviraptorosaurians are small, similar in size to *Caudipteryx*, about 1 m in length (Xu and Norell, 2006). However, the Oviraptorosauria also includes the 8 m-long *Gigantoraptor* which evolved in the Early Cretaceous (Xu et al., 2007). The trackmaker of NQ-T1 tracks may be related to large oviraptorosaurians. This interpretation remains uncertain because of a lack of diagnostic features in the tracks.

4.2.4. Footprint formation and behaviour

The tracks are preserved on surfaces with well-developed mud cracks. Generally, mud crack areas comprise cracked upper muddy ground and lower sandy deposits which had higher water content: i.e., they are associated with fining upwards sequences. The NQ-T1 trackmaker broke through the upper muddy layer, which was thinner, and registered tracks on the firm lower sandy layer, deforming the tracks. The reason why many tracks only have digit III traces may be that the trackmaker moved its center of gravity anteriorly and placed the greatest load on digit III, while other digits and the heel bore smaller loads and did not leave any clear traces. Such dynamics have been reviewed by Avanzini (1998: fig. 3c) with specific reference to *Grallator*.

Using the equation hip height = 4 × footprint length (Thulborn, 1990), and the average hip height to body length ratio of 1:2.63 (Xing et al., 2009), the trackmaker of the NQ-T1 trackway is estimated to have been 4.8 m in length. Using the stride length equation of Alexander (1976) (SL/h = 0.66) the trackmaker of the NQ-T1 is estimated to have been moving at 0.53 m/s.

Generally speaking, the speed of larger theropod trackmakers is relatively slow (walking), such as the 42 cm long *Eubrontes zigongensis* with an SL/h value of 1.18 (Xing, et al., 2014). The small trackmakers are relatively faster (walking to slow run), such as ~15 cm *Grallator* type from Qianjiadian site, their SL/h value is 1.46–2.91 (Xing et al., 2015b). In general, it is very rare for the NQ-T1 trackmaker to walk at such low speeds. However, this could possibly be due to the soft surface and movement on uncertain grounds.

4.3. Small ornithopod tracks

4.3.1. Description

Ornithopod trackways are rare in the Nanquan site (Figs. 2, 7, and 8; Table 2). All have a characteristic quadripartite morphology typical of *Caririchnium*. The tracks can be categorized in two groups based on their sizes. The smaller ones are shorter than 20 cm, with seven of them forming the trackway NQ-O1. Two larger ones are longer than 25 cm and catalogued as NQ-O2.

The four best preserved tracks in NQ-O1 trackway are 19.5 cm in length on average (N = 4). None of the NQ-O1 tracks have manus impressions. Their pes impressions are 18.8–20.6 cm in length. This is smaller than the lengths of the types of other *Caririchnium* ichnospecies (~35–40 cm). NQ-O1-LP1 is the best-preserved example among the NQ ornithopod tracks. The pes trace of O1-LP1 is mesaxonic, functionally tridactyl and digitigrade-semidigitigrade with a length of 20.6 cm. Pes traces show a quadripartite morphology, consisting of impressions of three digits and a heel pad separated by pronounced grooves, but which appear as ridges in natural impressions. Digit III trace is the shortest, while traces of digits II and IV are almost equal in length. Each digit trace has a strong and blunt claw or ungual mark. The heel pad is subrounded to triangular in shape. The average ML/MW ratio of NQ-O1 tracks is 1.0. The anterior triangle L/W ratio (degree of mesaxony) is 0.45. The interdigital divarication angle II–IV is 41°. The average pes pace angulation is 151°.

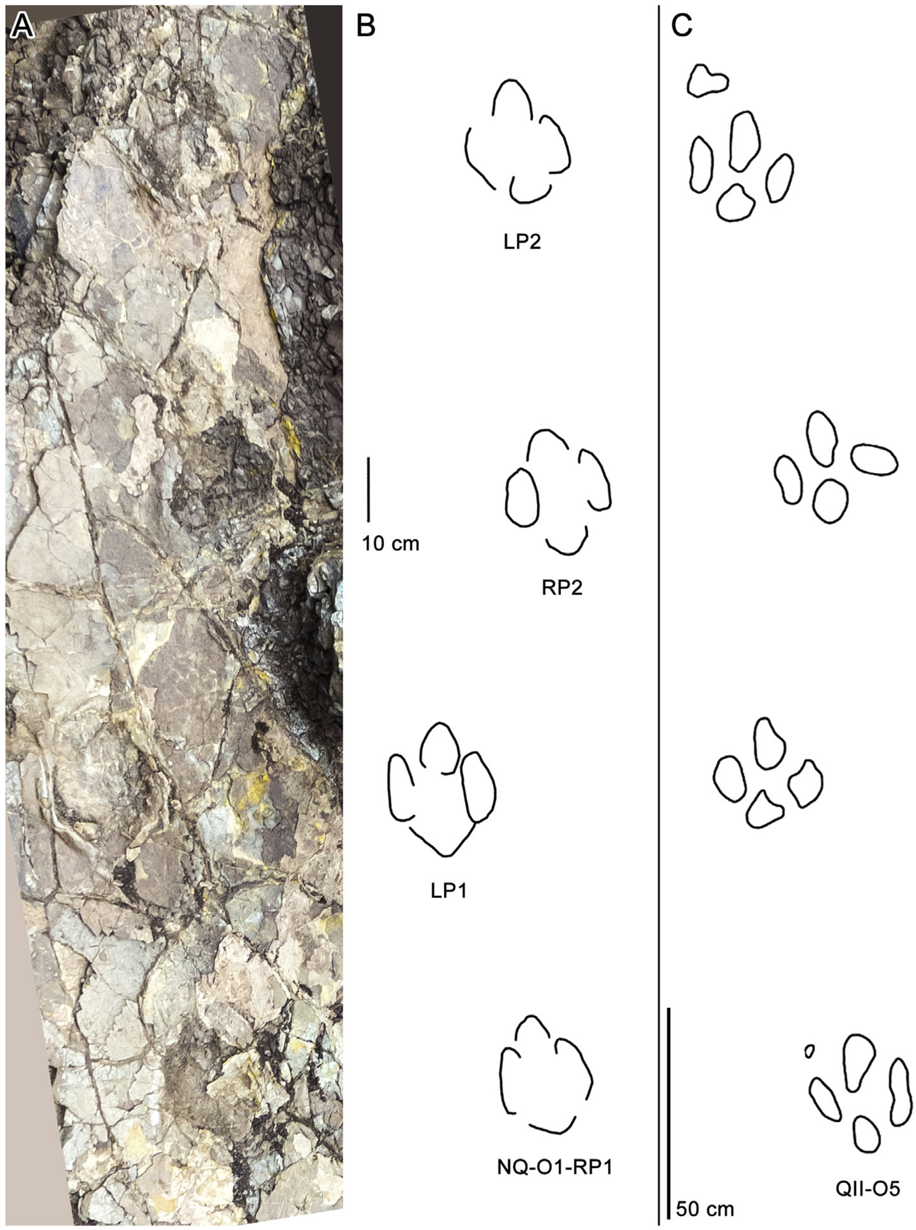

Fig. 7. Photograph (A) and interpretative outline drawing (B) of Nanquan ornithopod trackways NQ-O1, and the ornithopod trackway QII-O5 from Lotus site, Chongqing (C) (Xing et al., 2015c).

NQ-O2-LP1 is the best preserved track in NQ-O2 trackway and is 27.6 cm in length. It is largely similar to NQ-O1-LP1, except the anterior triangle L/W ratio which is 0.34 and lower than those of NQ-O1 tracks. The interdigital divarication angle II–IV is also narrower than in NQ-O1, namely 34°. The shallow possible manus trace is oval, with no discernible digit or claw marks. The long axis of the oval manus trace aligns with the antero-lateral margins of the pes.

4.3.2. Ichnotaxonomy

The Houzuoshan site, which is also located in the Dasheng Group, has yielded ornithopod tracks of *Ornithopodichnus* (Li et al., 2015). *Ornithopodichnus* was diagnosed as exhibiting wide (L/W < 1), short ornithopod pes tracks (Kim et al., 2009) with weak mesaxony (0.2–0.35, Xing et al., 2015c). However, NQ-O1 has L/W > 1 and relatively stronger mesaxony, and thus is more similar to *Caririchnium lotus* (Xing et al., 2007). The L/W ratio and mesaxony of *C. lotus* are 0.9–1.2 and 0.33–0.52 (Xing et al., 2015c). *Caririchnium* is widely distributed in the Lower Cretaceous deposits of China. It is known to occur in the Jiufotang (Hebei Province) and Tongfosi formations (Jilin Province) in north China, the Hekou group (Gansu Province) in northwest China, and the Jiaguan and Feitianshan formations (Sichuan Province) in southwestern China. *Caririchnium* is a characteristic Lower Cretaceous ichnogenus and present globally in strata of this age, for example in North America and Europe (Lockley et al., 2014b). Small *Caririchnium* tracks from the Dasheng Group (Shandong Province) expands the range of this ichnogenus.

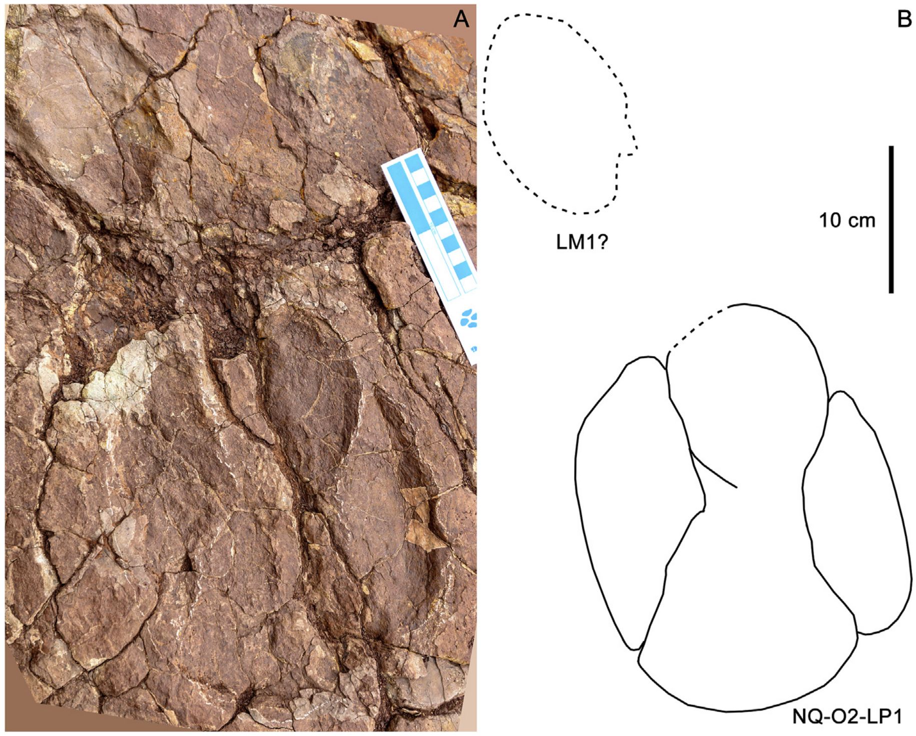

Fig. 8. Photograph (A) and interpretative outline drawing (B) of Nanquan ornithopod trackways NQ-O2.

5. Palaeoecology

The Nanquan site is a sauropod-dominated tracksite, whereas the Houzuoshan site, another site in the Dasheng Group is clearly theropod (*Asianopodus*) dominated, with ornithopod tracks accounting for 9% (Li et al., 2015). Generally, theropod-sauropod tracks domination is common in China during the Early Cretaceous (Lockley et al., 2014a).

Sauropod tracks are abundant with pes tracks ranging from 25 cm to 85 cm, reflecting trackmakers of different sizes. Large tracks are referred to *Brontopodus*, and small tracks are referred to *Parabrontopodus*. This pattern conforms to other sites in the Dasheng Group, like the Jishan tracksite (Xing et al., 2013). So far, sauropod tracks found in the Dasheng Group include small-sized, narrow-gauge and high heteropody *Parabrontopodus*-type tracks, as well as large-sized, medium/wide-gauge and low heteropody *Brontopodus*-type tracks from the Nanquan and Jishan sites. Large-sized, narrow-gauge and low heteropody sauropod trackway, cf. *Parabrontopodus* from Qingquansi site (Xing et al., 2017). This site also yields large-sized and small-sized wide-gauge and low heteropody *Brontopodus* type tracks (Xing et al., in press). The smallest pes impression is 17.6 cm in length, likely a result of juvenile sauropod trackmakers. We cannot exclude, therefore, that the described differences in gauge and heteropody are the result of ontogenetic growth also. The only skeletal remains of sauropods from the Lower Cretaceous of Shandong Province belong to the large titanosauriform, *Euhelopus zdanskyi* (Wiman, 1929; Wilson and Upchurch, 2009). The ichnological record suggests a more common occurrence of different sauropod groups in this area.

Caririchnium tracks are distributed on a weathered surface with mud cracks, which only yields ornithopod tracks. Three theropod trackways (NQ-T1–T3) are parallel, and the distances between three theropod trackways are similar. This suggests that the area could have been used as a common passage for theropods that engaged in group activity (McCrea et al., 2014).

Theropod tracks tend to appear on the same surface with sauropod tracks. Such a pattern resembles the Qijiang 'lotus' site and the Houzuoshan site, where surfaces containing ornithopod tracks lack sauropod tracks (Li et al., 2015; Xing et al., 2015c). This may be environment related (ornithopod prefer more humid habitats (Lockley, 1991; Lockley et al., 1994b; Mannion and Upchurch, 2010).

6. Results and conclusions

The use of drones in the exploration and documentation of track surfaces in steep terrain, make us can get provides a general overview and map of the track surface quickly. Details of tracks are relatively distinct on the photographs. The photos taken from different angles by the drones can be used for photogrammetry. However, a precise study still needs direct examination and documentation by classical outline drawings, especially tracks shorter than 20 cm in length or extremely shallow tracks.

1) Rapid investigations of tracks (especially those larger than 20 cm) preserved on vertical or prohibitively steep surfaces are made more effective via the use of drone technology. In some cases, rock climbing may be too time-consuming or dangerous, or the quality of tracks preserved may not warrant such effort. Here we can use drones to take images and produce track distribution maps by image processing software. For well-preserved tracks, images taken by drones can also be used for making 3D topographical reconstructions (via photogrammetry), even if the quality of documentation and clarity of details does not reach the level of a careful manual use of the camera.
2) The Nanquan site reveals multiple track-bearing layers dominated by sauropod tracks assigned to the ichnogenera *Brontopodus* and *Parabrontopodus*. Theropod tracks, cf., *Grallator* and ornithopod tracks *Caririchnium* have also been recorded but only at one horizon in each case.

3) The Nanquan site is one of several in the Dasheng Group belt that is evidence of the high abundance of dinosaur tracks in this region of Shandong Province, were many important sites have recently been described. This is in contrast to other sites which are theropod dominated. The Nanquan site indicates a local predominance of sauropod activity for an extended period of time.

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