

## Tetrapod track assemblages from Lower Cretaceous desert facies in the Ordos Basin, Shaanxi Province, China, and their implications for Mesozoic paleoecology



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### ARTICLE INFO

#### Keywords:

Ichnofacies

*Brasilichnium*

*Sarmientichnus*

Dromaeosaurs

Ichnotaxonomy

### ABSTRACT

Tetrapod ichnofaunas are reported from desert, playa lake facies in the Lower Cretaceous Luohe Formation at Baodaoshili, Shaanxi Province, China, which represent the first Asian example of an ichnofauna typical of the *Chelichnus* Ichnofacies (*Brasilichnium* sub-ichnofacies) characteristic of desert habitats. The mammaliform tracks, assigned to *Brasilichnium*, represent the first report of this ichnogenus from Asia. The assemblages also contain three different theropod trackway morphotypes: one very wide *Magnoavipes*-like morphotype, one relatively wide, broad-toed, small *Eubrontes*-like form with short steps and strides, and wide straddle, and an elongate morphotype (*Sarmientichnus*) with longer steps and narrower straddle representing a didactyl trackmaker, the latter being the first example of the enigmatic ichnogenus found outside its type area in Argentina. The *Sarmientichnus* occurrence, the first in Asia, has important implications, demonstrating that the trackmaker was not monodactyl, but didactyl with probable affinities to deinonychosaurs which are ichnologically well-represented in the Lower Cretaceous of Asia. Although morphologically distinctive, *Sarmientichnus* should be recognized as a “form” ichnotaxon compromised by suboptimal preservation. The combination of *Brasilichnium* isp., *Sarmientichnus* isp., and tridactyl theropod tracks, indicates mammaliforms and small theropods, and is comparable to ichnofaunas from similar desert facies on other continents. Thus, Cretaceous desert ichnofaunas from China are consistent with global ichnofacies predictions.

### 1. Introduction

Most tetrapod track assemblages from desert deposits are highly distinctive and representative of dune ecology and paleoecology. However, desert sedimentary facies, *sensu lato*, are variable typically including both eolian, dune, and associated interdune or playa lake facies, which are typically associated with localized flooding and the deposition of ephemeral lake deposits. Krapovickas et al. (2016) for example recognized three “desert landscape units”: i) eolian dunes, interdunes and sand sheets, ii) wet interdunes, and iii) playa lakes.

Late Paleozoic through Cenozoic dune deposits are generally dominated by tracks of arthropods (insects and arachnids), small reptiles and mammals or protomammals. Ichnologists have remarked on

the similarities between Late Paleozoic, Mesozoic (Lockley et al., 1994; Lockley and Hunt, 1995; Hunt and Lucas, 2007) and even Cenozoic dune ichnofaunas (Lockley et al., 2007), which have been characterized as the *Chelichnus* ichnofacies (Hunt and Lucas, 2007; Krapovickas et al., 2016), and also as the *Octopodichnus* or *Octopodichnus-Entradichnus* ichnofacies (Krapovickas et al., 2016). These two ichnofacies are essentially synonymous (Lockley et al., 2007a, 2007b) and more or less co-extensive with desert sand dune (erg) deposits. Thus, differences are mainly semantic, the former using a label based on a vertebrate ichnogenus, the latter based on an invertebrate.

The generalized notion of desert, dune or eolian ichnofaunas and ichnofacies may implicitly include local interdune subfacies in which track assemblages may differ in composition: i.e., “interdune” implies

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within the larger dune or eolian systems (McKee, 1979). There are few formations of predominantly eolian origin that are comprised entirely of dune deposits, without some units of interdune origin (McKee, 1979).

Generally speaking Paleozoic expressions of the *Chelichnus* ichnofacies, well represented in the western USA, are dominated, by the tracks of small protomammals (synspsids) and arachnids (e.g., Lockley et al., 1994) with rare lizard-like (lacertiform) tracks (Haubold et al., 1995). Mesozoic examples of the *Chelichnus* ichnofacies, well represented in North and South America, are characterized by relatively abundant synspsid tracks (*Brasilichnium*), arachnid tracks and footprints of small theropod dinosaurs (Lockley and Hunt, 1995; Hunt and Lucas, 2007; Leonardi, 1981, 1994). These ichnofaunas have been characterized as the *Brasilichnium* ichnofacies, (Lockley et al., 1994, 2004a; Lockley, 2007) which Hunt and Lucas (2007) regard as a subset of the *Chelichnus* ichnofacies, labelled the *Brasilichnium* ichnocoenosis. Cenozoic “eolian” deposit ichnofaunas, also labelled as *Chelichnus* ichnofacies have also yielded abundant small mammal tracks in association with insect trails (Lockley et al., 2007). Krapovickas et al. (2016) proposed five phases of colonization of desert paleoenvironments throughout the Phanerozoic of which the first two predate the colonization of continental interiors by tetrapods. This study, while important in recognizing “recurrent patterns” and the diversity of desert paleoenvironments, focused mainly on invertebrate traces, many of which represent infauna. In contrast, with the exception of tetrapod burrows, most tetrapod traces are epifaunal trackways.

Here we describe tetrapod track assemblages reported from dune and interdune facies developed in the Lower Cretaceous (Barremian) Luohe Formation of Shaanxi province, China (Li, 2017). The assemblage, described here from the Cretaceous “eolianites” in Shaanxi Province China, provide only the second report of *Sarmientichnus*, which, as in Argentina, co-occurs with theropod and small mammal tracks. This makes the Shaanxi ichnofauna exceptional for several reasons. Not only is it a Cretaceous example of an assemblage most similar to ones previously known only from the Jurassic, it is also the first such association from Asia, and the first Asian ichnofauna to be compared closely with the eolian ichnofacies: i.e., the *Chelichnus* ichnofacies. Moreover, we present evidence that ichnogenus *Sarmientichnus* is attributable to a deinonychosaurid trackmaker. This interpretation has both ichnotaxonomic and paleobiological implications for our understanding of the distribution of deinonychosaurian trackmakers and track preservation potential in space and time.

## 2. Geological setting

The Ordos Basin, a large depositional basin in central and western China occupying an area up to 90,000 km<sup>2</sup>, contains a relatively complete Phanerozoic stratigraphic sequence, with only Silurian and Devonian strata missing. In the center and western part of the basin, continental deposits more than 1000 thick formed in Early Cretaceous times (Xie et al., 2005). These rocks belongs to Zhidan Group and can be primarily divided into the Yijun, Luohe, Huachi, Huanhe, Luohandong and Jingchuan formations from bottom to top (Ma, 1998). The tracks described here come from the Luohe Formation, part of a large continental “red bed” sequence detailed below.

An important vertebrate fossil assemblage, known as the *Psittacosaurus* Fauna, occurs in the Jingchuan and Luohandong formations of the Ordos Basin. The following taxa are present: *Cheloniosaurus leios* (Brinkman and Peng, 1993a), *Sinemys gamera* (Brinkman and Peng, 1993b), *S. brevispinus* (Tong and Brinkman, 2013), choristoderes *Ikechosaurus sunailinae* (Brinkman and Dong, 1993), crocodyliformes *Shantungosuchus hangjinensis* (Wu et al., 1994), cf. *Theriosuchus* sp. (Wu et al., 1996), pterosaur Dsungaripteridae (Ji et al., 2017), Cerapoda *Psittacosaurus neimongoliensis*, *P. ordosensis* (Russell and Zhao, 1996), stegosaurs *Wuerhosaurus ordosensis* (Dong, 1993), ankylosaurs *Ankylosauria* indet. (Ji et al., 2016), sauropod cf. *Euhelopus* sp. (Hou et al., 2017), theropod *Sinornithoides youngi* (Russell and Dong,

1993; Currie and Dong, 2001), large size theropod teeth and *Dromaeosauridae* teeth (Ji et al., 2017), avian *Otogornis genghisi* (Hou, 1993), *Cathayornis chabuensis* (Li et al., 2008a), primitive mammal *Hangjinia chowi* (Godefroit and Guo, 1999).

Articulated or complete vertebrate fossils from the Ordos Basin are very rare, making species abundance and distribution difficult to determine for this Early Cretaceous fauna. Therefore, abundant trace fossils playing an important role in improving understanding of the ecology of the vertebrate record. There are about 17 tracksites located within the Luohandong and Jingchuan formations with over 1000 trackways reported, including saurischian tracks including the non-avian theropod tracks *Chapus* and *Asianopodus*, the sauropod track *Brontopodus* and the bird (avian theropod) track *Tatarornipes* (Li et al., 2009, 2011; Lockley et al., 2002; Lockley et al., 2011a; Lockley et al., 2014a, 2014b, 2014c). In addition, there are also non-avian theropod tracks, *Jialingpus*, reported from the Luohe Formation in Xunyi County at the southern margin of Ordos Basin (Xing et al., 2014).

Between September and November 2017 a survey of Danxia landforms terrain defined below (Peng, 2001), was undertaken in the study area in northern Shaanxi, by scientists from the Shaanxi Geological Survey Center. They found many dinosaur and other tetrapod tracks in the Luohe Formation near Zhongji Town, Shenmu City, at the northeast margin of Ordos Basin (Figs. 1, 2). These tetrapod tracks form assemblages (ichnofaunas) of a type never previously found in China, and therefore have important paleoecological and ichnofacies implications. Tang et al. (In press) briefly described these tracksites, but did not provide morphologic details of the ichnites.

## 3. Stratigraphic context

The Luohe Group was established by Clapp and Fuller (1926) and originally called the Luohe Sandstone, being defined as a loose massive medium-grained cross-bedded sandstone, pink, pale yellow or bright red in color. The studied section is that of (Clapp and Fuller, 1926). The type section is beside the Luohe River, 40–55 km southeast of Yan'an City, and extends northwest to an area near the Great Wall (Clapp and Fuller, 1926). Ma (1998) redefined the Luohe Formation as a stratigraphic sequence above the Anding Formation (or Yijun Formation) and below the Huanhe Formation or Pleistocene strata. The unit comprises purple or gray purple thick-to-medium grained arkose interbedded with siltstone and mudstone with locally interbedded conglomerate and shale. Large cross bedding can be seen in the sandstone layers (Fig. 3), often indicating alternating paleowind directions (Jiang et al., 2001).

In the present study area in the northeast margins of the Ordos Basin, the Luohe Formation is ~63.8 m thick and generally shows an angular unconformity with the Middle Jurassic Anding Formation below (Fig. 3B). Locally such angular unconformity is not discernable and the contact appears conformable. The Luohe Formation primarily comprises medium-fine grained arkose interbedded with fine sandstone, siltstone or brick red silty mudstone which represent an alternation of eolian and playa lake deposits of the type described by Jiang et al. (2001, 2004), and discussed below.

In China such red bed sequences have been referred to as Danxia landforms and defined, geomorphologically, as “red-colored sandstones and steep cliffs... developed through long-term erosion [which have] in recent years... been receiving international attention, [where] six examples in China became [part of] a UNESCO World Natural Heritage [site] in 2010” (Zhang et al., 2011). According to Peng (2001), Huang and Chen (2003) and Qi et al. (2005) good examples of Danxia landforms exist in northwestern China (Gansu and Shaanxi provinces). Most represent Cretaceous deposits.

The geology of the Luohe Formation in the Danxia landform landscapes of northern Shaanxi Province (Fig. 1) has been described in some detail by Jiang et al. (2001) with attention to paleowind indicators. These authors measured more than 125 foreset orientations indicating

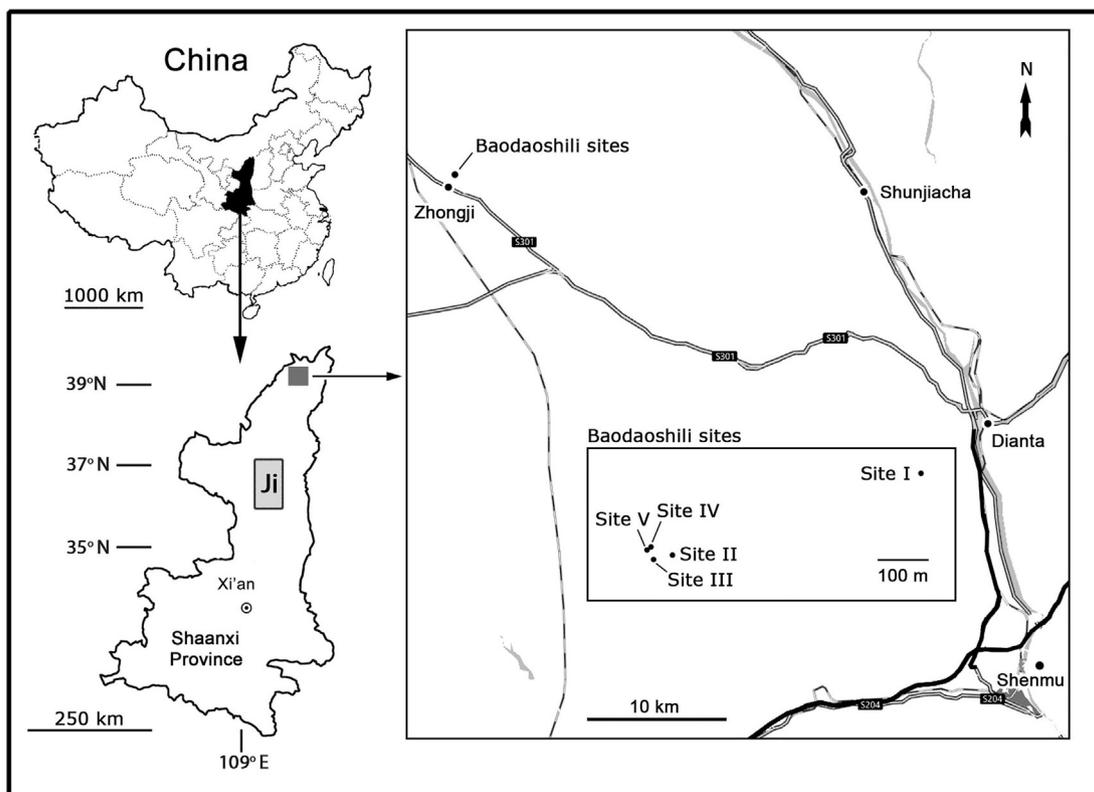


Fig. 1. Geographical setting showing the location of the Baodaoshili sites in northernmost Shaanxi Province, China. Area marked “Ji” indicates study area of Jiang et al. (2001).

alternating westerly and northeasterly wind directions in the early phases of Luohe Formation deposition giving way to predominantly westerly winds in the later stages. In a subsequent paper (Jiang et al., 2004, p. 729) described the Luohe Formation as representing an “eolian dominant” period with a duration representing at least the first, half (eolian half) of a ~1 Ma “I–grade” desert-lake cycle in which at least three-four  $10^3$ – $10^5$  a, II-grade “draa-wet-interdraa” cycles were identified. Draa can be taken to mean large scale accumulation of eolian sand as in the original definition of Wilson (1973).

Based on *Estheria* records, from local playa lake facies, Li (2017) suggest that the lower part of the Zhidan Group, is broadly correlative with the Barremian Yixian Formation of western Liaoning (Chen, 1988; Wan et al., 2013), with the Yijun, Luohe and Huanhe formations yielding a middle Jehol biota.

Thus, the Ordos Basin is dominated by desert deposits interbedded with multi-layer fluvio-lacustrine deposits, suggesting repeat desert expansions and retreat during the Cretaceous. The Luohe period represented the first heyday of desert deposition /expansion in this basin during the Cretaceous (Xie et al., 2005; Jiang et al., 2001, 2004). The horizontal bedding, low angle oblique bedding, mud cracks and raindrop imprints at these tracksites imply a shallow desert lake facies deposit (Tang et al. (In press)) with an eolian-dominant setting, where eolian dunes interfinger with interdune sand sheets (sensu Krapovickas et al., 2016). Generally, the Ordos Basin was arid at this time and

dinosaurs and other animals likely gathered near desert shallow lakes.

#### 4. Tracksite description

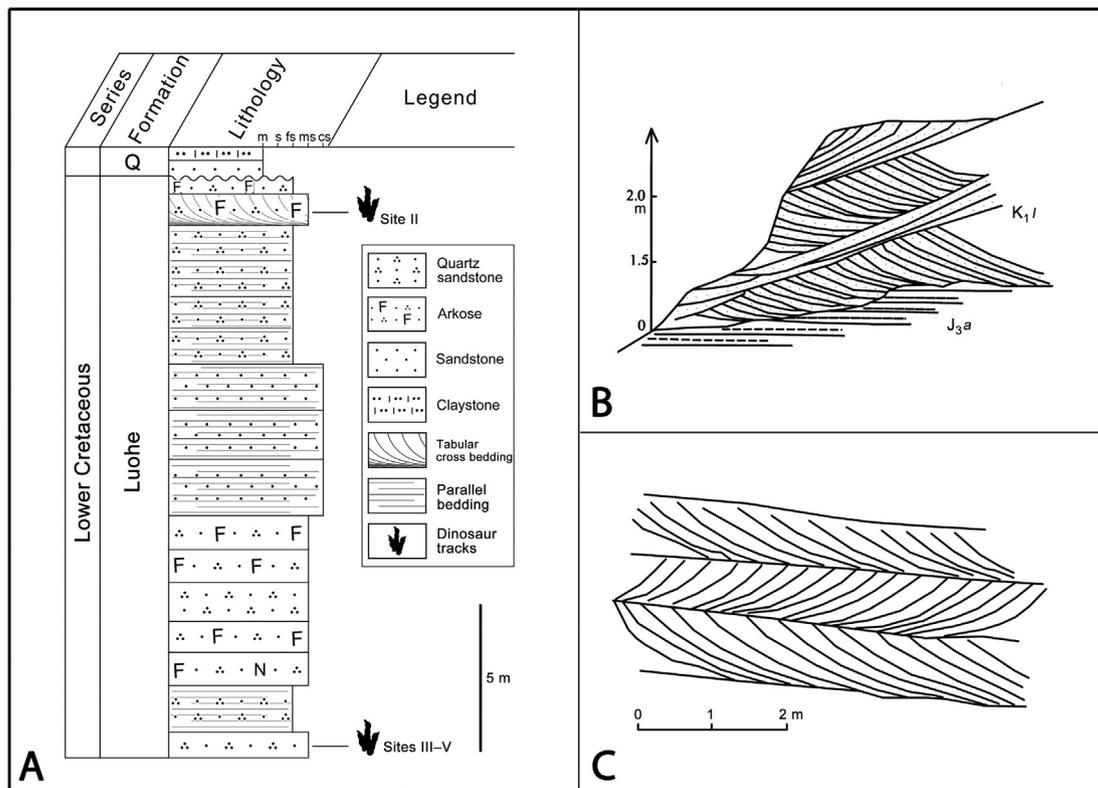
Tracks found in the Zhongji Town area are distributed along the east bank of Gonggegou reservoir in Baodaoshili Village. There are three dinosaur tracksites and two small tetrapod tracksites (Figs. 1 and 2) within the 30 km<sup>2</sup> of the Danxia landform landscape.

Site I (GPS: 39°10′28.82″N, 110° 2′50.81″E) yielded two tracks (Fig. 4) from the thin layer of argillaceous siltstone near the base in the lacustrine facies of the upper Luohe Formation. The track-bearing layer also reveals mud cracks.

Sites II–V are located in purple-red, thin-bedded medium-fine grained quartzose sandstone layers in playa facies of the upper Luohe Formation. Site II (GPS: 39°10′13.49″N, 110° 2′13.46″E) yields 21 tri-dactyl tracks (Fig. 5) and has hail and raindrop imprints in the track-bearing layers. Site III (GPS: 39°10′12.58″N, 110° 2′10.67″E) and Site V (GPS: 39°10′13.66″N, 110° 2′9.23″E) yield tracks made by small quadrupeds (Figs. 6 and 7). To date, Site IV (GPS: 39°10′14.05″N, 110° 2′9.78″E) has yielded 16 didactyl tracks (Figs. 4, 7 and 8) and has shallow current ripples, hail marks, raindrop imprints and invertebrate traces in the track-bearing layers.



Fig. 2. Photograph of Baodaoshili site III–V. Sites III and V yielded mammalian trackways (*Brasiliichnium* isp.) from different layers, Site IV yielded the didactyl trackway (*Sarmientichnus*) BT-DT2.



**Fig. 3.** A: Stratigraphic section showing position of track-bearing levels from Baodaoshili Sites, (F = feldspathic); B: schematic rendering of the stratigraphic relationship between Upper Jurassic Anding Formation ( $J_3a$ ) and the Lower Cretaceous Luohe Formation ( $K_1l$ ), near tracksite; C: shows alternating foreset directions attributed to alternating paleowind directions.

## 5. Methods

The low inclination of beds ( $\sim 10\text{--}20^\circ$  dip), at the main tracksite where sites III–V are located (Fig. 2), facilitated close access to the tracks and the making of chalk outlines, tracings, photographs and selected latex molds. Once outlines of the tracks over the whole outcrop had been chalked, five large sheets of transparent plastic were used to trace most of the trackway segments. All transparent plastics are scanned and made into an overall tracksite distribution map.

We obtained the following measurements of pes imprints and trackways: Track length and width, rotation, pes - pes pace angulation, step, stride and inner and outer trackway width. Trackways were numbered BD-T, and BD-R with “BD” indicating the Baodaoshili tracksite, “T” the theropod trackmaker, and “R” the early reptile/quadrupedal trackmakers. In the case of these quadrupedal trackmakers it is possible to estimate the glenoacetabular or body length using the method of Leonardi (1987) (Fig. 6).

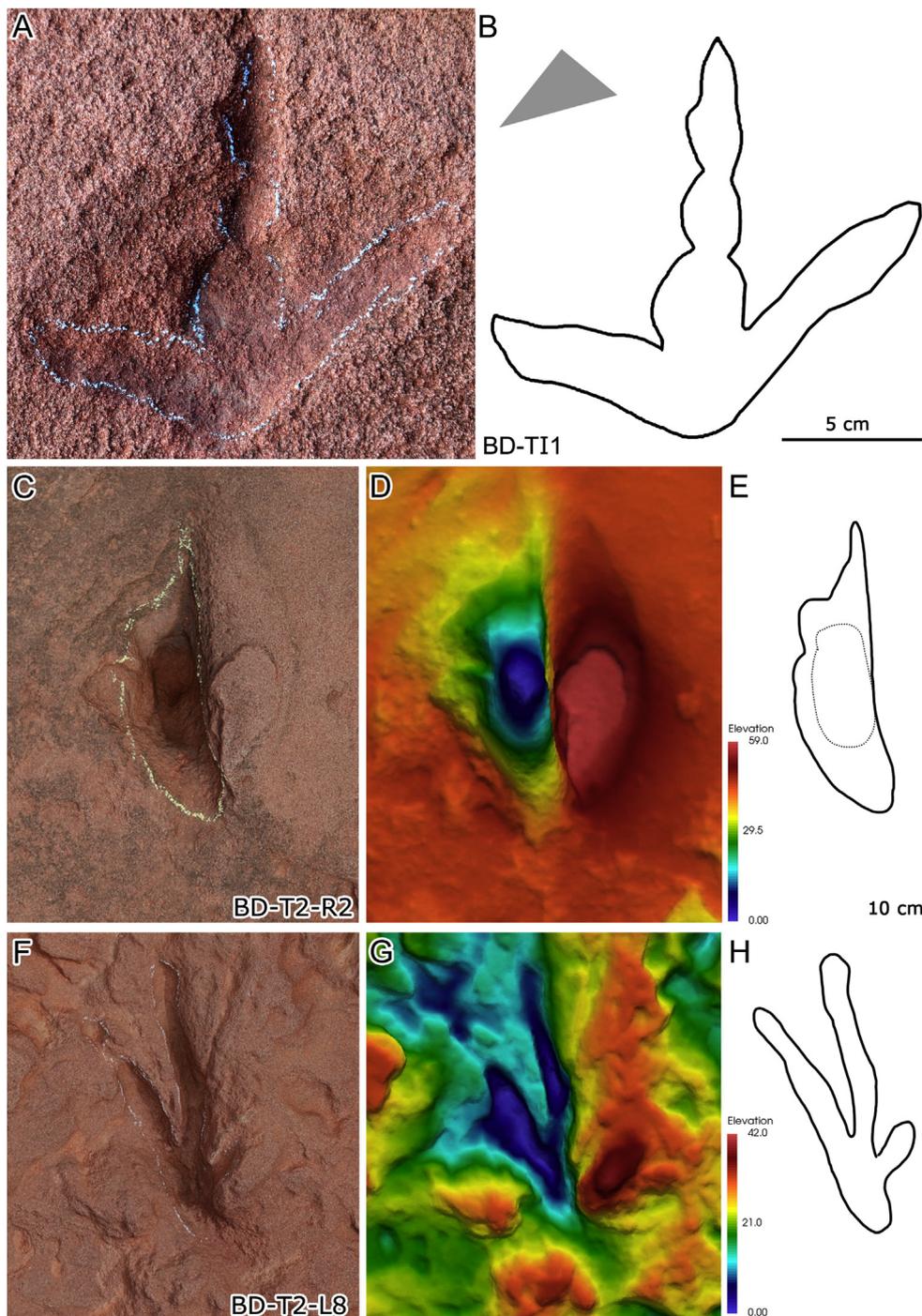
Two well-preserved in-situ didactyl theropod tracks BD-T2-R2 and BD-T2-L8 were digitally photographed (18 and 17 photographs respectively) from various perspectives under natural lighting conditions using a Canon EOS 5D Mark III. Photographic jpg image files were added to Agisoft Photoscan Professional Edition (version 1.2.6 build 2038 64 bit) to generate a scale-corrected model with sub-millimetre resolution (0.34 and 0.29 mm average linear distance between points respectively) following the procedure adapted from Romilio et al. (2017). The model was positioned to the centre 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 depth.

## 6. Description of trackways

### 6.1. Tridactyl tracks

The tridactyl dinosaur tracks described here include a continuously preserved trackway segment of a medium sized theropod with 21 footprints (20 paces = 10 strides) designated as BD T1 (tracks R1–R11) from Site II: Fig. 5. The tracks have mean lengths and widths of 13.3 cm and 9.5 cm respectively (L/W ratio = 1.4): Table 1. Step and stride lengths average 29.7 cm and 57.3 cm with a mean pace angulation of  $154^\circ$ . The mean digit divarication (II–IV) is  $72^\circ$  and the trackway shows a marked turn to the left after track R7. As shown in Fig. 5 the distal traces of digit III turn inward as is typical of many theropod tracks (Thulborn, 1990). The tracks resemble small *Eubrontes* isp., but this identification is tentative.

An isolated tridactyl track was recovered from Baodaoshili Site I (Fig. 4 top), and designated as BD-TI1. The track is 14.5 cm long and 15.8 cm wide (L/W = 0.9) with slender digit traces a wide divarication ( $\sim 110^\circ$ ). The digit III trace shows three phalangeal pad traces typical of theropods. Although similar in size to the tracks in trackway BD-T1, the morphology is quite different. Tracks with wide digit divarication and slender digit traces characterize ichnogenera like *Ornithomimipus*, *Irénichnites*, *Columbosauripus* (Sternberg, 1926, 1932) and *Magnovipes* assigned to ichnofamily Ornithomimipodidae (Lockley et al., 2011b). The track is close in size, shape and L/W proportions to all three of the latter ichnogenera, and differs only in having the digit traces more strongly impressed and connected in the heel area: compare Fig. 4 with Lockley et al. (2011b, Fig. 9). We therefore tentatively label the track *Magnovipes* isp. indet. As discussed below, the implication of this track is that there was an ornithomimid-like trackmaker active during Luohe Formation deposition, and that it was one of at least three theropod morphotypes that inhabited the region at this time.



**Fig. 4.** Photograph (A) and interpretative outline drawing (B) of tridactyl track BD-TI1 from Baodaoshili Site I. Photograph (C, F), 3D image (D, G) and interpretative outline drawing (E, H) of two didactyl tracks from BD-T2 trackway from Baodaoshili Site IV. The gray anterior triangle indicated the weak mesaxony.

## 6.2. Didactyl tracks

The didactyl dinosaur tracks described here, which frequently appear monodactyl include a continuously preserved trackway segment of a medium sized theropod with 21 footprints (20 paces = 10 strides) designated as BD-T2 (tracks L1–R8) from Site IV: Figs. 6–7. The tracks have mean lengths and widths of 15.4 cm and 4.8.5 cm respectively (L/W ratio = 3.3): Table 1. Step and stride lengths average 51.8 cm and 103.4 cm with a mean pace angulation of 177°. Only three tracks show any sign of slight digit divarication, giving a low average of 24°.

## 6.3. Comparison of tridactyl and didactyl tracks and trackways

Almost every feature of trackways BD-T1 and BD-T2 is different, except that based on footprint length the trackmakers were similar in size (FL 13.3 and 15.4 cm respectively). The trackmaker of BD-T1 was clearly tridactyl with a relatively wide footprint (L/W 1.4) and short step (29.7 cm) which averaged  $2.23 \times FL$ , with a correspondingly wide straddle (low pace angulation = 154°). In contrast the trackmaker of BD-T2, appears to have been didactyl with a much narrower footprint (L/W 3.3) and a longer step (51.8 cm) which averaged  $3.36 \times FL$ , with a correspondingly narrow straddle (pace angulation 177°). In short, the BD-T1 trackmaker created a much narrower trackway than the BD-T2

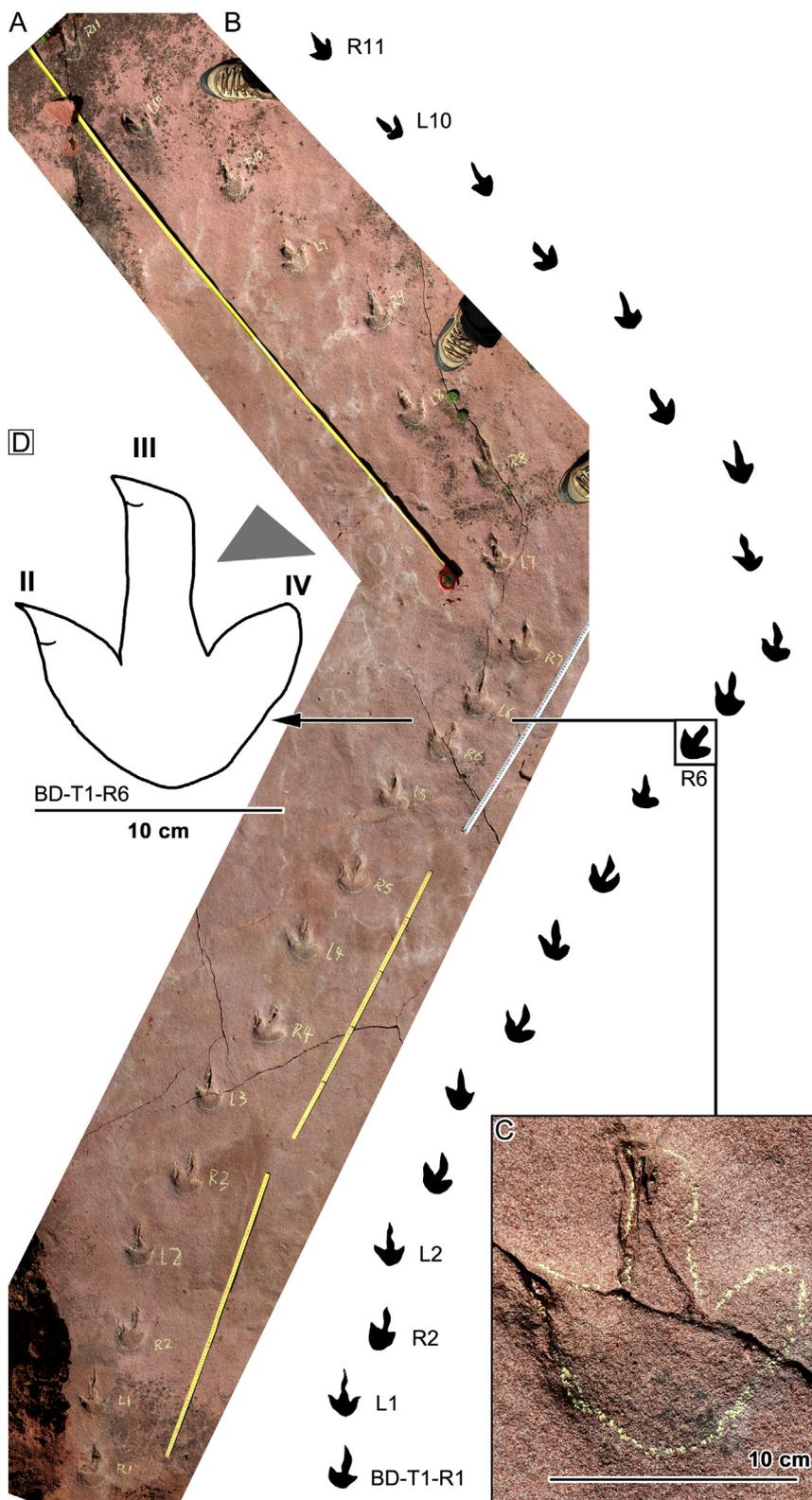
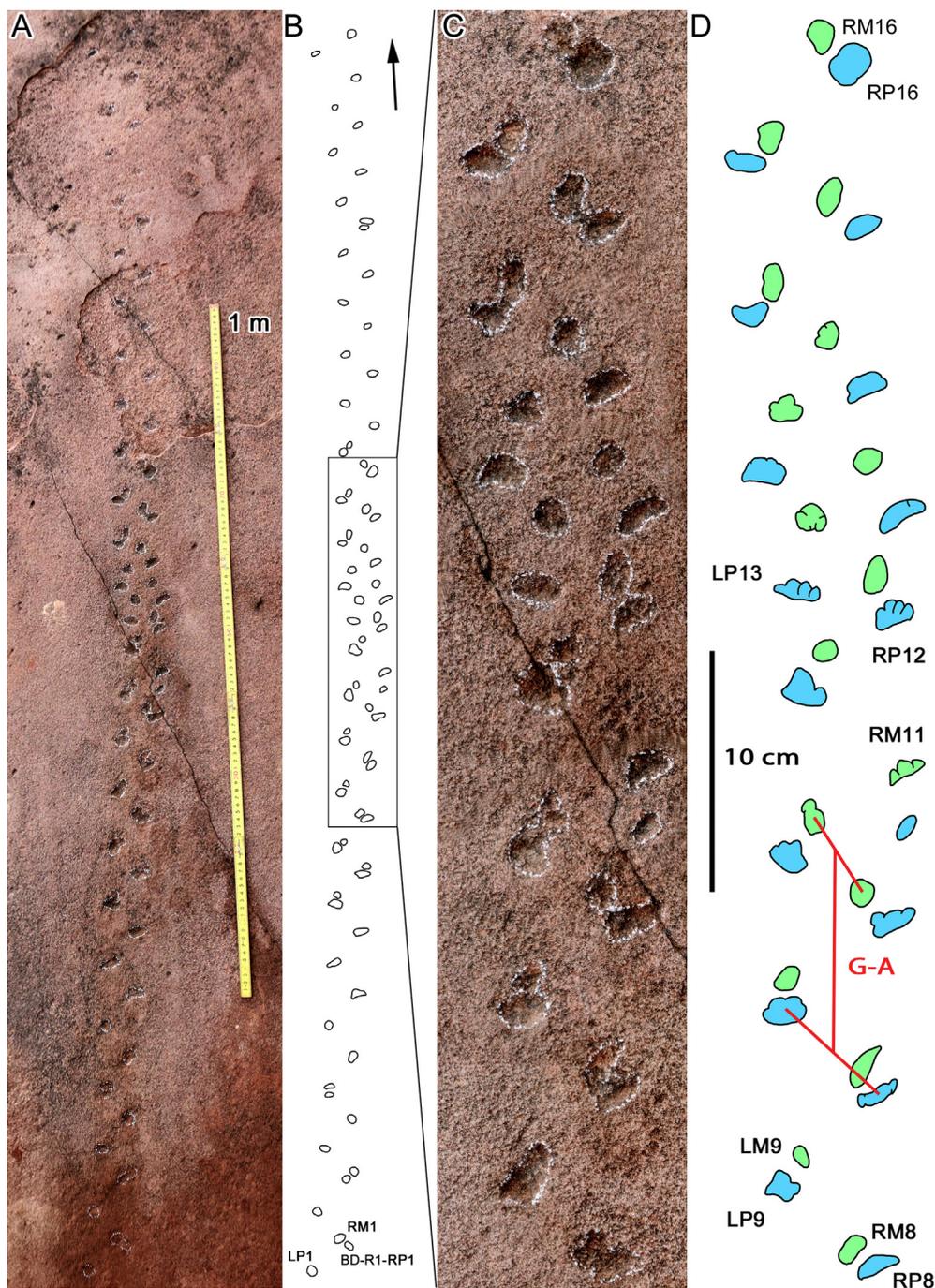


Fig. 5. Photographs (A, C) and Interpretative outline drawings (B, D) of theropod trackway BD-T1 and the well-preserved BD-T1-R6 from Baodaoshili Site II. The gray anterior triangle indicated the weak mesaxony.

trackmaker with steps averaging 50% longer. This could in part be a behavioral difference related to speed, but given the apparent differences in foot morphology the differences appear to also reflect trackmaker foot anatomy. However, as discussed below the differences due

to substrate must also be considered, especially in the case of BD-T2, labelled *Sarmientichnus* isp., which appears to represent a functionally monodactyl trackmaker (see Table 2).



**Fig. 6.** Photographs (A, C) and interpretative outline drawings (B, D) of the mammalian trackway *Brasilichnium* isp. BD-R1 and the well-preserved BD-R1-RP8 to RP16 from Baodaoshili Site III. D also shows estimated glenoacetabular (G-A) distance based on the methods of Leonardi (1987), here shown as red line parallel to trackway axis, which connects the mid-points between left and right manus and pes tracks made in same step cycle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

#### 6.4. Quadruped tracks

The trackway shown in Fig. 8 consists of an almost continuous series of 25 partial or complete left manus-pes sets, and the same number of right manus-pes sets. The central part of the trackway, between LM 7 and LM17 shows a continuous sequence of steps in which manus and pes tracks are clearly differentiated. However the proximal part of the trackway (between LP1 and RP6) as well as the distal part (between RP 17 and RP 25) is less complete with the smaller manus tracks not consistently visible in all steps.

Some pes tracks show short, indistinct toe traces, (e.g., RM11, shows

3 toe traces and RP12 and LP 13 each show 4) but in general these are not discernable. Most tracks are about as wide or wider than long (mean pes L and pes W, 1.1 cm and 1.6 cm respectively: L/W 0.78; mean manus L and W 1.0 and 1.3 respectively L/W 0.81). Manus and pes pace angulation is high (69° and 90° respectively). Step and strides short: 5.4 and 6.2 cm for pes and 4.2 and 6.2 cm for manus.

In addition to Trackway BD-R1 we have identified four other trackway segments (Fig. 6) assigned to *Brasilichnium*. The longest of these trackways, designated BD-R2 has pes tracks 2.2 cm long and 2.8 cm wide (L/W 0.79), with manus tracks 1.6 cm long and 2.0 cm wide (L/W 0.80). Thus, it represents a trackmaker with feet with similar

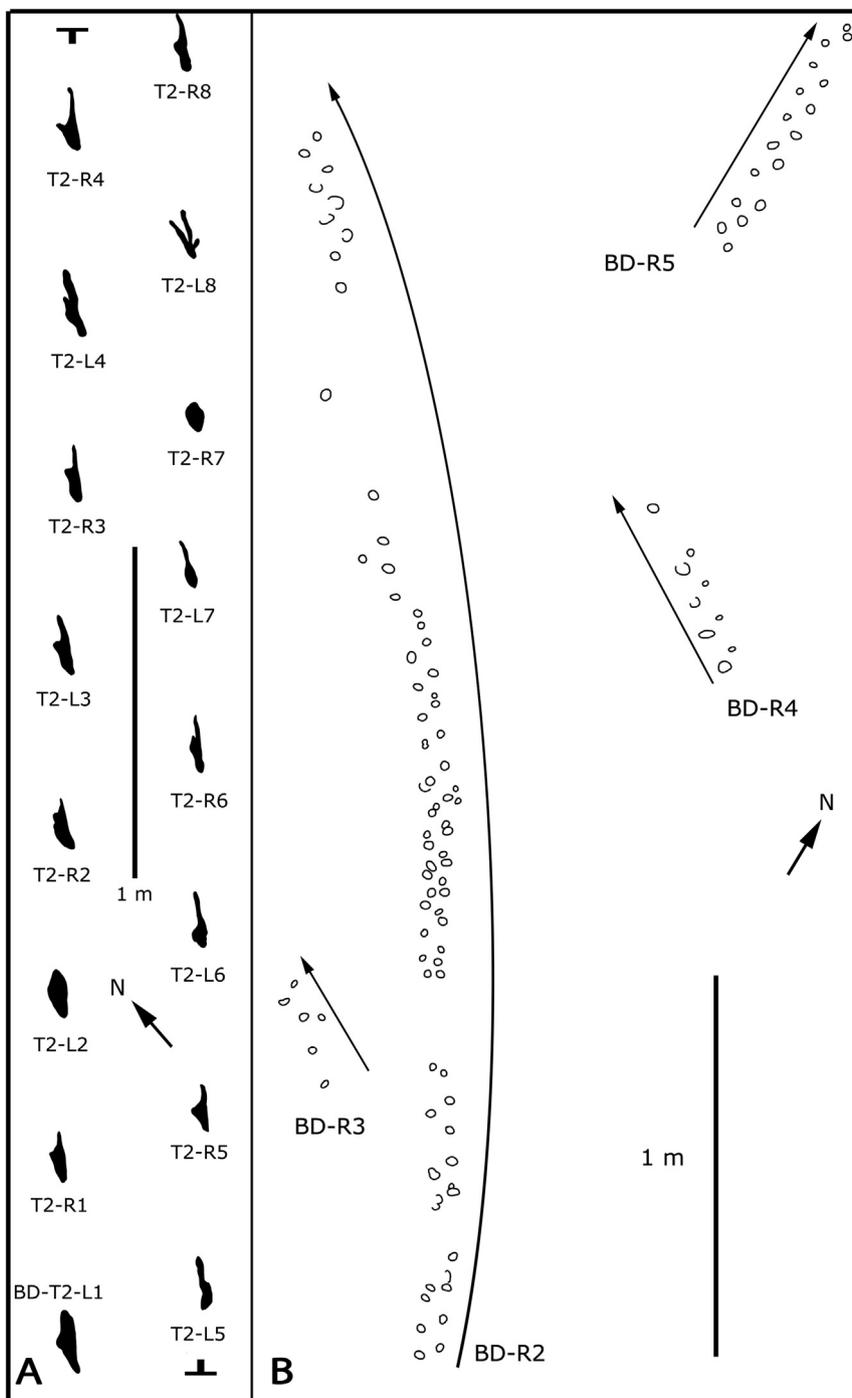


Fig. 7. Interpretative outline drawings of the didactyl trackway BD-T2 of Baodaoshili Site IV and the mammalian tracks BD-R2–R5 of Baodaoshili Site V.

proportions to the BD-R1 trackmaker but on average 71% larger (range of size difference is 57–100% depending measurement used).

### 6.5. Track database

The aforementioned tracks and trackways compile into a small database (crude census) of the total number of track making individuals active in the area, at two different times, represented by two different stratigraphic levels (Fig. 3A). This total amounts to three theropod individuals, each apparently representing a different morphotype, and up to five mammalian trackmakers. Two of the mammalian trackmakers were demonstrably different individuals based on size differences. Thus, a total of up to eight individuals registered tracks,

and these represent a diversity of four types (3 theropods and 1 mammalian). Based on tracks the theropods can all be described as medium sized and the mammalian as small.

## 7. Discussion

### 7.1. Implications of Luohe vertebrate track assemblages

In order to fully understand the significance of the Shaanxi assemblages described here, it is necessary to introduce two topics. The first is specific, and deals with Argentinian track assemblages from the Matilde Formation which are among the most distinctive and interesting currently known from the Mesozoic. The assemblages include three rare

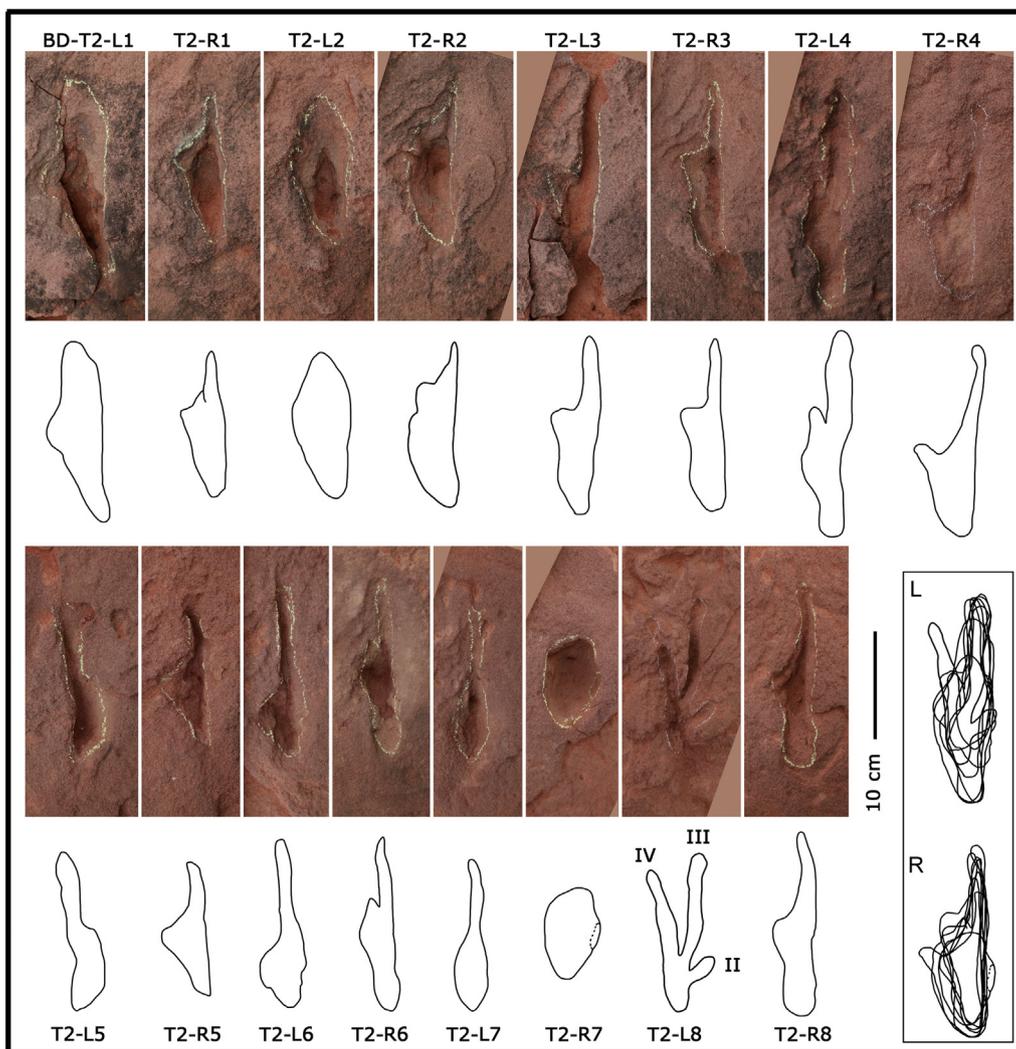


Fig. 8. Photographs and interpretative outline drawings of the didactyl trackway BD-T2 of Baodaoshili Site IV. Bottom right shows multiple overlays of track outlines.

ichnotaxa, originally described by Casamiquela (1964) that remain rare or virtually unknown after more than 50 years of advance in the study of tetrapod tracks. These tracks include the exceptionally well-preserved mammalian track *Ameghinichnus patagonicus* Casamiquela, 1964, and the purported small dinosaur tracks *Sarmientichnus scagliai* Casamiquela, 1964, *Wildeichnus navesi* Casamiquela, 1964, and *Deltatorrichnus goyenechei* Casamiquela, 1964. *S. scagliai* is of special interest in this study and to theropod ichnotaxonomy in general. The Argentinian assemblage, also includes exquisitely preserved insect tracks (*Hexapodichnus*) described by De Valais et al. (2003) which help constitute what De Valais (2010, p. 28–29) called an ichnofauna “exceptional in both diversity and abundance”... [and] “the most diverse and abundant one coming from rocks of equivalent age anywhere in South America.” The track-bearing layers form part of a volcanoclastic sequence of Middle Jurassic age consisting of “ashfall, reworked tuffs, welded tuffs, tuffaceous siltstones and fine-grained sandstones,” (op. cit., p. 29).

The second relevant topic to our understanding of the Luohe assemblages is the general subject of the desert, but specifically eolian, dune ichnofacies: i.e., *Chelichnus* ichnofacies (Hunt and Lucas, 2007; Krapovickas et al., 2016). This ichnofacies and its component sub-ichnofacies, ichnocoenoses or ichnofaunas such as the *Brasilichnium* ichnofacies (Lockley et al., 1994; Hunt and Lucas, 2007; Lockley, 2007) has been recognized throughout much of the Phanerozoic and much discussed as representative of desert, dune facies paleoecology.

However, it has not previously been recognized or discussed in the context of Asian ichnofaunas.

### 7.2. *Sarmientichnus* ichnotaxonomy revisited

The evidence presented here implies that the *Sarmientichnus scagliai* is an example of an extramorphological ichnotaxon and does not represent a monodactyl trackmaker as originally inferred by Casamiquela (1964). Dinosaurs with monodactyl feet (pes) are not known from the body fossil record. The second implication is that *Sarmientichnus* is likely of deinonychosaurian affinity, representing the only well-known group of dinosaurian trackmakers with didactyl footprints. The third implication is that didactyl deinonychosaurian-like trackmakers registered footprints as early as the Middle Jurassic, at least in Argentina. The fourth implication is that *Sarmientichnus* could be claimed as a subjective senior synonym of other later named ichnogenera proposed to name didactyl deinonychosaurian tracks.

According to Casamiquela (1964) the holotype of *S. scagliai* is represented by a trackway consisting of four footprints (two strides), with footprint lengths (L) and widths (W) of 130 mm and 39 mm respectively (L/W 3.33). De Valais (2010) re-described *Sarmientichnus scagliai* based on a larger sample of 37 tracks comprising 8 trackways. She inferred (op. cit. p. 35) that “the more complete tracks” display digit I and III impressions forming a continuous, single, single linear depression” but does not mention traces of digits II or IV. Given that the angle between

**Table 1**

Measurements of theropod tracks from Baodaoshili tracksite, Shaanxi Province, China.

Number	MLcm	MW cm	II-IV°	PL cm	SL cm	PA°	L/W
BD-T1-R1	15.5	10.2	82	25.5	48.5	148	1.5
BD-T1-L1	15.0	10.0	76	25.0	51.0	153	1.5
BD-T1-R2	14.0	8.5	63	27.5	54.0	146	1.6
BD-T1-L2	15.0	10.3	70	29.0	56.0	159	1.5
BD-T1-R3	13.5	10.2	70	28.0	56.5	150	1.3
BD-T1-L3	13.5	9.5	69	30.5	60.5	180	1.4
BD-T1-R4	12.7	11.0	83	30.0	58.5	159	1.2
BD-T1-L4	13.5	10.0	67	29.5	58.0	165	1.4
BD-T1-R5	13.7	9.2	60	29.0	55.0	158	1.5
BD-T1-L5	12.2	10.5	84	27.0	47.0	180	1.2
BD-T1-R6	12.5	10.0	69	20.0	41.0	162	1.3
BD-T1-L6	13.5	10.0	69	21.5	44.5	115	1.4
BD-T1-R7	13.0	9.5	76	31.0	61.5	165	1.4
BD-T1-L7	13.0	10.0	87	31.0	57.0	124	1.3
BD-T1-R8	14.5	8.5	61	33.5	65.5	143	1.7
BD-T1-L8	14.5	10.0	70	35.5	65.3	138	1.5
BD-T1-R9	13.5	8.0	69	34.5	69.0	166	1.7
BD-T1-L9	12.5	9.0	68	35.0	69.0	156	1.4
BD-T1-R10	12.8	7.0	63	35.5	70.0	156	1.8
BD-T1-L10	11.0	9.0	75	36.0	–	–	1.2
BD-T1-R11	10.5	9.5	77	–	–	–	1.1
Mean	13.3	9.5	72	29.7	57.3	154	1.4
BD-T2-L1	19.5	6.5	–	51.0	98.0	164	3.0
BD-T2-R1	13.5	5.0	–	48.0	98.5	180	2.7
BD-T2-L2	14.0	5.7	–	50.5	103.5	180	2.5
BD-T2-R2	15.0	4.3	–	52.5	105.0	180	3.5
BD-T2-L3	14.5	5.5	21	52.5	105.0	180	2.6
BD-T2-R3	15.7	4.3	–	52.5	107.0	180	3.7
BD-T2-L4	20.5	5.0	–	54.5	107.5	180	4.1
BD-T2-R4	18.5	6.5	32	53.0	103.0	169	2.8
BD-T2-L5	15.0	3.7	–	50.5	105.0	180	4.1
BD-T2-R5	13.0	5.0	–	54.5	105.0	169	2.6
BD-T2-L6	16.0	4.6	–	51.0	104.0	180	3.5
BD-T2-R6	16.0	3.4	–	52.5	93.5	180	4.7
BD-T2-L7	14.5	3.3	–	40.0	98.0	180	4.4
BD-T2-R7	8.7	5.5	–	57.0	115.0	180	1.6
BD-T2-L8	14.5	5.0	20	57.5	–	–	2.9
BD-T2-R8	16.7	3.7	–	–	–	–	4.5
Mean	15.4	4.8	24	51.8	103.4	177	3.3

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.

traces inferred to represent digits I and III is reported as “close to 170°” we take this to mean that the inferred digit I trace is a posteriorly directed hallux. She also mentions that “some tracks display a lateral deformation... of the sediment by the movement of digit III...” She accepted the inference of Casamiquiela (1964) that the tracks are theropodan and noted that some trackways show elongate “straight narrow marks” that “arise from the caudal tips of the footprints” but never from the end of the digit III trace. Nevertheless, they appear to be toe drag marks, which Melchor et al. (2004) considered might have been made by digit II and/or IV, but which De Valais (2010) infers to have been made by digit I. She concluded that no known theropod “has a pedal morphology matching *Sarmientichnus* tracks.” (op. cit. p. 36). These inferences raise two questions: 1) what was the morphology of the *Sarmientichnus* trackmaker foot: i.e., how many digits did it have, and how where they configured, and 2) are the tracks sufficiently well preserved to allow ichnologists to reconstruct foot morphology.

Coria and Paulina Carabajal (2004, p. 394) described *Casamiquielaichnus navesorum*, also from the Middle Jurassic La Matilde Formation, as representing a trackmaker “apparently with mono- or didactyl functional pedal anatomy. Footprint with prominence of central digit and great reduction of lateral digits marks.” The tracks resemble *S. scagliai*, as noted by Coria and Paulina Carabajal (2004), but are smaller (between 29 and 59 mm long), and at the time of their study these

**Table 2**

Measurements (in cm and °) of mammalian tracks from Baodaoshili tracksites, Shaanxi Province, China.

Number	ML cm	MW cm	PL cm	SLcm	PA°	L/W
BD-R1-RP8	0.07	0.19	0.51	0.71	83	0.37
BD-R1-LP9	0.13	0.15	0.56	0.74	86	0.87
BD-R1-RP9	0.06	0.20	0.52	0.71	81	0.30
BD-R1-LP10	0.11	0.18	0.57	0.64	73	0.61
BD-R1-RP10	0.12	0.19	0.50	0.40	47	0.63
BD-R1-LP11	0.14	0.14	0.50	0.69	66	1.00
BD-R1-RP11	0.12	0.06	0.72	0.89	94	2.00
BD-R1-LP12	0.16	0.14	0.48	0.41	55	1.14
BD-R1-RP12	0.14	0.15	0.40	0.42	51	0.93
BD-R1-LP13	0.07	0.19	0.53	0.51	54	0.37
BD-R1-RP13	0.07	0.21	0.58	0.55	58	0.33
BD-R1-LP14	0.10	0.18	0.56	0.63	69	0.56
BD-R1-RP14	0.08	0.17	0.55	0.65	70	0.47
BD-R1-LP15	0.08	0.15	0.58	0.65	70	0.53
BD-R1-RP15	0.13	0.08	0.55	0.68	72	1.63
BD-R1-LP16	0.07	0.17	0.60	–	–	–
BD-R1-RP16	0.18	0.17	–	–	–	–
Mean	0.11	0.16	0.54	0.62	69	0.78
BD-R1-RM8	0.07	0.14	0.44	0.75	115	0.50
BD-R1-LM9	0.06	0.09	0.45	0.74	105	0.67
BD-R1-RM9	0.08	0.2	0.48	0.73	100	0.40
BD-R1-LM10	0.11	0.07	0.47	0.66	101	1.57
BD-R1-RM10	0.1	0.11	0.38	0.55	85	0.91
BD-R1-LM11	0.08	0.14	0.43	0.7	85	0.57
BD-R1-RM11	0.07	0.17	0.59	0.81	111	0.41
BD-R1-LM12	0.1	0.09	0.38	0.56	98	1.11
BD-R1-RM12	0.1	0.16	0.36	0.47	84	0.63
BD-R1-LM13	0.11	0.13	0.34	0.46	76	0.85
BD-R1-RM13	0.1	0.13	0.4	0.53	90	0.77
BD-R1-LM14	0.11	0.13	0.35	0.54	107	0.85
BD-R1-RM14	0.09	0.12	0.32	0.58	102	0.75
BD-R1-LM15	0.08	0.15	0.42	0.59	100	0.53
BD-R1-RM15	0.1	0.17	0.35	0.67	107	0.59
BD-R1-LM16	0.14	0.1	0.48	–	–	1.40
BD-R1-RM16	0.14	0.11	–	–	–	1.27
Mean	0.10	0.13	0.42	0.62	98	0.81

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

authors considered the toe drag traces an important feature which distinguished *C. navesorum* from *S. scagliai*. Interestingly they record angles of divergence between digit traces III and IV, for two tracks from the same trackway, as 20° and 32° (mean 26°) They also include measurements for a third, clearly tridactyl track, from a different trackway which they report as showing an angle of 20° between digits traces III and IV and an angle of 32° between digit traces II and III. However, it should be noted that the Matilde Formation track assemblages include well preserved theropod tridactyl tracks named *Wildeichnus*, and that the track they describe and illustrate as tridactyl might be an example of *Wildeichnus*, not the ichnotaxon they named *C. navesorum*.

De Valais (2010) considered *C. navesorum* a subjective junior synonym of *S. scagliai*, inferring that *Sarmientichnus* remains a monospecific ichnogenus. We agree with this synonymy conclusion supported by de Valais' study of a larger sample of *S. scagliai* with multiple toe drag traces. However, we note that the weight of evidence suggests that *S. scagliai* was not made by a truly monodactyl trackmaker, and that there is evidence to support a didactyl pes morphology. De Valais, does not say this explicitly, but implies the same by synonymizing *C. navesorum* with *S. scagliai* without refuting the claims that the former include traces of digit IV. However, we also stress that both the South America ichnotaxa exhibit sub-optimal preservation as evident from published photographs and comments by Coria and Paulina Carabajal (2004) and De Valais (2010), and the uncertainty about the number and configuration of digit traces.

Given our agreement that *S. scagliai* has ichnotaxonomic priority

over *C. navesorum* (De Valais, 2010), the question arises “Does *Sarmientichnus scagliai* have priority over any other later named didactyl ichnotaxa? In order to demonstrate that *Sarmientichnus scagliai* Casamiquela, 1964 is a valid senior synonym of later named deinonychosaurian trackmakers like *Velociraptorichnus sichuanensis* Zhen et al., 1994, or *Dromaeosauripus hamanensis* Kim et al., 2008, it would be necessary to prove no important or diagnostic morphological differences between these ichnotaxa. In addition, it would be important to show that there are no differences attributable to extramorphological factors: i.e., preservation. It is clear that there is too much uncertainty about the morphology represented by *Sarmientichnus scagliai* tracks to synonymize them with any of the later named ichnotaxa. Moreover, there is abundant evidence that careful study of *Sarmientichnus* burdens it with the label of an extramorphological ichnotaxon, which despite probably representing a didactyl trackmaker, as implied by the synonymizing of *C. navesorum* (Coria and Paulina Carabajal, 2004) with *S. scagliai* (De Valais, 2010) and our use of the label *Sarmientichnus* isp. for the Shaanxi material, type *Sarmientichnus* does not show any completely unambiguous diagnostic features, and for this reason could be considered a *nomen dubium*. Thus, the *Sarmientichnus* label implies extramorphological preservation, not monodactyl trackmaker morphology, and could henceforward be referred to as “*Sarmientichnus*” to identify it as a form ichnotaxon. For this reason, we should not give *Sarmientichnus* priority over later named ichnotaxa in any formal sense. It is however, of paleobiological and paleogeographical interest to use the Shaanxi occurrence to show the possible affinity of *Sarmientichnus* to ichnotaxa of deinonychosaurian affinity.

Apesteguía et al. (2011) reported “probable” large-sized (16.4–28.8 cm long) dromaeosaurid tracks (labelled *Dromaeopodus?* isp.) from the Upper Cretaceous (Campanian) of Bolivia, and raised the question of whether this was the first ichnological evidence dromaeosaurids from South America. If correct the interpretation is consistent with Late Cretaceous records of dromaeosaurid body fossil records from the region. However, without refuting, the claim it is somewhat compromised by the “poor to moderate” quality preservation which these authors admit, in some cases showing the “impressions of digits III and IV joined into a single mark, with no evidence at all of digit II” (Apesteguía et al., 2011, p. 664). Thus, despite being larger than Argentinian and Chinese *Sarmientichnus*, in some cases even these large tracks appear monodactyl. Given that we here consider the possibility that *Sarmientichnus* isp. might be of dromaeosaurid affinity, at least four conclusions arise: i) there may be two dromaeosaurid ichnites (ichnogenera) represented in South America: *Sarmientichnus* from the Middle Jurassic and *Dromaeopodus?* from the Late Cretaceous, ii) no Early Cretaceous dromaeosaurid tracks are known from the region, despite being most abundant during this epoch in other regions, iii) both ichnogenera are poorly preserved and may appear monodactyl, and iv) the dromaeosaurid affinity of these ichnites is uncertain and so open to dispute.

### 7.3. The possible deinonychosaurian affinity of *Sarmientichnus*

Working from the latest studies of *S. scagliai* (De Valais, 2010) we infer that the trackmaker was functionally didactyl. Formal ichnotaxonomic studies of Cretaceous deinonychosaurid tracks recognize four ichnogenera all based on type material from the Lower Cretaceous of Asia. These, with their respective type species, are: *Velociraptorichnus sichuanensis* (Zhen et al., 1994) *Dromaeosauripus hamanensis* (Kim et al., 2008), *Menglongipus sinensis* (Xing et al., 2009) and *Dromaeopodus shandongensis* (Li et al., 2008a, 2008b). In addition, new ichnospecies of *Dromaeosauripus* have been named as *D. jinjuensis* (Kim et al., 2012) and *D. yongjingensis* (Xing et al., 2013a, 2013b), and a new ichnospecies of *Velociraptor* was also named as *V. zhangii* (Xing et al., 2015a, 2015b): see Lockley et al. (2016a) for review. All these ichnotaxa are based on well-preserved trackways most of which show digit proportions and in some cases digital pad impressions quite clearly. In short all these Lower

Cretaceous trackways from Asia, are attributed with a high degree of confidence to deinonychosaurid trackmakers, as are two other Lower Cretaceous track and trackway sites yielding *Dromaeosauripus* isp. indet., from North America (Lockley et al., 2014a, 2016a, 2016b), and a site from Germany that yields unnamed deinonychosaurid tracks (Lubbe et al., 2009; Lockley et al., 2016a). Late Cretaceous deinonychosaurian track reports (Apesteguía et al., 2011; Lockley et al., 2016a) are rare, of questionable quality and outside the scope of this study.

Given this abundance of evidence for deinonychosaurian trackmakers in the Lower Cretaceous of Asia, it is not surprising to find the site reported here from the Luohe Formation of Shaanxi represents another Lower Cretaceous didactyl track occurrence, implying a deinonychosaurian trackmaker. However, in the 16-footprint trackway described here the majority of tracks appear to register only one digit trace (digit III), thus closely resembling *Sarmientichnus* (sensu Casamiquela, 1964; De Valais, 2010) and appearing to represent a “monodactyl” trackmaker. It is only the clearly didactyl track L8 which falsifies this interpretation and indicates, apparently proves, a didactyl trackmaker. This evidence implies the trackmaker was a deinonychosaur with feet consistent with the size and morphology of the trackmakers of various *Velociraptorichnus* and *Dromaeosauripus* ichnospecies.

This evidence helps refute the suggestion that the *Sarmientichnus scagliai* represented a monodactyl trackmaker. It also weakens the original diagnosis of the ichnospecies. As already suggested by the *Sarmientichnus* trackmaker was probably functionally didactyl. Had these authors suggested a deinonychosaurian affinity, they could have claimed the first South American occurrence, before the report of Apesteguía et al. (2011).

Although not explicitly stated by Coria and Paulina Carabajal (2004) and tacitly accepted by De Valais (2010), we infer that the *Sarmientichnus* trackmaker may have carried digits III and IV close together when traversing soft substrates, causing didactyl trackmakers to register digit III and IV traces as a single impression (cf. Apesteguía et al., 2011, p. 664). As noted by Gatesey et al. (1999) theropod dinosaurs adducted their digits towards the mid line (digit III) especially during the kick off or extraction phase of the step cycle when traversing soft substrates.

The question of the affinity of *Sarmientichnus* has already raised many puzzling questions and uncertain inferences: i.e., it could represent a functionally monodactyl, (Casamiquela, 1964; De Valais, 2010) didactyl or tridactyl (Coria and Paulina Carabajal, 2004), or an extramorphological expression of any one of these trackmaker morphologies. If didactyl as inferred here, *Sarmientichnus* likely represents a functionally didactyl Jurassic deinonychosaurian, as the skeletal record would allow (Xu and Zhang, 2005). Postulating a Lower Cretaceous deinonychosaurian trackmaker in this part of China is entirely consistent with the growing deinonychosaurian track record. For example, as reviewed by Lockley et al. (2016a), there is a published record of 10 known deinonychosaurian tracksites in the Lower Cretaceous of China (Xing et al., 2009; Xing et al., 2013a, 2013b; Xing et al., 2015a, 2015b; Xing et al., 2016a, 2016b; Lockley et al., 2016a), to which we must add the present site and a site in Shandong Province (Xing et al., 2018) making a total of 12 Chinese sites from the Lower Cretaceous. Moreover, troodontid fossils have previously been reported from the area (Russell and Dong, 1993; Currie and Dong, 2001), as well as teeth of small dromaeosaur (Ji et al., 2017).

### 7.4. *Brasilichnium*, distribution and mammalian affinities of *Brasilichnium*

*Brasilichnium*, originally named from the eolian Botucatu Formation of Brazil (Leonardi, 1981, 1994; Fernandes and Carvahlo, 2008) has traditionally been attributed to a mammalian morph of unknown taxonomic affinity. The tracks have also traditionally been dated as Jurassic, with the inference that the trackmakers were likely derived therapsids rather

than true mammals (Mammalia). Tracks labelled *Brasilichnium* are abundant in the eolian Botucatu Formation, but absent, rare or little known from other facies. In North America *Brasilichnium* is abundant in the Lower Jurassic eolian formations of the Glen Canyon Group (Lockley, 2011), but unknown or rare in most non-eolian facies, although it may occur in localized interdune or playa deposits within widespread eolian facies (Lockley et al., 2014b, Fig. 15). In short, almost all North and South American occurrences are associated with eolian or dune facies, making it one of the more facies-specific or facies-faithful ichnogenera known. In this regard *Chelichnus*, formerly *Laoporus* in older literature (Gilmore, 1926, 1927, 1928), which is morphologically similar to *Brasilichnium* (Lockley et al., 2004a, 2004b) is also highly facies-specific and almost exclusively found in eolian facies. The Baodaoshili occurrence of *Brasilichnium* is not only the first in China, but also in all of Asia. This is also the first Asian report of an ichnofauna in eolian /desert facies.

As with many track morphotypes from eolian facies, fine detail is often lacking. The detailed morphological differences between the manus and pes in *Brasilichnium* has proven difficult to understand beyond recognizing that the manus is and generally situated anterior to the pes if not overlapped (Lockley, 2011, and references therein). Therapsid body fossils known from the area include the Eutriconodont *Hangjinia* (Godefroit and Guo, 1999).

### 7.5. Paleocological implications

Based on the trackway descriptions presented above, the three theropod ichnotaxa, tentatively labelled (with likely theropod trackmaker groups) as *Sarmientichnus* isp. (deinonychosaurid), small *Eubrontes* isp. (indeterminate theropod), and *Magnoavipes* isp. (ornithomimid-like theropod), the Luohe ichnofauna contained quite a diverse theropod fauna, recognizable from a small sample. Based on the footprint lengths of these trackmakers (15.4, 13.3, and 14.5 cm respectively) they were all relatively small animals. Using a footprint length-hip height ratio of 1:4.5 as proposed by Thulborn (1990) for small theropods these animals stood between only ~60 and ~70 cm at the hip. i.e., they were turkey sized. Likewise, the mammaliomorph trackmakers were small animals no larger than small house cats, with an estimated glenoacetabular length of ~8.5 cm based on the method Leonardi (1987), applied to mammaliomorph trackmakers. Such a track assemblage is consistent with a desert ecosystem dominated by small carnivorous tetrapods. The co-occurrence of *Brasilichnium* isp., a mammaliomorph track, with theropod tracks, including *Sarmientichnus* isp., is strongly reminiscent of the *Brasilichnium* ichnofacies (sensu Lockley et al., 1994), also referred to as the *Chelichnus* ichnofacies (sensu Hunt and Lucas, 2007) and the eolian or evolving desert ichnofacies (sensu Krapovickas et al., 2016), which these authors subdivide into subfacies: i) eolian dunes, interdunes and sand sheets, ii) wet interdunes, and iii) playa lakes. These various facies overlap to varying degrees (Hunt and Lucas, 2007; Lockley, 2007; Krapovickas et al., 2016), and may yield similar tetrapod ichnofaunas.

### 8. Conclusions

The Baodaoshili track assemblages are the first reported from an “eolian dominant” desert facies in China, and in fact from all of Asia. Some of the localized track-bearing layers may be classified as interdune or playa deposits. However, the co-occurrence of *Brasilichnium* isp., a mammaliomorph track, with theropod tracks, including *Sarmientichnus* isp., is strongly reminiscent of the eolian, dune or desert ichnofacies, referred to by some authors as the *Brasilichnium* ichnofacies or the *Chelichnus* ichnofacies.

The occurrence of *Sarmientichnus* isp., previously described as a monodactyl track, is the first report beyond the *Sarmientichnus* type locality in the Jurassic of Argentina. However, it is well known that the preservation of this ichnotaxon in the type area is suboptimal, and

difficult to understand. Moreover, as we show here, the trackmakers were didactyl at least in the case of the Chinese occurrences and some of the Argentinian sites, and so most likely of deinonychosaurian affinity. This interpretation implies a) that *Sarmientichnus* is an extra-morphological “form” ichnotaxon of dubious utility, b) that didactyl trackmakers were active in the Middle Jurassic in South America, as global body fossil occurrences allow, and c) that we can add the Baodaoshili site, as the 12th deinonychosaurian occurrence, to the growing list of deinonychosaurid tracksites in the Lower Cretaceous of China.

### Acknowledgments

The authors thank Chen Li for their participation in field research. This research was funded the National Natural Science Foundation of China (No. 41790455, 41772008), the Fundamental Research Funds for the Central Universities (No. 2652017215), the State Key Laboratory of Palaeobiology and Stratigraphy (Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences) (No. 173127). We also thank Christian Meyer, University of Basel, and Howard Falcon-Lang, editor for *Palaeogeography Palaeoclimatology Palaeoecology*, who helped improve the manuscript substantially.

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