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Research paper

Dinosaur, bird and pterosaur footprints from the Lower Cretaceous of Wuerhe asphaltite area, Xinjiang, China, with notes on overlapping track relationships

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Abstract

An assemblage with well-preserved dinosaur, bird and pterosaur footprints has been found in deposits of the upper Tugulu Group (Lower Cretaceous) of the Wuerhe asphaltite area (Junggar Basin, Xinjiang, northwestern China). The dinosaur footprints are similar to the theropod ichnogenus *Jialingpus*, and the bird footprints to shorebird-like footprints. The isolated tridactyl imprint of a pterosaur manus resembles the ichnogenus *Pteraichnus*. All morphotypes are also known from another locality in the Junggar Basin, the Huangyangquan tracksite. The different size-classes of theropod footprints are inferred to indicate adult and juvenile individuals. The paleoenvironment was clearly favorable for the co-existence of mixed-age theropod communities, shorebird-like birds, and pterosaurs. An interesting feature is the unusual preservational mode and overlap of footprints that show plastic deformation without fracturing.

Keywords: Wuerhe district; Upper Layer of the Tugulu Group; Lower Cretaceous; Shorebird tracks; Theropod tracks; Pterosaur tracks

1. Introduction

The Wuerhe district is located at the northwestern border of the Junggar Basin. A number of mostly isolated bird and non-avian dinosaur footprints have been found in the Lower Cretaceous Tugulu Group at the Huangyangquan tracksite in this area. The bird footprints are referred to *Koreanaornis dodsoni*, *Goseongornipes* isp., *Aquatilavipes* isp., and *Moguiornipes robusta*. The non-avian dinosaur footprints pertain to cf. *Jialingpus* isp., *Asianopodus* isp., and *Kayentapus* isp. (Xing et al., 2011a). Recent discoveries include *Deltapodus* trackways that can be assigned to thyreophorans (Xing et al., 2013) as well as turtle and pterosaur tracks.

During the subsequent exploration, Mr. Jianfu An, the curator of Moguicheng Dinosaur and Bizarre Stone Museum, discovered another tracksite at an asphaltite mining area approximately 14 km east of the Huangyangquan tracksite. This assemblage also includes dinosaur and bird footprints. Although few in number, the tracks exhibit unusual overlapping phenomena and differ significantly in size from those previously found in the Huangyangquan tracksite.

2. Institutional abbreviations

MGCM = Moguicheng Dinosaur and Bizarre Stone Museum, Xinjiang, China. **MGUH** = Geological Museum,

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University of Copenhagen, Denmark. "**A**" in specimen numbers refers to the asphaltite layer.

3. Geological setting

The Wuerhe asphaltite mine (46°5′6.25″ N, 85°45′49.97″ E, WGS 84) of Karamay covers an area of 0.78 km^2 to the east of Wuerhe, on the edge of the Gurbantunggut Desert. The asphaltite was first discovered by a Russian scholar named Vladimir A. Obruchev in 1905 (Obruchev, 1988). The asphaltite tracksite is located in the asphaltite mining area, at 46°4′46.50″ N, 85°46′1.25″ E, WGS 84 (Fig. 1).

The Tugulu Group along the northwestern margin of the Junggar Basin cannot be divided into subunits as easily as they have been differentiated along the southern and eastern margins of the basin, where, in ascending order, the Qingshuihe, Hutubihe, Shengjinkou, and Lianmuqin formations have been defined. At present, the northwestern outcrops of the Tugulu Group can only be divided into Upper, Grey-green, and Lower layers, none of which are readily correlated with the four formations from the southern and eastern margins of the basin (Academy of Prospecting and Developing, Xinjiang Bureau of Petroleum, 1977, 1996, 1997). The asphaltite tracksite is stratigraphically higher than the Huangyangquan tracksite, pertaining to the Upper Layer of the Tugulu Group of the Lower Cretaceous (Albian, Yu, 1990; ?Aptian–Albian, Maisch et al., 2004). The sediments of the asphaltite tracksite are redder than those of the Huangyangquan tracksite, which probably suggests that the oxidation is more extensive. At the asphaltite tracksite, a succession of fourteen layers with grey sandy mudstones and light green-grey sandstones bordering the mined asphaltite has been documented. The footprints occur at the interface of the first and second layer (Fig. 2).

4. Ichnology

4.1. Theropod tracks

Material

Fourteen natural casts, cataloged as MGCM.A1a, b; 2a, b; 3; 4a–f; 5a, c; 6 from the asphaltite tracksite (Figs. 3–5 and Table 1). These tracks show a significant size range (footprint length ~6.6–15.1 cm), indicating individuals of different sizes or species.

Description

Well-preserved and essentially complete specimens include MGCM.A1b (Fig. 3A, B and 5), MGCM.A4a, and MGCM.A5a (Figs. 4A–D and 5). Other footprints are more or less overlapped or incomplete. In MGCM.A1b, A4a, and A5a the digit III trace is the longest and digit IV is longer than digit II. The phalangeal pad formula is x-2-3-3-x in MGCM.A1b and A4a, with the length and width of the distal pad of digit IV being unusually large. The latter, possibly preservational, feature may account for the digit IV trace apparently having 3 rather than 4 digital pads in these two tracks, in contrast to the more typical x-2-3-4-x formula in MGCM.A5a. A large oval metatarsophalangeal area is positioned at the proximal intersection of digit long axes forming a prominent "heel"; tapering claws are visible on all digits. For the thirteen theropod tracks documented from the asphaltite tracksite, the average length:width ratio is 1.44 (ranging between 0.94 and 1.82). The ratio of A4d (0.94) is clearly an underestimate because it lacks an impression of the metatarsophalangeal region; that of MGCM.A1b, which has a long claw impression on digit III, is 1.82. The average divarication angle between digits II and IV is 58° (ranging between 45° and 64°).

The asphaltite tracksite includes a number of small theropod tracks and isolated digit imprints: MGCM.A4d, MGCM.A4e, MGCM.A4f, and MGCM.A6. Among them, MGCM.A4d and

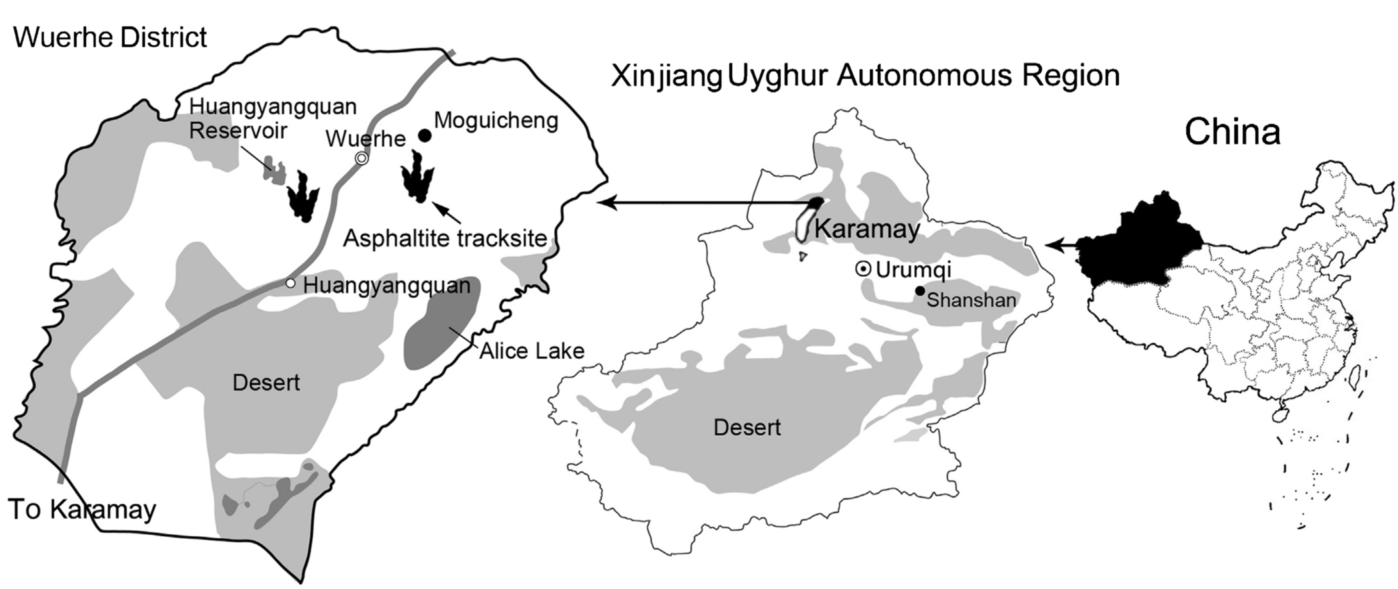

Fig. 1. Geographic map of the Wuerhe track locality (indicated by the footprint icon).

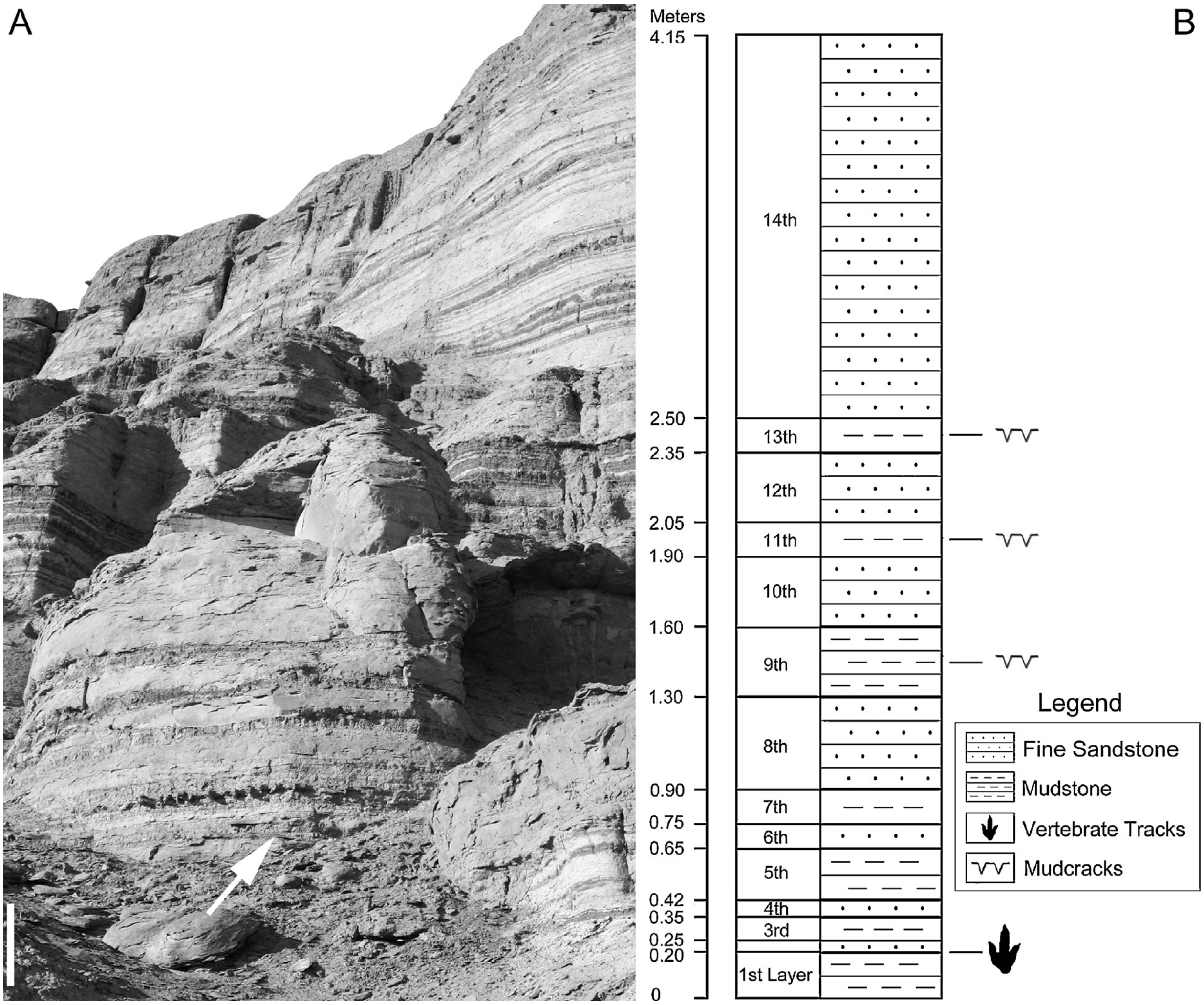

Fig. 2. Asphaltite tracksite. (A) Photograph, the white arrow demarcates the track-bearing layer, scale bar = 1 m. (B) Section with position of the track-bearing layer.

Table 1
Measurements (in cm and degrees) of theropod, bird and pterosaur tracks from asphaltite tracksites.

MGCM.	R/L	ML	MW	LD I	LD II	LD III	LD IV	II–III	III–IV	II–IV	L/W
A1a	L	8.5	>5.8	–	>3.9	6.4	5.0	–	29°	–	<1.47
A1b	R	14.4	7.9	–	6.6	7.3	9.1	20°	25°	45°	1.82
A1c	R	3	2.7	–	1.3	1.9	1.7	46°	34°	80°	1.11
A2a	L	>9.8	>7.4	–	>5.3	>4.9	>6	–	–	–	–
A2b	R	9.8	7.5	–	–	6.8	4.5	29°	28°	57°	1.31
A2c	R?	4.4	4.4	–	>1.2	3.8	>1.6	–	–	–	1
A3	R	>10.3	8.3	–	6.7	>7.2	>5.5	25°	29°	54°	1.24
A4a	L	14	8.4	–	6	9.3	6.2	27°	26°	53°	1.67
A4b	R	10.4	6.2	–	4	6.4	4.8	30°	33°	63°	1.67
A4c	L?	10.4	7.6	–	4.5	8	4.8	28°	32°	60°	1.37
A4d	L	6.6	7	–	4	6.6	5	34°	30°	64°	0.94
A4e	L?	6	–	–	–	5	3.6	–	–	–	–
A4f	–	–	–	–	–	5.4	–	–	–	–	–
A4g	L	5.5	4.6	–	2.1	4.4	3.0	38°	43°	81°	1.2
A5a	L	>12.7	11.7	–	7.1	>7.5	7.7	33°	27°	60°	>1.1
A5b	L	5.4	5.3	–	2.5	4.3	3.0	47°	54°	101°	1.02
A5c	L	15.1	–	–	–	11.1	7.4	–	25°	–	–
A6	L	6.7	4.4	–	3.1	5.3	3.5	22°	31°	53°	1.52
A7	–	6.7	2.9	3.1	3.5	4.8	–	–	–	–	2.31

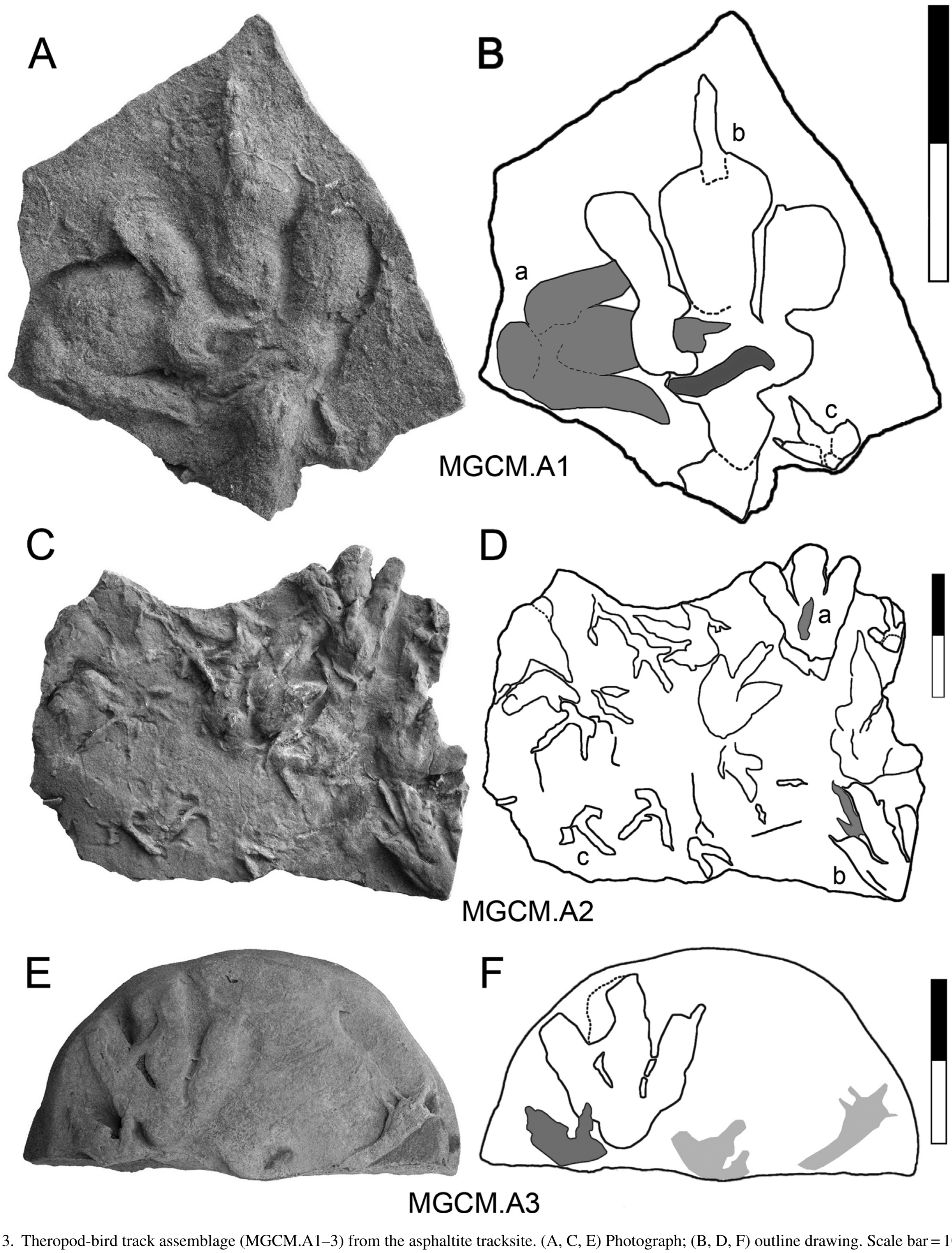

Fig. 3. Theropod-bird track assemblage (MGCM.A1–3) from the asphaltite tracksite. (A, C, E) Photograph; (B, D, F) outline drawing. Scale bar = 10 cm.

MGCM.A6 are relatively well preserved, the former with three digits but without a metatarso-phalangeal portion; the latter is similar to MGCM.A5a: its phalangeal pad formula is also x-2-3-4-x, rather than x-2-3-3-x, but digit III only has the appearance of having two digit pads, like MGCM.A1b. A single digit overlap on digit III of MGCM.A2a can probably be referred to this same type. Digit III is most deeply impressed in all of these tracks.

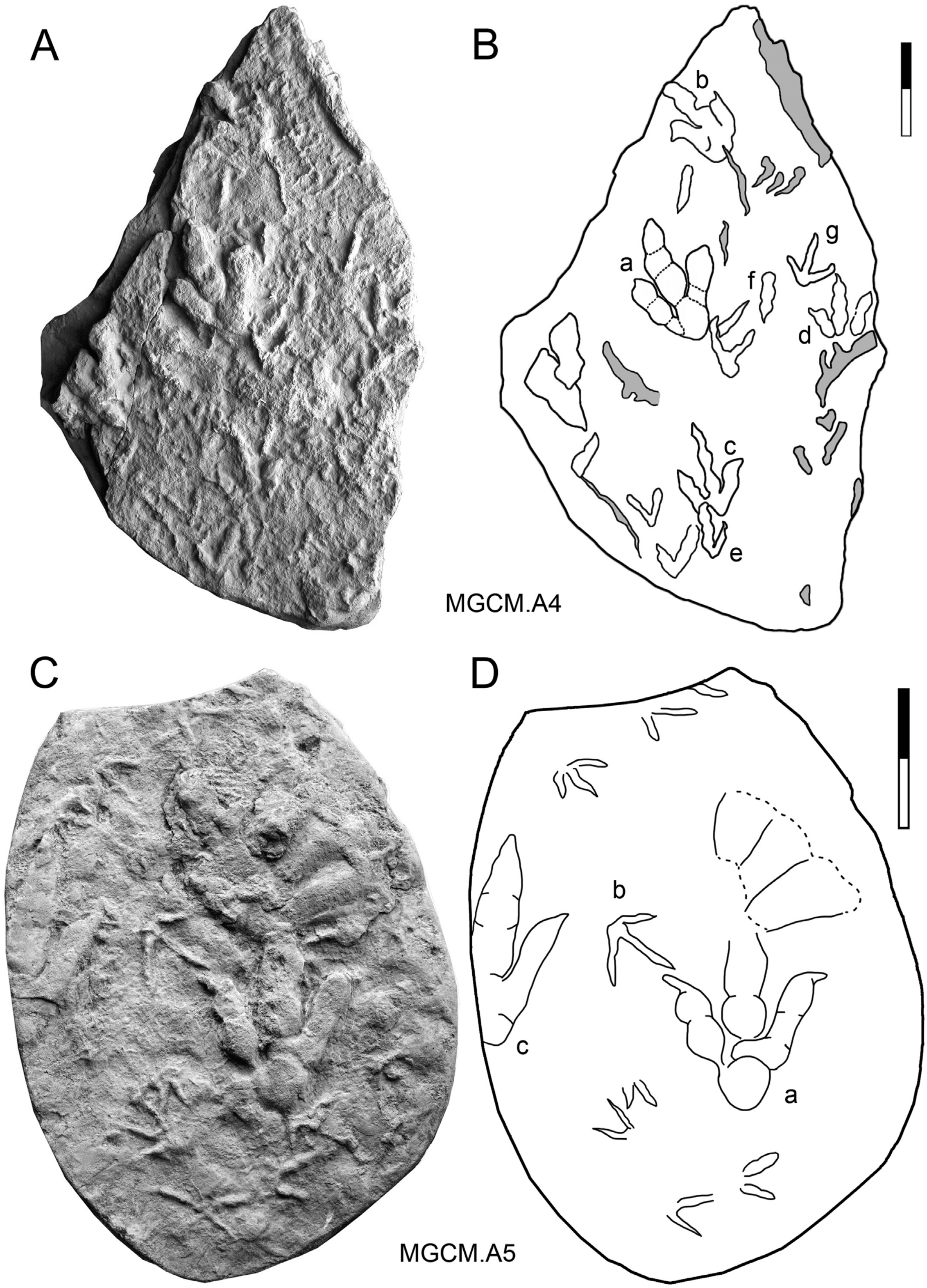

Fig. 4. Theropod-bird track assemblage (MGCM.A4–5) from the asphaltite tracksite. (A, C) Photograph; (B, D) outline drawing. Scale bar = 10 cm.

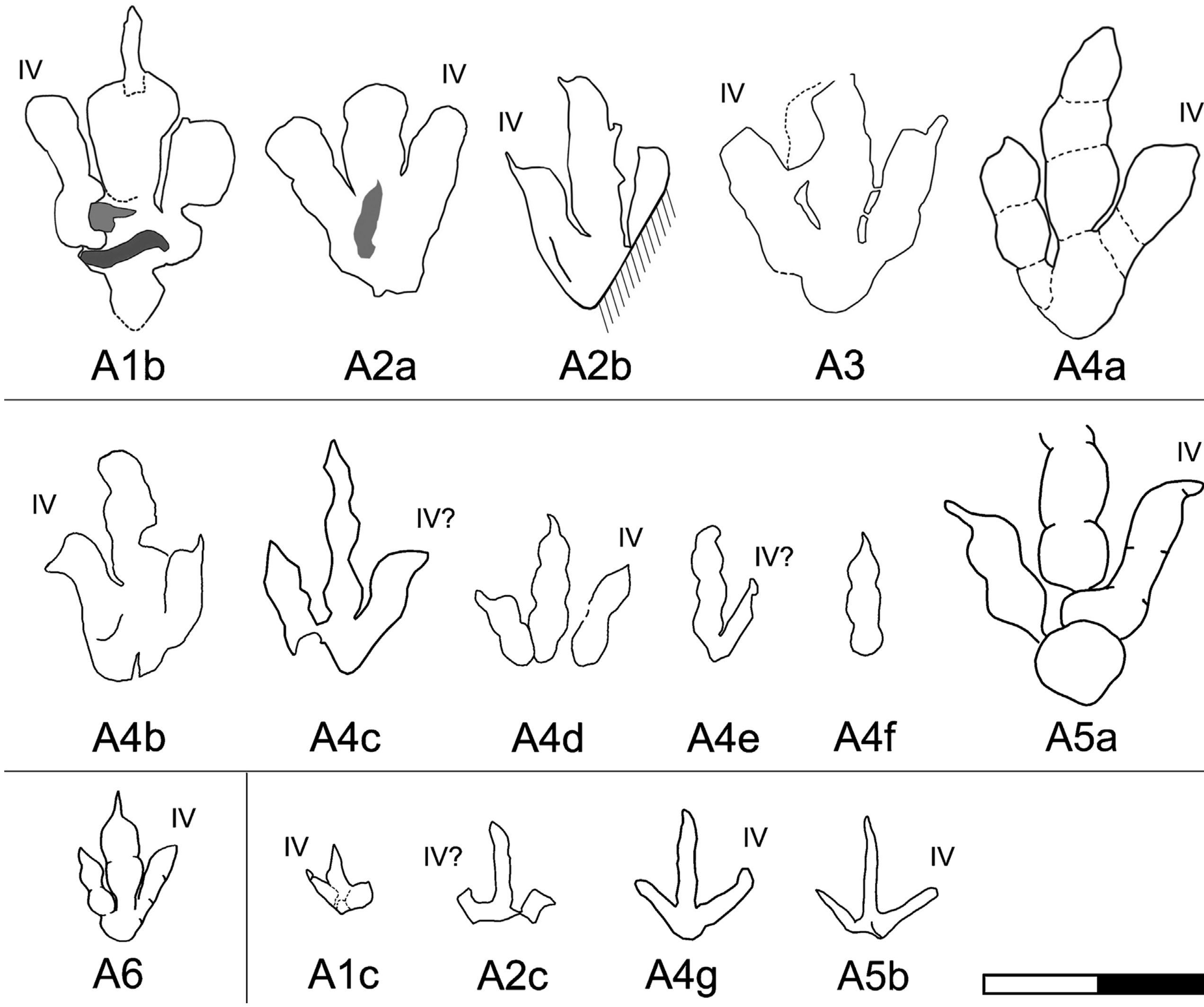

Fig. 5. Outline drawings of theropod and bird tracks from the asphaltite tracksite. The number IV points to the digit IV prints. Scale bar = 10 cm.

Discussion

Most features of MGCM.A5a, like digit proportions and pad configuration, are similar to those of *Jialingpus* (Xing et al., 2011a) from the Huangyangquan tracksite; the track can therefore be tentatively attributed to this ichnogenus. The lack of diagnostic features of other theropod tracks, such as MGCM.A2b and MGCM.A4b, makes it impossible to attribute them to a particular ichnotaxon.

MGCM.A4d and A6 are the smallest complete theropod tracks from the asphaltite and Huangyangquan tracksites. MGCM.A4e and A4f are considered as belonging in this same small category although they are incomplete. These tracks are much larger than *Grallator emeiensis* (Zhen et al., 1994) and *Minisauripus chuanzhuensis* (Zhen et al., 1994; Lockley et al., 2008), and are more similar to *Menglongipus sinensis* (Xing et al., 2009) in size. However, there is no similarity between MGCM.A4d, A6 and the other small footprints in morphology, which are attributed to birds (as discussed in 4.2.). MGCM.A4d and A6 are similar to the unnamed tracks from the Sijiaban tracksite Type A (Fujita et al., 2007). The Sijiaban tracks Type A pertain to the *Grallator* type, their divarication angle between digits II and IV is 49.6° (Fujita et al., 2007), which is less than that of MGCM.A4d and A6.

The digit II: digit III: digit IV length ratios in MGCM.A4d, A4a, A5a and A6 are 1:1.7:1.3; 1:1.6:1.3; 1:?:1.1; 1:1.7:1.1, respectively, which suggests that these specimens have similar morphological characteristics. Based on how the theropod tracks yielded from the same region are similar in morphology but vary in size (Fujita et al., 2007; Xing et al., 2011b), MGCM.A4d and A6 probably represent juvenile individuals of the same trackmaker as MGCM.A4a and A5a, respectively. The length of MGCM.A4c is intermediate between the lengths of MGCM.A4a and A4d, and may suggest another ontogenetic stage.

4.2. Bird tracks

Material

The MGCM has collected approximately ten bird tracks from the asphaltite tracksite. All of these tracks are natural casts, the best preserved of which are cataloged as MGCM.A1c, 2c, 4g, and 5b (Figs. 3–5 and Table 1). These tracks vary significantly in size for small bird tracks (Table 1), ranging in length from 3.0–5.5 cm. This covers the range of size between *Koreanaornis* (smallest) to *Aquatilavipes* (medium sized) and *Tatarornipes* (largest): see Kim (1969), Currie (1981) and Lockley et al. (2012) respectively. However, some size variation may be caused by difference in preservation, and no other evidence indicates these tracks represent different ichnotaxa.

Description and discussion

Few of the bird tracks are complete enough to provide reliable measurements. However, MGCM.A4g and MGCM.A5b are well preserved. The length:width ratio of four tracks ranges from 1 to 1.2. MGCM.A4g is the best preserved track. Digit III is directed forward and is longest, and digit II is shorter than digit IV in length. The divarication angle between digits II and III is less than that between digits III and IV. The divarication angle is 81° between digits II and IV. These characteristics are similar to those of the Koreanaornipodidae track from the Huangyangquan tracksite (Xing et al., 2011a), and both can presumably be attributed to the same ichnotaxon. Based on size they are closer to *Tatarornipes* (Lockley et al., 2012) than to *Koreanaornis*, but this assignment cannot be made with confidence on the basis of such a small sample. The divarication angle between digits II and IV of MGCM.A5b is slightly larger than in MGCM.A4g. MGCM.A2c is poorly preserved, digit III is the most distinct, and the outer digits are faint but discernible; compared to digit III, the outer digits are very short, partly due to the incomplete preservation. A similar situation is known from some theropod footprints, such as *Zhengichnus* (Zhen et al., 1986) and *Taupezia* (Delair, 1963; Harris, 1998). However, such comparisons are of limited significance because they are probably related to poor or unusual preservation.

MGCM.A1c is also fairly well-preserved. The length:width ratio of the track is 1.11. Digit III is directed forward and is the longest, digit II is shorter than digit IV in length, but is more robust than the other two digits. The divarication angle between digits II and III is larger than that between digits III and IV. The divarication angle between digits II and IV is 80°. The metatarsophalangeal region is nearly circular. Some characteristics of MGCM.A1c are similar to those of bird tracks, including: small size, large divarication angle (110–120°) between digits II and IV, anisodactyly, and length:width ratios ≤1.0 (Lockley et al., 1992; McCrea and Sarjeant, 2001; McCrea et al., in press). However, MGCM.A1c is an isolated imprint and the only specimen from the asphaltite tracksite representing this morphotype. A reliable assignment to a particular ichnotaxon is not possible, and therefore it is here tentatively identified as an indeterminate bird track.

4.3. Pterosaur track

Material

The MGCM has collected one tridactyl footprint from the asphaltite tracksite. This footprint is a well-preserved natural cast, which is cataloged as MGCM.A7 (Fig. 6 and Table 1).

Description and discussion

MGCM.A7 is an isolated natural cast. Three distinct digit traces are preserved in high relief (convex hyporelief), with no other distinct convex traces around the footprint. The shape is diagnostic of a pterosaur manus. The possibility that it is an incompletely preserved crocodilian track or a turtle track can be excluded as highly unlikely on the grounds that both these track types typically show parallel or sub parallel to only slightly divergent digit traces. In the case of crocodilians, for example, complete tracks show a tetradactyl pes and a pentadactyl manus (Kubo, 2008). Likewise, turtle tracks are typically tetradactyl or pentadactyl. Based on the general shape (outline), and swollen convex shape of the proximal area around the shorter proximal digit traces (probably I and II), MGCM.A7 is comparable to many pterosaur manus tracks reported in the literature (e.g., Lockley et al., 1995; Mazin et al., 2003; Lockley and Harris, in press). The detailed diagnostic pterosaurian morphology can be outlined as follows: long digit III oriented posteriorly, short digit II facing posterolaterally, short digit I oriented anterolaterally, and medial rim curving outwards.

The asphaltite tracksite was discovered near the Huangyangquan tracksite (Fig. 1), and the ichno-associations from both localities are basically consistent (Xing et al., 2011a, 2013). The discovery of a pterosaur track from the asphaltite tracksite supports this view. It is an important addition to the increasing pterosaur ichnofossil record from China. To date, pterosaur tracks from China have only been assigned to *Pteraichnus* (Xing et al., 2012a). MGCM.A7 is similar in size to *Pteraichnus* isp. from Shandong Province (Xing et al., 2012b), and slightly smaller than *Pteraichnus saltwashensis* (Stokes, 1957) and *Pteraichnus stokesi* (Lockley et al., 1995). MGCM.A7 is also consistent with the updated diagnosis of *Pteraichnus* (Lockley and Harris, in press); however, the traces of digits I–III of MGCM.A7 are strongly rounded and blunter than those of many *Pteraichnus* ichnospecies. This is probably the effect of substrate conditions rather than morphology. Until more complete material is found at the locality, we tentatively assign these tracks to *Pteraichnus*.

5. Overlapping tracks

MGCM.A1a–A1c are preserved on a single slab (Fig. 3). Digit II of MGCM.A1b is overlapped and traversed, respectively, by digits II and III of MGCM.A1a. Pad 1 of digit II in MGCM.A1b was plastically deformed to a U-shape when the foot of the MGCM.A1a trackmaker penetrated the substrate (Fig. 3A, B and 5). This indicates moist sediment with optimal conditions for track preservation. Additionally, one single ?digit trace is overlapped by the metatarsophalangeal region of MGCM.A1b. Similar overlap situations are seen in MGCM.A2a and A2b (Figs. 3C, D and 5). The former overlaps an isolated deep digit trace by the shallower, proximal part of its digit III. This implies that the small single digit trace was made before the substrate was further compacted by the large trackmaker that produced MGCM.A2a. Likewise, because digits III and IV of MGCM.A2b are deeper than the small theropod digit trace between these two digit traces, it was presumably made

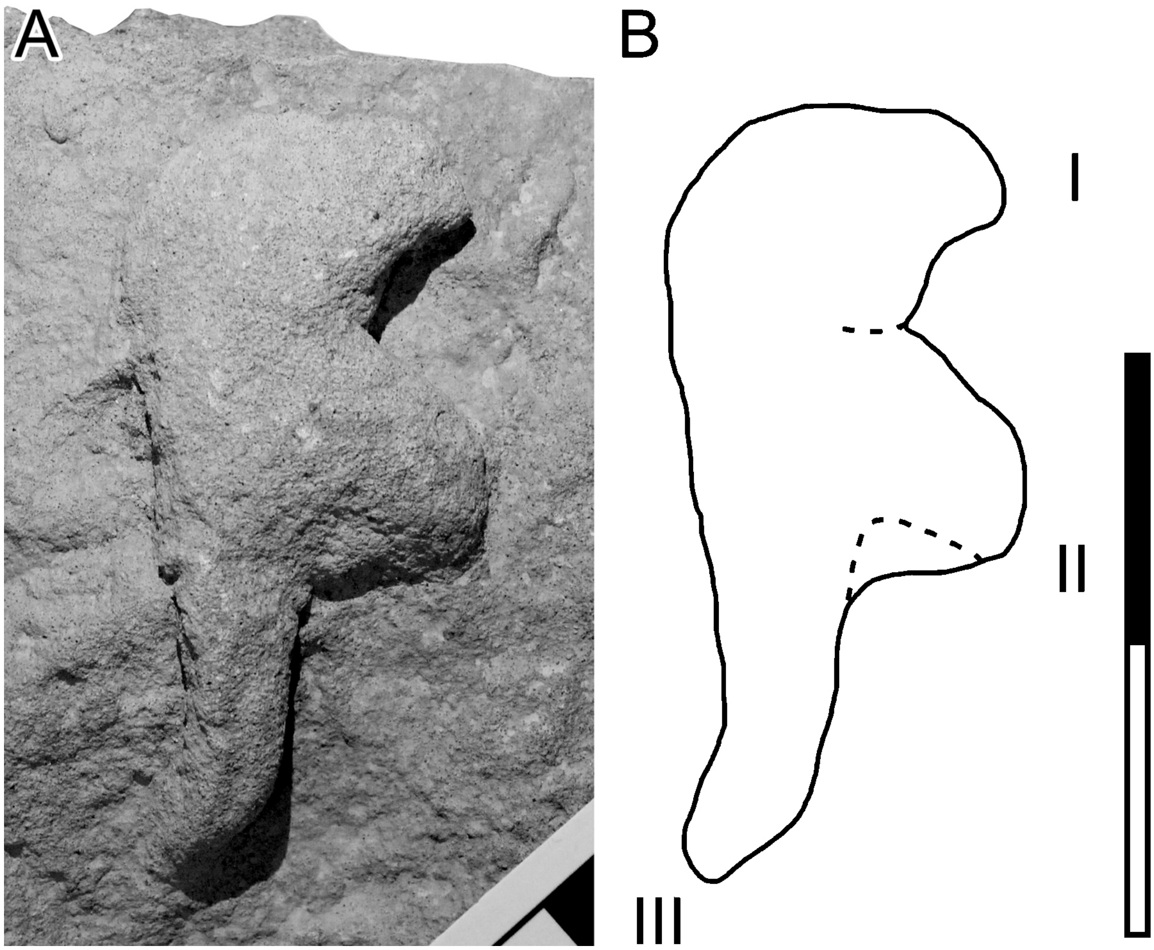

Fig. 6. Pterosaur manus imprint (MGCM.A7) from the asphaltite tracksite. (A) Photograph; (B) outline drawing. Scale bar = 5 cm.

later. This overlapping phenomenon is not rare for tracks, and it often occurs in sauropods and quadrupedal ornithischians when the pes oversteps the manus (e.g., Paul, 1998; Lockley et al., 2002), in ornithopods when two pes tracks overlap (Milner et al., 2006, fig. 4E, F), or more generally on surfaces trampled by different individuals. Obviously, overlapping of pes tracks of bipedal trackmakers indicates the overlap of tracks made by different individuals. Interestingly, although overlapping tracks of both avian and non-avian theropods are common in high density assemblages, well-preserved overlapping tracks have rarely been studied in detail in theropod track assemblages. The overlap phenomenon is influenced by the consistency of the sediments, and by the depths of the tracks made by animals of different sizes and weights. In their research on emu tracks, Milàn (2006) concluded that the ideal track cast is most easily formed in deep, semi-firm sediments (e.g., MGUH 27476 and 27477 cited in that paper). The preservation conditions of the tracks at the asphaltite tracksite are similar to the above-mentioned conditions, although the sediment was firmer. This resulted in overlapped tracks retaining much of their original shapes. One of the general conclusions that arise from these observations is that, where a small track (or part of a track) is deeper than the large track that overlaps it, partly obliterating it (as in MGCM. A2a), the small track was most likely made first. If one were to infer that the overlapping relationships were reversed, it would be difficult to explain how the small tracks made such a clear impression in the already compacted floor of the large track. In the case of MGCM.A2b, the large track is deeper and may have been made first. However, this is not absolutely certain as the large and deeper track may have cut through a part of the smaller, shallower one when the substrate conditions were more or less the same.

6. Paleoecology

At the asphaltite tracksite, both theropod and bird tracks co-occur on the same surfaces. This is also known from other locations such as the Chuanzhu (Zhen et al., 1994), Junan (Li et al., 2005), the Madigou tracksites (Lockley et al., 2006), and many tracksites from the Chabu area of Nei Mongol (Li et al., 2009, 2011; Lockley et al., 2012). However, the association of different size-classes of theropod tracks (MGCM.A4a, MGCM.A4d) and bird tracks (MGCM.A4g) has not been discussed in any detail. One explanation is that various age groups of *Jialingpus* track makers were represented, but the asphaltite sample is too small to make a definitive determination based on a statistical analysis of size frequencies. The difference in the size of the shorebird tracks is less easy to explain as size classes of a single species. This is because most shorebird-like tracks represent adults in the case of modern trackmakers (Lockley and Harris, 2010). Thus, small differences in size and morphology may represent different species, but could also be related to preservation. Thus, it is possible that the size range observed at the asphaltite site (bird track length 3.0–5.5 cm) represents a diversity of aviantrack makers.

The asphaltite sedimentary facies represent deltaic lowlands that might have offered sufficient food resources for small theropods and birds to frequent the shorelines of water bodies in a fluvio-lacustrine habitat. The tracks therefore represent an example of the shorebird ichnofacies (sensu Lockley et al., 1994), which was also characterized as the *Grallator* ichnofacies by Hunt and Lucas (2007). Predator-prey relationship between non-avian dinosaurs and birds may have existed as recently suggested by Xing et al. (2012c).

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