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The first dinosaur tracksite from Xinjiang, NW China (Middle Jurassic Sanjianfang Formation, Turpan Basin) —a preliminary report

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Abstract: A new dinosaur tracksite was discovered in a steeply inclined sandstone layer of the Middle Jurassic Sanjianfang Formation in the Shanshan area of the Turpan Basin. The site is the first record of dinosaur footprints from Xinjiang Province in northwestern China. More than 150 tridactyl theropod dinosaur footprints are preserved as positive hyporeliefs on the lower bedding plane of a fine-grained sandstone body. Most of the footprints are isolated and appear to be randomly distributed. Some show well defined phalangeal pads, heels and rarely indistinct impressions of the distal part of the metatarsus. Two distinct morphotypes are present: a larger type with relatively broad pads shows similarities to *Changpeipus* and *Megalosauripus*, and a slightly smaller, slender and gracile type which is similar to *Grallator*, *Eubrontes* and *Anchisauripus*. In both morphotypes, digit III is the longest with a length between 11.4 and 33.6 cm. A single imprint shows prominent scratches, probably formed during slipping of the track maker.

Key words: Dinosauria; Theropoda; dinosaur track; dinosaur footprint; Middle Jurassic; Turpan Basin; Xinjiang

Introduction

In September 2007, a team of the Sino-German Joint Group on Mesozoic stratigraphy and paleontology of continental basins in Northwest China successfully prospected Middle and Late Jurassic sediments of the Turpan Basin, Xinjiang, for vertebrate fossils. Among the new discoveries is a spectacular outcrop exhibiting a large number of dinosaur footprints. The new tracksite is situated about 20 km east-northeast of Shanshan city (Fig. 1). A provisional excavation in September 2007 was cancelled after only seven days because of unworkable weather conditions. Another short examination of the tracksite took place in early November 2007. Consequently, we present a preliminary report.

Geological Setting

The arid Turpan Basin is a small intermontane foreland-like basin formed during the Late Permian (Shao *et al.*, 1999). It is bordered by the central

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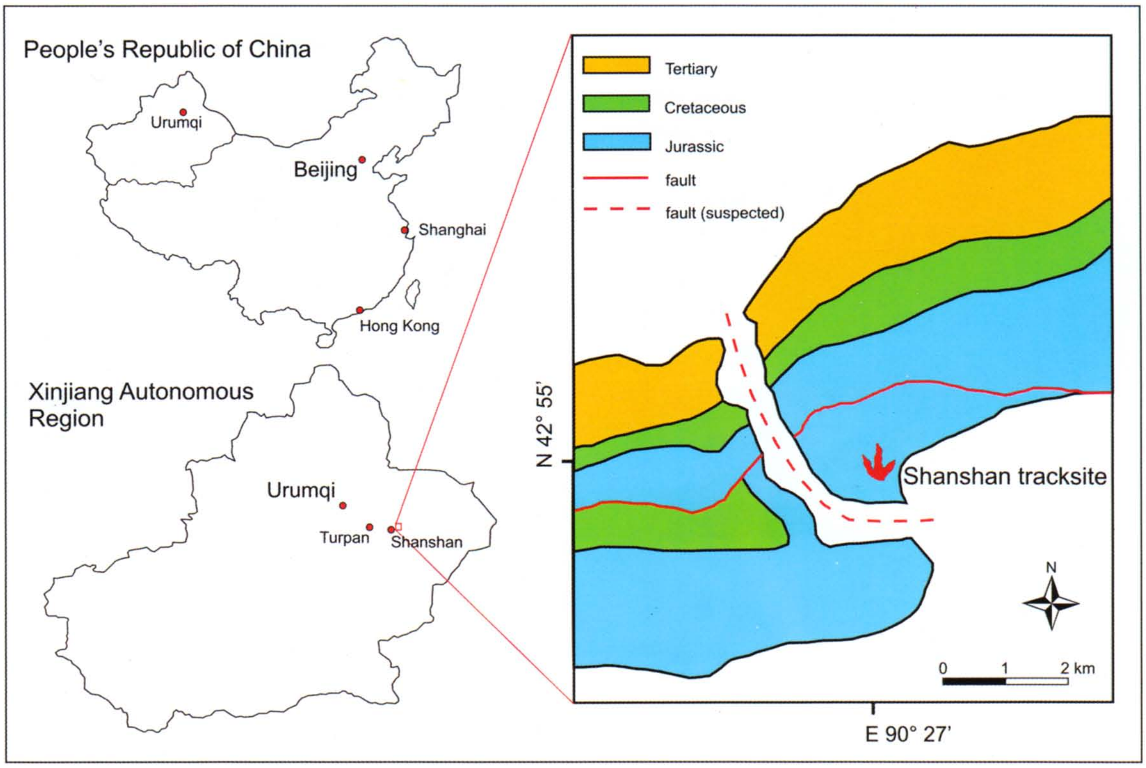
Tian Shan mountain range in the west, the Bogda and Harlik Mountains in the north-west, and the Juelu-otage Mountains in the south. Beyond the mountain ranges lie the Junggar Basin to the north and the Tarim Basin to the south.

The central ridge of the Turpan Basin contains excellent exposures of Jurassic, Cretaceous, and Paleogene non-marine clastic sediments yielding invertebrate and vertebrate fossils (Dong, 1992; Zhao, 1980). The Jurassic sediments are divided into the Middle Jurassic Sanjianfang and Qiketai Formations, and the Upper Jurassic Qigu and Karazha Formations (Dong, 1997).

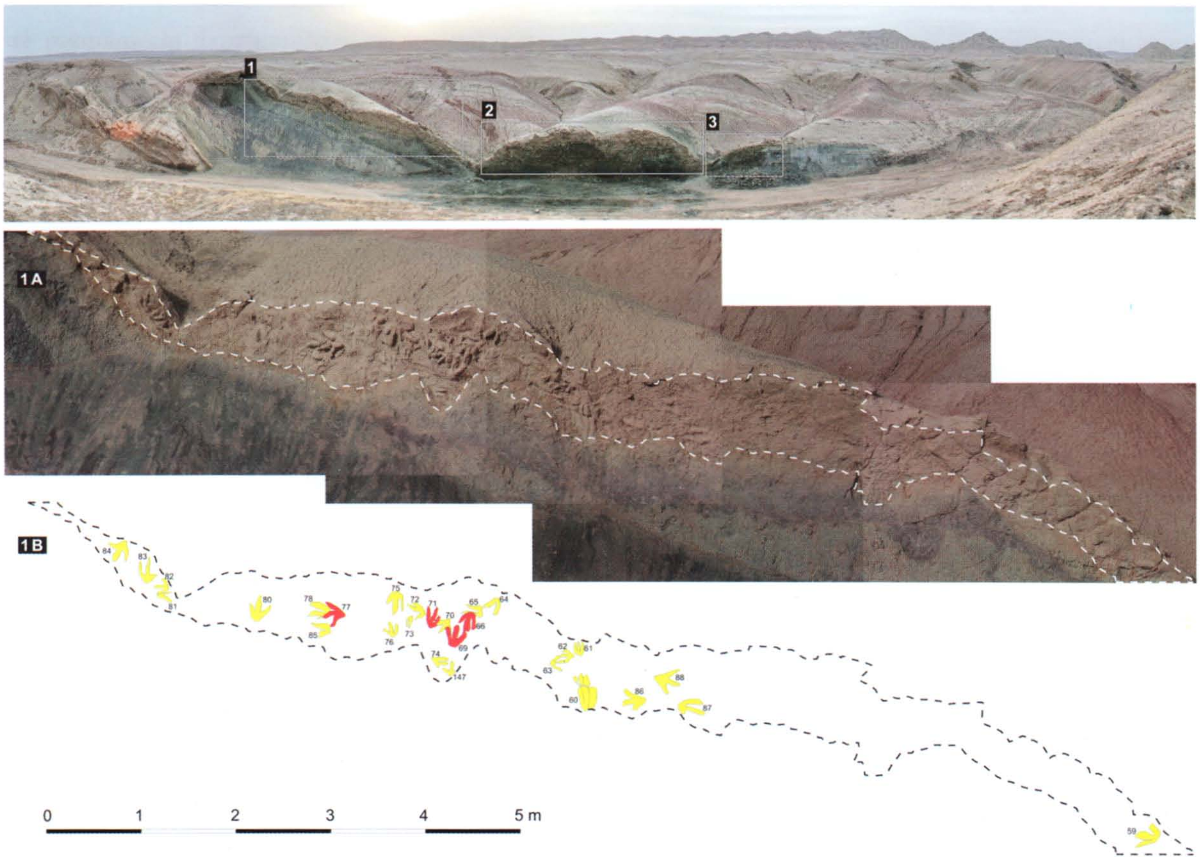


Showing outcrop of Jurassic, Cretaceous, and Paleogene strata and the new Shanshan tracksite locality.

Fig. 1 Outline map of the Shanshan area in northwestern China

Preliminary field mapping and analyses of satellite images and aerial photographs indicate that the Shanshan tracksite can be assigned to the Middle Jurassic Sanjianfang Formation. The Sanjianfang Formation is exposed in the middle and at the northern and western margins of the Turpan Basin (Shao *et al.*, 1999) and consists of a 400 m thick succession of brown, red, grey, yellow, or green mudstones and siltstones intercalated with fine to coarse yellow sandstone layers. The sediments were deposited in a fluvial-lacustrine facies (Regional Stratigraphic Correlation Group of Xinjiang Uygur Autonomous Region, China, 1981; Zhou and Dean, 1996). Fossil plants, pollen, gastropods, and bivalves (*Pseudocardinia*) have been reported from the Sanjianfang Formation (Regional Stratigraphic Correlation Group of Xinjiang Uygur Autonomous Region; China, 1981; Zhou and Dean, 1996), but hitherto no vertebrates or trace fossils (Dong, 2004).

The original footprints occur in greenish and sometimes purple colored mudstones, which commonly contain turtle bones, the first record of fossil bone material in the Sanjianfang Formation. However, due to rapid erosion of the soft mudstones, original track imprints are not detectable. Instead, the footprints are preserved as natural casts. Together with invertebrate traces they form positive hyporeliefs on the lower bedding plane of a steeply inclined, yellow, sometimes greenish or brownish fine-grained sandstone body (Figs. 2-4).

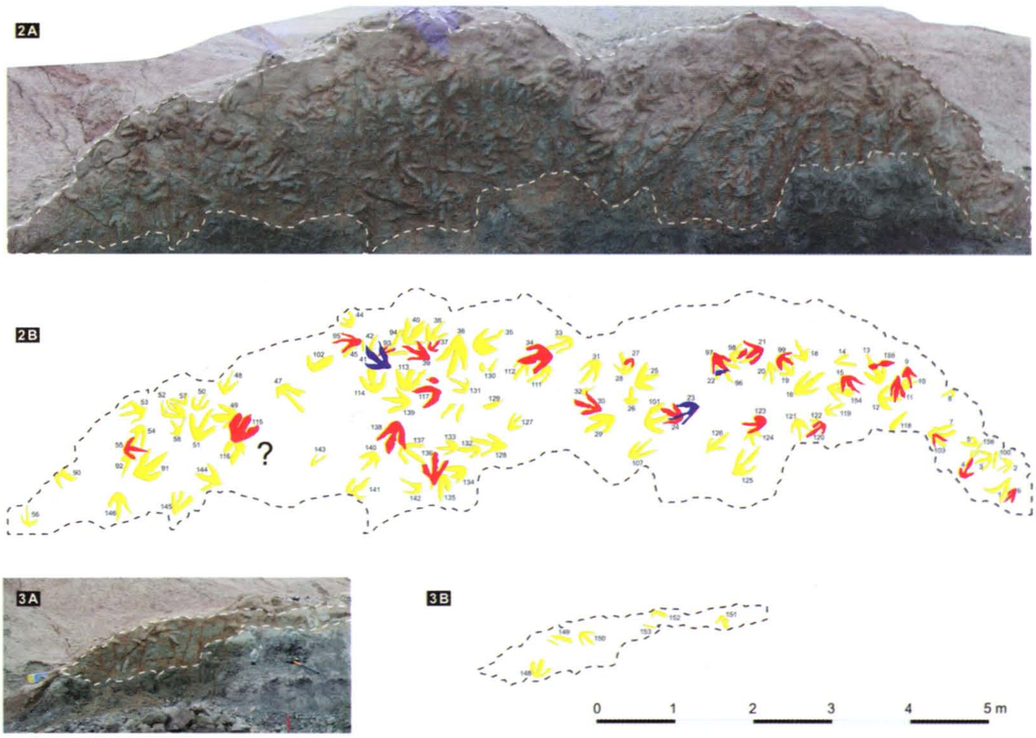


Boxes with numbers indicate sections with footprints. A1: Photograph of Section 1; B1: Plan of footprints in Section 1 with field numbers and imprints marked in color. Yellow denotes the youngest footprint; red denotes footprints that were overprinted byyellow'footprints. Dashed lines mark the exposure of the track-bearing layer.

Fig. 2 Shanshan tracksite: panoramic view and left section

The resistant sandstone wall is naturally exposed in a gully (Fig. 2) and has a thickness of approximately 30 cm. It strikes in a NE-SW direction; dipping approximately 70° to NW. Footprints have been uncovered in the sandstone in an area about 30 m long and up to 3 m high. Approximately 100 m to the NE, the same sandstone layer again has been weathered out as a wall, this time from the upper side of the stratum. Tentative removal of some sandstone blocks has revealed similar hyporelief footprints on the lower bedding plane, indicating a vast extension of the tracksite.

The surrounding sediments consist of yellowish, green, purple, and red-brownish mudstones, partially developed as paleosols. Another sandstone layer occurs about 6 m below the track-bearing layer. At the tracksite, this second sandstone body includes occasional lags-deposits with large quartzite clasts. Within a distance of about 1 km to the northeast, gastropods as well as bivalves occur commonly in this horizon,



2A: Photograph of Section 2; **2B**: Plan of footprints in Section 2 with field numbers; **3A**: Photograph of Section 3; **3B**: Plan of imprints in Section 3 with field numbers. Dashed lines mark the exposure of the track-bearing layer. Footprints in 2B and 3B are marked in color. Yellow denotes the youngest footprints, red denotes footprints that were overprinted byyellow'footprints, blue denotes footprints that were overprinted byred'footprints.

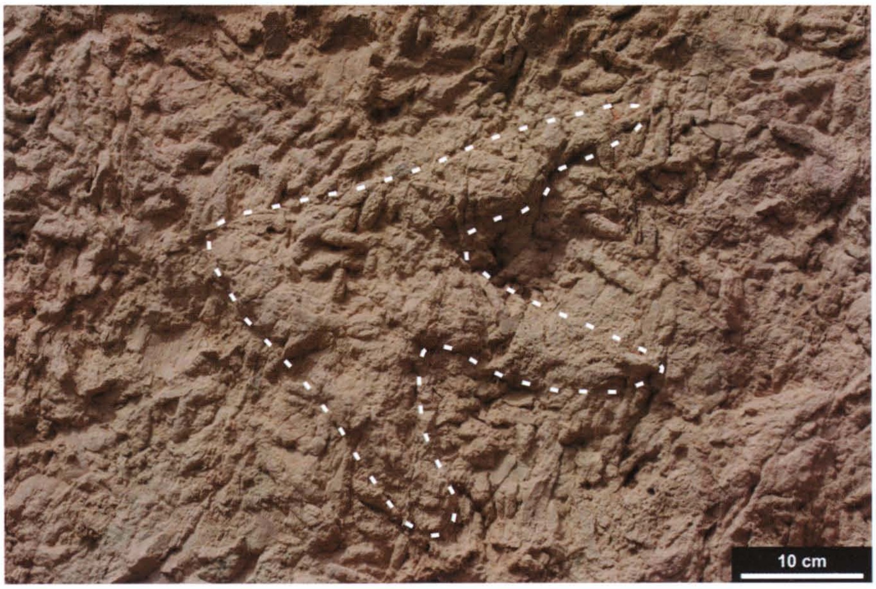
Fig. 3 Photographs of the sections and the footprints

forming a sand-rich coquina. Study of these invertebrate fossils is in progress.

Material and methods

In spite of careful excavation of the footprints it was impossible to save the original track horizon in the mudstones. The best approach to excavate and clean the natural casts in the sandstone layer was by applying water to the adhering residual mudstones. Moisture expansion and subsequent disintegration of the mudstones led to an easy removal of the sediment cover. Excavated footprints were then allowed to dry and hardened with acetone-based acrylic lacquer. About 3 m^2 of the overhanging sandstone layer collapsed during preparation. Five well-preserved footprints have already been saved from the collapsed parts and are now housed in the Research Center of Paleontology, Jilin University in Changchun, China (collection numbers: CAD07-SS001 to CAD07-SS005).

Due to the overhang of the footprint layer, drawing undistorted outlines of the footprints on transparent plastic film proved impossible. Instead it was decided to document the footprints from digital photographs. However, all measurements were taken from the original footprints, except some pace and stride lengths which have been measured from the digitized map of the tracks. All clearly identifiable footprints have been serially numbered and footprint parameters have been measured in the field using cord, set square and protractor. The following data were collected: length of the digits (including claw impressions, both with and without heel); maximum width of the digits; dimensions of the heel; total width of the footprint (measured between the distalmost tips of digits II and



footprint 88; most plausible outline marked with dashed line.

Fig. 4 Bioturbated sandstone with *Lockeia* bivalve traces and an obscured theropod footprint

IV); distance between the distalmost extremity of digits II and IV and the median axis of digit III; angle between digits II and IV and digit III (measured between the median axes of the concerned digits); orientation of the digits; maximum and average depth of impression of the footprint.

All figures show the actual footprint orientation in the field and not the original orientation. The original orientation is inverted because of exposition of the footprint layer from the lower bedding plane. Left footprints on all figures represent originally right imprints and vice versa. The original orientation is listed in Table 1. If a digit was sufficiently well preserved to be evaluated, but lacked some parts, the respective measurements were taken nevertheless. The obtained values, if affected by loss of material, were then treated as minimum values (preceded by " > " in Table 1).

The measurements represent preliminary data and only the most diagnostic values are included in the table. Footprints are sorted by length of digit III and not by total pes length, because the latter includes a partial metatarsus impression, which is often too poorly defined for precise measurements.

In case footprint orientation (right/left) could not be determined, the left digit, as visible in the field with the footprint pointing upwards, is listed as digit II and the right digit as IV. Index: " > " preceding values: the feature is affected by loss of material and is supposed to be larger than the value measured; nm: not measurable; FW/FL: ratio of footprint width and footprint length. The mean ratios of FW/FL are 0.76 for morphotype A, 0.79 for morphotype B, 0.80 for footprints with uncertain attribution, and 0.78 for all footprints.

Footprints were measured as soon as they were uncovered and identified. If possible, trackway parameters such as pace (step) and stride length were measured too. Because of the preliminary status of the excavation, data were not yet subjected to in-depth statistical analyses. It is our intention to compile more data in the future and publish a detailed analysis on the tracksite elsewhere.

Table 1 Measured data of the Shanshan footprints

Number	Right /left	Length of digit II (mm)	Length of digit III (mm)	Width of digit III (mm)	Length of digit IV (mm)	Width of footprint (mm)	Length of footprint (mm)	Angle between II and III (°)	Angle between III and IV (°)	Total divarication (°)	FW /FL
Morphotype A											
61	L	131	>83	46	121	193	>183	40	30	70	—
63	L	>123	183	39	141	175	242	30	30	60	0. 72
69	L	>199	>205	66	241	284	>321	40	35	75	—
3	L	130	215	77	180	260	287	42	26	68	0. 91
78	L	168	238	64	152	228	~320	42	40	82	0. 71
4	L	~140	240	60	161	263	340	45	30	75	0. 77
96	L	161	264	52	207	307	374	45	55	100	0. 82
21	L	nm	~270	60	220	~240	~360	60	35	95	0. 67
66	L	190	294	116	171	225	361	30	30	60	0. 62
115	L	246	320	90	260	296	455	38	22	60	0. 65
77	R	210	210	100	205	310	335	48	40	88	0. 93
30	R	>151	229	68	174	257	329	34	34	68	0. 78
41	R	180	245	70	220	285	335	40	40	80	0. 85
34	R	194	247	98	~139	~358	377	35	48	83	0. 95
16	R	174	281	83	170	225	446	20	25	45	0. 50
11	R	177	300	57	>95	nm	382	30	40	70	—
91	R	286	330	117	291	303	493	27	26	53	0. 61
36	R	238	336	89	274	339	470	33	39	72	0. 72
26	?	nm	>149	66	nm	nm	>235	36	31	67	—
19	?	176	211	47	35	270	306	45	60	105	0. 88
5	?	120	215	61	~28	201	263	30	12	42	0. 76
37	?	nm	220	55	nm	nm	nm	nm	nm	—	—
49	?	191	237	90	>43	278	390	29	24	53	0. 71
76	?	190	253	64	nm	nm	nm	55	nm	—	—
40	?	125	255	85	76	315	370	30	30	60	0. 85
7	?	251	~260	64	57	280	400	40	40	80	0. 70
12	?	>119	262	81	41	~310	383	35	45	80	0. 81
85	?	nm	268	89	64	nm	335	nm	57	—	—
15	?	160	269	53	64	274	372	33	45	78	0. 74
54	?	>120	300	60	44	nm	431	40	35	75	—
102	?	nm	317	13	>180	nm	nm	nm	nm	—	—
84	?	269	326	121	76	382	465	39	35	74	0. 82
Morphotype B											
70	L	130	171	60	180	~270	313	25	40	65	0. 86
71	L	200	205	51	145	235	360	30	35	65	0. 65
20	L	174	210	48	210	245	319	25	30	55	0. 77
72	L	>110	>215	62	>84	nm	nm	47	44	91	—
23	L	190	262	~55	242	281	382	40	30	70	0. 74
92	? L	nm	275	68	nm	nm	~370	nm	nm	—	—
81	? R	nm	172	51	nm	nm	~260	nm	nm	—	—
48	R	>75	254	49	200	nm	340	29	43	72	—
32	?	96	114	28	82	122	197	44	28	72	0. 62
67	?	nm	>120	36	125	nm	>175	nm	20	—	—
37	?	nm	152	29	76	nm	nm	nm	36	—	—
50	?	119	172	43	109	191	266	22	26	48	0. 72
14	?	nm	193	46	nm	nm	nm	nm	nm	—	—

Table 1 (Continued)

Number	Right /left	Length of digit II (mm)	Length of digit III (mm)	Width of digit III (mm)	Length of digit IV (mm)	Width of footprint (mm)	Length of footprint (mm)	Angle between II and III (°)	Angle between III and IV (°)	Total divarication (°)	FW /FL
Morphotype B											
28	?	133	209	66	151	225	284	35	35	70	0.79
59	?	131	223	72	~198	333	281	60	55	115	1.19
55	?	160	244	55	nm	nm	>330	50	60	110	—
83	?	nm	292	61	221	nm	~380	nm	36	—	—
Uncertain attribution											
38		100	>50	>30	165	nm	>160	35	30	65	—
8		110	111	52	nm	nm	nm	50	nm	—	—
22		nm	144	44	nm	nm	nm	nm	nm	—	—
99		110	144	47	130	236	222	25	55	80	1.06
112		>110	156	53	124	188	nm	34	38	72	—
82		145	161	41	nm	nm	~237	70	nm	—	—
27		120	162	35	151	240	274	40	30	70	0.88
111		nm	164	66	141	~196	249	42	37	79	0.79
100		nm	166	54	63	nm	229	nm	34	—	—
24		124	169	65	176	252	261	35	55	90	0.97
39		>90	>175	61	125	240	>300	40	35	75	—
18		nm	190	38	103	nm	300	40	45	85	—
97		160	191	58	171	284	289	45	37	82	0.98
109		100	194	52	nm	nm	nm	26	nm	—	—
2		nm	195	55	142	270	322	60	30	90	0.84
42		>145	198	61	nm	262	298	30	40	70	0.88
35	? R	104	199	50	~135	~200	298	33	44	77	0.67
25		142	214	112	187	379	339	40	50	90	1.12
10		95	218	43	171	170	263	40	30	70	0.65
9		>52	221	49	133	nm	322	40	70	110	—
106		104	222	49	nm	nm	nm	40	nm	—	—
6		150	230	70	171	171	322	37	49	86	0.53
90		190	230	80	>115	nm	nm	nm	nm	—	—
114		130	230	70	140	275	380	40	40	80	0.72
65		155	>230	45	nm	225	>350	30	22	52	—
64		233	233	65	211	nm	nm	nm	45	—	—
31	R	196	234	47	142	231	334	22	32	54	0.69
113		246	~236	70	150	~300	~360	30	37	67	0.83
80	? R	180	237	79	168	350	343	49	49	98	1.02
101		154	249	69	207	363	416	34	30	64	0.87
75	? R	142	254	38	151	269	344	40	40	80	0.78
88	? L	191	256	51	171	259	357	40	40	80	0.73
29	L	201	267	79	218	225	388	38	37	75	0.58
117		>140	275	72	223	nm	nm	40	40	80	—
108		nm	290	83	nm	nm	nm	nm	nm	—	—
13	L	135	321	61	204	291	441	40	30	70	0.66
86		>251	380	61	192	~300	485	30	20	50	0.62
33		nm	nm	nm	nm	nm	nm	nm	nm	—	—
60		nm	nm	nm	nm	nm	512	nm	nm	—	—
93		nm	nm	nm	nm	nm	>270	nm	12	—	—
98		140	nm	nm	170	340	nm	nm	nm	—	—
104		168	nm	70	157	310	nm	37	55	92	—

Description

The Shanshan tracksite currently consists of 155 exposed tridactyl mesaxonic footprints, preserved as natural casts. The footprints are in seemingly random distribution, in different stages of preservation and partially harmed by recent weathering. Some footprints show well defined phalangeal pads, heels and, in some cases, indistinct impressions of the distal part of the metatarsus. One footprint (no. 60) shows prominent retro-scratches. Based mainly on their general appearance, the footprints can be divided into two distinct morphotypes:

Morphotype A:

These footprints are longer than wide and generally of deltoid shape (Fig. 5). The total width ranges from 17.5 cm to 38.2 cm. A heel is more or less well defined. Digit III is the longest, with a length of 18.3-33.6 cm. Digits II and IV are approximately 25% shorter than digit III, with digit II tending to be slightly longer than digit IV.

Phalangeal pads are moderately well defined; four pads can be found on digit III, with the proximalmost being confluent with the heel; two pads can be distinguished on digit II and three pads on digit IV. The pads tend to be as long as broad or slightly longer than broad, separated by relatively shallow constrictions, which gives this footprint morphotype a massive appearance. Digit III is clearly the broadest, attaining its maximum width, ranging from 3.9 cm to 12.1 cm, in its distal half.

The average angle between digits II and III is 37° and between digits III and IV, 40°, resulting in a total divarication of approximately 77°. Digits II and III often have their tips deflected medially (away from digit IV). The interdigital area is deeper indented between II and III than between III and IV. Distinctive V-shaped claw impressions mark the distal tip especially of digits II and III.

Morphotype B:

The footprints are elongate and have a slender and gracile appearance (Fig. 6). The total width of the footprints is 12.2-33.3 cm. A heel is present but weakly defined. Digit III is the longest, attaining a length of 11.4-29.2 cm. Digits II and IV are subequal in length and approximately 30% shorter than digit III. Three well defined phalangeal pads can be found on digit III, with a possible fourth pad being part of the heel, two pads on digit II and three on digit IV. The phalangeal pads are elongate. Especially on digit III, their width decreases towards the distal tip of the digit, the broadest part of the digit (2.8-7.2 cm) being in its proximal half. The average divarication between digits II and IV is 73°, with subequal angles between digits II and III and digits III and IV. No clear difference between both interdigital areas has been observed. Well defined V-shaped and pointed claw impressions can be found at the tip of the digits. The claw impressions tend to be smaller than those of morphotype A.

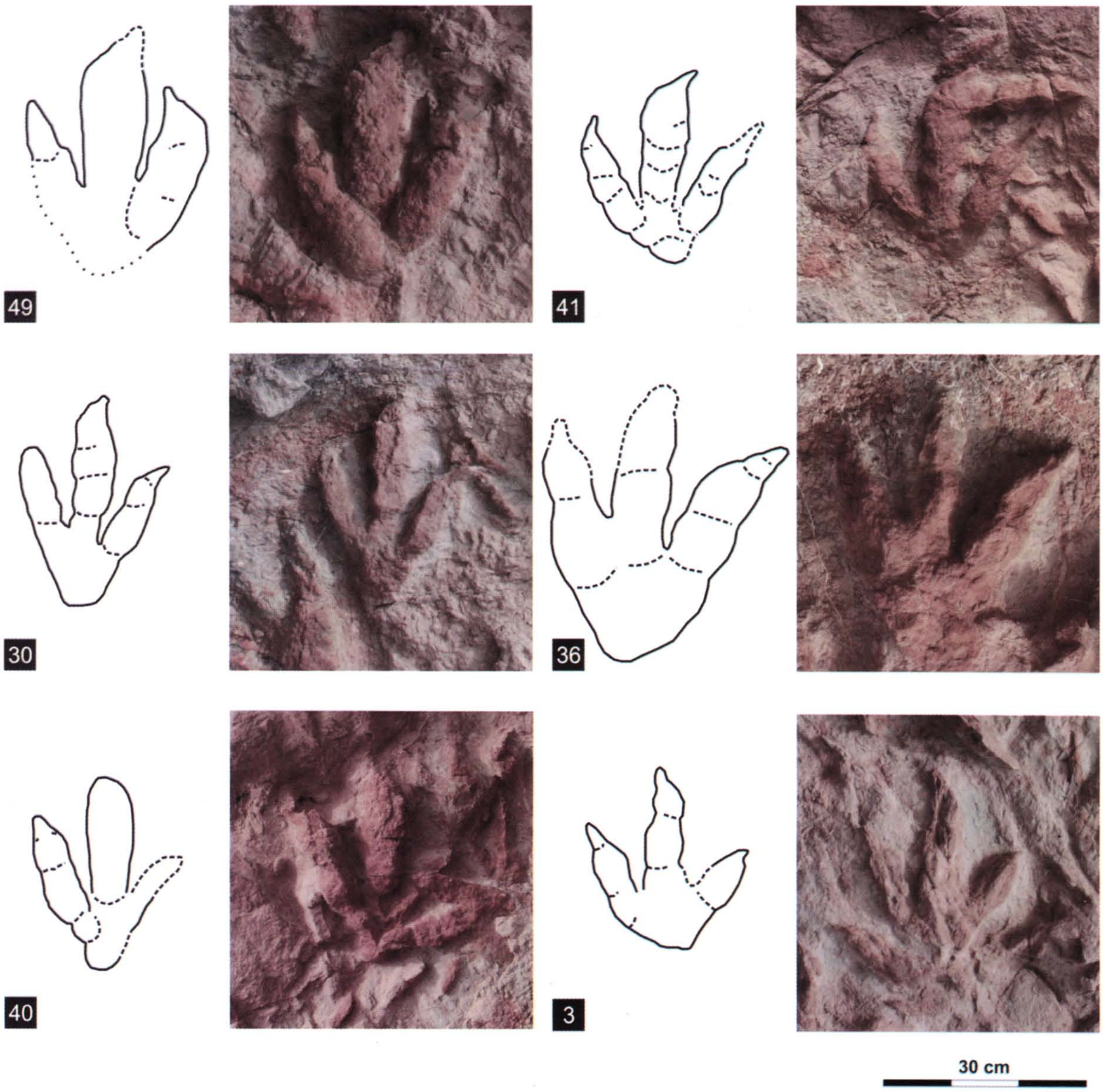
Trackways:

Despite the large number of footprints at the Shanshan tracksite, only a few seem to be part of discernable trackways (Fig. 7). One probable trackway has been identified during field work (TW1). It is composed of four footprints, which are, in consecutive order of locomotion: numbers 91, 115, 102 and 40. The footprints belong to morphotype A and are of comparable size (footprint 40 is somewhat shorter than the other three footprints). The step length between footprints 91 (R) and 115 (L) is 134 cm and 127 cm between footprints 115 (L) and 102 (? R), the stride length (R-L-R) is 269 cm. The footprints point towards the axis of locomotion. The trackway width is small, but has not been determined due to the imprecise graphical measurement.

Other possible trackways have been identified from photographs. Footprints 36 and 138 (no measurements available) seem to be part of a trackway (TW2). The step length between footprints 36 (R) and 138 (? L) (graphically measured) is 110 cm.

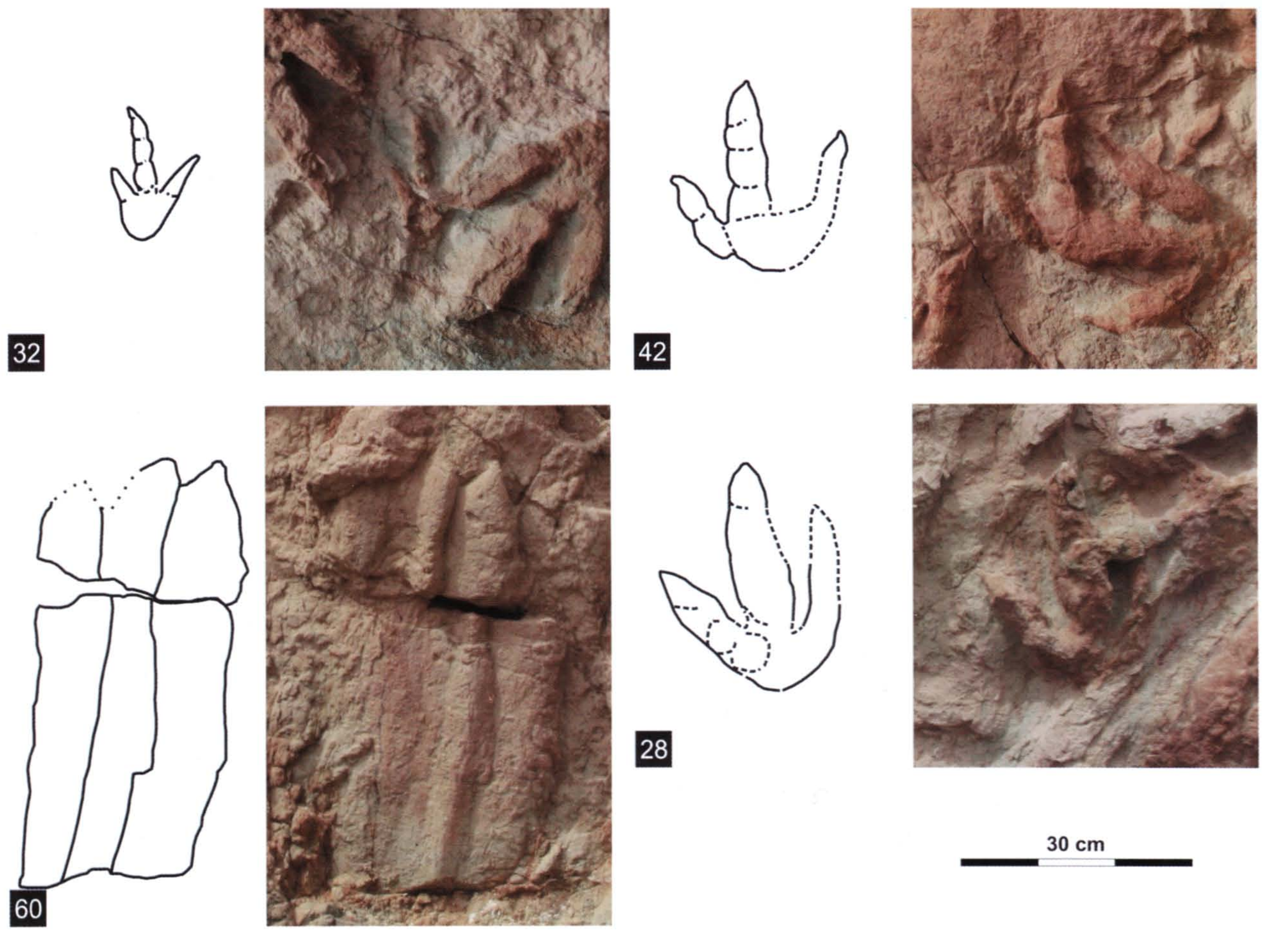
Another possible trackway (TW3) could be composed of footprints 125 and 16 (no measurements available). The graphically estimated step length between footprints 125 (? L) and 16 (R) is 124 cm. In both cases, measurements of trackway width would be insignificant, because only two footprints are present in each of the presumed trackways.

It is questionable whether footprints 123, 24, 30, [missing footprint], 131, 39, and 95 as well as footprints 97, 99, 154, and 12 form trackways (TW4 and TW5), respectively. Although the footprints of both possible trackways seem roughly aligned, the dimensions diverge considerably in some cases and poor



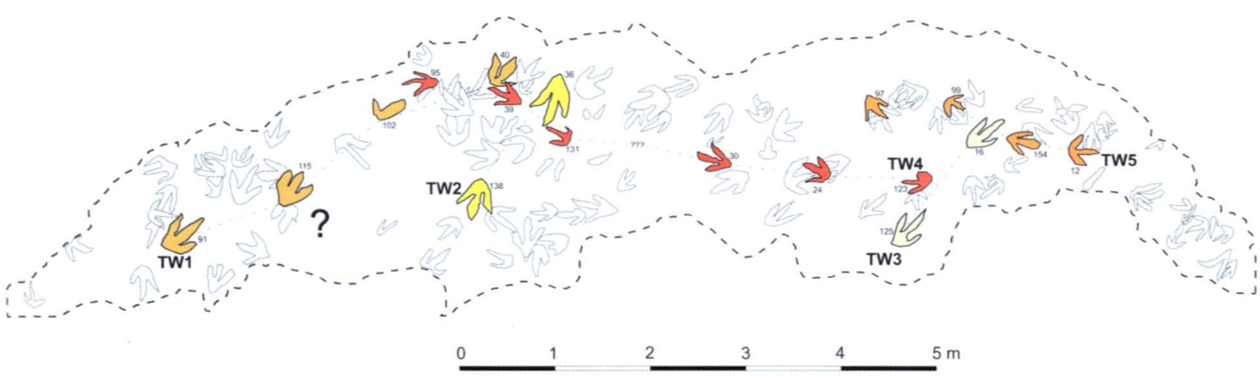
A from the Shanshan tracksite in detail as outline drawings (left) and photographs (right) with field numbers. Same scale.

Fig. 5 Well preserved imprints of morphotype A



B (top row) and of uncertain attribution (bottom row) in detail as outline drawings (left) and photographs (right) with field numbers. Footprint 60 shows prominent retro-scratches, probably formed during slipping. The movement along the fault line has been corrected in the line drawing of 60. Same scale.

Fig. 6 Well preserved imprints of morphotype B and uncertain attribution



Identified among the Shanshan footprints from Section 2. For discussion, see text.

Fig. 7 Five possible trackways (TW1-TW5)

preservation makes determination of some of the concerned footprints impossible. Both possible trackways have more or less curved midlines, preventing graphical determination of trackway width.

Invertebrate trace fossils:

Positive hyporeliefs of invertebrate traces occur commonly in some parts of the sandstone. The traces are often slightly curved, 1-5 cm long and 1-2 cm wide, giving them sausage-like appearance. In some areas, invertebrate traces obscure the morphology of footprints (Fig. 4).

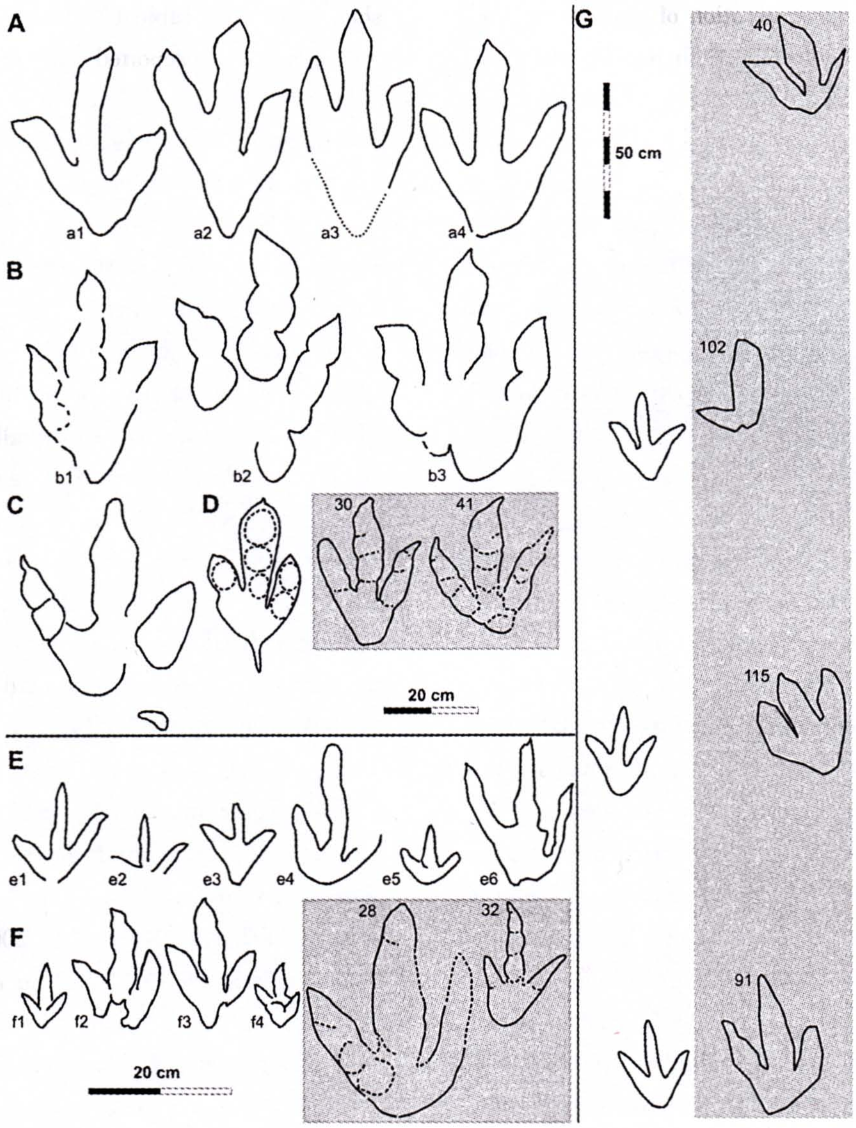
Comparison

Potential tridactyl trackmakers comprise only theropod (including birds) and ornithopod dinosaurs. Birds had not yet evolved in the Middle Jurassic; and avian footprints generally have unique shapes (i. e., slim digits with a length larger than two thirds of footprint length, digit width distally and proximally identical, divarication between II and IV often > 90°, Thulborn, 1990) which are different from the Shanshan footprints. Only pes imprints have been found at the Shanshan tracksite. Because poor preservation or destruction of manus imprints is implausible, the footprints must have been produced by bipedal theropods or ornithopods, both groups having been reported from the Middle Jurassic of China. Several basal ornithopods are known from the Middle Jurassic of China (Barrett *et al.*, 2005; He, 1979; He and Cai, 1983; Peng, 1990, 1992), but no footprints have been assigned to them and the morphology of the foot skeleton gives no secure hint to footprint shape. Generally, basal ornithopod footprints are tridactyl or tetradactyl, often U-shaped in outline, and frequently consist only of digit imprints. The imprints of toes II, III, and IV are parallel-sided or slightly tapered, and all three are roughly equal in width. The mean ratio of footprint width (FW) / footprint length (FL) is 0.91 ± 0.18 (Thulborn, 1990) for small ornithopods, which contrasts the ratio of about 0.78 for the Shanshan footprints (Table 1). Finally, the body sizes of < 2 m of hitherto reported Chinese Middle Jurassic ornithopods are too small for the Shanshan footprints (see below). Consequently, we consider these footprints as having not been produced by ornithopods.

The Shanshan footprints correspond well in all criteria to those of tridactyl theropod footprints (Thulborn, 1990). For example, the V-shaped imprints reveal three large and forwardly spreading digits (II, III, IV) with large and sharply pointed claws. Digit III is the longest and the subequally long digits II and IV show an almost symmetrical pattern. The Shanshan FW/FL ratio (0.78; Table 1) fit data of coelurosaurs (FW/FL: 0.73 ± 0.19) and carnosaurs (FW/FL: 0.77 ± 0.14) (Thulborn, 1990). While the interdigital angles II-III and III-IV are roughly equal as in other theropod footprints, the total divarication of digits II-IV (up to 115°; Table 1) is very high for carnosaurs, but well in the range of coelurosaurs (up to 180°, Thulborn, 1990).

A large variety of tridactyl theropod footprints have been found in China (Chen *et al.*, 2006; Fujita *et al.*, 2007; Li D. *et al.*, 2006; Li J. *et al.*, 2006; Li and Zhang, 2000; Lu *et al.*, 2007; You and Azuma, 1995; Young, 1960; Zhen S *et al.*, 1994; Zhen *et al.*, 1989). Many of the Chinese theropod footprints are Cretaceous in age, but nevertheless show similarities to the Shanshan footprints (Fig. 8) and will be discussed briefly.

You and Azuma (1995) described five trackways from the Early Cretaceous of Luanping, Hebei, including two different sized theropod trackways. The footprints of "track A" are relatively small and digitigrade, and were probably produced by a small gracile theropod. The imprints of "track B" are much larger and must have been produced by a large theropod such as an allosaurid. The footprints of "track B" fit in size, shape, and divarication of digits to the Shanshan footprints: the length of digit III (21.6 cm), the divarication of digits II-III (30°), digits III-IV (36°),



A (marked in grey; field numbers 30, 41; compared with A-D; same scale) and B (marked in grey; field numbers 28, 31; compared with E, F; same scale) with similar footprints from the literature.

A: *Changpeipus carbonicus*, sketches of footprints of at least two animals from the Middle Jurassic of Sungsankan/Huinan (redrawn after Young, 1960). Footprints are preserved as negatives in sandstone.

B: Some Upper Jurassic megalosaur footprints (redrawn from Lockley *et al.*, 1996): b1: "*Megalosauripus*" from Portugal; b2: "*Megalosauripus*" from Arizona-Utah; b3: "*Megalosauripus*" *uzbekistanicus* from Turkmenistan-Uzbekistan;

C: *Bueckeburgichnus maximus* from the Lower Cretaceous B ckeberg Formation of Germany (Lockley *et al.*, 2004). Note hallux impression (digit I).

D: *Changpeipus xuiana* from the Middle Jurassic Yima Formation of Yima County (Henan Province). Outline drawing based on a artificial negative print (redrawn from Lu *et al.*, 2007).

E: Footprint outlines of a small gracile theropod from the Middle Jurassic of the Cleveland Basin (Yorkshire) (redrawn from Whyte *et al.*, 2007, e1 = Bix, e2 = Bxiv, e3 = Bxi, e4 = Bvii, e5 = Bxiii, e6 = Bvi). The footprints are comparable to *Grallator*, *Anchisauripus*, and *Eubrontes*.

F: Footprint outlines of a small theropod (*Grallator*, *Anchisauripus*, or *Eubrontes*) from the Bathonian Kilmaluag Formation of Isle of Skye/United Kingdom (redrawn after Clark *et al.*, 2005, e1 = GLAHM 114912/16, e2 = field specimen, e3 = GLAHM 114912/1, e4 = GLAHM 114904).

G: Comparison between a large carnosaur trackway from the Early Cretaceous of Luanping/Hebei province (redrawn after "track B" of You and Azuma, 1995), left, and the Shanshan trackway TW1 (morphotype A; footprints with field numbers), right. Same scale.

Fig. 8 Comparison of Shanshan morphotypes

and digits II-IV (66°) (You and Azuma, 1995) are in agreement with the average values of Shanshanmorphotype A (18.3-33.6 cm, 37°, 40°, 77°); and the digits II are slightly longer than the digits IV.

The ichnotaxa *Paragrallator yangi* (Li and Zhang, 2000) as well as *Grallator emeiensis* or *Neograllator emeiensis* (Zhen *et al.*, 1994) are too small to be considered for the Shanshan footprints. The tridactyl and mesaxonic "type 2" and "type 3" theropod footprints from the Hekou Group, Gansu province, (Li D. *et al.*, 2006) are also smaller in length than the Shanshan footprints. The "type 2" footprints are similar to *Changpeipus* and the "type 3" footprints are possibly an ichnospecies of *Grallator*. Li D. *et al.* (2006) separate footprints of "type 2" and "type 3" by their average stride length. However, because stride length depends on speed, this separation is invalid. A comparison with the Shanshan track stride length is complicated because of the rarity of preserved trackways at Shanshan. Average footprint length is much larger in "type 2" (147 mm compared to 118 mm in "type 3") but still too short to fit Shanshan footprints of morphotype A (length of digit III: 18.3-33.6 cm).

Fujita *et al.* (2007) described three types of tracks probably belonging to *Grallator* from the Upper Jurassic Tuchengzi Formation of Liaoning province. "Track C" has the largest footprints with an average length of digit III of 105.9 mm which is shorter than in Shanshan morphotype B. The digits IV are longer than the digits II. This is not observed in Shanshan morphotype A or B.

Changpeipus carbonicus was first described by Young (1960) from the Middle Jurassic of Huinan and Fuxin (Fig. 8A). Size (length of III: 292-383 mm), shape, and divarication (II-III: 25°-29°; III-IV: 20°-48°) fit well data of Shanshan morphotype A. Total divarication between digits II and IV of *Changpeipus carbonicus* is 65.2°-92°. However, the values of II-IV in Young's dataset are unusual in being not identical with the sum of II-III and III-IV, respectively. The footprints are preserved as negatives with typical deltoid outlines. The fourth digits are distinctively longer than the second digits (length of II: 158-270 mm; length of IV: 244-300 mm), in contrast to Shanshan morphotype A.

The footprints of *Changpeipus xuiana* from the Middle Jurassic Yima Formation of Yima, Henan, are similar in length and divarication of digits (II-III: 25°; III-IV: 32°) (Lu *et al.*, 2007). The pads of digit III are distally wider than proximally similar to Shanshan morphotype A. Contrary to morphotype A, digit II is slightly shorter than digit IV. Additional shape differences to the Shanshan footprints are caused by clear metatarsal impressions at the back of the footprints.

A large number of theropod footprints are known from the Middle Jurassic of the UK (Clark and Barco Rodriguez, 1998; Clark *et al.*, 2005; Day *et al.*, 2004; Marshall, 2005; Whyte and Romano, 2001; Whyte *et al.*, 2007). Marshall (2005) described small theropod footprints from the Bathonian Valtos Sandstone Formation of the Isle of Skye. They are much smaller (footprint length nearly 80 mm) than the Shanshan footprints and have a different shape, with digit II as the largest. The first trackway from the Valtos Sandstone Formation (Clark and Barco Rodriguez, 1998) was compared with *Grallator/Eubrontes* but has a different shape to the Shanshan footprints. An ornithopod as possible track maker has also been discussed for this trackway.

Other footprints from the Isle of Skye are known from the Bathonian Kilmaluag Formation (Clark *et al.*, 2005). These imprints belong to *Grallator*, *Anchisauripus*, or *Eubrontes*. These three ichnotype genera may belong to one track maker or group of track makers with different size and age stages (Olsen, 1980). There are shape similarities between the Kilmaluag Formation footprints and the Shanshan footprints, but the size of the UK footprints (8-22 cm) is slightly smaller than the Shanshan footprints.

Characichnos tridactylus has been described from the Aalenian Saltwick Formation of Whitby (Yorkshire) (Whyte and Romano, 2001). The elongated digits and shape are different to the Shanshan footprints. The morphology of *Characichnos tridactylus* is a product of a specific animal behavior, but different tetrapods not only dinosaurs could have produced these traces.

A Middle Jurassic vertebrate ichnofauna dominated by dinosaurs was reconstructed from the Cleveland Basin of Yorkshire (Whyte *et al.*, 2007). Larger tridactyl footprints linked to *Megalosaurus* (Whyte *et al.*, 2007) are different in shape to Shanshan morphotype A (Fig. 8). The digits of morphotype A are wider at the distal end than at the proximal end, in opposition to the *Megalosaurus* footprints from the Cleveland Basin. Smaller footprints of a gracile theropod were compared with *Grallator*, *Anchisauripus*, and *Eubrontes*. With a nearly identical size, III as the longest digit, and all three digits narrowing distally, the footprints are similar to Shanshan morphotype B.

Some Middle Jurassic trackways are preserved in Oxfordshire (Day *et al.*, 2004). The footprints diagnosed as *Megalosauripus* are at least 16% larger (length of digit III: 39 cm) than Shanshan morphotype A. Digits II and IV are similar in width and are approximately three-quarters of the length of digit III like in the Shanshan footprints.

Bueckeburgichnus maximus (Fig. 8C) from the Lower Cretaceous Bueckeberg Formation of northern Germany has been described with a tetradactyl footprint (Lockley *et al.*, 2004; Thulborn, 2001). The impression of the hallux (digit I) is often very small and may not have been recognized, resulting in a tridactyl outline similar to the Shanshan footprints. In *Bueckeburgichnus*, digit III is the longest, being slightly longer and broader than digit IV. Both are moderately slender and straight. The weakly curved digit II is the shortest, except for digit I. Footprint size including the heel is moderate to large, with a maximum length of 71 cm. Divarication of II-IV is 65°-70°, similar to the Shanshan footprints. Size and shape of *Bueckeburgichnus* matches many Shanshan footprints, but digit IV is longer than digit II and digit III narrows distally which differs from morphotype A at least. *Bueckeburgichnus maximus* has also been discussed as an ichnospecies of *Megalosauripus* (Lockley *et al.*, 2004; Thulborn, 2001).

Discussion

Morphotype A at the Shanshan locality was made by a large theropod. It is similar to *Changpeipus* (Lu *et al.*, 2007; Young, 1960) and "Track B" of Luanping (You and Azuma, 1995). Some tracks attributed to *Megalosauripus* (e. g., from Arizona-Utah, Portugal, and Turkmenistan-Uzbekistan, Lockley *et al.*, 1996) also show similarities to morphotype A (Fig. 8B), but most *Megalosauripus* footprints are different. Megalosaur tracks have a variable morphology and are widely distributed in time (late Oxfordian late Albian) and space (Europe, Asia, North America, Australia). Currently, the concept of megalosaur footprints is still an ichnotaxonomic waste basket (Lockley *et al.*, 1996, 1998; Lockley *et al.*, 2004). The track maker of morphotype A was probably a large carnosaur with estimated hip heights ranging from 1.2-2.3 m (calculated after Thulborn, 1990). Hence, the morphotype A trackmakers probably had body sizes comparable to *Allosaurus fragilis* (calculated hip height: 1.68 m, Henderson, 2003). The slightly larger *Sinraptor dongi* from Upper Jurassic sediments in the nearby Junggar Basin (Currie and Zhao, 1993) could have been the trackmaker, but no *Sinraptor* material has been found in the Turpan Basin until now. The Middle Jurassic theropod *Gasosaurus constructus* (Dong and Tang, 1985) from Dashanpu, Zigong, also should be considered as possible trackmaker.

The footprints of morphotype B were made by a slightly smaller theropod, possibly a coelurosaur. The estimated hip heights of morphotype B are 1.0-1.9 m (calculated after Thulborn, 1990). The slender and gracile footprints are similar to *Grallator*, *Eubrontes*, and *Anchisauripus*, which possibly all represent different age and size appearances of the same dinosaur genus or family (Olsen, 1980). Olsen and Galton (1984) synonymized the names *Eubrontes* and *Anchi-*

sauripus with *Grallator* and subdivided subichnogenera, but disagreed that these footprints were made by just one dinosaur taxon or even family of archosaurs. Li and Zhang (2000) used *Eubrontes*, *Anchisauripus* and *Grallator* as separate ichnogenera.

There are three possible scenarios for genesis of the "slip footprint" (footprint no. 60) in water-saturated mud. It may represent swimming, or a footprint of a dinosaur slipping either backwards or forwards in the mud. The single find of a "swimming footprint" seems implausible, and another argument against this interpretation comes from hip height estimations. The center of mass is below the water surface in freely swimming animals (Henderson, 2004), and the center of mass in theropods has nearly the same height as the hip (Henderson, 1999). Hence, water depths of up to 2 m would have been necessary for formation of swimming tracks. Coombs (1980) estimated water depths of 1.5-2.5 m for swimming *Eubrontes* tracks from the Lower Jurassic at Rocky Hill (Connecticut). However, such water depths seem implausibly deep for the Shanshan tracksite.

During acceleration, a dinosaur may slip backwards. Conversely during deceleration, the animal may slip forwards. These would seem more plausible explanations for footprint no. 60, but no claw marks are preserved at either end of the footprint, making further interpretation difficult. The muddy floodplain depositional environment also is considered a potentially slippery environment, supporting interpretation as slip marks. Careful crossing of unstable, slippery ground is indicated by footprints of one of the trackways pointing inwards (Figs. 7, 8G; TW1) and by the high total divarication of digits II-IV of some carnosaur footprints (morphotype A; Table 1).

The relationship between footprint size and depth of impression is variable. The largest animals did not necessarily produce the deepest footprints. This improper correlation might suggest different locomotion speeds or variable sediment plasticity during genesis of the tracksite. However, the footprints do not indicate a linear pattern in the sediment plasticity (i.e. changes of water content) as the relatively deepest impressions are not always the oldest. There are at least three generations of footprints visible (footprints 69-72) which all must have been formed during the period when the mud was moist and plastic. We estimate the duration of this time interval between several hours and several weeks.

The invertebrate traces probably originate from bivalve activity and represent ? *Lockeia siliquaria* (Radley *et al.*, 1998), an ichnotaxon which can occur in conjunction with dinosaur footprints (e.g., Marshall, 2005). Because *Lockeia* traces obscure the morphology of footprints (Fig. 4), bivalve activity must have occurred later than footprint formation. It is plausible that *Lockeia* bioturbation originated directly in the sand layer before lithification.

Conclusion

The Shanshan tracksite represents the first evidence of fossil vertebrates in the Middle Jurassic of the Turpan Basin and the first dinosaur footprints in Xinjiang. Two morphotypes of theropod dinosaur footprints can be distinguished, one of a large carnosaur, the other of a slightly smaller coelurosaur, but final identification of ichnotaxa is currently not possible due to the preliminary status of our field work and the confusing ichnotaxonomic state of theropod dinosaur footprints. Detailed conclusions about the Shanshan trackmakers are difficult because the majority of the footprints currently consist of isolated footprints instead of trackways.

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