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Re-description of the partially collapsed Early Cretaceous Zhaojue dinosaur tracksite (Sichuan Province, China) by using previously registered video coverage

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ABSTRACT

A re-description of the Early Cretaceous Zhaojue dinosaur tracksite (Sichuan Province, China) is the major focus of the present work. The tracksite is located in an active copper mine, and a dinosaur track-bearing surface of about 1500 m^2 (named tracksite I) initially discovered in 1991, has since almost completely collapsed due to ongoing quarry activities. Only about 5% of the initial surface still remains in place (named "remaining tracksite"), while due to the collapse a few new but rather poorly-preserved tracks were unearthed on an underlying level. While the tracks still in place were studied using common field techniques, a schematic tracksite map of the collapsed surface was drawn based on a "corrected orthophotograph" that was generated from overview photographs and from video frames. Fortunately, the resolution of some of the close-up video frames is sufficiently high to observe general track morphology, and to re-interpret previously wrongly identified trackways. Here, we report a quite diverse ichnocoenosis consisting of sauropod, ornithopod, theropod, and pterosaur trackways and isolated tracks. The sauropod trackways belong to the *Brontopodus*-type and were possibly left by medium-sized titanosaurs. One of the sauropod trackways turns around and makes an astonishingly narrow turn of more than 180° with very pronounced "off-tracking" of the manus with respect to the pes. Such unusual trackways are important for the reconstruction of sauropod locomotion. The theropod trackways were left by small and medium-sized animals with the imprint morphology being similar to that of the ichnogenera *Grallator* and *Eubrontes*. Large tridactyl tracks with blunt toes are tentatively identified as ornithopod tracks and may be described as *Caririchnium*-type *tracks*. Pterosaur tracks can be assigned to *Pteraichnus*. The association of pterosaur with small theropod tracks is rather unusual, and this tracksite further corroborates the frequent presence of large ornithopods in inland environmental settings.

1. Introduction

The Sichuan Basin is famous for its rich Jurassic dinosaur faunas, whereas those from the Cretaceous are scarcely known. Thus, Early Cretaceous dinosaur tracksites are important to fill this faunal gap (Zhen et al., 1994; Xing et al., 2007, 2011a, 2013), and among the Sichuan tracks, those from the Zhaojue region are exceptional.

In September 1991, while mining copper, in Sanbiluoga Village (Sanchahe Township, Zhaojue County) in Sichuan Province (Fig. 1), a very large surface with various dinosaur trackways (here designated as "tracksite I" or "original tracksite") was exposed in the Lower Cretaceous Feitianshan Formation. However, it was only in December 2004 that Jiefang Ebi from the Zhaojue County Bureau of Culture, Multimedia, Press, Sport and Tourism investigated these tracks. The track-bearing surface spans approximately 1500 m^2 and displays at least twelve discrete trackways (Figs. 2A, 3). In February 2006, Kui Li and Jian Liu from the Museum of Chengdu University of Technology re-studied the tracksite and published two abstracts

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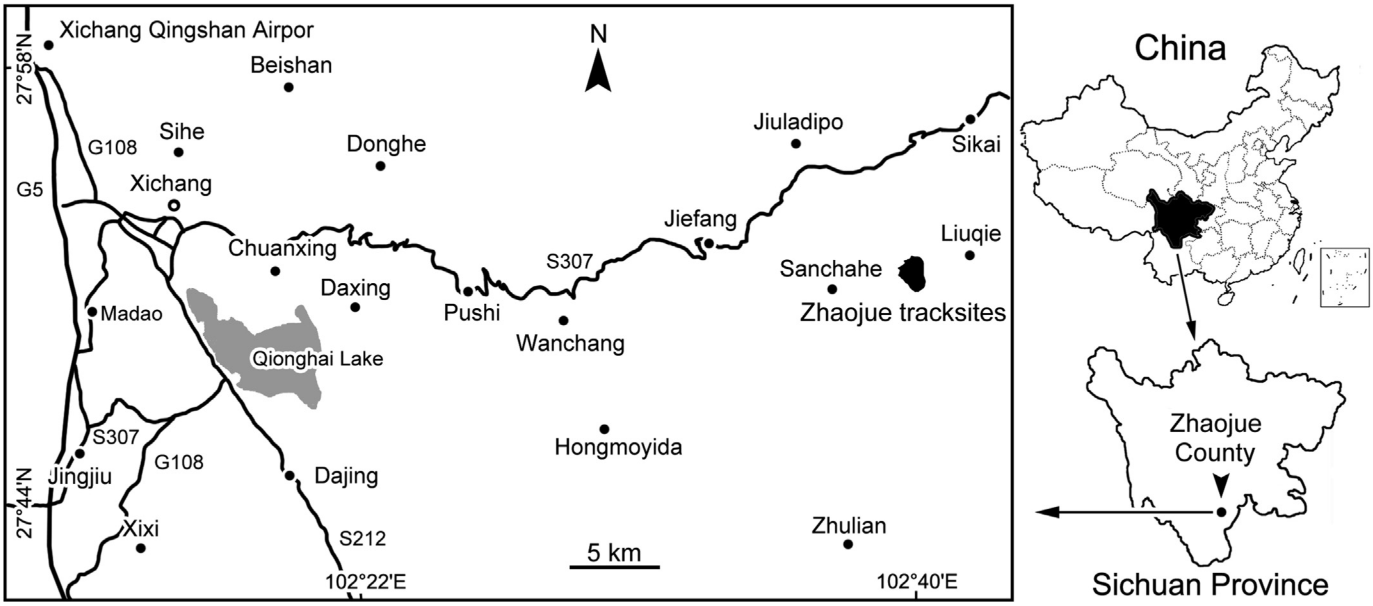

Fig. 1. Geographical setting of the Zhaojue tracksite (footprint icon) within Sichuan Province, China.

indicating that there were more than 1000 vertebrate tracks at tracksite I, including tracks of sauropods, theropods, and pterosaurs (Liu et al., 2009, 2010).

Unfortunately, between 2006 and 2009, the largest part of tracksite I collapsed due to ongoing mining operations and resulting landslides (Fig. 2B). The collapsed track-bearing bed was approximately one meter in thickness, and included several layers with tracks. The first author of the present paper investigated the tracksite in 2012 and 2013, and by that time, 95% of tracksite I had collapsed. The remaining part (here designated as "remaining tracksite"), and representing about 5% of the original tracksite is located in the southernmost extremity of the location (Fig. 2B), exhibiting around 100 tracks (Fig. 4). Underneath the collapsed strata, ten tracks were newly exposed. These are mainly sauropod and theropod undertracks. A new tracksite, named tracksite II was discovered on the slope opposite tracksite I in the same quarry, and it belongs to the same Feitianshan Formation. Xing et al. (2013) described the dinosaur track assemblage of tracksite II, including the first definitive non-avian theropod swim trackway from China. Herein we re-evaluate the fauna of tracksite I based on the scant remaining material, photographs and on analysis of video material shot in 2006 prior to the collapse of tracksite I.

2. Material and methods

2.1. The remaining tracksite

Due to the steepness of the bedding planes (40–50°) at both the remaining southern part of tracksite I and tracksite II (Xing et al., 2013), it was necessary to use climbing ropes during the study of track-bearing surfaces.

In order to make accurate maps, essential for areas scheduled for destruction by ongoing quarry operations, tracks were photographed, outlined in chalk, and traced on large transparent plastic sheets. In addition a representative area with well-preserved tracks was mapped by hand using a chalk grid. Several natural casts were collected, and latex moulds of the best-preserved tracks were made. Additionally, detailed tracings of selected tracks were made on transparent acetate film. Latex moulds, plaster replicas, and tracings are deposited in the collections of the Huaxia Dinosaur Tracks Research and Development Center (HDT) and the University of Colorado Museum of Natural History (UCM).

For the trackways of quadrupeds, gauge (trackway width) was quantified for pes and manus tracks using the ratio between the width of the angulation pattern of the pes (WAP) or manus (WAM) and the pes length (PL) or manus width (MW), respectively (according to Marty, 2008; Marty et al., 2010). The (WAP/PL)-ratio and (WAM/MW)-ratio were calculated from pace and stride length, assuming that the width of the angulation pattern intersects the stride under a right angle and at the approximate midpoint of the stride (Marty, 2008). If the (WAP/PL)-ratio equals 1.0, the pes tracks are likely to touch the trackway midline. If the ratio is smaller than 1.0, tracks intersect the trackway midline, and are considered to be narrow-gauge trackways (*sensu* Farlow, 1992; see also Romano et al., 2007). Accordingly, a value of 1.0 separates narrow-gauge from medium-gauge trackways, whereas the value 1.2 was arbitrarily fixed between medium-gauge and wide-gauge trackways, and trackways with a value higher than 2.0 are considered to be very wide-gauge (Marty, 2008; Marty et al., 2010).

Track rotation was measured with respect to the stride length between two consecutive pes/manus tracks, with positive values indicating an outward rotation (see also Marty, 2008: Fig. 2.11).

Photogrammetric images were produced from three photographs (taken by film camera in 2006) which were converted into scaled, highly accurate 3D textured mesh models using Agisoft Photoscan (http://www.agisoft.ru/) (Falkingham, 2012). The mesh models were then imported into Cloud compare (http://www.danielgm.net/cc/) where the models were rendered with accurately scaled colour topographic profiles (Falkingham, 2012).

2.2. Photo and video documentary of tracksite I

Prior to the collapse of tracksite I, overview photos were taken and kindly provided by Sichuan Daily (initially figured in January 14, 2005), Liangshan Daily (initially figured in June 19, 2012), Mr Jiefang Ebi, and Prof. Kui Li. However, they lack a scale and more

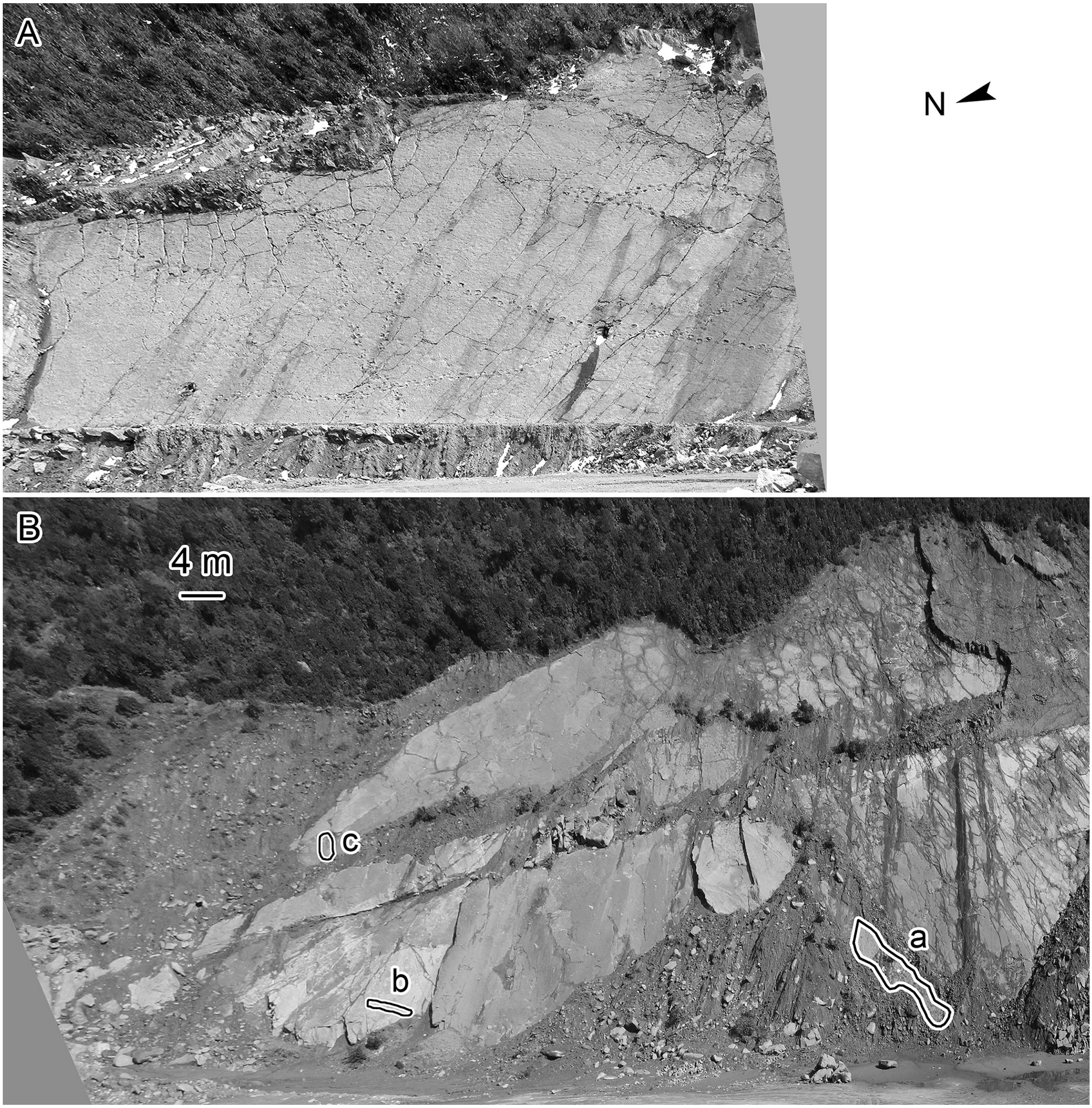

Fig. 2. Photographs of tracksite I with same scale. (A), corrected overview photograph of original surface. (B), tracksite I after collapse, with the position of the remaining portions (a) with respect to the map as shown in Fig. 3; (b) and (c) indicate the position of theropod tracks on the new exposed underlying level.

detailed close-ups. These overview photos (e.g. in Fig. 2A, the original photo is 2268 × 1699 pixel) are low-angle shots with respect to the track-bearing surface and provide a good idea about the general track and trackway distribution.

A video documentary "*Footprints Exploration*" was shot by Sichuan Television and was featured in the program *Ten Minutes for Tonight* on May 8, 2006. The original video lasts six minutes (Link: http://www.xinglida.net/mov). Sichuan Television and Zhaojue Administration of Cultural Relics provided the footage from the filming for analysis, and has permitted the use of this video material for scientific analyses.

The footage was edited by Final Cut Pro X (a non-linear video editing software developed by Apple Inc.). In total, approximately 3600 frames were cut out and saved in .png format. About 1500 of these frames were useful for the analysis of tracksite I. Many frames exhibit close-ups of the tracks and trackways, and allowed to study gross track morphology as well as to compare some tracks with images of humans and human feet in order to establish a gross scale.

In general, the video material does not have a very high resolution (resolution 720 × 576, 25 frames per second). However, the angle with respect to the track-bearing surface is higher (more

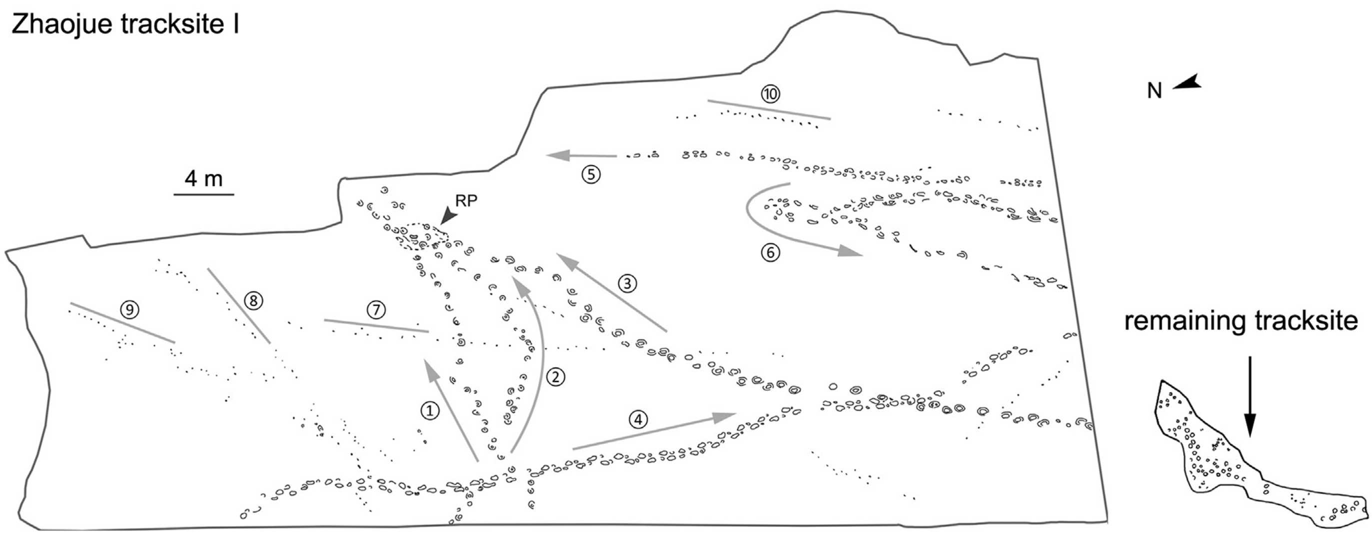

Fig. 3. Interpretative outline drawing of tracksite I, the left part based on the corrected photograph shown in Fig. 2A; the right part is the remaining tracksite (shown in Fig. 2B (a)). Arrows indicate the moving direction of trackways. This could not be established for the trackways of small bipedal dinosaurs (lines without arrows). Trackways 1–3 were left by ornithopods, trackways 4–6 by sauropods, and trackways 7–10 by small theropods. RP = Rallying Point or crossroads of ornithopod trackways.

vertical) than in the original overview photos, and therefore allowed us to adjust the original overview photos in Adobe Photoshop CS6 (using Photomerge to create panoramas) and DxO Optics Pro v9.1.3 in order to obtain a "corrected orthophoto" with minimal distortion regarding the position of the tracks and the distances between tracks for most of the original tracksite I, as shown in Fig. 2A. Based on this corrected orthophoto, the site map shown in Fig. 3 was drawn.

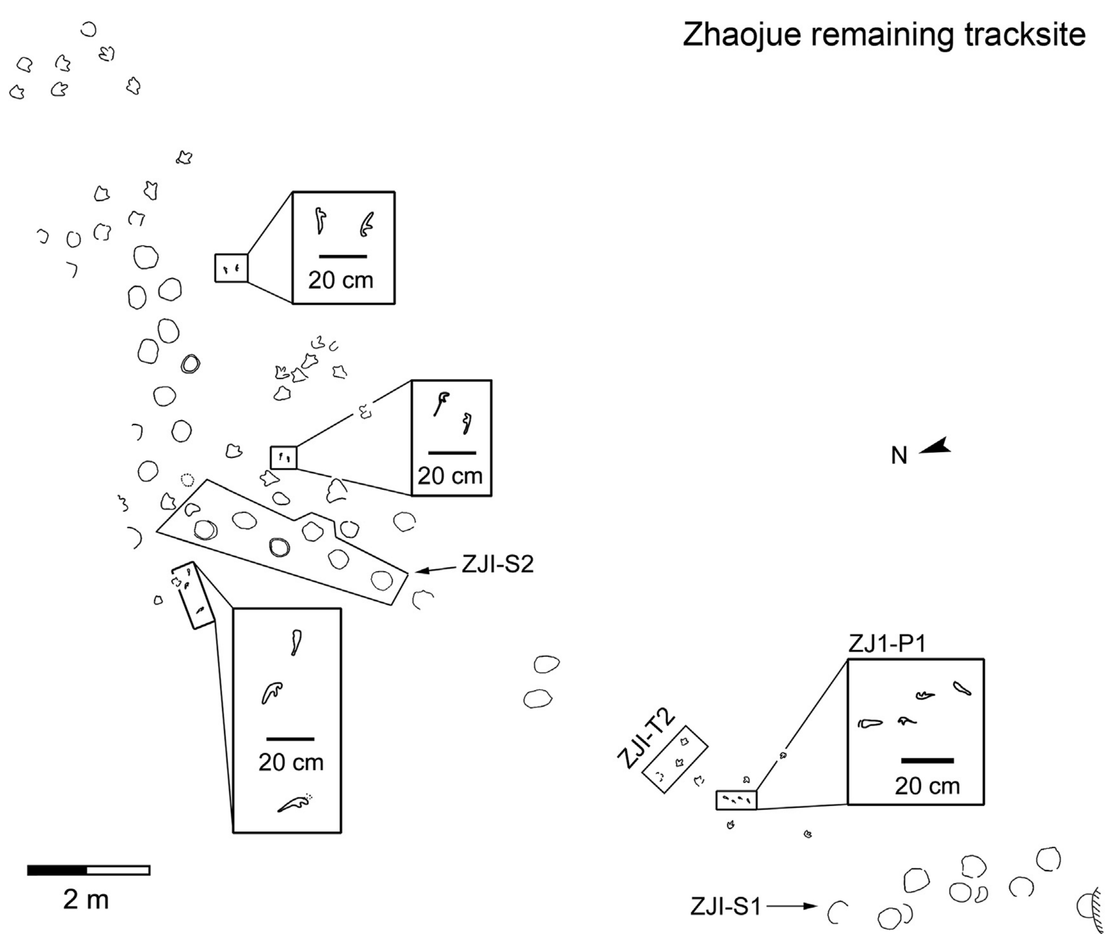

Fig. 4. Interpretative outline drawing of the remaining tracksite with sauropod (ZJI-S1, ZJI-S2), theropod (ZJI-T2) and pterosaur (ZJI-P1) tracks and trackways. Pair of pterosaur manus tracks in upper box = UCM 214.269,pair in middle box = UCM 214.270, two manus tracks in lower (left) box = UCM 214.271 and 214.272.

3. Geological setting

The Cretaceous-Paleogene sequence in the Liangshan Region is divided into the Lower Cretaceous Feitianshan Formation, the Upper Cretaceous Xiaoba Formation, and the Paleocene Leidashu Formation (The author team of Continental Mesozoic Stratigraphy and Paleontology in Sichuan Basin of China, CMSPSC, 1982; Gu and Liu, 1997). The Cretaceous strata are mainly composed of fluviatile deposits (Editorial Committee of Liangshan Yi Autonomous Prefecture Local Records, 2002). The Feitianshan Formation is a 302–1090 m thick unit of fluvial deposits including red clastic sediments, and was first assigned to the Upper Jurassic (CMSPSC, 1982), but has since been identified as Lower Cretaceous (Wei and Xie, 1987). The upper member of the Feitianshan Formation consists of alternations of mixed purplish-red and grayish-purple feldspar-quartz sandstone and purplish-red and brick-red calcareous siltstone and mudstone beds of variable thickness (Fig. 5). Large areas with ripple marks can be seen in Fig. 2A, and such features were previously described from the fluvial sediments of the Feitianshan Formation by Chen (1979). The Feitianshan Formation sandstones are rich in copper (Qin and Zhou, 2009), for which this Formation is mined at various places. The discovered dinosaur tracks were exposed during the exploitation of the copper mine.

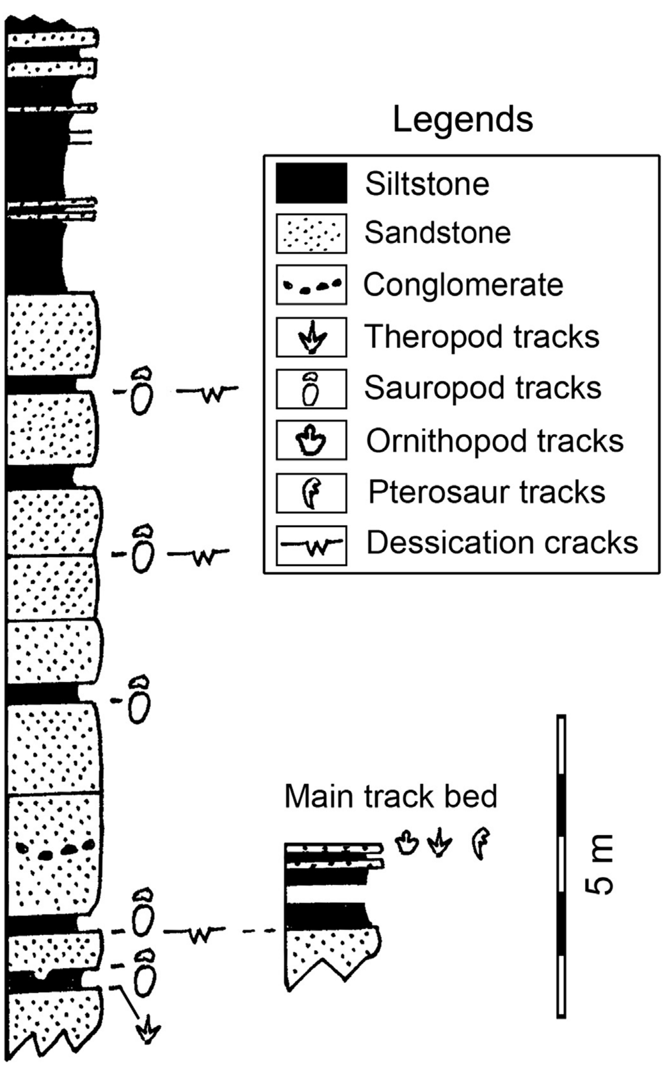

Fig. 5. Stratigraphic section of dinosaur tracksite Zhaojue I.

4. Description of tracks on the remaining southernmost part of tracksite I

4.1. Sauropod tracks

Description of the trackways.— There are at least 31 sauropod tracks in the southernmost part of the Zhaojue tracksite I (Fig. 4) with two trackways being well-defined. Trackway ZJI-S1 is pes-dominated consisting of two pes – manus track pairs, and six pes tracks that are not associated with manus tracks. These are catalogued as ZJI-S1-LP1–RP4, RM1, 2 (Fig. 6; Table 1). The sauropod trackway ZJI-S2 is pes-only and consists of six pes tracks and only one possible manus track catalogued as ZJI-S2-LP1–LP4. A natural cast (track fill) from ZJI-S1-RP2 was collected by the Zigong Dinosaur Museum, and was catalogued as ZDM201306-5. Other track casts still remain in the field.

The ZJI-S1 trackway contains the best-preserved sauropod tracks of the remaining Zhaojue tracksite I. All the pes and manus impressions exhibit two distinct parts. The internal part consisting of the true track *sensu stricto*, while the external part is made up of sediment displacement rims around the internal part. In ZJI-S1, the average manus track length is 14.2 cm and the average width is 31.5 cm, while the average pes track length is 40.1 cm and the average width is 35.6 cm.

The pes track ZJI-S1-RP2 and the manus track RM2 are the best-preserved (Fig. 6B). The latter is U–shaped with a length:width ratio of 0.5. It lacks discernible claw marks. Its metacarpophalangeal region is concave, the track slightly rotated outward (9°). The pes track ZJI-S1-RP2 is oval, with a length:width ratio of 1.2. The distance between RP2 and RM2 is 11 cm. Digits do not exhibit claw marks.

Generally the pes tracks show a metatarsophalangeal pad region that is smoothly curved. The manus tracks are rotated outward by an average of 17°. This value is smaller than the average outward rotation of the pes tracks (39°). The mean depth of the pes track ZJI-S1-RP2 (ZDM201306-5) is 10.5 cm, while the depth of the corresponding manus track ZJI-S1-RM2 is only 4 cm. The mean pace angulation for the pes tracks is 96°.

Regarding their overall morphology, the pes tracks of the ZJI-S2 trackway are similar to those of the ZJI-S1 trackway, even though their mean pes length (32.6 cm) is slightly smaller than the one of the latter. Also, the outward rotation of the pes tracks (32°) is slightly less pronounced than in the ZJI-S1 trackway. We emphasize that the ZJI-S2 trackway is not as well-defined as the S1 trackway, and the attribution of some of the pes tracks is somewhat doubtful.

Discussion.— The pes and manus morphology and trackway configuration of both the ZJI-S1 and –S2 trackways is typical for sauropod trackways (Lockley, 1999, 2001; Marty et al., 2010), even though most manus tracks are missing and both trackways are best-described as pes-only to pes-dominated trackways (following the terminology of Marty et al., 2006). Such trackways have frequently been regarded as those of relatively fast moving sauropods, where the pes frequently overprints the manus (e.g. Meyer, 1990). However, as the only preserved manus track of trackway ZJI-S1 is much shallower than the preceding pes track, it is possible that – at least some – manus tracks are not visible due to imperfect preservation (see also Lockley & Rice, 1990) rather than providing definitive proof that that they have been overprinted by a subsequent pes track.

Most sauropod trackways in China, especially those of Cretaceous age, are wide- (or medium-) gauge and are therefore referred to the ichnogenus *Brontopodus* (Lockley et al., 2002). The ZJI-S1 trackway is wide-gauge, with a (WAP/PL)-ratio of 1.3 (range 1.2–1.3) (Marty, 2008), whereas the less well-defined trackway

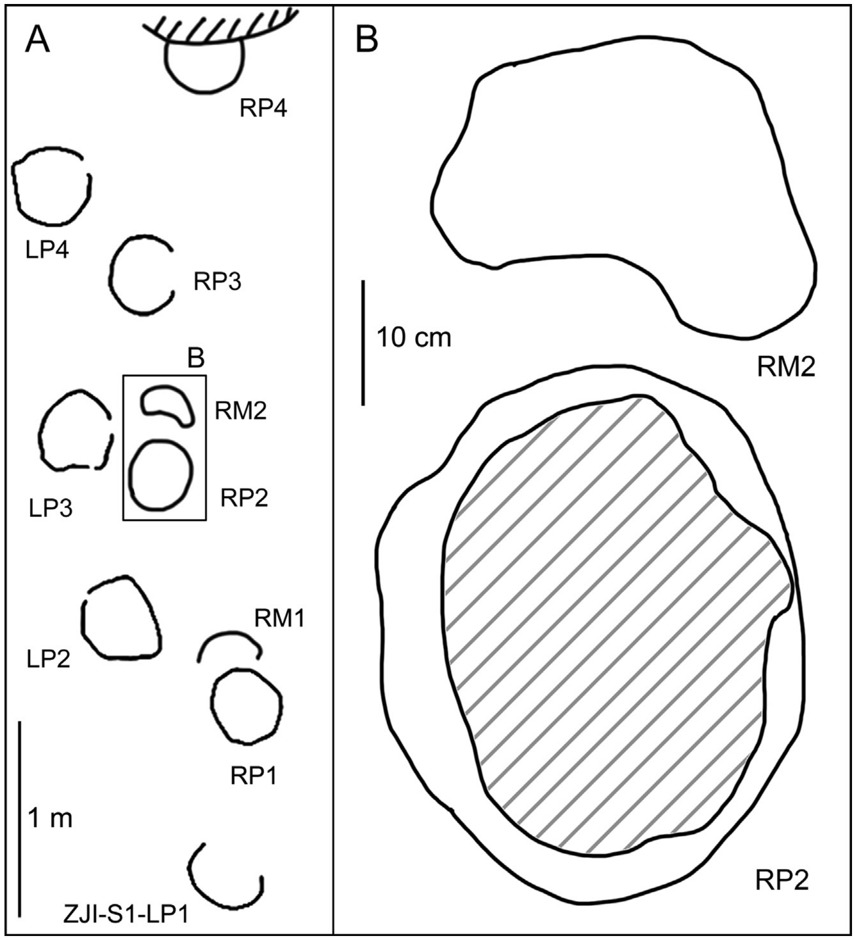

Fig. 6. (A) Interpretative outline drawing of sauropod trackway (ZJI-S1) from the remaining tracksite. (B) Close-up of the tracks ZJI-S1-RP2 and RM2. The pes still carries the track fill (hatched area).

ZJI-S2 is narrow-to medium-gauge with a (WAP/PL)-ratio ranging between 0.8 and 1.2, with an average of 1.0.

The ZJI-S1 trackway is consistent with the characteristics of *Brontopodus* type trackways, which are 1) wide-gauge; 2) have large and outwardly directed pes tracks that are longer than broad; 3) have U–shaped manus prints; and 4) show a low degree of heteropody (ratio of manus to pes size) (Farlow et al., 1989; Lockley et al., 1994; Santos et al., 2009; Marty et al., 2010). The mean heteropody of the ZJI sauropod tracks is 1:2.6 (range 2.3–2.8; $n = 2$). This is close to *Brontopodus birdi* (1:3) and significantly less than in

Table 1

Track and trackway parameters of the sauropod trackways from the Zhaojue tracksite I, Sichuan Province, China. All measurements in cm, except angles in degrees and WAP/PL, which is dimensionless. Abbreviations: PL: pes length; PW: pes width; PR: pes rotation; ML: manus length; MW: manus width; MR: manus rotation; PL: Pace length; SL: Stride length; PA: Pace angulation; L/W: length/width; WAP: Width of the angulation pattern of the pes (calculated value); WAP/PL: dimensionless ratio used to characterize trackway width (after Marty, 2008; Marty et al., 2010); —: measurement not possible or not applicable.

Number	PL	PW	PR	ML	MW	MR	PL	SL	PA	L/W	WAP	WAP/PL
ZJI-S1-LP1	40.0	—	40°	—	—	—	90.6	142.2	109°	1.1	—	—
ZJI-S1-RP1	38.1	35.3	30°	—	—	—	83.9	125.8	98°	—	51.4	1.3
ZJI-S1-RM1	—	—	—	13.5	32.8	9°	—	130.6	—	1.2	—	—
ZJI-S1-LP2	45.5	38.6	43°	—	—	—	83.2	98.4	97°	1.2	55.5	1.2
ZJI-S1-RP2	36.9	30.7	35°	—	—	—	55.5	102.6	88°	—	47.5	1.3
ZJI-S1-RM2	—	—	—	14.9	30.1	—	—	—	—	1.0	—	—
ZJI-S1-LP3	38.3	39.6	45°	—	—	—	94.0	123.3	82°	1.3	50.0	1.3
ZJI-S1-RP3	40.7	32.5	—	—	—	—	68.5	—	100°	1.1	51.3	1.3
ZJI-S1-LP4	41.1	36.9	—	—	—	—	—	—	—	1.1	—	—
Mean	40.1	35.6	39°	14.2	31.5	9°	79.3	120.5	96°	1.1	51.2	1.3
ZJI-S2-LP1	33.0	31.3	35°	—	—	—	—	88.8	—	1.1	—	—
ZJI-S2-RP1	—	—	—	—	—	—	—	—	—	—	—	—
ZJI-S2-LP2	30.0	32.5	37°	—	—	—	71.0	108.0	—	0.9	—	—
ZJI-S2-RP2	30.8	27.7	28°	—	—	—	65.5	122.0	107°	1.1	36.8	1.2
ZJI-S2-LP3	31.9	31.2	29°	—	—	—	80.0	135.0	117°	1.0	34.9	1.1
ZJI-S2-RP3	37.4	27.6	—	—	—	—	70.5	—	128°	1.4	31.6	0.8
ZJI-S2-LP4	32.4	31.3	—	—	—	—	—	—	—	1.0	—	—
Mean	32.6	30.3	32°	—	—	—	71.8	113.5	117°	1.1	34.4	1.0

the narrow-gauge ichnotaxa *Breviparopus* (1:3.6; Dutuit and Ouazzou, 1980) or *Parabrontopodus* (1:4 or 1:5; Lockley et al., 1994).

The dinosaur track record from the Cretaceous Sichuan Basin is dominated by theropods and ornithopods (Xing et al., 2011a), but three sauropod tracksites were recently discovered within the Sichuan Basin, at the Lotus tracksite near Qijiang, Chongqing City (unpublished data), the Jiefang tracksite (Xing et al., in press), and the Zhaojue tracksite II (Xing et al., 2013). The latter sauropod trackways were assigned to the ichnogenus *Brontopodus* by Xing et al. (2013), and the trackways from the Lotus and Jiefang tarcksites also resemble *Brontopodus*-type trackways. The wide-gauge of the *Brontopodus*-type trackways suggests that the tracks were left by titanosaurian sauropods (Wilson and Carrano, 1999; Lockley et al., 2002). This suggests that titanosaurian sauropods had a wide distribution throughout the Lower Cretaceous in Sichuan, and the new record from the Zhaojue tracksite I further supports this view.

4.2. Theropod tracks

Description of tracks and trackways. — There are at least nine tridactyl tracks located on an underlying level beneath where the former track level of tracksite I had collapsed. Moreover, one well-preserved isolated natural mould from the original (upper, remaining) surface, catalogued as ZJI-T1 (Fig. 7A; Table 2), and one well-preserved trackway catalogued as ZJI-T1 that is composed of three consecutive natural moulds from the new (lower, after the collapse) surface, catalogued individually as ZJI-T1-R1–R2 (Fig. 7D; Table 2). There are another 25 tridactyl tracks located in the remaining southernmost part of tracksite I. Among these, one trackway is well-preserved. This trackway is composed of three consecutive natural moulds, catalogued as ZJI-T2-L1–L2 (Fig. 7C; Table 2). The two best-preserved isolated natural moulds were catalogued as ZJI-TI3 and ZJI-TI4 (Fig. 7B; Table 2). The original tracks all remain in the field.

The ZJI-T1 trackway shows three successive tridactyl tracks. Of these, ZJI-T1-R2 is better preserved and exhibits well-discernible digit impressions. The other two tracks are poorly preserved. The pace angulation of 152° indicates a trackmaker with a rather narrow stance as is typical for theropods (Lockley and Meyer, 2000). The isolated track ZJI-TI1 is well preserved, and similar to ZJI-T1-R2 in general morphology, but has a strong indentation behind digit II, corroborating that ZJI-TI1 can be assigned to a theropod trackmaker.

The pes length of the ZJI-T1 tracks ranges from 20.4 to 26.4 cm, which is a medium size for theropod tracks. Digit III is the longest, and sharp claw impressions are visible on each digit. Digital pad impressions are indistinct. The metatarsophalangeal region is well developed robust and positioned in line with the long axis of digit III. The digits have a high divarication angle (52°–68°).

There are approximately 25 larger (range 22.8–34.2 cm, average 27.5 cm) tridactyl tracks on the remaining part of tracksite I, all poorly-preserved, and not part of any distinct trackways, but similar to ZJI-T1-R2 and ZJI-TI1 in overall morphology.

The trackway ZJI-T2 shows three successive tridactyl tracks. The average length of these tracks is merely 12.7 cm, that is only 53% the size of ZJI-T1. ZJI-T2-R1 is the best preserved track, with the digit III impression being the longest and best defined, followed by digits II and IV, and with sharp claw impressions on all three digits. Digital pad impressions are indistinct, but the metatarsophalangeal region is well developed, elongated into a "heel" and positioned in line with the long axis of digit III. The digits have a high total divarication angle of 70°. ZJI-T2-L1 is poorly preserved, exhibiting only the distal parts of the digits. ZJI-T2-L2 also shows an elongated metatarsophalangeal pad.

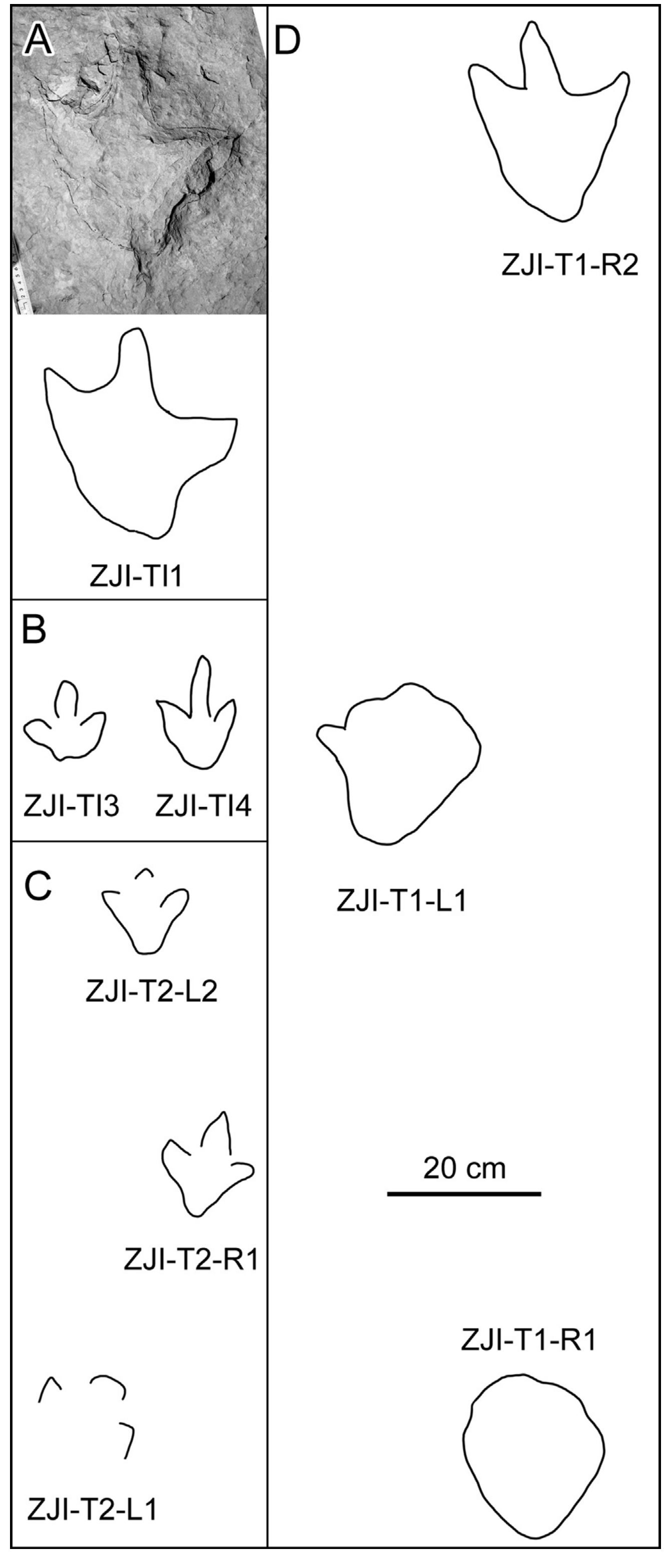

Fig. 7. Photograph and interpretative outline drawings of isolated theropod tracks (A, B), and the theropod trackways ZJI-T1, and -T2 (C, D). A and D are new tracks that appeared after the collapse of tracksite I on an underlying level (see the small area b and c from Fig. 2B); B and C are from the remaining tracksite (the small area a from Fig. 2B).

Except for lacking an elongated metatarsophalangeal pad, ZJI-TI3 is similar to ZJI-T2-R1, with a high total divarication angle of 89°. ZJI-TI4 has a longer digit III than the other small tridactyl tracks. Furthermore, there are approximately five small (range

Table 2
Track and trackway parameters of the theropod tracks from the Zhaojue tracksite I, Sichuan Province, China. All measurements in cm except angles in degrees. Abbreviations: L: maximum pes length; W: maximum pes width (measured as distance between the tips of digits II and IV); II-III: divarication angle between digits II and III; III-IV: divarication angle between digits III and IV; II-IV: divarication angle between digits II and IV; PL: Pace length; SL: Stride length; PA: Pace angulation; L/W: length/width; —: measurement not possible or not applicable.

Number	L	W	II-III	III-IV	II-IV	PL	SL	PA	L/W
ZJI-T1-R1	20.4	—	—	—	—	88.0	176.5	152°	—
ZJI-T1-L1	21.0	—	—	—	—	96.0	—	—	—
ZJI-T1-R2	26.4	20.2	21°	31°	52°	—	—	—	1.3
ZJI-T2-L1	—	—	—	—	—	37.4	66.4	140°	—
ZJI-T2-R1	14.1	11.9	34°	36°	70°	33.4	—	—	1.2
ZJI-T2-L2	11.2	10.9	33°	34°	67°	—	—	—	1.0
ZJI-TI1	27.2	25.5	39°	29°	68°	—	—	—	1.1
ZJI-TI3	10.8	11.0	40°	49°	89°	—	—	—	1.0
ZJI-TI4	14.8	10.5	34°	24°	58°	—	—	—	1.4

10.8–14.4 cm) tridactyl tracks that are consistent with ZJI-T2-R1 regarding their overall morphology.

Discussion.— Because of the small number and rather poor preservation of the theropod tracks of Zhaojue tracksite I, an assignment to a particular ichnotaxon cannot be made. Early Cretaceous theropod tracks from China are generally divided as follows: large tracks (more than 15 cm) have been attributed to *Chapus* from Chabu, Inner Mongolia (Li et al., 2006); *Asianopodus* from Junan, Shangdong (Li R.H., pers. comm; Lockley, unpublished data); *Therangospodus* and *Megalosauripus* from Chicheng, Hebei (Xing et al., 2011b); cf. *Therangospodus* from Linsu, Shandong (Xing et al., 2013); cf. *Irenesauripus* from Chishui, Guizhou (Xing et al., 2011a) and Zhaojue tracksite II (Xing et al., 2013); whereas the only small tracks (less than 15 cm) from Shaanxi, Xinjiang, Liaoning have been attributed to *Jialingpus* (Xing et al., 2014b).

In general, the large tracks from the Zhaojue tracksite I are most similar to the ichnogenus *Eubrontes* whereas the smaller tracks resemble the ichnogenus *Grallator*. However, they have a greater total divarication angle than is typical for the Early Jurassic ichnotaxa *Eubrontes*, *Anchisauripus*, and *Grallator* (Olsen et al., 1998), and this can also be observed for Early Cretaceous theropod tracks from North America (e.g. Lockley et al., 1998: Fig. 6). The theropod tracks of Zhaojue tracksite I have a large metatarsophalangeal area similar to that of *Eubrontes* (?) *glenrosensis* (Shuler, 1935) and *Megalosauripus* (Lockley et al., 1998). According to Olsen (1980), Weems (1992), and Lockley (2009), theropod tracks can be differentiated on the basis of mesaxony: i.e., the degree to which the central digit (III) protrudes anteriorly beyond the medial (II) and lateral (IV) digits. The tridactyl tracks from Zhaojue tracksite I are characterized by weak to moderate mesaxony (average 0.53, range 0.47–0.58, $N = 3$), which is typical of the ichnofamily (or morphofamily) Eubrontidae. Thus, we tentatively attribute the large tridactyl tracks of Zhaojue tracksite I to the ichnogenus*Eubrontes*.

The metatarsophalangeal area of the small-sized tridactyl tracks at the Zhaojue tracksite I is morphologically distinct from the larger tracks, but these differences may be partially the result of preservation. For example, ZJI-TI3 is similar to the larger tracks, but lacks an elongated metatarsophalangeal region. This may be related to substrate consistency and moisture content at the time of track formation that significantly influence track morphology (Manning, 2004; Milàn and Bromley, 2008; Marty et al., 2009; Jackson et al., 2010; Xing et al., 2011a: Fig. 4; Xing et al., 2014a).

4.3. Pterosaur tracks

Description of the trackway.— Eleven pterosaur tracks (eight manus and three pes imprints), with different orientations, were recorded (Figs. 4, 8) (Table 3). Six manus tracks were replicated using latex and plaster for the University of Colorado collections (UCM 214.269-214.272: see Figs. 4 and 8). Only three of them could be attributed to a discernable trackway: i.e., ZJI-P1 consists of one pes and two manus prints. The tracks P1-LP1 and P1-LM1 are a manus-pes pair while P1-RM1 is a manus track not associated with a pes track. The mean lengths and widths of the manus tracks are 7.6 cm and 2.8 cm, and mean lengths and widths of the pes tracks are 8.9 cm and 2.8 cm. The only pace length available, for the manus, is 13.3 cm.

The isolated tracks consist of two pes and six manus imprints. The larger manus tracks are 14.3–14.8 cm in length ($n = 2$) and the smaller manus tracks are 10.6–12.6 cm in length ($n = 4$). This difference reflects several different sized individual trackmakers.

ZJI-PI-P1, a pes track, is located very close to the trackway ZJI-P1 and is very similar in size to the ZJI-P1 pes. Therefore, it is possible that both were produced by the same animal. However, the distance to the trackway and its orientation does not match the given trackway pattern. Therefore it is considered here as an isolated imprint. Above the pes track ZJI-PI-M3 digit I, another digit impression possibly reflects polydactylia, and may record slippage or sliding by the ZJI-PI-M3 trackmaker.

Discussion.— All tracks, including those belonging to the trackway, can be assigned to *Pteraichnus*. The pes tracks, despite lacking digit traces, are elongated, and at least two of them are subtriangular in shape. The manus tracks are tridactyl, showing 2-3 well-preserved digit impressions. They are asymmetrical with the toes increasing in length from digit I to III. Digit III is orientated posteriorly, similar to the condition in *Pteraichnus saltwashensis* that was described from the Late Jurassic of Arizona by Stokes (1957).

Pterosaur manus tracks are often better-preserved and more numerous than pes tracks, due to differences in the weight distribution (Lockley et al., 1995). This pattern is reflected in the Zhaojue tracksite I, which consists of eight manus and three pes tracks.

Based on the length of manus tracks, we can establish three size classes, one of them close to 14 cm, another close to 11 cm and the last one with 7.5 cm. These differences in the length must reflect differences in the size of the animals, and so it is possible to confirm the presence of at least three individuals. It is impossible to infer whether or not they might represent distinct species of trackmaker.

Many *Pteraichnus* trackways described from around the world show a large trackway width and a long step. The manus tracks are usually located laterally to the pes tracks. The manus ZJI-P1-LM1 is located slightly more inward relative to the pes (ZJI-P1-LP1), the pace (ZJI-P1-LM1 and RM1) is very short, and the trackway width of the manus is small, about 10 cm. This pattern could be explained by the slow movement of the trackmaker. On the other hand, overstepping can also not be excluded, if the animal was moving very fast.

Also, the random distribution of trackways is unlikely to represent floating or semi-floating animals as described in García-Ramos et al. (2000) and Lockley and Wright (2003), because of the presence of a short trackway segment that shows a walking configuration, and the absence of characteristic elongate pes claw traces produced by the dragging of the feet (Lockley and Wright, 2003; Lockley et al., 2014).

5. Video analysis of the original tracksite I

5.1. Overview

Trackways no. 1–3 were made by large bipedal ornithopods, and measure approx. 27, 31 and 55 m in length. Trackways no. 4–6 were left by quadrupedal sauropods, and are approximately 63, 30 and 45 m in length. Trackways no. 7–10 measure approximately 36, 23, 16 and 26 m in length and can be attributed to bipedal theropods. Except

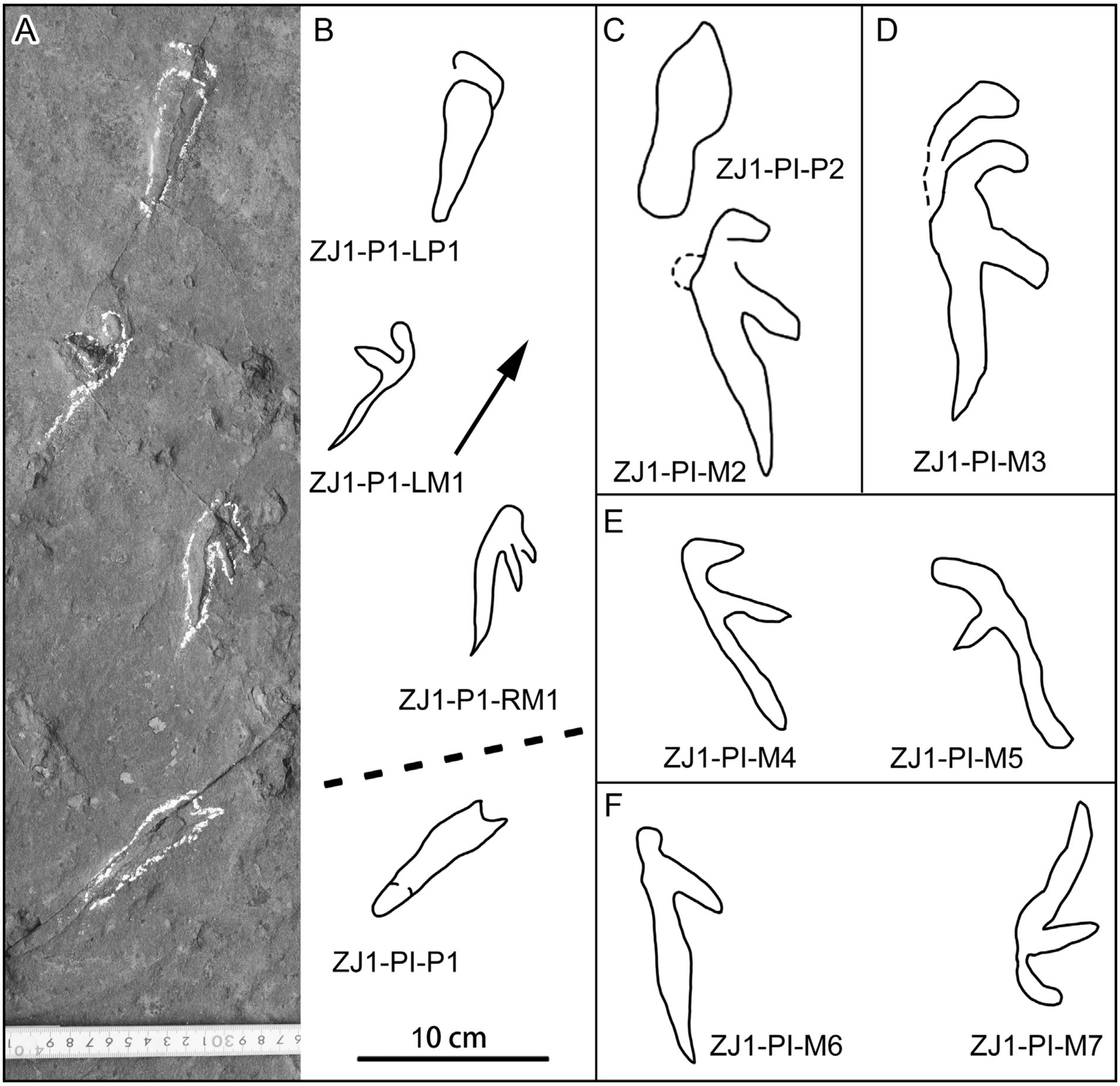

Fig. 8. Remaining tracksite. Photograph and interpretative outline drawing of the pterosaur trackway ZJI-P1 (A–B), and of selected isolated pterosaur pes and manus tracks (C–F). Dashed line in B indicates that ZJI-PI-P1is also an isolated track and not related to the trackway.

Table 3
Track parameters of the pterosaur tracks from the Zhaojue tracksite I, Sichuan Province, China. All measurements in cm except angles in degrees. Abbreviations: L: maximum length; W: maximum width; LD I: length of digit I; LD II: length of digit II; LD III: length of digit III; I–II: angle between digits I and II; II–III: angle between digits II and III; L/W: ML/MW; —: measurement not possible or not applicable. Pterosaur tracks measured using the methods of Sánchez-Hernández et al., 2009, fig. 4.

Number	L	W	LD I	LD II	LD III	I–II	II–III	L/W
ZJ1-P1-LP1	8.9	2.8	—	—	—	—	—	3.2
ZJ1-P1-LM1	7.4	2.8	2.5	3.0	6.0	57°	67°	2.6
ZJ1-P1-RM1	7.9	2.9	2.9	3.9	7.0	29°	30°	2.7
ZJ1-PI-P1	8.3	2.1	—	—	—	—	—	4.0
ZJ1-PI-P2	10.6	4.0	—	—	—	—	—	2.7
ZJ1-PI-M2	14.3	4.8	3.8	6.6	12.0	64°	35°	3.0
ZJ1-PI-M3	14.8	6.1	5.4	6.7	11.0	60°	54°	2.4
ZJ1-PI-M4	11.4	3.9	3.3	5.7	9.3	50°	38°	2.9
ZJ1-PI-M5	11.8	3.7	4.3	3.9	8.5	61°	69°	3.2
ZJ1-PI-M6	12.6	3.8	1.4	5.5	11.7	96°	43°	3.3
ZJ1-PI-M7	10.6	4.1	3.1	4.6	9.1	69°	45°	2.6

for the trackways of small bipeds, walking directions are easily discernable, and the majority of the trackways are heading northeast.

Trackways no.1–3 converge from different directions finally crossing and overprinting each other. Some tracks of trackway no. 4 left by a sauropod, partially infer with tracks of trackways no. 1–3. Lacking an accurate scale bar, the track size of trackway no. 4 can only be estimated based on the known total length of the tracksite. The pes tracks are estimated to be approximately 40 cm long, and the manus tracks to be 15 cm long, which is generally consistent with the sauropod tracks that remain in the western and southernmost part of tracksite 1. Pes tracks commonly have an outward rotation.

The tracks of trackway no. 5 are particularly shallow, and were either left later than the other trackways, or they may represent undertracks of an overlying level. Trackway no. 6 is a turning trackway. Trackways no. 7–10 only consist of small pits and are probably small tridactyl (under)tracks or pterosaur tracks. See Figs. 9–11.

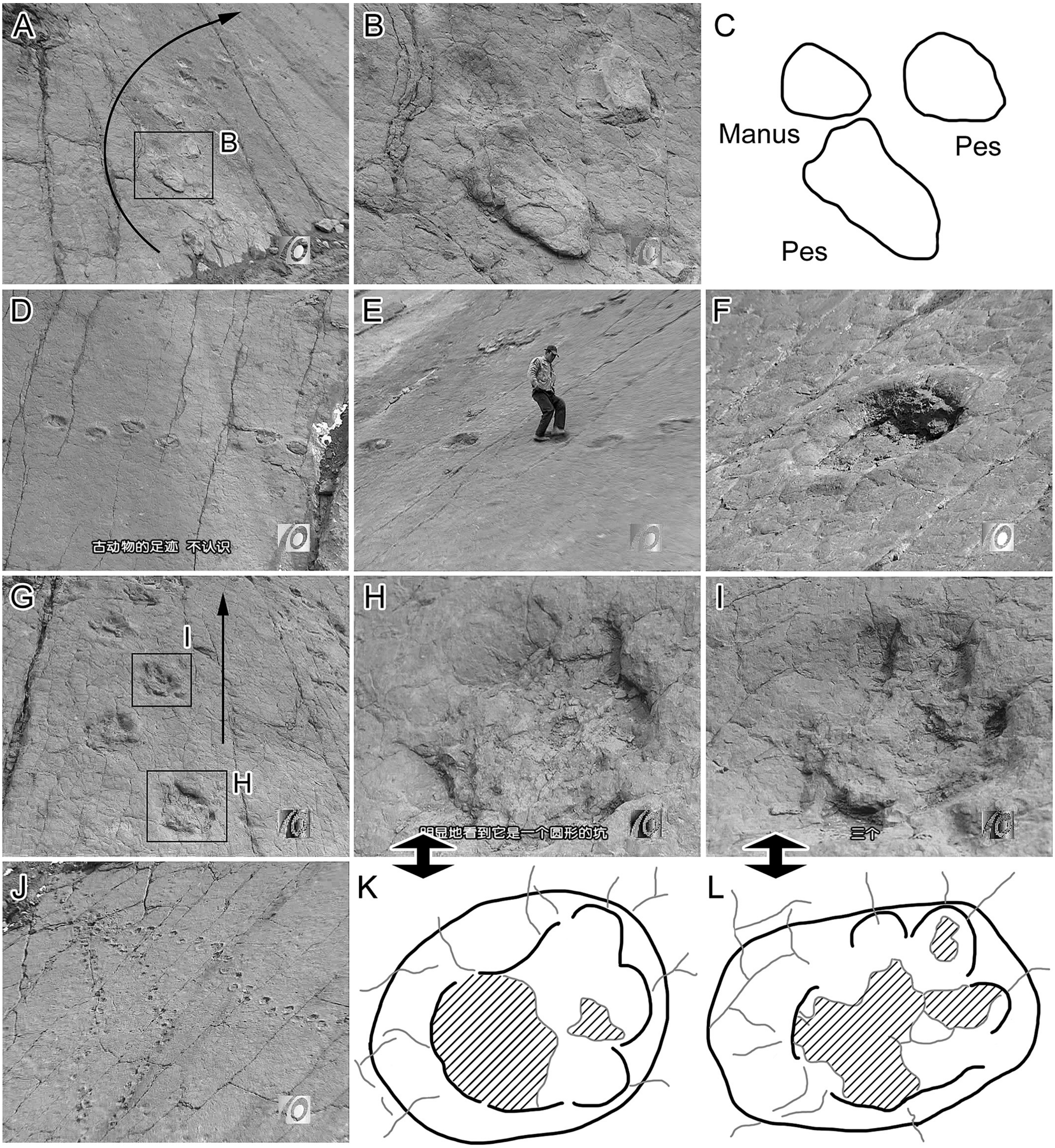

Fig. 9. Tracksite I. (A, B) Video frames and (C) interpretative outline drawing of sauropod trackway no. 4. (D–F) Video frames of purpoted bipedal ornithopod trackway no. 3. (G) Frame of the purpoted bipedal ornithopod trackway no. 2; note pronounced inward rotation of the pes tracks. (H, I) Selected two right tracks of purpoted ornithopod trackway no. 2 and corresponding interpretative outline drawings (K, L), (J) Video frame of the purpoted bipedal ornithopod trackways no. 1–3, note crossroads at the top of the photograph.

5.2. Sauropod trackways

Description of the trackways.— There were at least three (no. 4–6) trackways of sauropods at the Zhaojue original tracksite I. Taking the partial tracks of trackway no. 4 (Fig. 9A–C) as an example, these trackways have the following characteristics: the pes tracks are longer than wide, the manus tracks are sub-oval in shape, and there is a high degree of heteropody between pes and manus tracks. These trackways can be identified as *Brontopodus*–type sauropod trackways (Santos et al., 2009).

The main characteristics of trackways no. 4–6 are generally consistent. The most peculiar feature shows trackway no. 6, which

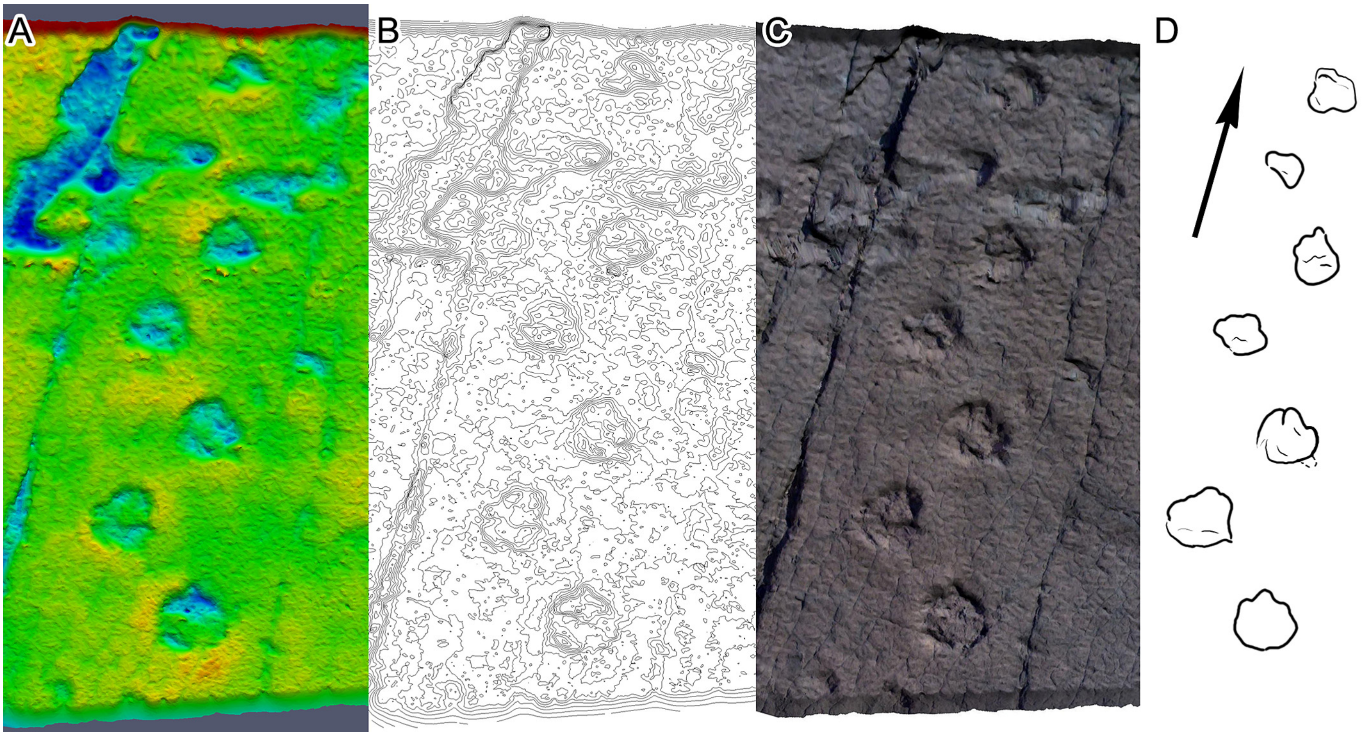

Fig. 10. The 3D height map (warm colours are high, cooler colours are low) (A), contour map (B), textured render (C), and interpretative outline drawing (D) of purpoted bipedal ornithopod trackway no. 2.

records a turning around of the trackmaker in a very tight turn (Fig. 11). Before the turn point, trackway no. 6 is heading to 20°, after the turn towards 228°. Thanks to a video close-up (Fig. 11B), track distribution at the turning point can be reconstructed with some confidence (Fig. 11D, E). The turn itself is very narrow and consists of eleven pes and ten manus tracks (Fig. 11D–G). Left and right tracks partially overlap, and the turn exhibits an "off-track" phenomenon for the left pes and manus tracks (Fig. 11G).

Discussion.— Based on a turning trackway, Ishigaki and Matsumoto (2009) determined that the large sauropod manus-pes trackway midline gap at the turning point is analogous to the off-tracking phenomenon of a turning front wheel steered four-wheeled vehicle. The same phenomenon can be observed in the Zhaojue trackway no. 6. The trackway midline of the pes (Fig. 11E) and the trackway midline of the manus (Fig. 11F) show a substantial degree of off-tracking (Fig. 11G).

Such an extreme turning around behaviour is so far not known from the sauropod track record. The best-preserved examples of turning sauropod trackways are those from the Central High Atlas Mountains, Morocco (Ishigaki and Matsumoto, 2009), and from Copper Ridge, Utah, USA (Lockley, 1990, 1991). Other turning sauropod trackways have been reported from Europe, such as Fenoglia Island, Croatia (Mezga and Bajraktarevic, 1999), Lommiswil/Oberdorf tracksite, Switzerland (Meyer, 1990, 1993; Lockley and Meyer, 2000), Lagosteiros Bay, Portugal (Meyer et al., 1994), and the Dazu tracksite, Chongqing, China (Lockley and Matsukawa, 2009). However, all these trackways show rather "broad" turns, and do not represent a complete directional reversal. They record a directional change of 56° (Ishigaki and Matsumoto, 2009), 61°(Meyer, 1993), 66°(Lockley, 1990, 1991) and 115° Lockley and Matsukawa (2009).Completely turning around or "reversal trackways with such narrow turns are only known from Late Jurassic tracksites in the Canton Jura (NW Switzerland), but are as yet not published (unpublished data, Palaeontology A16, by Marty, D).

5.3. Probable ornithopod tracks

Description of the trackway.— The trackways no. 1-3 from site I closely resemble tridactyl trackways that occur at Zhaoue site II that were confidentially assigned to ornithopods (Xing and Lockley, in press). Based on the track measuring video sequence (video 00:07:06), the diameter of the pes of trackway no. 1 is approximately 50 cm. Footage of trackway no. 3 (Fig. 9D, E) includes a sequence where a local adult human male walks on the tracks, a close-up is shown of the man's feet stepping in one of the footprint impressions. This permits estimating the dimensions of the trackway, which evidently also indicates quite a narrow trackway of a biped with a moderately long step. The identity of this local man is unknown, but he appears to be of roughly average size. The average foot length of Southwest Chinese males is 24.5 cm (Qiu, 2005). Thus the track diameter is estimated to be approximately 50 cm. In the video, two close-ups (Fig. 9H, I) reveal the form of the anterior part of trackway no. 2 (Fig. 9G). From the close-up of trackways no. 1–3, it can be assumed that all three are generally consistent in morphology, and were left more or less at the same time.

In Figs. 9G, and 10, the pace angulation of the lowermost three tracks (a–c) of trackway no. 3 is approximately 100°, which is atypical of large ornithopods (such as Xing et al., 2009: Plate II), and more typical of large quadrupedal dinosaurs. However, this low pace angulation is not consistent all along the trackway, and it could also be related to a slowing-down. The close-up Fig. 9H and I exhibit the details of the two right pes tracks visible in Fig. 9A. As illustrated on the corresponding interpretative sketch (Fig. 9K and L), these tracks generally have three round and blunt digit impressions, and the bottom of the tracks shows ridges between the digits, even though some tracks show some evidence of four digit impressions. Most tracks have gently curved cross sections rather than pronounced angular edges. The surface is covered with medium-sized desiccation cracks, that formed after that the tracks were left.

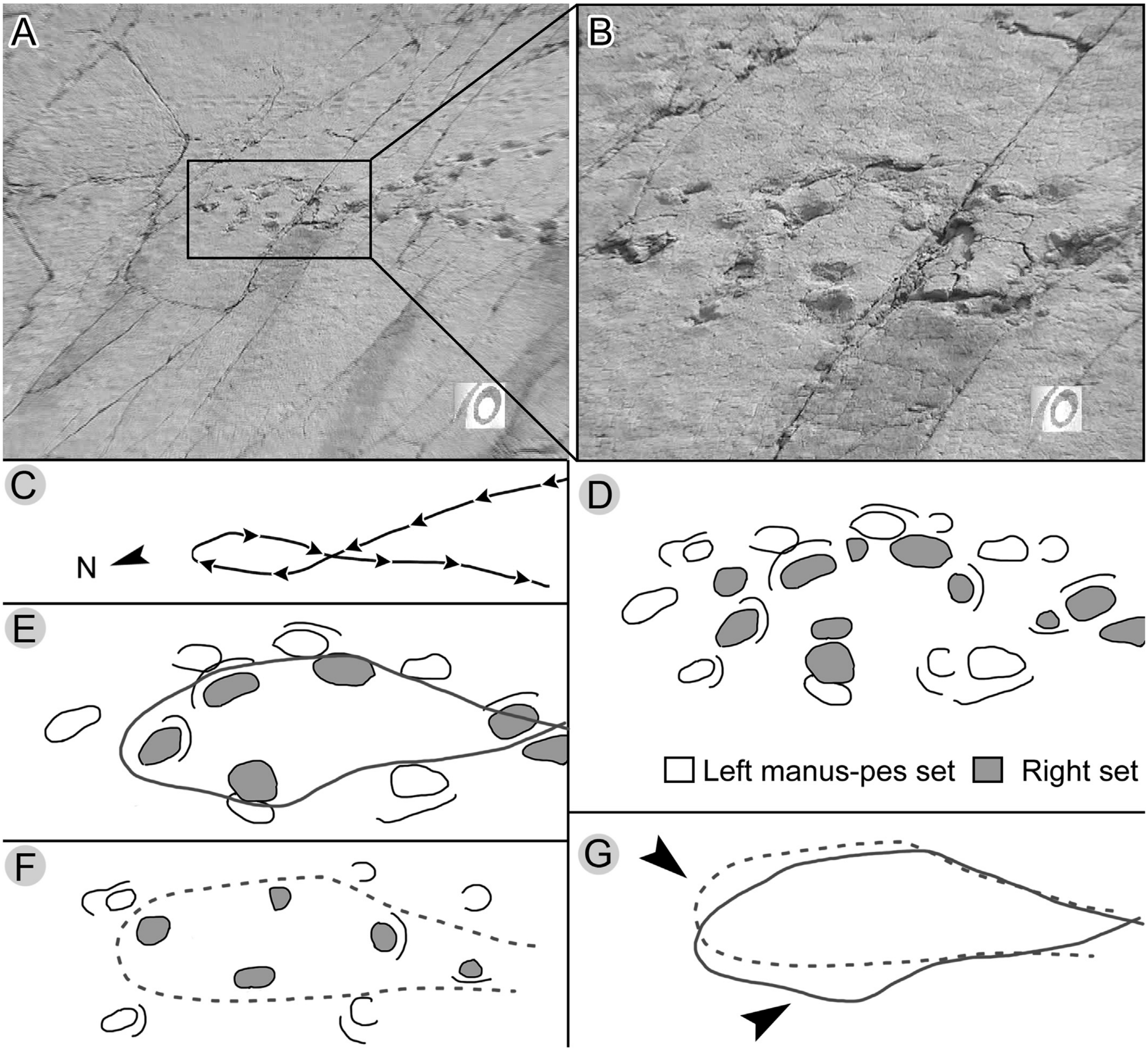

Fig. 11. Tracksite I. Video frames (A, B), and schematic drawing (C) of the turning sauropod trackway no. 6. The moving direction of trackway no. 3 as shown in (C) is based on A and B; (D) Schematic outline drawing based on B; (E) Schematic outline drawing showing the pes only; F, Schematic outline drawing showing the manus only; (G) Trackway midlines of pes (solid line) and manus (dashed line), exhibiting the off-tracking phenomenon of the manus with regards to the pes.

Trackway no. 3 clearly overprints sauropod trackway no. 4. The probable ornithopod tracks are larger and deeper than the sauropod tracks due to the heavier weight of the trackmakers and/or different weight distribution with a shift toward the hindlimbs. Alternatively the trackways were made at different times.

Discussion.—In the video, Kui Li from The Museum of Chengdu University of Technology, Chengdu stated that these tracks pertain to sauropods (video 00:04:03). However, three blunt ungual marks are clearly present in most of the tracks of the Zhaojue no. 1–3 trackways, and therefore the trackways appear to be those of bipeds. These features, together with an apparent inward rotation of the tracks (Fig. 9G), suggest an ornithopod trackmaker (Thulborn, 1990; Lockley, 1991). The tracks are circular with blunt digits and a wide heel pad impression, similar to *Caririchnium* (Lockley, 1987; Xing et al., 2007, 2013). *Ornithopodichnus* (Kim et al., 2009; Lockley et al., 2012; Xing and Lockley, in press) has pes tracks with a weak mesaxony and with very thick, broad U-shaped digit impressions shallowly separated only in the distal part. These characteristics appear consistent with those observed in trackways no. 1–3. *Caririchnium* may have been made by both bipeds and quadrupeds (Xing et al., 2007) and is a common ichnogenus, typically attributed to iguanodontiforms and hadrosauriforms (Lockley, 1987). At the Zhaojue tracksite II, several *Caririchnium*–type tracks were discovered (Xing et al., 2013), and these are similar to the trackways no. 1–3.

Some of these large, tridactyl tracks show evidence of four digit impressions and therefore are not unequivocally diagnostic for an ornithopod trackmaker. Even though, this could also be related to erosion, without closer inspection, which is now impossible, the identification of these trackways will remain ambiguous, and we thus prefer to refer to the trackways no. 1–3 as purported ornithopod trackways.

6. Discussion

The Zhaojue tracksite I contains tracks of sauropods, pterosaurs, large and small non-avian theropods, and large ornithopods. The large theropod tracks suggest that different individuals probably walked across the area repeatedly, as observed also at the Shanshan theropod tracksite in Xinjiang Province (Xing et al., 2014a). The pterosaur tracks vary in size and direction, indicating several pterosaur individuals. Pterosaur tracks have been previously described in close association with bird tracks, (Kim et al., 2006; He et al., 2013; Xing et al., 2013). However, ichnoassemblages with pterosaur and small theropod tracks are less commonly reported. Some Early Cretaceous maniraptoran theropods from China are known to have fed on fish (Xing et al., 2013) as are compsognathids (Dal Sasso and Maganuco, 2011), and accordingly both small theropods and pterosaurs may have been exploited the same aquatic food resources. Alternatively, pterosaurs are also known to have occasionally been the prey of small theropods (Hone et al., 2012). The presence of water bodies attracting different vertebrates is also indicated by the orientation of trackways no. 1–3 that are inferred to have been left by large ornithopod trackmakers converging at the same "rallying point" or "crossroads" (RP of Fig. 3), and that are distinctly crossing in this area while being more randomly oriented away from this spot. By analogy with modern, large-sized ungulates (Cohen et al., 1993), large ornithopod trackmakers were possibly converging on water bodies or some preferred destinations.

Remarkably, the turning around sauropod trackway no. 6, was first moving towards the "crossroads" of the large-sized ornithopod trackways no. 1–3, and then, about 25 m before this point, it turned around. The inference cannot be excluded that these four trackways (no. 1–3, 6) were left (more or less) at the same time, and that the sauropod trackmaker turned back in order to avoid confrontation with the ornithopods. However, this suggested behaviour is of course very speculative and can not be proven. There are overprinting relationships between these trackways that would have allowed us to establish their relative timing. However, the close-up video frames do not allow us to identify this kind of detail unequivocally. Therefore the relative timing of the trackways remains unknown.

Abundant small tridactyl trackways were discovered, some of them parallel to the large ornithopod trackways, and some tangential to it. These small tridactyl tracks are indistinctly visible in the video. Small *Ornithopodichnus* trackways were recently described from the Zhaojue tracksite II (Xing and Lockley, in press; Xing et al., 2014c). The confirmed presence of both small ornithopods and small theropods makes it difficult to resolve the identity of these small tridactyl trackways.

Matsukawa et al. (2006) argued that the distribution of large saurischian and large ornithopod tracks in the Cretaceous of East Asia suggests that the former group is more typical of southern or interior continental regions and the latter group more typical of northern and coastal settings. However, in recent years, large ornithopod tracksites have frequently been discovered from inland settings of southwestern China (Xing et al., 2007; Xing et al., 2013), and this study further corroborates the common presence of large ornithopods in inland environmental settings. Many sauropod tracksites have also been discovered from coastal regions (Zhang et al., 2012; Xing et al., 2013). These new discoveries indicate that, during the Cretaceous, saurischian and large ornithopod had a wider environmental distribution in China, than previously assumed.

7. Conclusions and perspectives

The Early Cretaceous Zhaojue dinosaur tracksite I in Sichuan Province, China shows a diverse ichnocoenosis reflecting the presence of sauropods, small and medium-sized theropods, pterosaurs, and possibly large ornithopods. This is documented on a new map based on a corrected orthophotography that was generated on video frames and overview photos of the original (now collapsed) surface. Small remaining parts as well as newly exposed tracks from underlying layers provide additional information. The general composition of the site I ichnoassemblage is quite similar to that of site II (Xing et al., in press). This gives confidence in the interpretations presented here on the basis of photographs of the lost surfaces.

The morphology and trackway pattern of the sauropod tracks are similar to the wide-gauge ichnogenus *Brontopodus*. The extreme narrow turn (complete reversal) of the trackmaker and "off-tracking" of the manus relative to the pes, as documented in one example, is a peculiar feature not known thus far from other sauropod trackways. This sheds light on the behaviour and locomotion of (wide-gauge) titanosaurs, the possible trackmakers, and of sauropods in general. Their manoeuvrability was evidently more flexible than might formerly have been predicted. The theropod trackways show some similarities with the ichnogenera *Grallator* and *Eubrontes*, however an exact assignment is impossible due to the lack of morphological details. The trackways and imprints of large bipedal ornithopods resemble the ichnogenus *Caririchnium* and show characteristic features such as the three rounded and blunt digit impressions, the wide "heel" pad and the "toed-in" orientation of the footprints. Their size on the original surface cannot exactly be determined but the presence of a human foot on the video sequence allows a rough estimation. Pterosaur trackways are dominated by typical tridactyl manus imprints but also show a few subtriangular-shaped pes tracks preserved. Different track sizes prove the presence of several individuals. The irregular pattern and random distribution of the imprints in the trackways could suggest floating or semi-floating trackmakers, although the lack of toe drag traces makes this inference uncertain.

The presence of large ornithopods and their co-occurrence with sauropods in an inland setting environment is a further evidence for their broad ecological adaptability. Another notable feature in the assemblage is the association of small theropod and pterosaur tracks.

Technically, the documentation of the Zhaojue tracks opens up perspectives for the use of video coverage and videogrammetry in the reconstruction of tracksites. High resolution 3D models from laserscan and photogrammetry technics are of increasing importance if traditional geo-conservation of tracksites fails as in the case of destructive and prolonged mining activity.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.cretres.2014.09.010.