古生物学报,48(4):662 - 671(2009 年 12 月)
Acta Palaeontologica Sinica, 48(4):662 - 671(December, 2009)

河北侏罗-白垩纪界线最古老的恐爪龙类足迹

邢立达[1)] 杰瑞德 D 哈里斯[2)] 孙登海[3)] 赵慧强[4)]

1) 中国地质科学院地质研究所,北京 100037,Xinglida@gmail.com; 2) 迪克西州立学院自然科学系,美国犹他 84770;
3) 赤城县职业技术教育中心,河北张家口 075500; 4) 赤城县国土资源局,河北张家口 075500

提要 记述中国河北省赤城县倪家沟化石点一组恐龙行迹,并命名一新属新种——中国猛龙足迹(*Menglongipus sinensis* ichnogen. et ichnosp. nov.)。足迹来自土城子组,位于侏罗-白垩纪界线。相邻的义县组曾发现最古老的恐爪龙类骨骼化石,而中国猛龙足迹的发现表明恐爪龙类早在义县组之前便出现在该地区。中国猛龙足迹的造迹者体长约 65cm,非常接近于基干的近鸟类。此外,为四川伶盗龙足迹(*Velociraptorichnus sichuanensis*)的模式标本提供更多细节,并讨论驰龙类足迹型与其他兽脚类足迹之间的联系。

关键词 猛龙足迹 恐爪龙类足迹 土城子组 侏罗-白垩纪界线

THE EARLIEST KNOWN DEINONYCHOSAUR TRACKS FROM THE JURASSIC-CRETACEOUS BOUNDARY IN HEBEI PROVINCE, CHINA

XING Li-da[1)], JERALD D Harris[2)], SUN Deng-hai[3)] and ZHAO Hui-qiang[4)]

1) *Institute of Geology, Chinese Academy of Geological Sciences, Beijing* 100037, *China*, *Xinglida@gmail.com;*
2) *Physical Sciences Department, Dixie State College*, 225 *South* 700 *East*, *St. George*, *Utah* 84770, *USA;*
3) *Chicheng County Vocational Education Center*, *Zhangjiakou* 075500, *China;*
4) *Chicheng County Bureau of Land and Resources*, *Zhangjiakou* 075500, *China*

Abstract Herein we describe a single trackway that pertain to *Menglongipus sinensis* ichnogen. et ichnosp. nov. from the Nijiagou track site in the Chicheng county, Hebei Province, China. The tracks occur in the Tuchengzi Formation, which spans the Jurassic-Cretaceous boundary. The discovery of *M. sinensis* indicates that deinonychosaurians occupied this area prior to deposition of the Yixian Formation, from which the oldest deinonychosaur body fossils in the region have been found. The body length (about 65cm) of the *M. sinensis* track maker is very similar to that estimated for basal paravians. Additional details are provided about the type *Velociraptorichnus sichuanensis*, and the association between dromaeopodid and other theropod tracks is discussed.

Key words *Menglongipus sinensis*, deinonychosaur track, Tuchengzi Formation, Jurassic-Cretaceous boundary

1 INTRODUCTION

The Tuchengzi Formation is the primary geologic unit exposed in the Liaoxi-Jibei (western Liaoning-northern Hebei) area, and its stratigraphy, sedimentology, and paleontology have been comprehensively studied (Ji *et al.*, 2004). Dinosaur tracks, primarily those of theropods, are abundant in this unit, with the most common basically of the *Grallator* morphotype (Yabe *et al.*, 1940; Shikama, 1942; Young, 1960; Matsukawa *et al.*,

收稿日期: 2009-09-09

2006; Zhang *et al*., 2004; Fujita *et al*., 2007). Larger tracks have been attributed to *Anchisauripus* (Sullivan *et al*., 2009), and others to birds (Lockley *et al*., 2006).

The ichnofamily Dromaeopodidae (Li *et al*., 2007) includes tracks made by didactyl deinonychosaurian theropods. Dromaeopodid tracks both were first discovered and are particularly common in China, including *Velociraptorichnus sichuanensis* from the ? Early Cretaceous of E'mei, Sichuan Province (Zhen *et al*., 1994), an unnamed dromaeosaurid track from the Early Cretaceous of Yongjing, Gansu Province (Li *et al*., 2006), and *Velociraptorichnus* and *Dromaeopodus shandongensis* from the Early Cretaceous of Junan, Shandong Province (Li *et al*., 2007). Reports outside of China include unnamed ichnites of dubious quality from the Early Cretaceous of Utah (Lockley *et al*., 2004) and *Dromaeosauripus hamanensis* from South Korea (Kim *et al*., 2008). The smallest of these tracks are about 10cm long. In 2008 and 2009, the senior author was invited by the Chicheng County Bureau of Land and Resources to study dinosaurs from exposures of the Tuchengzi Formation in the area. During this study, new didactyl tracks were discovered. The Tuchengzi Formation is primarily Early Cretaceous in age but includes the Jurassic-Cretaceous boundary (Davis, 2005; Sun *et al*., 2007; Zhang *et al*., 2009), making these not only the earliest known deinonychosaur tracks but also the smallest.

2 INSTITUTIONAL ABBREVIATIONS

LDRC = Lufeng Dinosaur Research Center, Yunnan, China. GSLTZP = Fossil Research and Development Center of the Third Geology and Mineral Resources Exploration Academy of Gansu Province, China. LRH-dz = Li Rihui-Dasheng, Qingdao Institute of Marine Geology, China Geological Survey, China.

3 GEOLOGICAL SETTING

The tracks were discovered on the southern slope of Siliang Mountain, Nijiagou village, Yangtian township, Chicheng County, Zhangjiakou City, Hebei Province (N 40°47′13″, E 115°53′33″) (Fig. 1). The fossil-bearing horizon is a grayish-purple, conglomeratic sandstone in the Tuchengzi Formation. The Tuchengzi Formation unconformably overlies the andesitic lavas of the Tiaojishan Formation and contacts the overlying high-Mg lavas of the Lower Cretaceous Zhangjiakou Formation in an angular unconformity (Davis, 2005). The Tuchengzi (also called the Houcheng) Formation in Hebei Province partially overlaps in age the Tuchengzi Formation in western Liaoning Province (Swisher *et al*., 2002). This suggests that

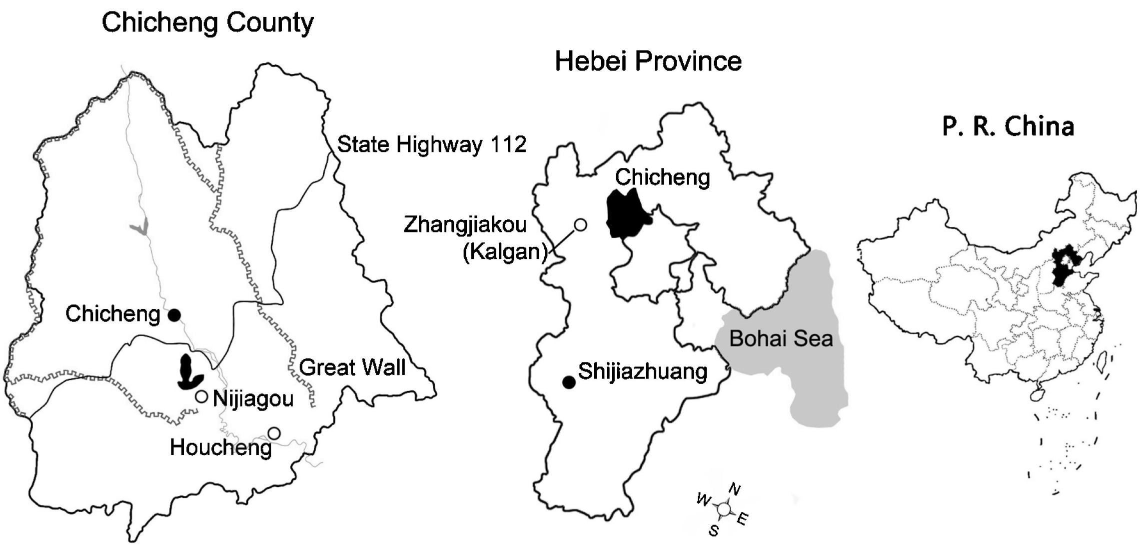

Fig. 1　Geographic map of the dinosaur footprint locality (indicated by the footprint icon)

Tuchengzi sedimentation was probably diachronous (Davis, 2005). The minimum age of the Tuchengzi Formation was measured at 136—139 Ma (Swisher *et al*., 2002; Zhang *et al*., 2009), and its maximum age is 147 Ma (Zhang *et al*., 2009). The tracks occur in a horizon high in the Tuchengzi Formation, but it is not presently possible to determine whether the tracks are latest Jurassic or earliest Cretaceous in age.

4 SYSTEMATIC ICHNOLOGY

Dinosauria Owen, 1842

Dromaeopodidae Li, Lockley, Makovicky, Matsukawa, Norell, Harris and Liu, 2008

Menglongipus sinensis **ichnogen. et ichnosp. nov.**

Etymology From the Chinese "Menglong", meaning vigorous dragon; and from the Greek "podus", meaning foot. Menglong refers to the ostensibly fierce nature of the track maker. The specific epithet refers to the holotype locality in China.

Holotype A complete natural mold, cataloged as T.A.1, from the Nijiagou tracksite. An artificial mold of the track, (Figs. 2—3, Table 1) is stored at the Lufeng Dinosaur Research Center, where it is cataloged as LDRC-v. x.8. The original track remains in the field.

Paratypes T.A.2—4, three additional natural molds in the same trackway as the holotype (Figs. 2—3, Table 1). Artificial molds of the tracks are stored at the Lufeng Dinosaur Research Center, where they are cataloged as LDRC-v. x. 9—11. The original tracks remain in the field.

Holotype locality and horizon Tuchengzi Formation, Upper Jurassic-Lower Cretaceous (Tithonian-Valanginian). Nijiagou tracksite, Chicheng, Hebei Province, China.

Diagnosis Small, didactyl theropod track that lacks manus and tail traces. The digit III:digit IV length ratio of T.A.1 is 2.36 (average value of T.A.1—4 is 1.8), differentiating the ichnotaxon from *Velociraptorichnus*, *Dromaeopodus*, and *Dromaeosauripus*, in which digit IV is almost as long as digit III. Digit II, when present, is represented only by a short, round impression located at the proximomedial margin of digit III. The divarication angle between digits III and IV ranges from 40°—44°, wider than in *Velociraptorichnus*, *Dromaeopodus*, or *Dromaeosauripus*.

Description The *Menglongipus* trackway exhibits a very narrow stance with a pace angulation of 180°, also supporting that the tracks represent a single trackway registered by a single track maker. The length:width ratio of T.A.1 is 1.67. Discernible claw marks were observed on digits III and IV. Digital pads are indistinct, but based on the photogrammetric maps (Fig. 2E—H), it appears that digit III has at least two pads and digit IV at least one. Digit impressions do not substantially taper distally. The divarication angle between digits III and IV averages 42° and ranges from 40° to 44°. The metatarsophalangeal region is small; no distinct border demarcating a pad divides this region from either digit III or IV. For the trackway, the step lengths are: T.A.1—2: 45cm, T.A.2—3: 32cm, T.A.3—4: 66cm. The long axis of T.A.1 has a markedly different orientation from those of T.A.2—4 (Fig. 3B), suggesting a change in the direction of movement at the beginning of the trackway. A substantial gap separates T.A.3 from T.A.4. T.A.3 and T.A.4 appear to lie on different surfaces, but it is actually the same surface that has been offset by about 0.5cm by a small fault. The greater distance between T.A.3 and T.A.4 than the other tracks may indicate that the track maker suddenly accelerated. Both T.A.3 and T.A.4 are deeper than T.A.2, suggesting also a greater force of impact in T.A.3 and T.A.4. In T.A.3, the distal ends of the digits are more deeply impressed than the metatarsophalangeal region is smaller (Fig. 2G), indicating a more powerful launch phase. T.A.4, however, has the opposite configuration: a deeper metatarsophalangeal region than distal digit impressions (Fig. 2H). Without subsequent tracks, it is difficult to determine the meaning of this difference.

Comparisons Numerous *Grallator* tracks are preserved at the Nijiagou tracksite; the only excep-

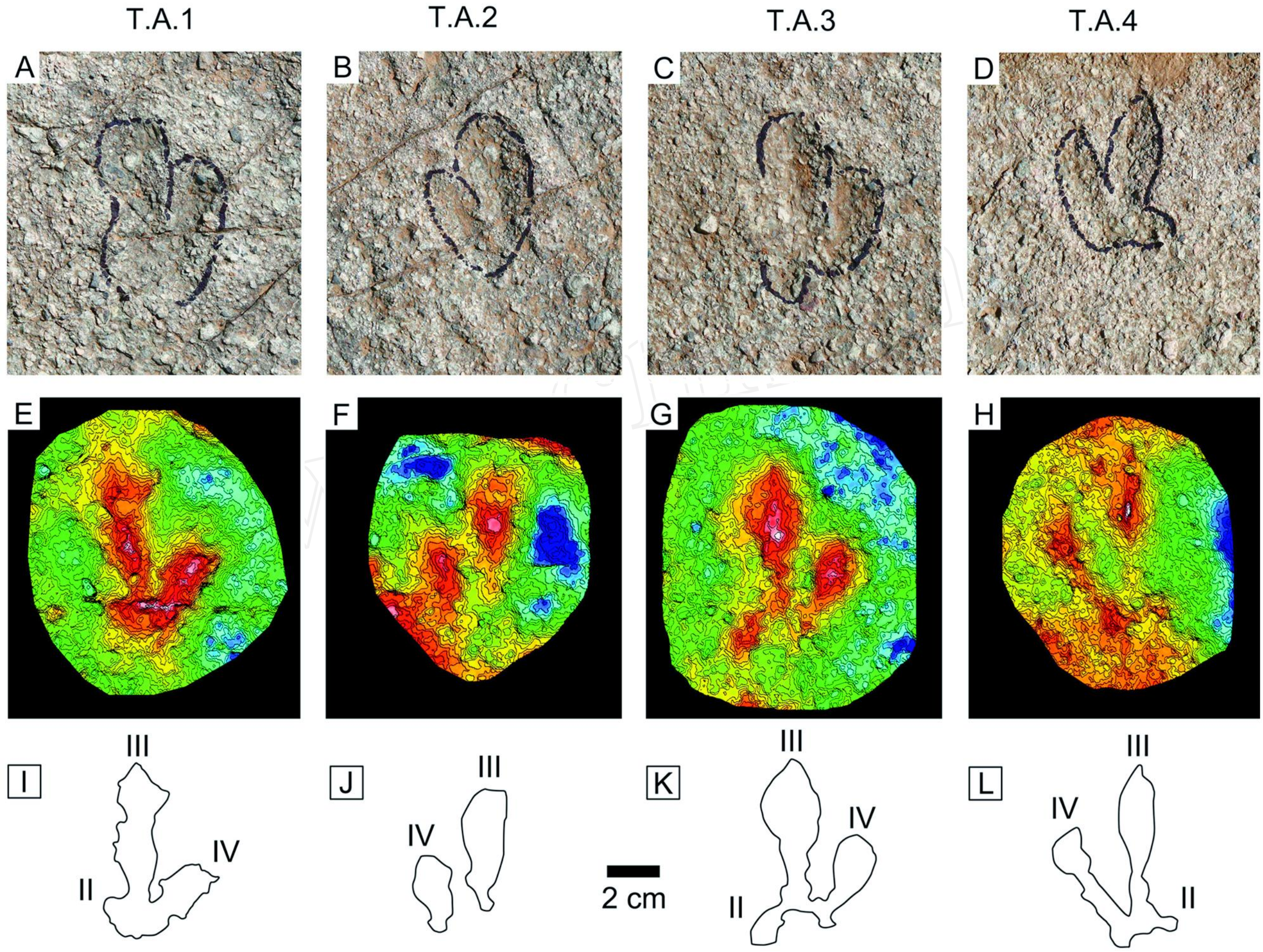

Fig. 2 Nijiagou didactyl tracks

A—D. Photographs of T. A. 1—4 taken at a slightly oblique angle to the track surface. The black outlines in the figure were drawn by persons unknown prior to the present analysis; they approximate the edges of the tracks, but are not exact profiles of the footprints. E—H. Computerized photogrammetry of artificial molds of tracks T. A. 1—4 with 0.12mm contour lines. Color banding reflects topography (blue-green = highest, red-white = lowest). I—L: Outline drawings made from the photogrammetric maps of T. A. 1—4.

tions are the four didactyl tracks T. A. 1—4. To better distinguish the didactyl tracks from *Grallator* morphotype tracks, molds were scanned with a Non-contact Grating-Type Structured Light 3D Scanning System (JiRui II, made in Beijing JiRui Xintian technology Co., Ltd.) to obtain the 3D data; the software (JiRui 3D image analysis software) generated photogrammetric models of the fossils. The results (Fig. 2E—H) suggest that the apparent didactyly in T. A. 1—4 is genuine. However, the substrate of the site is conglomeratic, which means it would be highly resistant to deformation. On such a surface, a light, tridactyl track maker bearing minimal weight on digit II would leave a didactyl track. In the Tuchengzi Formation *Grallator*-type tracks (Yabe *et al.*, 1940; Shikama, 1942; Young, 1960; Matsukawa *et al.*, 2006; Zhang *et al.*, 2004; Fujita *et al.*, 2007), the divarication angles between digits are considerably narrower than in T. A. 1—4. Even in larger tracks, such as *Anchisauripus* (Sullivan *et al.*, 2009), the divarication angles between digits II—IV is 30.5°. Tuchengzi *Grallator* tracks demonstrate relatively consistent morphology across the conglomeratic substrate, suggesting that the greater divarication angles exhibited by T. A. 1—4 reflect genuine differences in track maker foot morphology and, as a result, ichnological distinction.

Fujita *et al.* (2007) described *Grallator*-type tracks from the Tuchengzi Formation at the Sijiaban tracksite, in Liaoning; they divided the tracks into three size categories representing juvenile

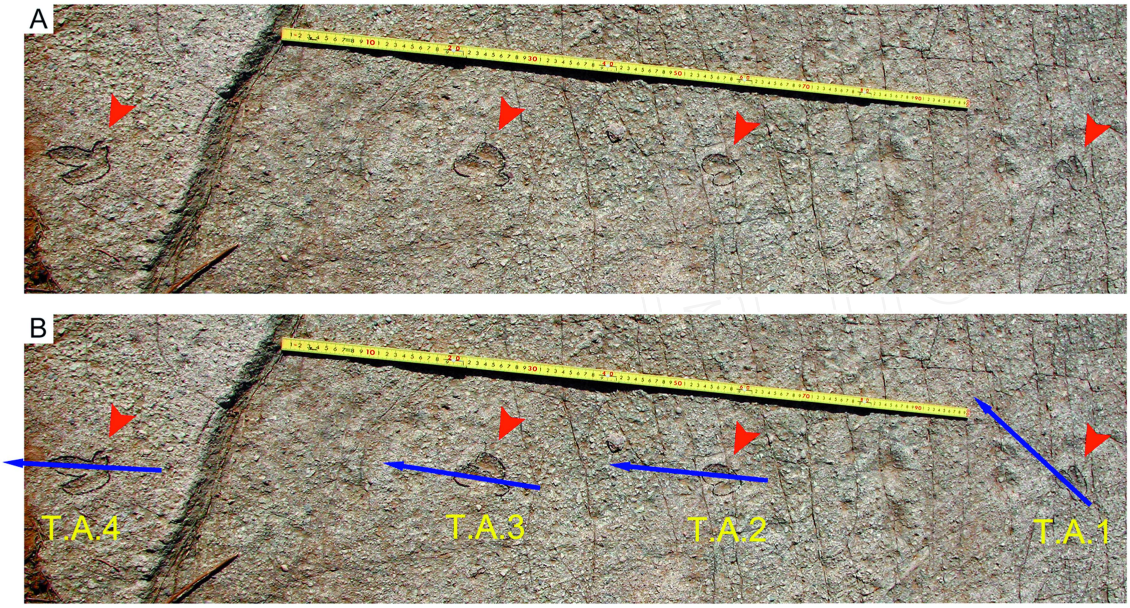

Fig. 3 T. A. 1 —4 trackway

A. photograph; B. same as A with tracks T. A. 1 —4 numbered. Blue arrows indicate the forward direction of each footprint. Scale bar = 1m.

Table 1 Measurements (in cm; ° as noted) of T. A. 1 —4.

Measurement	Specimen T. A.			
	1	2	3	4
Maximum length	6.7	—	5.8	6.5
Maximum width *	4	3.4 ***	4.6	4.7
Width between top of digits III and IV	4.58	3.75	4.17	4.25
Length: width ratio	1.68		1.26	1.38
Length of digit III **	5.2	4.6 ***	5.5	5.8
Length of digit IV **	2.2	3 ***	2.7	4
Angle between digits III and IV	44°	40° ***	44°	41°

* A line parallel to the axis of the track was drawn from the outer margin of digit II; measurement was taken as the vertical distance from the outer margin of digit IV to the line.

** Measured the distance from the tip of the digit to a line drawn perpendicular to the digit axis and that is tangent to the adjacent hypex.

*** Incomplete.

(A), subadult (B), and adult (C) ontogenetic stages. The average lengths of types A—C are 4.5cm, 13.4cm, and 16.7cm, respectively; divarication angles between digits II-III and III-IV are 26.5° and 23.5°, 21.7° and 15°, and 25.2° and 21.2°, respectively. Even in the smallest (4.5cm long) *Grallator*-type tracks, the divarication angle between digits III-IV is merely 23.5°, a value substantially different from T. A. 1 —4.

Grallator-type tracks are also abundant at the Nijiagou tracksite. As an example, track T. B. 6 (from trackway T. B. 1 —12) (Fig. 4), which lies close to the T. A. 1 —4 trackway, has a length of 19.7cm, a length/width ratio of 1.7, and divarication angles between digits II-III and III-IV of 25° and 22°, respectively. All these characteristics accord with the characteristics of *Grallator* per Olsen *et al*. (1998). Digit III of T. B. 6 is 10.4cm long; digit IV is 6.7cm long, so the ratio of their lengths is 1.55, a value markedly different from T. A. 1 — 4. In addition, digit II is as deeply impressed as digits III and IV in T. B. 6.

If T. A. 1 —4 are hypothesized as *Grallator*-type tracks that, for some reason, lack impressions of digit II, the divarication angles between digits III-IV should still be close to the values from tridactyl *Grallator*-type tracks, as should the relative lengths of digits III and digit IV. This phenomenon has been demonstrated experimentally with emu tracks made in different substrates (Milàn, 2006, fig. 12). In total, T. A. 1 —4 can not be reasonably referred to aberrant, Tuchengzi Formation *Grallator*-type tracks, but instead most parsimoniously represents a didactyl track maker. The wider divarication angles in T. A. 1 —4 may therefore represent compensation by digits III and IV for the loss of digit II as a weight-bearing digit to provide a larger, more stable surface area on

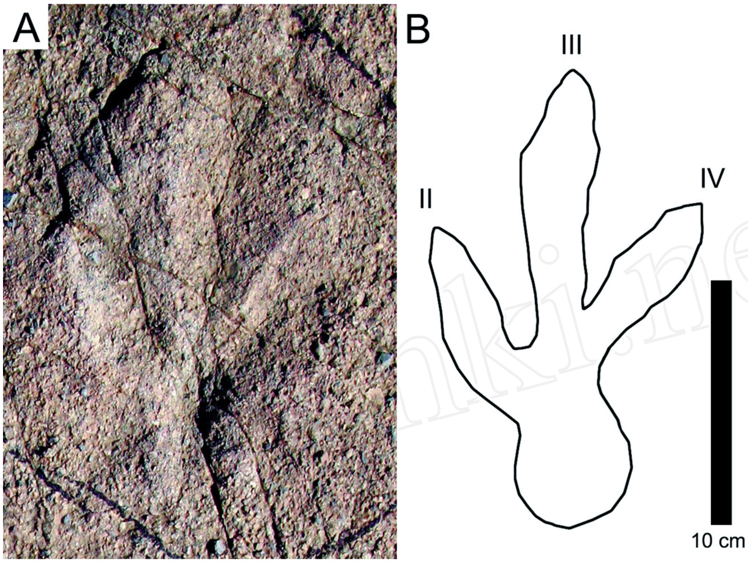

Fig. 4　*Grallator*-type track (T. B. 6) from the Nijiagou tracksite

A. photography; B. online drawing.

which the track maker walked.

Zhen *et al*. (1994) indicated the following characteristics in the description of *Velociraptorichnus sichuanensis*: "Bipedal, digitigrade form, didactyl structure in walking, with claws at the end of toes, the ratio of pace to the length of foot is 4.4 :1, with small angle between toes. No manus or caudal impressions." This description lacks a fair amount of detail. The *Velociraptorichnus* specimens (CFEC-B-1, CFEC-B-2, CFEC-B-3) were restudied for the present analysis (Fig. 5A, 5B). They are indeed narrow, didactyl tracks, with subequal digit III and IV lengths. Digit III is slightly wider than digit IV, and both bear discernible claw marks. Digital pads are indistinct to nonexistent. Digit II is represented only by a short, round impression that is at least partially embedded within the impression of digit III at its proximomedial edge. The large metatarsophalangeal region is hemispherical and not separated from the digits by a distinct border. The average length:width ratio across the sample is 1.77. The length: width ratio of *Velociraptorichnus* tracks from the Tianjialou Formation of Junan (Fig. 5C), Shandong Province (Li *et al*., 2007) is 2.2. Except for possessing stronger claw marks on digits III and IV, the Tianjialou tracks do not differ markedly from CFEC-B-1.

In these other didactyl tracks, digit III is characteristically almost equal in length to digit IV. The ratio of digit III: digit IV lengths of *V. sichuanensis* CFEC-B-1 is 1.3 (6.2 cm/4.7 cm; this value provided by Zhen *et al*. (1994) is 0.9). For the Junan *Velociraptorichnus*, the ratio is 1.2. In *Menglongipus sinensis*, the ratio of T. A. 1 is 2.36 based on the photogrammetric map (Fig. 2E—H). Moreover, the impression of digit II in the Nijiagou tracks tends to be more external to the impression of digit III than in the *Velociraptorichnus* sample. The divarication angles between digits III and IV of *V. sichuanensis* range from 21°—28° (Zhen *et al*., 1994); in the Junan *Velociraptorichnus*, the divarication angle is 23°. In comparison, the angles in *Menglongipus sinensis* range from 41°—44°.

Aside from *Velociraptorichnus*, dromaeopodid occurrences include a possible didactyl track from Utah (Lockley *et al*. 2004), didactyl tracks from the Hekou Group near Yongjing, Gansu Province (Fig. 6; Li *et al*., 2006), *Dromaeopodus shandongensis* (Li *et al*., 2007), and *Dromaeosauripus hamanensis* from South Korea (Kim *et al*., 2008). These tracks are narrower than *Menglongipus*, and the widths of each pad in these tracks are more or less consistent. Digit III is almost equal to digit IV in length, and there is a well developed meta-

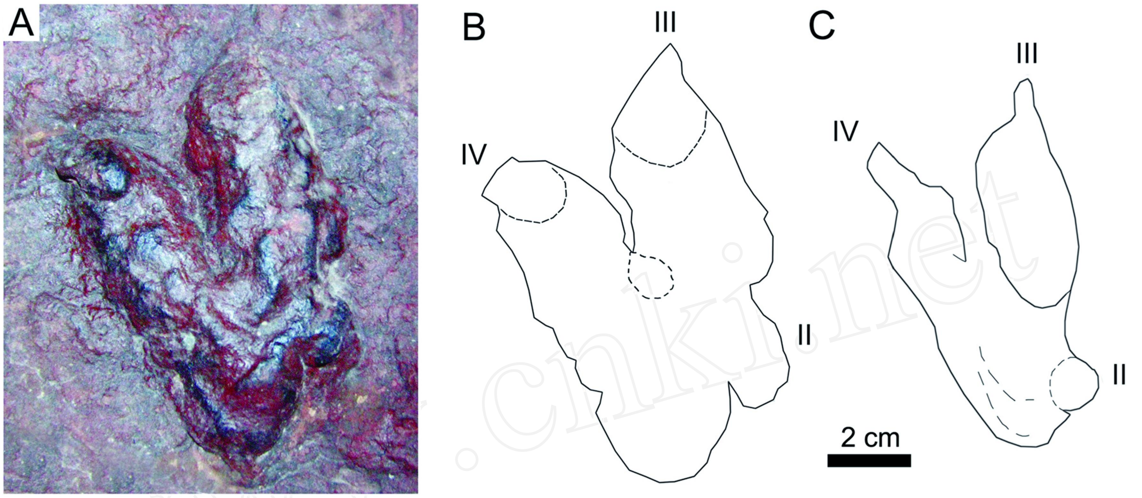

Fig. 5 Small-sized didactyl tracks from China

A. photograph of *Velociraptorichnus sichuanensis* from E'mei County, Sichuan Province; B. outline drawings of A; C. outline drawing of *Velociraptorichnus* isp. from Junan, Shandong Province (C from Li *et al*., 2007).

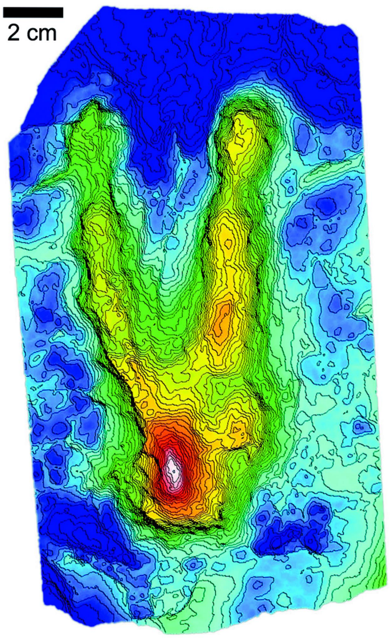

Fig. 6 Computerized photogrammetry with 0.2mm contour lines of a didactyl track (GSL TZP-S2-TE04L) from the Hekou Group near Yongjing, Gansu Province (Li *et al*., 2006)

Color banding reflects topography (blue-green = highest, red-white = lowest).

tarsophalangeal region (except in *Dromaeosauripus*). The only character that these tracks share with *Menglongipus sinensis* is that digit II is not embedded within the impression of digit III. *M. sinensis* contrasts with these other prints by having digits III and IV expand distally. Additionally, the differences in length between digits III and IV are distinct, and the metatarsophalangeal region is very small (Fig. 2I—L). The divarication angles between digits III and IV are 16° and 21° in *D. shandongensis* and the Yongjing tracks, respectively, both smaller than the 41°—44° angles exhibited by *M. sinensis*. These differences support placing the Nijiagou tracks in a new ichnotaxon.

Discussion Deinonychosaurians (Dromaeosauridae and Troodontidae) were functionally didactyl, non-avian theropod dinosaurs that flourished in the Cretaceous and were widely distributed globally. Teeth possibly representing dromaeosaurids occur in the Middle Jurassic (Bathonian) of England (Metcalf *et al*., 1992), but the oldest well-substantiated deinonychosaur is an as-yet undescribed troodontid from the Upper Jurassic (Kimmeridgian to Tithonian) Morrison Formation (Hartman *et al*., 2005). The discovery of *Menglongipus sinensis* in the Tuchengzi Formation provides new evidence for the existence and distribution of deinonychosaurians around the Jurassic-Cretaceous boundary. Deinonychosaurian body fossils are known in western Liaoning in the much younger, Lower Cretaceous (Barremian-Aptian) Yixian Formation, which is a lateral correlate of the Zhangjiakou Formation that unconformably overlies the Tuchengzi Formation. Yixian Formation deinonychosaurians include the dromaeosaurids *Graciliraptor* (Xu and Wang, 2004a), *Microraptor* (Xu *et al*., 2000; Hwang *et al*., 2002), and *Sinornithosaurus* (Xu *et al*., 1999) and the troodontids *Mei* (Xu and Norell, 2004), *Sinusonasus* (Xu and Wang, 2004b), and *Sinovenator* (Xu *et al*., 2002). *Menglongipus sinensis* tracks demonstrate that deinonychosaurians lived in the same region roughly 15 million years earlier. It is not yet possible to determine whether *Menglongipus* tracks were made by a dromaeosaurid or a troodontid.

The hip height of a track maker can be estimated using the formula: hip height ≈4 ×footprint length (Henderson, 2003). The average ratio of hip height to body length in theropods (averaged from members of a variety of theropod clades) is 1 ∶2.63 (Xing *et al*., 2009). Based on these estimates, the body length of the *Menglongipus sinensis* track maker is 66.6cm. This estimate very similar to that (about 65cm long) estimated for a basal paravian by Turner *et al*. (2007).

Ichnological Associations Dromaeopodid tracks are currently known from Sichuan, Shandong, Gansu and Hebei provinces in China, Chu Island in South Korea, and possibly Utah, USA. *Velociraptorichnus sichuanensis* from Sichuan Province was discovered together with *Grallator emeiensis* (Zhen *et al*., 1994) and *Minisauripus chuanzhuensis* (Zhen *et al*., 1994; Lockley *et al*., 2008); both *G. emeiensis* and *M. chuanzhuensis* are extremely small footprints (2.7cm and 3cm long, respectively, claws included). *Velociraptorichnus* and *Dromaeopodus shandongensis* in Shandong Province (Li *et al*., 2007) were also discovered along with tridactyl theropod tracks, including larger (LRH-dz 73:49cm long) and smaller (LRH-dz 71-1:8.5cm long) tracks; the lengths of most tracks range between 15—26cm (Li *et al*., 2005). Based on the original descriptions and drawings, the smaller tracks appear to be of the *Grallator* morphotype (sensu Olsen *et al*., 1998). Furthermore, 3—6cm long *Minisauripus zhenshuonani* tracks (Lockley *et al*., 2008) were discovered at the same site. The Yongjing dromaeosaurid tracks from Gansu Province (Li *et al*., 2006) were associated with three types of theropod tracks (Zhang *et al*., 2006), some of which could pertain to *Grallator* (Li *et al*., 2006). *Dromaeosauripus hamanensis* and *Minisauripus* from Chu Island (Lockley *et al*., 2008) and the possible didactyl Utah occurrence (Lockley *et al*., 2004) were also discovered in association with abundant tridactyl theropod tracks.

The consistent co-occurrence of dromaeopodid tracks with tridactyl theropod tracks is noteworthy, as is their rarity compared to the latter at each site. Feet capable of registering *Grallator* morphotype tracks were widely distributed in small-medium sized theropods (other than dromaeosaurids and troodontids). This indicates that deinonychosaurs occupied similar ecosystems as other theropods, but that deinonychosaurians may have occupied ecological niches distinct from those occupied by more typical, tridactyl theropods, and that deinonychosaurians only rarely entered the track-preserving environments favored by their tridactyl relatives. Also noteworthy is the relatively consistent association of *Minisauripus* and dromaeopodid tracks, which suggests a close ecological association between the makers of these two tracks.

Acknowledgements The authors thank Ji Qiang, Liu Yongqing, and You Hailu (Institute of Geology, Chinese Academy of Geological Sciences, Beijing, China), Li Daqing (Fossil Research and Development Center, Third Academy of Geology and Mineral Resource Exploration of Gansu Province, Lanzhou, China) for their critical comments and suggestions on this paper. Thanks to Li Rihui (Shandong Fourth Institute of Geological and Mineral Survey, Shandong, China) and Li Jianjun (Department of Paleontology, Beijing Natural History Museum, China) for access to specimens and data. Guo Man, Zhao Chuang (China Aviation Media Group) and Shen Guifei (Chicheng County Vocational Education Center, Zhangjiakou, China) provided invaluable assistance during the field expedition. Zhao Chuang drew the pictures and restorations. This research was supported by the Chinese Ministry of Science and Technology (973 Project, 2006CB701405), China Geological Survey, Palaeobiology Program of Chinese National Geography International (CNGi) and China Aviation Media Group.

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