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Middle Jurassic theropod trackways from the Panxi region, Southwest China and a consideration of their geologic age

Li-Da Xing [a,b,*], Martin G. Lockley [c], Zhong-Dong Li [d], Hendrik Klein [e], Jian-Ping Zhang [a], Gerard D. Gierliński [f,g], Yong Ye [h], W. Scott Persons IV [b], Long Zhou [d]

[a] School of the Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China
[b] Department of Biological Sciences, University of Alberta, 11455 Saskatchewan Drive, Edmonton, Alberta T6G 2E9, Canada
[c] Dinosaur Tracks Museum, University of Colorado Denver, PO Box 173364, Denver, CO 80217, USA
[d] Geophysical Team of Sichuan Bureau of Geological and Mineral Investigation and Exploration, Chengdu 610072, Sichuan, China
[e] Saurierwelt Paläontologisches Museum, Alte Richt 7, D-92318 Neumarkt, Germany
[f] JuraPark, ul. Sandomierska 4, 27-400 Ostrowiec Świętokrzyski, Poland
[g] Polish Geological Institute, Rakowiecka 4, 00-975 Warszawa, Poland
[h] Zigong Dinosaur Museum, Zigong 643013, Sichuan, China

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Abstract

Theropod footprints from the Middle Jurassic Xincun Formation in the Panxi region (Sichuan Province, Southwest China) show strong similarities to the ichnogenus *Kayentapus*. They are characterized by slender digits, wide digit divarication, and a characteristic pad configuration that is different from other Jurassic theropod ichnotaxa. At the Shansong tracksite, three trackways are present, each consisting of four consecutive tracks (stride and pes lengths up to 200 cm and 36 cm, respectively). The speed of the trackmakers has been calculated with values between 1.1 and 1.4 m/s. The assemblage is a further document of a Middle Jurassic occurrence of this morphotype that is basically known from the Lower Jurassic deposits elsewhere. This could be due to peculiarities of theropod communities in this region, reflecting a different paleobiogeographic distribution pattern in the Middle Jurassic. Biostratigraphically, ostracods lend support to a Middle Jurassic age of the trackbearing unit. This corresponds partly with data from the Shangshaximiao Formation that is considered to be of Middle Jurassic age based on ostracods but Late Jurassic age based on vertebrate skeletons. The ichnological record and the presence of *Kayentapus*-like footprints in both units support a Lower–Middle Jurassic age.

Keywords: Middle Jurassic; Theropod trackway; *Kayentapus*; Panxi region

1. Introduction

The Panxi (Panzhihua–Xichang) region is situated at the eastern end of the Himalayan mountain range and the southeastern corner of the Tibetan Plateau (Fig. 1A), and covers the area between the Central Yunnan Basin and the Sichuan Basin. Although the Central Yunnan Basin is famous for abundant fossils of the Early Jurassic prosauropod *Lufengosaurus* (Young, 1951) and the Middle Jurassic sauropod *Chuanjiesaurus* (Li et al., 2011; Sekiya, 2011) and the Sichuan Basin is famous for skeletons of the Middle Jurassic sauropod *Shunosaurus* and the Late Jurassic sauropod *Mamenchisaurus* (Peng et al., 2005), Panxi's Mesozoic vertebrate fossil records is poorly known by comparison. The fossil track record of the Panxi region, therefore, is significant and has a great potential to contribute to our understanding of Chinese Jurassic dinosaur fauna distributions.

Huidong County and the Shansong tracksite are located in the south of the Panxi region (Fig. 1A). Early in the 1980s, dinosaur tracks were discovered in Huidong County by a geological prospecting team, but were never formally described (Wang, 1988). In 2002, footprints from Huidong County were independently collected by the Slave Society of Yi Nationality Museum (SSM) and the Huidong Culture and Sports Bureau (HDCSB).

* Corresponding author at: Department of Biological Sciences, University of Alberta, 11455 Saskatchewan Drive, Edmonton, Alberta T6G 2E9, Canada.
E-mail address: xinglida@gmail.com (L.-D. Xing).

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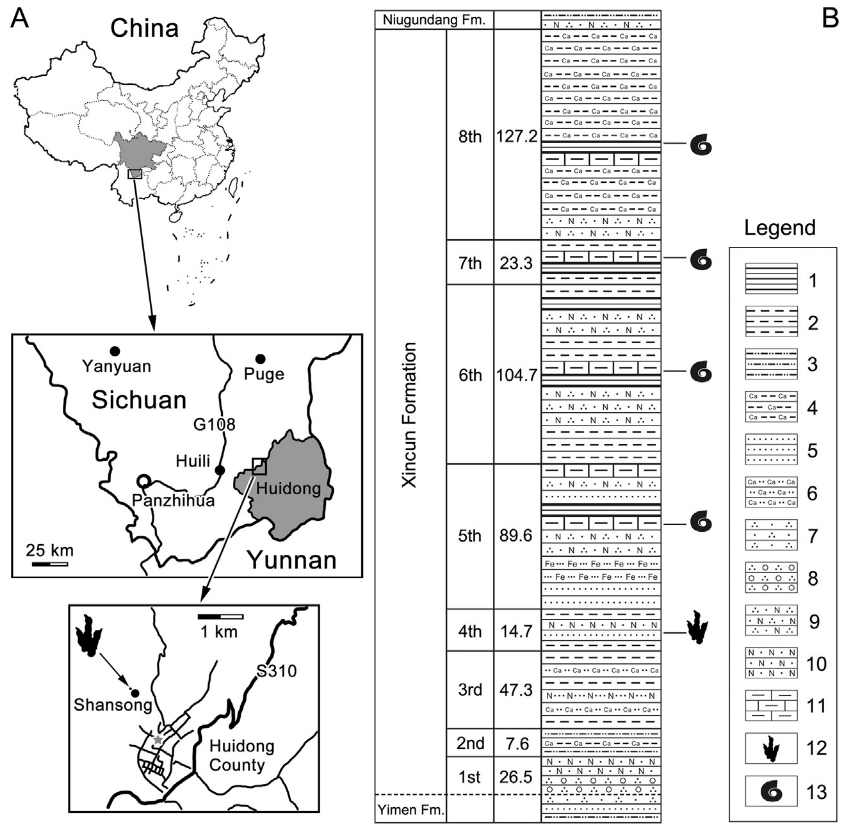

Fig. 1. (A) Geographic map indicating the location (footprint icon) of the Shansong dinosaur footprint locality in Liangshan Yi Autonomous Prefecture, Sichuan Province, China. (B) Stratigraphic section of the Middle Jurassic in the study area with the Xincun Formation and the position of the track-bearing strata (emended from Gu and Liu, 1997). Illustration: 1, shale; 2, mudstone; 3, silty mudstone; 4, calcareous mudstone; 5, siltstone; 6, calcareous siltstone; 7, quartz sandstone; 8, quartz conglomerate; 9, Feldspathic quartz sandstone; 10, Arkosic sandstone; 11, Marl; 12, dinosaur tracks; 13, invertebrate fossils.

Unfortunately, these excavations compromised the integrity of the site and no map recording the original position of the tracks has been published.

Of the eight footprints collected by the Huidong Culture and Sports Bureau, seven were collected by directly incasing the tracks with plaster, without a protective intermediate cover, such that now the plaster cannot be safely removed and the form of the tracks is entirely obscured. Only one footprint (HDCSB-1) from the Huidong Culture and Sports Bureau was accessible to observation. The two footprints collected by Liangshan Yi of the Autonomous Prefecture Museum (SSM-1 and SSM-2) were examined.

Table 1
Measurements (in cm) of tracks from Shansong tracksite.

Number	R/L	ML	MW	II	III	IV	II–III	III–IV	II–IV	SL	PL	L/W
SSA1	R	>23.7	29.8	14.6	>14.1	19.5	–	–	–	156.4	85.5	–
SSA2	L	28.8	30.6	19.1	18.7	20.1	40°	46°	86°	–	80.2	0.9
SSA3	R	28.0	31.7	16.9	16.9	18.7	45°	53°	98°	–	77.5	0.9
SSA4	L	27.3	27.1	14.6	17.6	18.4	33°	43°	76°	–	–	1.0
SSB1	R	28.5	22.1	16.8	17.2	18.2	37°	38°	75°	174.4	89.9	1.3
SSB2	L	27.9	22.0	15.7	17.0	18.5	35°	28°	63°	167.5	88.0	1.3
SSB3	R	28.2	23.9	16.8	16.4	16.8	30°	45°	75°	–	84.5	1.2
SSB4	L	28.1	23.0	14.2	17.6	18.9	46°	39°	85°	–	–	1.2
SSC1	L	31.2	31.7	16.3	20.0	–	34°	–	–	198.8	102.0	1.0
SSC2	R	34.0	>23.6	17.5	19.0	–	>28°	–	–	200.0	100.4	–
SSC3	L	31.2	30.4	18.2	19.0	15.6	41°	53°	94°	–	100.0	1.0
SSC4	R	36.2	35.7	17.7	26.0	16.3	52°	47°	99°	–	–	1.0
HDCSB-1	R	35.5	28.1	>11.2	23.7	20.8	36°	28°	64°	–	–	1.3
SSM-1	–	>32.9	>16.5	–	26.6	–	–	–	–	–	–	–
SSM-2	R	27.4	30.7	19.7	16.9	20.6	38°	56°	94°	–	–	0.9

R/L, right/left; ML, maximum length; MW, maximum width measured between the tips of digits II and IV; II, length of digit II; III, length of digit III; IV, length of digit IV; II–III, angle between digits II and III; III–IV, angle between digits III and IV; II–IV, angle between digits II and IV; SL, stride length; PL, pace length; L/W, ratio of maximum length/maximum width.

In 2012, the lead author was informed of dinosaur tracks in Huidong County by the *Liangshan Daily*. Jun-feng Zhao (special members of the Geophysical Team of the Sichuan Bureau of Geological and Mineral Investigation and Exploration, Chengdu, China), Long Zhou (an author of this paper), and Yan Zhang (a volunteer) explored this tracksite in May 2012.

Institutional abbreviations

HDCSB = Huidong Culture and Sports Bureau, Sichuan, China; SSM = Slave Society of Yi Nationality Museum, Sichuan, China.

2. Geological setting

The Jurassic strata of Zhaojue–Huili region are primarily fluvial facies that consist of red pyroclastic rock and mudstone. The lithology of the southern strata is similar to that in Wuding and Lufeng of Yunnan Province. The Jurassic strata can be divided into the Yimen Formation (Lower Jurassic), the Xincun Formation (Middle Jurassic), the Niugundong Formation (Upper Jurassic), and the Guangou Formation (Upper Jurassic). The mamenchisaurid *Tonganosaurus hei* (Li et al., 2010) and prosauropods (Wang, 1988) have been discovered in the Yimen Formation. Fishes and reptiles, including pliosaurids, are known from the Xincun Formation (Song, 2011). However, these fossils are yet to be thoroughly studied (Wang, 1988).

The Xincun Formation consists of non-uniformly interbedded purplish-red mudstone and shale, silty mudstone, calcareous mudstone, grayish-white siltstone, and quartz sandstone, containing ostracods, conchostracans and bivalves, with a thickness of 450–800 m (Gu and Liu, 1997). Dinosaur tracks occur in exposures of the Xincun Formation along the road of Shansong Village, Huidong County, Liangshan Yi Autonomous Prefecture, Sichuan Province (Fig. 1A) (Panxi Geological Team, Sichuan Bureau of Geology and Mineral Exploration and Development, 1977–1984; Wang, 1988). The layer containing dinosaur tracks (Fig. 1B) is composed of gray-purple siltstone showing ripple marks. It is inclined at a gradient of 60° and exposed across an area of approximately 40 m^2.

3. Ichnotaxonomy

Material

There are approximately forty natural molds of tridactyl footprints of bipeds at the Shansong tracksite. Of these, twelve tracks belong to three distinct trackways (SSA–SSC, SS = Shansong) (Figs. 2 and 3, Table 1). All other tracks are isolated and not part of discernible trackways. None of these tracks have been collected, and at the time of writing, all remain in the field.

Locality and horizon

Xincun Formation, Middle Jurassic. Shansong tracksite, Liangshan Yi Autonomous Prefecture, Sichuan Province, China.

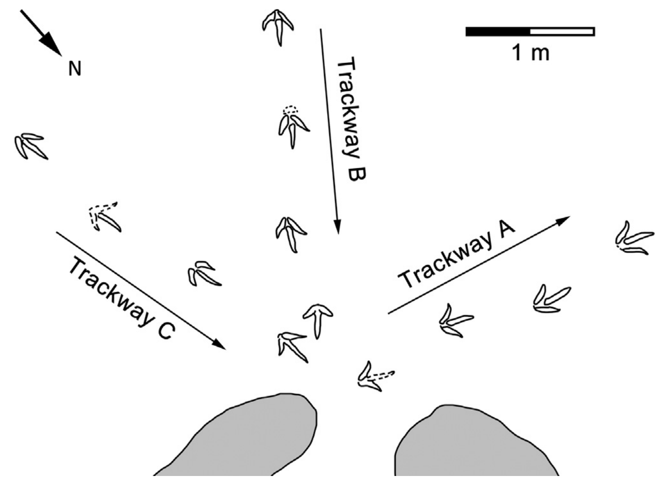

Fig. 2. Map with *Kayentapus* trackways SSA–SSC at Shansong tracksite.

Description

Trackways SSA–SSC each consist of four tracks (1–4) (Figs. 3A, B and 4). The individual tracks are large (27.3–28.8 cm in length) tridactyl theropod tracks. Manus and tail traces are absent. The length/width ratios of these tracks range from 0.9 to 1.0. Track SSA2 (Fig. 3A and B) is representative of the track morphology. Digit III projects the farthest anteriorly, followed by digits II and IV. Some digit impressions reveal indistinct pad impressions. The proximal region of digits II and IV forms an indistinct U-shaped metatarsophalangeal region that lies nearly in line with the axis of digit III. The footprints of trackway A have wide divarication angles (76–98°). Trackway A is narrow (pace angulation about 141°) and characterized by long stride lengths (156 cm on average), given a mean footprint length of 28 cm.

Based on the length and divarication of the footprint, SSM-1 is probably derived from trackway C. SSM-1 (Fig. 3C and D) is also similar to SSA2, but much deeper. Each digit of SSM-1 has a sharp claw mark, especially digit II, which is the longest and the most distinct.

Overall, the footprints of trackways B and C are similar to those of trackway A (Fig. 4), but the digit traces are more widely spaced in SSC. The average divarication angle of the footprints forming trackways B and C is 82°. Trackways B and C are narrow (pace angulation 152–157°, 158–173° respectively).

Based on the similar proportions, HDCSB-1 (Figs. 3E, F and 4) and SSM-1 (Fig. 4) are probably derived from trackway C; however, SSM-1 is poorly preserved. HDCSB-1 is a poorly preserved right footprint and deeper than, but otherwise similar to, the other footprints. The "metatarsophalangeal region" shows a robust profile, but lacks details—possibly a result of damage during collection.

Preservation

The footprints from the Shansong tracksite show a remarkable pattern of different weathering. In some cases this seems to

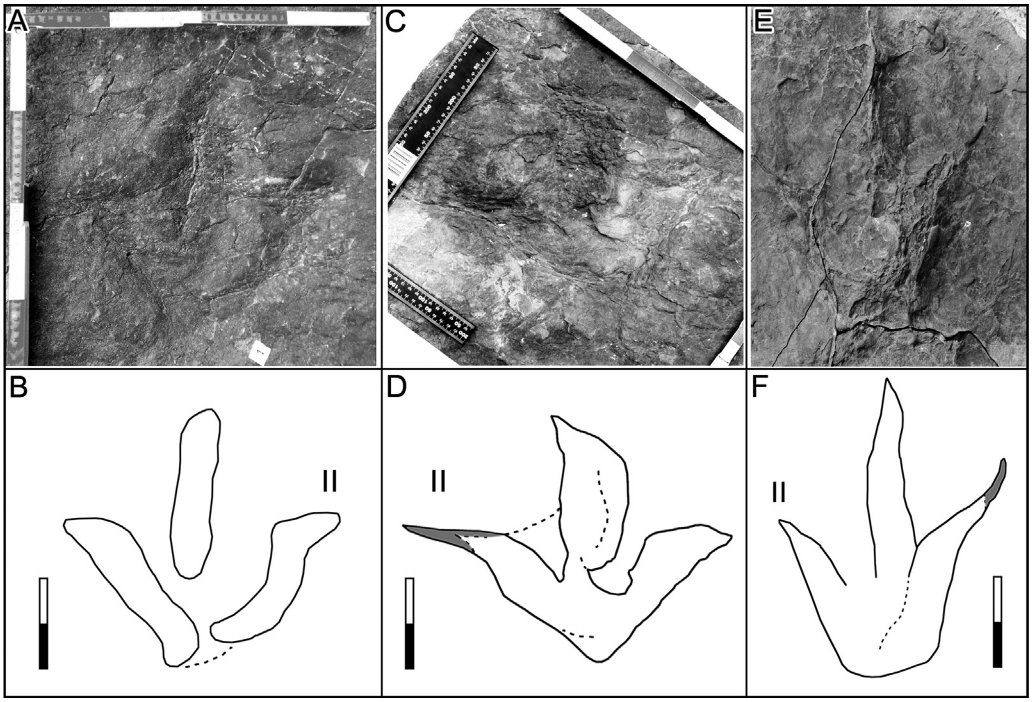

Fig. 3. Shansong *Kayentapus* footprints SSA2, SSM-2, and HDCSB-1. (A, C and E) Photographs; (B, D and F) outline drawing (scale bar = 10 cm).

affect their overall shape and might challenge future ichnotaxonomic considerations. A detailed description and discussion will follow in a different paper.

Discussion

Kayentapus is the ichnogenus name applied to relatively large (pes length ∼35 cm) tridactyl tracks of a bipedal theropod dinosaur, originally described by Welles (1971). Welles' description was based on a trackway with long steps from the Lower Jurassic Kayenta Formation of Arizona (Lockley et al., 2011). *Kayentapus hopii* is characterized by the absence of a hallux impression and the preservation of the metatarsophalangeal pad of digit IV well separated from the rest of the digit impressions (Welles, 1971; Lockley et al., 2011). In addition, compared to *Eubrontes*, *Kayentapus* is more gracile, with wider digit divarication (60–75° between digits II and IV of *K. hopii*), and differs in the anterior and posterior triangle configurations (Lockley, 2009; Lockley et al., 2011).

The shape of the Shansong tracks strongly resembles those of *Kayentapus* tracks: i.e., it lacks the robust characteristics such as the wide digit traces associated with *Eubrontes* (Olsen et al., 1998) and *Changpeipus* (Xing et al., 2009a). However, because of the poor preservation that may have resulted from original substrate conditions and weathering, the tracks lack sufficient morphological detail to be assigned to a specific ichnospecies with confidence. On the other hand, the Shansong material perfectly demonstrates the morphological variation of *Kayentapus* footprints owing to different preservation. Similar observations have been made on *Kayentapus* tracks from other localities (Gierliński, 1996; Lockley et al., 2011; Ősi et al., 2011).

4. The speed of Shansong trackmakers

The type trackway of *Kayentapus hopii* allows us to calculate speed (v) using the formula of Alexander (1976): $v = 0.25\, g^{0.5} \cdot \mathrm{SL}^{1.67} \cdot h^{-1.17}$, where g = gravitational acceleration in m/s; SL = stride length; and h = hip height, estimated as 4.9 times foot length (FL), using the ratio for large theropods proposed by Thulborn (1990). The type trackway of *Kayentapus hopii* (Welles, 1971) gives an estimated speed of ∼4.03 m/s (∼14.51 km/h), and the referred trackway an estimated speed of ∼5.5 m/s or ∼19.8 km/h (Lockley et al., 2011). The possible *Kayentapus* trackway from Sichuan, China (*Schizograllator xiaohebaensis*, Zhen et al., 1986) (Lockley and Hunt, 1995) gives an estimated speed of ∼12.0 km/h (Lockley et al., 2011).

Based on the measurements of trackways, we calculated a speed of ∼1.1 m/s or ∼4.1 km/h (trackway A); ∼1.3 m/s or ∼4.8 km/h (trackway B); and ∼1.4 m/s or ∼5.1 km/h (trackway C). The body length of the track maker of the Shansong tracks can be estimated by using the average hip height to body length ratio of 1:2.63 (Xing et al., 2009b) and the formula: hip height ≈4× footprint length (Henderson, 2003), and is approximately 2.9–3.5 m. The trackmaker was, therefore, slightly larger than those of the two Late Jurassic theropod tracks from the Shangshaximiao Formation, Chongqing (approximately 2.6–2.8 m, and 3 m).

5. Biostratigraphic implications

The lithologic characters of the lower units of the Xincun Formation (Panxi region), the Zhanghe Formation (Central Yunnan Basin), and the Upper Lufeng Formation (Lufeng Basin) have long been considered consistent evidence of

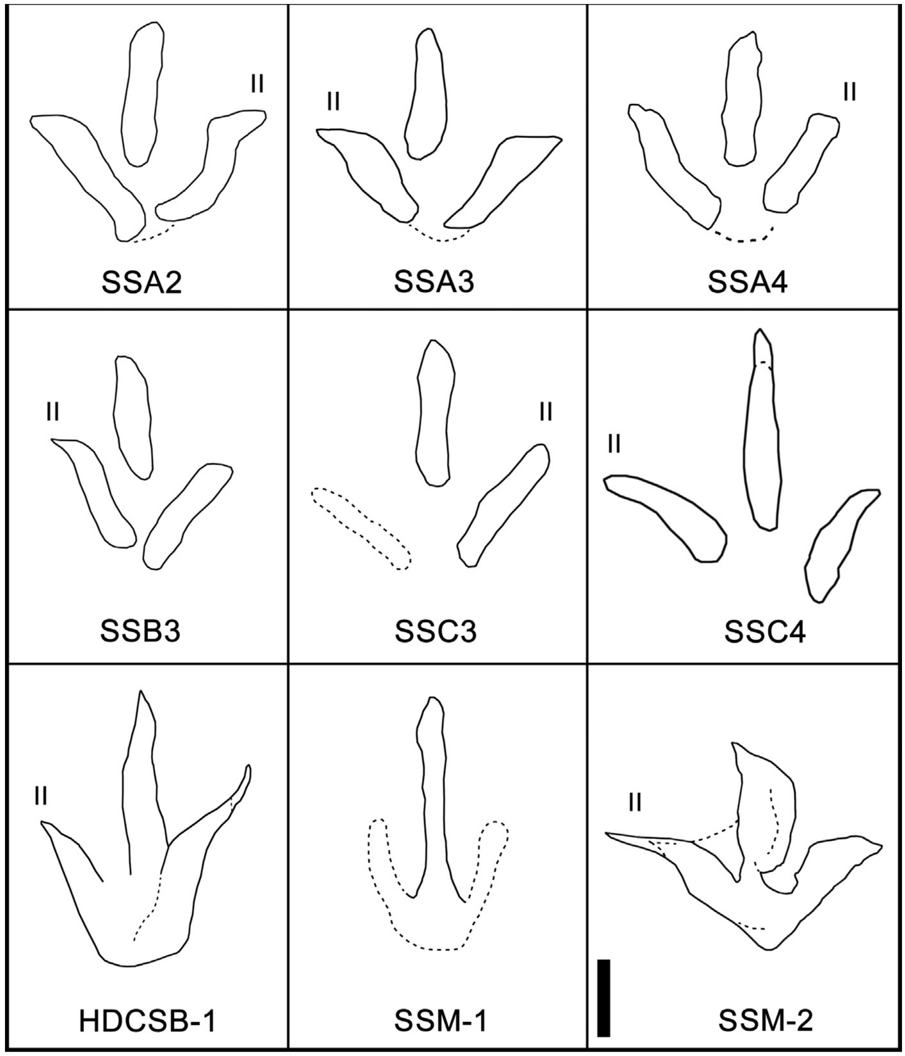

Fig. 4. Outline drawings of Shansong *Kayentapus* footprints (scale bar = 10 cm).

fluvial facies deposits (Wang, 1988). In addition, the assemblage with bivalves, ostracods, conchostracans and vertebrate fossils (*Chuanjiesaurus* from the Upper Lufeng Formation, and the *Yuanmousaurus* fauna from the Zhanghe Formation) (Lü et al., 2006) is identical across the three formations (Wang, 1988).

The ostracods of the Panxi region are comparable to those from the Shangshaximiao Formation, the Xiashaximiao Formation, and the Xintiangou Formation (Wei and Xie, 1987), and coincide with the characteristics of the Middle Jurassic. Currently, it is credible that the Xiashaximiao Formation and the Xintiangou Formation pertain to the Middle Jurassic (Wang, 1988; Gu and Liu, 1997; Peng et al., 2005). However, the geological age of the Shangshaximiao Formation is controversial. Invertebrate fossils indicate a Middle Jurassic age, whereas vertebrate fossils exhibit the characteristics of the Late Jurassic (Peng et al., 2005; Wang, 2010; Xing et al., in press).

The Shansong *Kayentapus*-like tracks from the Xincun Formation are similar to the Nan'an tracks from the Shangshaximiao Formation (Lockley et al., in press; Xing et al., in press) that are assigned to cf. *Kayentapus* (Xing et al., in press). This might indicate that, based on vertebrate tracks, the geological age of the Shangshaximiao Formation has to be re-considered as Middle Jurassic (however, as mentioned above, this conflicts with the record of vertebrate skeletons). In North America and Europe, convincing examples of *Kayentapus* and *Kayentapus*-like tracks are generally reported only from the Lower Jurassic, where they are typically associated with *Grallator*, *Eubrontes*, *Anomoepus*, and *Otozoum* (Lockley and Hunt, 1995; Lucas, 2007). Similar assemblages, but without *Otozoum*, are reported from China in both the Lower and Middle Jurassic (Lockley et al., in press). This suggests either that there is some doubt about the reliability of age determinations in the Jurassic terrestrial successions of Asia and other regions, or that what are traditionally regarded as the Lower Jurassic assemblages in North America (and Europe) were longer-lived and more commonly found in the Middle Jurassic in east Asia. Based on preliminary evidence of the late occurrences of the typical Early Jurassic North American ichnogenera in younger Asian deposits (Lockley et al., in press), this latter scenario is possible, though as yet unverified by definitive corroborating biostratigraphic evidence. This problem is unlikely to be resolved until reliable biostratigraphic and ichnotaxonomic data are more comprehensively synthesized.

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