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ORIGINAL RESEARCH

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A Preliminary Review of Dinosaur Track Assemblages from the Tuchengzi Formation in North China

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ABSTRACT

In northern China, mainly within Western Liaoning, Northern Hebei and Beijing, vertebrate skeletons from the Tuchengzi Formation (Upper Jurassic to Lower Cretaceous) are scarce. However, many new dinosaur track discoveries have been made in the past ten years. So far, 19 dinosaur track sites have been found in the Tuchengzi Formation, collectively containing 2,637 individual tracks and representing at least 2,091 trackmakers. This track record has become an essential understanding of the Tuchengzi dinosaur fauna. The abundant Tuchengzi track record includes six non-avian theropod ichnogenera *(Asianopodus, Eubrontes, Grallator, Menglongipus, Therangospodus,* and *Velociraptorichnus),* three bird ichnogenera *(Aquatilavipes, Pullornipes,* and *Koreanaornis),* two sauropod ichnogenera *(Brontopodus* and cf. *Parabrontopodus* isp.), and a possible ornithopod ichnogenus (cf. *Dinehichnu).* This assemblage is saurischian-dominated, consistent with most Jurassic and Cretaceous track sites in China. The presence of deinonychosaurian tracks is consistent with the rich skeletal record from the Yanliao Biota or Jehol Biota. The bird tracks are consistent with the history of shorebirds in Jehol Biota. The existence of ornithopod tracks is doubtful and needs further discoveries to be confirmed.

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1 Introduction

The Middle-Upper Jurassic Yanliao Biota and the Lower Cretaceous Jehol Biota in northern China have been the subject of intense paleontology research for over a decade, especially instances of unusually preserved soft tissues, such as dinosaur feathers, mammals with fur, and angiosperms with petals and other delicate structures (Zhou et al., 2010; Pan et al., 2013). The temporal gap between the record of the Yanliao Biota and the Jehol Biota is nearly equivalent to the age of the Tuchengzi Formation (Xu et al., 2014). As such, the Tuchengzi ichnofauna has the potential to bridge the evolutionary history of northern China's most well-studied and understood Mesozoic terrestrial faunas.

The Tuchengzi Formation was deposited in a series of rift basins during the transition period from the Late Jurassic to Early Cretaceous. The formation is exposed in northern Hebei Province, north of Beijing, and western Liaoning Province. It is a set of typical clastic continental red beds that formed under

hot and arid paleoclimate conditions (Xu et al., 2014). It was widely believed that the paleogeographic environment of the Tuchengzi Formation was hot and arid, with the terrestrial flora and fauna relatively "scarce" (Xu et al., 2011; Liu et al., 2012). Few non-track fossils have been reported from the Tuchengzi Formation but include a small number of conchostracans (Wang et al., 2013), plants (Zheng et al., 2001), spores and pollen (Pu et al., 1982). Vertebrate skeletal fossils are scarce, and the currently described dinosaur material consists of one brachiosaurid sauropod (Dong, 2001) and two basal ceratopsians: *Chaoyangsaurus youngi* (Zhao et al., 1999) and *Xuanhuaceratops* (Zhao et al., 2006).

At present, a total of 19 dinosaur track sites have been recorded in this area (Yabe et al., 1940; Zhang et al., 2004; Chen et al., 2006; Fujita et al., 2007; Sullivan et al., 2009; Matsukawa et al., 2006; Lockley et al., 2006; Xing et al., 2009, 2011, 2012, 2014, 2015, 2019, 2021a, 2021b; Ju et al., 2021) (Figure 1). These include the therapods *Grallator* (Yabe et al.,1940; Zhang et al., 2004; Fujita et al., 2007; Sullivan et al., 2009; Xing et al., 2009, 2012, 2015, 2021a, 2021c; Ju et al., 2021), *Therangospodus* (Xing et al., 2009, 2011, 2012, 2014), *Megalosauripus* (Xing et al., 2011, 2012) and *Menglongipus* (Xing et al., 2009); the primitive birds *Pullornipes, Aquatilavipes,* and *Koreanaornis* (Lockley et al., 2006; Xing et al., 2020); the sauropods *Brontopodus* (Zhang et al., 2012; Xing et al., 2015, 2021a, 2021c,) and cf. *Parabrontopodus* (Zhang et al., 2012; Xing et al., 2015); and the purported ornithopod tracks cf. *Dinehichnus* (Zhang et al., 2012; Xing et al., 2015). The degree of correspondence between body fossils and tracks (Lockley, 1991) makes the Tuchengzi Formation a typical Type 2b deposit, track-dominated.

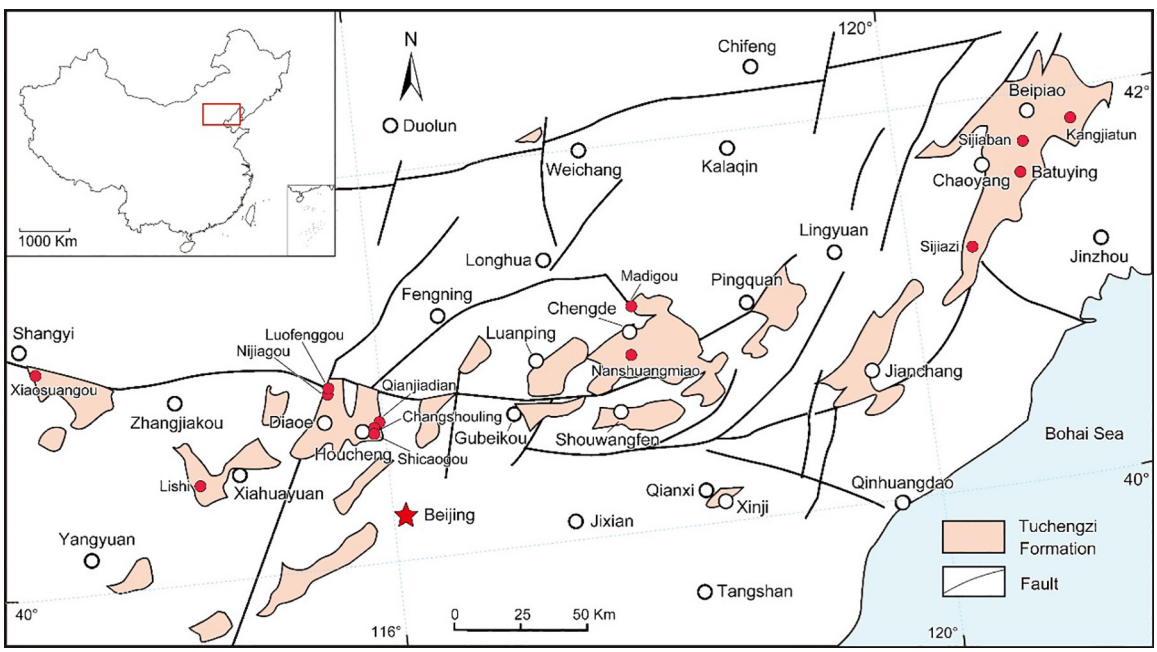

Figure 1. Location of dinosaur track sites from the Tuchengzi Formation in North China.

2 Geological setting

The Tuchengzi Formation is a series of terrestrial red clastic sediments occurring between the Tiaojishan and Zhangjiakou (or Yixian) formations. The age of the Tuchengzi Formation has been determined at 156-139 Ma (Wan et al., 2020). Invertebrate fossil assemblages, Estheria and Ostracoda, and isotopic studies

indicate that the Jurassic-Cretaceous boundary is located between the second and Third Members of the Tuchengzi Formation (Wan et al., 2020). The sedimentary facies of the Tuchengzi Formation are generally interpreted as forming in alluvial fan, braided river, delta and shallow lake environments (Xu et al., 2011).

The lithologic assemblage is dominated by grayish-purple to purplish-red conglomerate, gravelly coarse sandstone, medium-fine-grained sandstone, purplish-red argillaceous siltstone and silty mudstone, followed by grayish-green silty mudstone. In a few basins, the upper portion of the formation contains rhyolite volcanic rock and gypsum layers. The top is in angular unconformable contact with the overlying Lower Cretaceous Zhangjiakou Formation in Heibei Province or the Lower Cretaceous Yixian Formation in Liaoning Province. The bottom of most relict basins have parallel unconformable (or conformable) contact with the underlying Tiaojishan Formation/Lanqi Formation, and a few basins are in unconformable contact with the Archaean, Paleozoic and Indosinian granites (Wan et al., 2020).

The Tuchengzi Formation is exposed in an east-west direction in the northern region of North China, stretching from the Shangyi-Tumulu and Houcheng basins in the west, crossing the Luanping, Xinchengzi, and Shouwangfen-Dazhangzi basins, and extending to the Pingquan Basin in the east. The Tuchengzi Formation is well developed in the Beipiao and Jinlingsi-Yangshan basins and is almost completely exposed in Batuying Township (Wang, 2004; Wan et al., 2020).

Currently, there is no consensus regarding the subdivisions of the Tuchengzi Formation. Two schemes have been proposed, including three and four lithologic members. In the same division scheme, the definition and thickness of sections differ as described by different authors, and these inconsistencies have hampered regional stratigraphic correlation. The typical section of the Tuchengzi Formation in Batuying Township, Beipiao City, was described by Wang et al. (2004). This scheme is followed here to delineate the various track-bearing layers. The Tuchengzi Formation is generally divided into three lithological members: the First Member consists of purple-red tuffaceous and silty shales with siltstone and conglomerates at the base. The Second Member is dominated by interstratified purple-red polymictic conglomerates and feldspathic sandstone, with silty shales and large-scale cross beddings developed in local sandstones. The Third Member consists of interstratified green tuffaceous feldspathic sandstones, zeolite and purple-red fine-grained polymictic conglomerates, among which large scale cross-bedding is commonly developed within green sandstones (Zheng et al., 2010).

3 Site distribution

In the 1940s, Japanese scholars Yabe et al. (1940) discovered many dinosaur tracks in the Tuchengzi Formation of Sijiazi Village, Yangshan Town, Beipiao City, Liaoning Province. They named them *Jeholosauripus ssatoi,* presumed to be Early Cretaceous in age. The second significant discovery in the Tuchengzi Formation was made in 1992 when American and Chinese scholars found non-avian theropod and bird tracks on the ground of the Chengde Summer Resort; however no formal description of these tracks was published. After 2000, with the implementation of more geological survey projects, the study of Tuchengzi dinosaur tracks has significantly been developed, and scholars have discovered nearly twenty new track sites. These track sites are mainly distributed in western Liaoning Province, Hebei Province and north of Beijing.

The track sites in the study area include:

Four track sites in western Liaoning province

1) Sijiazi Site, Beipiao: Theropod tracks (Yabe et al., 1940; Matsukawa et al., 2006)

2) Sijiaban Site, Beipiao: Theropod-dominated tracks (Zhang et al., 2004; Fujita et al., 2007)
3) Kangjiatun Site, Beipiao: Bird tracks (Lockley et al., 2006)
4) Batuying Site, Beipiao: Sauropod tracks (Xing et al., 2021a)

Six tracksites in Hebei province
5) Madigou Site, Chengde: Theropod and bird tracks (Lockley et al., 2006; Xing et al., 2019)
6) Nijiagou Site, Chicheng: Deinonychosaurians and other theropod tracks (Xing et al., 2009; Xing et al., 2012)
7) Nanshuangmiao Site, Chengde: Theropod tracks (Sullivan et al., 2009; Xing et al., 2021b)
8) Luofenggou Site, Chicheng: Theropod tracks (Xing et al., 2011)
9) Shangyi Site, Zhangjiakou: Theropod-dominated tracks (Liu et al., 2012; Xing et al., 2014)
10) Lishi Site, Zhangjiakou: Sauropod-theropod tracks assemblage (Xing et al., 2021c; Ju et al., 2021)

Nine tracksites in Beijing
11–17) Qianjiadian Sites, Yanqing: Sauropod-theropod track assemblage and possible ornithopod tracks (Zhang et al., 2012; Xing et al., 2015)
18) Shicaogou Site, Yanqing: Sauropod-theropod track assemblage (Xing et al., 2015)
19) Changshouling Site, Yanqing: Sauropod-theropod track assemblage (Xing et al., 2015)

4 Dinosaur track assemblages

4.1 Sijiazi Site

Sijiazi track site is located in Sijiazi Township, Yangshan Town, Beipiao City, Liaoning Province. It was first discovered in 1939 by S. Sato, a Japanese geologist from Mansyu Kogyo Kaihatu Kaisya (Manchukuo Industry Development Company). During his fieldwork, two sandstone slabs were collected. Yabe et al. (1940) described the track site, which was the first dinosaur track site known in the Tuchengzi Formation. When reported by Yabe et al. (1940), it was estimated that there were more than 4,000 tracks. Subsequent investigations revised this number to about 1,170 and provided a track distribution map but no detailed descriptions (Matsukawa et al., 2006). Yabe et al. (1940) believed that the tracks were Cretaceous in age. New fission dates obtained by FTD methods give an age of 145.9 Ma for ash beds associated with the dinosaur track-bearing beds (Lockley et al., 2006). Liu et al. (2012) also classified the Sijiazi tracksite into the Third Member of the Tuchengzi Formation, based on lithostratigraphic evidence. This paper follows this classification.

The Sijiazi Site footprints are small tridactyl tracks, with distinct heel margins, lacking digit traces running outwards or backwards. Two lateral digits are almost equally width, and the medial digit is somewhat broader (Yabe et al., 1940). Yabe et al. (1940) described the tracks as a new ichnogenus and ichnospecies, *Jeholosauripus ssatoi*. However, *Jeholosauripus* was considered a junior synonym of *Grallator* by Zhen et al. (1989).

4.2 Sijiaban Site

Sijiaban track site locates in Sijiaban Village, Nanbajiazi Township, Beipiao City, Liaoning Province. The track site was first discovered in 2004 and had yielded nearly 100 dinosaur tracks (Zhang et al., 2004). There are different opinions on the age of the track site. Zhang et al. (2004) concluded that the site is located at the top of the Second Member to the bottom of the Third Member, based on rock strata comparisons. The age of the Tuchengzi Formation has measured 153± 9 Ma by Fujita et al. (2007) through FTD methods. It should belong to the First Member of the Tuchengzi Formation based on this age. Based on lithostratigraphic evidence, Liu et al. (2012) and Xu et al. (2014) inferred that the Sijiaban site was between 137-139 Ma in age, making it part of the Third Member. This paper

follows the classification from Liu et al. (2012) and Xu et al. (2014).

Zhang et al. (2004) interpreted the track site as dominated by theropod tracks, with only two sauropod tracks and one ornithopod tracks. The theropod tracks were catalogued and described, of which the largest is 29.5 cm in length and 19 cm in width, and the smallest is 4 cm long and 3 cm wide. Small tracks predominate, constituting nine narrow-gauge theropod trackways (Zhang et al., 2004).

In October 2004, the Sino-Japanese-Korean expedition conducted fieldwork at the Sijiaban track site. The expedition counted and recorded 119 theropod tracks (Fujita et al., 2007), which were divided into three types (type A, B, and C) according to the size. Type A is small tridactyl tracks and is the most numerus (100 individual tracks), with a mean length of 4.46 cm, a mean length/width ratio of 0.64, and a mean divarication angle of 49.6° between digits II and IV. Type B are medium sized. Only three individual Type B tracks were found, with a mean length of 13.41 cm, mean length/width ratio of 0.55, and mean divarication angle between digits II and IV of 36.7°. Type C (14 individual tracks) are the largest, with a mean length of 16.73 cm, mean length/width ratio of 0.66, and mean divarication angle between digits II and IV of 45.6°. Aside from absolute size, the three types are very similar and consistent with *Grallator*. Therefore, Fujita et al. (2007) suggested that these tracks could represent ontogenetic variation (presumably, juvenile, subadult, and adult) of the same theropod taxon.

4.3 Kangjiatun Site

Kangjiatun track site is located in Kangjiatun Village, Daban Town, Beipiao City, Liaoning Province, about 15 km southwest of the main Yixian feathered dinosaur locality. From 1999 to 2001, the Sino-Japanese-American Expeditions investigated the track site (Matsukawa et al. 2006).

The exact age of the Kangjiatun track site is unknown, and it is located about 40 m above the track-bearing layer of the Sijiazi site. Thus, Lockley et al. (2006) inferred the age of Kangjiatun tracksite is between 145.9 and 139.4 Ma. In this paper, the Kangjiatun track site is assigned to the Third Member of the Tuchengzi Formation.

Lockley et al. (2006) described and discussed the three bird trackways (trackway A/B/C) at the site in detail, which they suggested to be the oldest known bird tracks in China and named *Pullornipes aureus* (Lockley et al., 2006). The tracks are subsymmetric and functionally tridactyl. The average length and width are 4.1 cm and 4.4 cm, respectively. The tracks have a wide digit divarication of about 115°. The hallux (Digit I) is always separate from the impressions of the other three digits. The three trackways are all narrow, with an average step length of 15.6 cm and an average stride of 31.2 cm (Lockley et al., 2006).

4.4 Batuying Site

The Batuying track site is located in Batuying Township, Beipiao City, Liaoning Province, near Baijiawopu, in Batuying of Beipiao. In the spring of 2019, staff from the Liaohe Operations Department of the Bureau of Geophysical Prospecting Equipment, China National Petroleum Corporation, discovered several sauropod tracks in Batuying Township. In June 2021, Xing Lida's team inspected this site and confirmed it as the second reliable sauropod tracksite in the Tuchengzi Formation (Xing et al., 2021a). Xing et al. (2021a) identified the track site as located in the Third Member of the Tuchengzi Formation according to SHRIMP Zircon U-TH-Pb isotope determination (137.3± 1.0Ma, Wang et al., 2013).

The site can be divided into two areas, with 64 tracks. Four of the trackways are medium gauge and referred to *Brontopodus* type. Taking the best-preserved trackway with the most representative morphology as an example, the

tracks are arranged in parallel with an average length of 52.5 cm, average manus length/width ratio of 0.7, average pes length/width ratio of 1.5, the manus prints are strongly rotated outwards by about 86°, the pes prints are shifted outwards on average by 20°, the average pace angulation of the manus traces is 111°, while the average pace angulation of pes is 123°. Xing et al. (2021a) speculated that the sauropod track markers at Batuying site had longer front limbs than the makers of other sauropod trackways found previously in other regions of China were likely brachiosaurids.

4.5 Madigou Site

The Madigou track site locates in Shibanwo Village, Mengjiayuan Township, Chengde City, Hebei Province. In 1992, the ecologist Richard T. T. Forman from Harvard University and Runhua Huang, director of the Department of Geography at Peking University, first found more than 20 bird and non-avian dinosaur tracks on stone slabs laid on the ground of Chengde Summer Resort.

Lockley et al. (2006) found one bird trackway composed of four consecutive tracks on the stone slabs of Madigou quarry, with an average length of about 4.4 cm and the step length of 11.5-12.0 cm. Lockley et al. (2006) referred it to as cf. *Aquatilavipes.* During 2013-2018, Xing et al. investigated the area many times and collected many fossils and data from the Madigou site, Chengde Mountain Resort, Xumi Fushou Temple, and Putuo Zongcheng Temple (Potala Palace). According to lithostratigraphy, the site is located in the First Member of the Tuchengzi Formation (Xing et al., 2020). One hundred seventy-four tracks of non-avian theropod and bird tracks were sorted out, including 134 isolated tracks and 15 trackways.

Xing et al. (2020) recognized two morphotypes among the non-avian theropod tracks. The didactyl theropod tracks were identified as deinonychosaurian: *Velociraptorichnus* isp. Four didactyl tracks were found, with an average length of 8.7 cm and digits III and IV impressions of roughly equal length and width. The tridactyl theropod track, containing at least 140 tracks and five trackways, was further divided into two ichnogenera: *Eubrontes* and *Grallator.* The cf. *Eubrontes* tracks have an average length of 13.4 cm (4.1-23.4 cm), with a relatively significant digits II-IV divarication averaging 83° (54°-126°), an ML/MW of 0.9-1.4, and mesaxony of 0.4-0.6. The cf. *Grallator* tracks have a small digits II-IV divarication average of 59°, a length and width ratio of about 1.7, while the mesaxony is larger than 0.7.

Bird tracks included at least eight trackways and four isolated tracks. In general, the Madigou bird tracks are small (average maximum length of 3.4 cm), wide (average maximum width of 4.7 cm), sub-symmetric, functionally tridactyl tracks, the digit impressions are long and slender, and the average divarication of digits II-IV is 111°. A small hallux can be seen in some tracks. These tracks are referred to *Koreanaornis* type (Xing et al., 2020).

A single possible sauropod track is also present at the Madigou site (Xing et al., 2020). It measures 28.9 cm long and 22.6 cm wide but is incomplete distally (Xing et al., 2020). There are no digit impressions or claw traces (Xing et al., 2020).

It is worth noting that, unlike other sites, “Madigou” refers to both the local Shibanwo Village and the several kilometres around it, a total area of at least 1000 m2, where any tuffaceous sandstone may preserve track fossils. Many Chinese institutions and some private collectors have collected tracks from the site.

4.6 Nijiagou Site

The Nijiagou track site is located on the southern slope of Siliangshan Mountain, Nijiagou Village, Yangtian Township, Chicheng County, Zhangjiakou City, Hebei Province. Based on stratigraphy, Liu et al. (2012) classified this site as within the Third Member of the Tuchengzi

Formation. The Nijiagou track site was discovered in 2008 and first described in 2009. Xing et al. (2009) discovered a didactyl dinosaur trackway, and named *Menglongipus sinensis,* which is includes the earliest and smallest known deinonychosaurian tracks. The *Menglongipus* trackway consisted of four continuous tracks. And the trackmaker was presumed to be about 65 cm long, a size similar to basal paraves (Xing et al., 2009). The discovery of *Menglongipus* provides new evidence for the existence and distribution of deinonychosaurians near the Cretaceous boundary. In addition to *Menglongipus,* many *Grallator* types have been discovered at Nijiagou site.

Xing et al. (2012) found several theropod trackways and a pair of possible theropod crouching traces at the site. The traces preserve a left metatarsal impression and associated ischial and possibly the pubic callosity traces. In addition, four well-preserved tridactyl theropod tracks were recorded, with an average length of 18.8 cm (range 18.2-19.6 cm) and length/width ratio of 1.4-1.7. Xing et al. (2012) referred these four tracks to *Therangospodus* isp.

4.7 Nanshuangmiao Site

The Nanshuangmiao tracksite is located in Nanshuangmiao Village, Shangbancheng Township, Huangqiwanzi Town, Chengde City, Hebei Province. The age of the site is close to 152 Ma (Sullivan et al., 2009), making it part of the First Member of the Tuchengzi Formation.

Sullivan et al. (2009) conducted the initial investigation at this site and found eight isolated, small theropod tracks. Many contemporaneous theropod tracks from the Tuchengzi Formation in Liaoning province are identified as *Grallators,* but Sullivan et al. (2009) argued that the tracks at Nanshuangmiao were larger, with a length of 28.8 cm, and should be referred to *Anchisauripus.* Sullivan et al. (2009) further inferred that the tracks were likely those of oviraptorids.

Xing et al. (2021b) reinvestigated the site and counted 55 tracks preserved in two layers, among which 49 isolated tracks were preserved in the upper layer. One trackway and three isolated tracks were preserved in the lower layer. The average length of the 25 best-preserved theropod tracks from all layers is 16.1 cm, the maximum length is 25.2 cm, and the minimum length is 6.4 cm. The average length/width ratio is 1.7, which is consistent with *Eubrontes.* The tracks have an overall (II-IV) divarication angle of 49° (N=16) and moderate mesaxony (0.64, N=16), in both these respects the tracks fall between the typical values for *Anchisauripus* and *Eubrontes.* The tracks were temporarily referred to grallatorid-eubrontid assemblage (Xing et al., 2021b), and their trackmakers are probably not limited to oviraptorids.

4.8 Luofenggou Site

The Luofenggou tracksite is located in Zhanghao Village, Yangtian Township, Chicheng County, Zhangjiakou City, Hebei Province. Based stratigraphy, Liu et al. (2012) classified the site into the Third Member of the Tuchengzi Formation. Tracks were first discovered in February 2001 by Denghai Sun from the Chicheng Vocational Education Center. In April and October of the same year, Zhiming Dong, from Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, and Azuma Yoichi, from Dinosaur Museum of Fukui Prefecture, Japan, conducted field investigations at the site, but no articles were published. In 2008 and 2009, a team lead by Xing Lida restudied the dinosaur tracks exposed in the region. Xing et al. (2011) assigned 163 of these tracks to *Therangospodus* isp. The well-preserved tracks are between 16-38.3 cm in length and with a roughly 1.3-1.5 in length/width ratio. However, most of the tracks on the layer are difficult to identify more trackways. The few identified trackways are short, usually consisting of only 3-4 tracks. A single

large track, with a length of 38.3 cm and a width of 27.5 cm, was found, with a large and circular metatarsophalangeal area. This exceptionally large theropod track was inferred to *Megalosauripus* isp by Xing et al. (2011).

Five possible theropod swimming traces are preserved in the lower layer of the track site. These traces differ from other theropod tracks in being mostly elongated, with gradually sharp claw traces or scratches, and without any impression of the metatarsophalangeal area. Xing et al. (2011) speculated that these swimming traces were left by 2-3 trackmakers.

4.9 Shangyi Site

The Shangyi tracksite is located in Xiaosuangou Town, Shangyi County, Zhangjiakou City, Hebei Province. Liu et al. (2012) described more than seventy dinosaur tracks at the site, including those of sauropod and theropod. Based on lithostratigraphic evidence, Liu et al. (2012) classified this site into the Third Member of the Tuchengzi Formation. Xing Lida's team visited the site in April 2013, however, after more than a year of weathering, some tracks had become indistinct and broken. Xing et al. (2014) reviewed and described seventy-three theropod tracks, and the sauropod tracks previously described by Liu et al. (2012) were identified as possible ornithopod tracks.

There are at least fifty-four theropod tracks at Shangyi tracksite, and the average divarication angle between digit II and digit IV is 54° (range 43°-61°). The average length/width ratio is 1.66, and the average mesaxony is 0.69 (N=36). Therefore, the theropod tracks of Shangyi tracksite are temporarily all referred to cf *Therangospodus* (Xing et al., 2014).

Two possible ornithopod trackways consist a total of 19 tracks, most of which are circular impressions without obvious digit marks. Manus prints are absent. The maximum length/width ratio is 1.0. The average length of the pes tracks in the two trackways is 15.1 cm (N=15) and 12.1 cm (N=4), respectively, and the average stride length is 48.2 cm and 52.3 cm. The two trackways represent two different trackmakers. It may be possible to infer kind of social behavior from trackways (Xing et al., 2014).

4.10 Lishi track site

The Lishi track site is located southwest of Lishi Village, Guocun Town, Xuanhua District, Zhangjiakou City, Hebei Province. The site was discovered in April 2020 by The Regional Geological Survey Institute of Hebei Geological and Mining Bureau, which documented more than 100 tracks. Xing et al. (2021c) conducted a comprehensive survey at the site in September 2020, sorting out 363 total tracks, including large sauropods and theropods (Xing et al., 2021c). In another independent study, Ju et al. (2021) reported tracks found at the Lishi track site and suggested that the tracks be assigned to the *Grallater-Anchisauripus-Eubrontes* assemblage.

There are two different opinions on the age of the track-bearing beds of the Lishi track site. Based on zircon dating data (142.2± 0.9 Ma), Xing et al. (2021c) suggested that the track-bearing beds belonged to the Third Member of the Tuchengzi Formation. Based on the weighted average age of tuff zircon U-Pb (152.3± 0.3 Ma), Ju et al. (2021) believed that the track-bearing beds are located in the First Member of the Tuchengzi Formation. In this paper, the Lishi track site is temporarily assigned to the Third Member of the Tuchengzi Formation.

The Lishi tracksite can be divided into five areas. The preserved tracks include the sauropod *Brontopodus* and well-preserved track named *Asianopodus wangi* (Xing et al. 2021c). The sauropod tracks total 148, range in length from 31.2 cm to 59.6 cm, and include 89 isolated tracks and seven trackways. Xing et al. (2021c) divided these tracks into three categories according to size: 31-40 cm

(two trackways), 41-50 cm (three trackways), and 51-60 cm (two trackways). Despite their size differences, the overall morphology remains relatively uniform. Thus, the tracks were assigned to *Brontopodus* (Xing et al., 2021c).

There are 144 theropod tracks, including 18 trackways and 24 isolated tracks. The tracks were divided into two morphotypes based on size. Morphotype A are large tridactyl tracks with an average length of about 30 cm, length/width ratio of 1.6, medium mesaxony of 0.65, and relatively small divarication angle (about 50°) between digit II and IV. Digit III is 62% of the total pes length. This morphotype represents a new *Asianopodus* ichnospecies, and Xing et al. (2021c) named it *Asianopodus wangi.* Morphotype B is more minor, about 9-14 cm in length, and has a mesaxony of 0.76. Morphotype B shows a slender tridactyl shape, similar to grallatorid (Xing et al., 2021c).

4.11 Qianjiadian Sites

The Qianjiadian tracksites are situated in the Yanqing Global Geopark in the northern part of Yanqing, Beijing, and the site is the first record of dinosaur tracks in Beijing. Tracks were first discovered during a field investigation in July 2011, and Zhang et al. (2012) reported at least three dinosaur track sites in this area. The preliminary research indicated that these tracks include those of thyreophorans, theropods, ornithopods and possibly sauropods (Zhang et al., 2012). However, the purported thyreophoran tracks were reidentified as sauropod tracks in subsequent studies (Xing et al., 2015). He et al. (2017) conducted LA-ICP-MS dating of the Tuchengzi Formation in Qianjiadian Basin, Yanqing, and found that the middle and upper Tuchengzi Formation date to 157.13± 0.96 Ma, making them part of the Second Member of the Tuchengzi Formation.

In August-September of 2013 and April 2014, Xing et al. (2015) reinvestigated and described the Qianjaidian tracks further and recognized nine new track sites, with 133 tracks, including Qianjiadian track sites I-VII, Shichaogou and Changshouling track sites.

The Qianjiadian site I is divided into upper and lower layers, with a total of 186 tracks and 14 trackways, including theropod, sauropod and ornithopod tracks. Tracksite II is dominated by sauropod tracks but has been suffered substantial weathering, and there are no clear trackways. Tracksite III contains about seventy sauropod tracks and one theropod track, with no distinct trackway. Tracksite IV contains ~20 sauropod tracks. Tracksites V and VI contain ten sauropod tracks, respectively. Tracksite VII contains four sauropod tracks.

All sauropod tracks at the Qianjiadian track sites can be divided into three morphotypes. Morphotype A is a distinctly wide-gauge trackway. The mean track length is 53.5 cm. The characteristics of Morphotype A are consistent with *Brontopodus* types found in other regions (Farlow et al., 1989; Lockley et al., 1994; Santos et al., 2009). Morphotype B is a narrow, medium-size sauropod trackway. The mean pes length ranges between 22.7-37.3 cm. Morphotype B is tentatively assigned to cf. *Parabrontopodus* isp. (Xing et al., 2015) Morphotype C contains the pes-only trackway with a mean pes length of 11.9 cm, the smallest sauropod trackway at the Qianjiadian track sites. All pes prints are oval, without digital marks. Morphotype C is considered to have been left by juvenile trackmakers of Morphotype A and B (Xing et al., 2015).

The theropod tracks at Qianjiadian track sites can be divided into two morphologies. Morphotype A includes 35 total tracks and seven trackways. The tracks range in size from 5.5 cm to 30 cm, with an average length/width ratio of 1.5. Morphotype A is characterized by weak to moderate mesaxony, an average of 0.51 (range 0.33-0.56), and an average pace angulation of 172°. Morphotype A is tentatively attributed to cf. *Eubrontes;* Morphotype B includes six trackways

and 11 isolated tracks, with stronger mesaxony (average 0.69). Morphotype B has been referred to *Grallator* isp (Xing et al., 2015).

4.12 Shicaogou Site

The Shijiaogou track site is located in Yanqing National Geopark, Yanqing District, Beijing in the Second Member of the Tuchengzi Formation. Six sauropod tracks and one theropod track are preserved, in addition to abundant ripple marks and invertebrate trails (cf. *Monocraterion* isp.) (Xing et al., 2015). One set of sauropod manus and pes prints are well-preserved. The pes print is approximately 80 cm long and has a length/width ratio of 1.3. Overall, the sauropod tracks are similar to *Brontopodus* type tracks (Xing et al., 2015). One isolated theropod track is a possible didactyl deinonychosaurian track. This track is 10.8 cm long, with a length/width ratio of 2.0. Digit IV is longer than digit III, and the divarication angle is 27° (digits III-IV) (Xing et al., 2015).

4.13 Changshouling Site

The Changshou track site is located in Yanqing National Geological Park, Yanqing District, Beijing. The track area is in the Second Member of Tuchengzi Formation, and the site has yielded three sauropod tracks and one theropod track. The isolated theropod track is 28 cm long, with a length/width ratio of 1.4. The metatarsophalangeal pad is developed, similar to *Asianopodus* in morphology and location (Xing et al., 2015). Two sauropod tracks constitute a single pace, with an average length of 51 cm. There are insufficient morphological details to support assigning the sauropod tracks to a specific ichnogenus.

4 Discussion and Conclusions

So far, 19 dinosaur track sites have been found in the Tuchengzi Formation, and 2,637 dinosaur tracks (including swimming tracks and crouching tracks) have been documented (Figure 2, Tables. 1 and 2). The tracks represent at least 2,091 trackmakers, of which 85.45% are tridactyl non-avian theropods, 0.24% are didactyl theropods, 0.77% are birds, 13.35% are sauropods, and 0.19% are ornithopods. Sauropods and theropods tracks (non-avian tridactyl theropods including didactyl deinonychosaurians + sauropods) are as high as 99.04% 99.81% if bird tracks are included, which indicates that there is an absolute dominant saurischian fauna in the Late Jurassic-Early Cretaceous in the northern part of North China. The Tuchengzi dinosaur ichnofauna is a Type 2b deposit (Lockley, 1991), where the skeletal fossil evidence is entirely inconsistent with the ichnofauna.

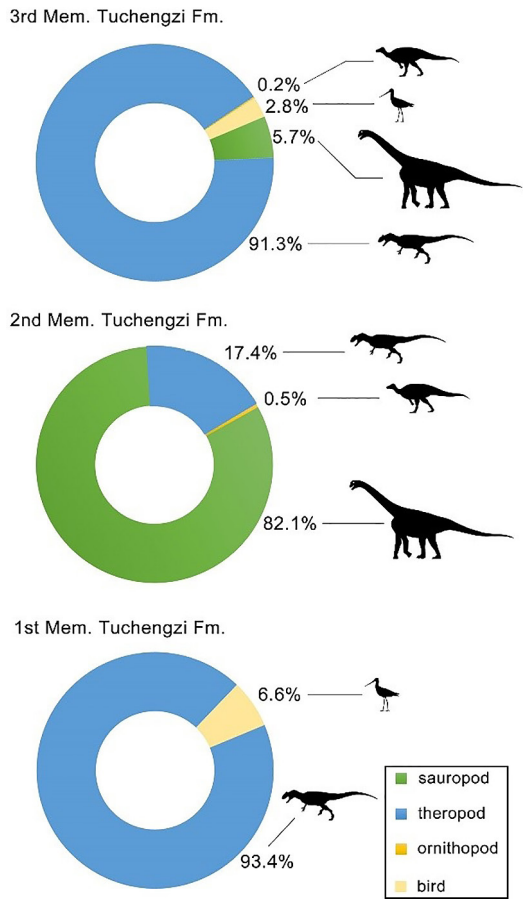

Figure 2. The ratio of dinosaur trackmakers in three members from the Tuchengzi Formation.

	Track site	Location	Age	Mem.	Track type	Total	Is	Tw	References
1	Sijiazi (Yangshan)	Chaoyang, Liaoning	145.9 Ma (Lockley et al., 2006)	3rd	Theropods	1170	1170	0	Yabe et al., 1940, Shikama, 1942; Young, 1960 Zhen et al., 1989, Matsukawa et al., 2006
2	Sijiaban	Beipiao, Liaoning	153± 9 Ma? (Fujita et al., 2007)	3rd	Theropods Ornithopods	201	164	9	Zhang et al., 2004, Matsukawa et al., 2006, Fujita et al., 2007
3	Kangjiatun	Beipiao, Liaoning	145.9-139.4 Ma (Lockley et al., 2006)	3rd	Birds	48	0	3	Lockley et al., 2006
4	Batuying	Beipiao, Liaoning	137.3± 1.0 Ma (Wang et al., 2013)	3rd	Sauropods	64	5	4	Xing et al., 2021a
5	Madigou	Chengde, Hebei	—	1st	Theropods Birds	174	134	15	Matsukawa et al., 2006, Lockley et al., 2006, Xing et al., 2020
6	Nanshuangmiao	Chengde, Hebei	~ 152 Ma (Sullivan et al., 2009)	1st	Theropods	63	60	1	Sullivan et al., 2009 Xing et al., 2021b
7	Nijiagou	Chicheng, Hebei	—	3rd	Theropods	25	1	4	Xing et al., 2009, Xing et al., 2012
8	Luofenggou	Chicheng, Hebei	—	3rd	Theropods	131	112	6	Xing et al., 2011, Xing et al., 2015
9	Shangyi	Shangyi, Hebei	—	3rd	Theropods Ornithopods	73	51	3	Liu et al., 2012, Xing et al., 2014
10	Lishi	Zhangjiakou, Hebei	142.2± 0.9 Ma (Xing et al., 2021)	3rd	Theropods Sauropods	363	113	25	Xing et al., 2021c
11	Qianjiadian IL	Yanqing, Beijing	157.13± 0.96 Ma (He et al., 2017)	2nd	Theropods Sauropods Ornithopods	28	15	4	Xing et al., 2015
	Qianjiadian IU				Theropods Sauropods	158	48	15	
12	Qianjiadian II					15	15	0	
13	Qianjiadian III					70	70	0	
14	Qianjiadian IV				Sauropods	20	20	0	
15	Qianjiadian V					10	10	0	
16	Qianjiadian VI					10	10	0	
17	Qianjiadian VII					4	4	0	
18	Shicaogou	Yanqing, Beijing	157.13± 0.96 Ma (He et al., 2017)	2nd	Theropods Sauropods	7	5	1	
19	Changshouling	Yanqing, Beijing	157.13± 0.96 Ma (He et al., 2017)	2nd	Theropods Sauropods	3	1	1	
20	**TOTAL**	—	—	—	—	**2637**	**2008**	**91**	

Table 1. The abundance of dinosaur trackmakers from the Tuchengzi Formation of North China.
Note: Abbreviations: Mem, Member; Is, Isolated tracks; Tw, Number of trackways.

	Track site	Sauropod			Theropod			Bird			Ornithopod			Tm
		Ra	Is	Tw	Ra	Is	Tw	Ra	Is	Tw	Ra	Is	Tw	
1	Sijiazi (Yanshan)	—			*Grallator ssatoi (Jeholosauripus)*			—			—			1170
					100%	1170	0							
2	Sijiaban	sauropod indet.			*Grallator ssatoi*			—			ornithopod indet.			173
		1.2%	2	0	98.3%	161	9				0.5%	1	0	
3	Kangjiatun	—			—			*Pullornipes aureus* *Aquatilavipes*			—			3
								100%	0	3				
4	Batuying	*Brontopodus*			—			—			—			9
		100%	5	4										
5	Madigou	—			cf. *Eubrontes* cf. *Grallator* *Velociraptorichnus* isp.			*Aquatilavipes* *Koreanaornis*			—			149
					91.3%	130	—	8.7%	4	9				
6	Nanshuangmiao	—			grallatorid-*eubrontid*			—			—			61
					100%	—	—							
7	Nijiagou	—			*Menglongipus sinensis* grallatorid *Megalosauripus* isp. *Therangospodus* morph.			—			—			5
					100%	—	—							
8	Luofenggou	—			*Megalosauripus* isp. *Therangospodus* morph. ? Swim tracks			—			—			118
					100%	—	6							
9	Shangyi	—			*Therangospodus*			—			ornithopod indet			55
					96.3%	—	2				3.7%	0	2	
10	Lishi	*Brontopodus*			*Therangospodus* *Megalosauripu* *Asianopodus wangi*			—			—			129
		67.4%	89(80)	—	32.6%	24	18							
11	Qianjiadian IL	*Brontopodus* cf. *Parabrontopodus*			*Grallator*			—			cf. *Dinehichnus*			19
		84.2%	14	—	10.5%	1	1				5.3%	0	1	
	Qianjiadian IU	*Brontopodus type* cf. *Parabrontopodus*			*Eubrontes* *Grallator*			—			—			63
		47.6%	21	—	—	21	12							
12	Qianjiadian II	sauropod indet.			—			—			—			15
		100%	15	—										
13	Qianjiadian III	sauropod indet.			—			—			—			70
		100%	70	—										
14	Qianjiadian IV	sauropod indet.			—			—			—			20
		100%	20	—										
15	Qianjiadian V	sauropod indet.			—			—			—			10
		100%	10	—										
16	Qianjiadian VI	sauropod indet.			—			—			—			10
		100%	10	—										

	Track site	Sauropod			Theropod			Bird			Ornithopod			Tm
		Ra	Is	Tw	Ra	Is	Tw	Ra	Is	Tw	Ra	Is	Tw	
17	Qianjiadian VII	sauropod indet. 100%	4	—	—			—			—			4
18	Shicaogou	*Brontopodus* type 83.3%	4	—	cf. *Dromaeosauripus* —	1	0	—			—			6
19	Changshouling	sauropod indet. 50%	0	—	cf. *Asianopodus* 50%	1	0	—			—			2
20	**TOTAL**	—			—			—			—			**2091**

Table 2. The diversity of dinosaur tracks from the Tuchengzi Formation of North China. **Note:** Abbreviations: Ra, Ratio; Is, Isolated tracks; Tw, Number of trackways; Tm, Number of trackmakers.

Theropod tracks are the most abundant in the Tuchengzi Formation. Most are small tridactyl tracks that can be compared with tracks from the Yixian Formation (miciraptorans, tyrannosaurs, oviraptorosaurs) and tracks of the small feathered dinosaurs from the Tiaojishanm Formation (Avialae). A total of four tridactyl non-avian theropod ichnogenera *(Grallator, Eubrontes, Asianopodus, Therangospodus)* have been found. About 1870 small tracks (length < 25 cm) accounted for 98% of the tridactyl theropod tracks. There are about thirty-six large tracks (length > 25 cm), accounting for 2%. The largest track is from the Nijiagou track site, which is 58.7 cm in length. The didactyl deinonychosaurian tracks include *Menglongipus sinensis* and *Velociraptorichnus* isp. The deinonychosaurian tracks are 8.4-10 cm long, and the estimated trackmaker length is 99.4-118.4 cm, similar to the typical bipedal deinonychosaurians from the Jehol Biota (Zhou et al., 2010). Bird tracks include *Pullornipes aureus, Aquatilavipes* isp. and *Koreanaornis* isp. The avian tracks are between 3.4 and 4.4 cm in length. They are comparable to the Jehol Biota's specialized 'shorebirds' clade, such as *Longicrusavis houi* (O'Connor et al., 2010), *Gansus zheni* (Liu et al., 2014), *Iteravis huchzermeyeri* (Zhou et al., 2014).

The sauropods tracks show low diversity, with only two substantiated ichnogenera: *Brontopodus* isp. and cf. *Parabrontopodus* isp. There are about 14 large tracks (> 50 cm in length) accounting for 3.4% of the total sauropod tracks, 387 medium tracks (20-50 cm in length) accounting for 92.1%, and 19 small tracks (< 20 cm in length) accounting for 4.5%. The medium-wide gauge of the trackways suggests brachiosaurid or titanosauriforme affinities (Wilson et al., 1999; Lockley et al., 1994; Xing et al., 2015, 2021a, 2021b), which is consistent with known brachiosaurid skeletal materials from the middle section (Second and Third Members) of the Tuchengzi Formation (Dong, 2001).

Ornithopod tracks are found at Sijiaban, Shangyi and Qianjiadian sites, with only one ichnogenus represented: cf. *Dinehichnus.* Some scholars speculated that these tracks are made by small-sized basal ornithopods or basal cerapods (Xing et al., 2014). However, it is doubtful whether there is evidence of ornithopod in the Tuchengzi Formation because all possible ornithopod tracks are poorly preserved. No ornithopod body fossils have been recorded in Yanliao Biota, but ornithopods are known from the Jehol Biota (Zhou et al., 2010). A total of 19 dinosaur track sites have been found in the Tuchengzi Formation, with 2637 dinosaur tracks representing at least 2091 trackmakers. This track record has become an essential sample for understanding the Tuchengzi dinosaur fauna. Most of the tracks of the Tuchengzi Formation are located in the Third Member of the Tuchengzi Formation, including eight-track sites (68.3%), followed by the Second Member (19.9%) with nine-track

sites, and the First Member (11.8%) with two-track sites. Considering that the nine-track sites of the Second Member are all located in the Qianjiadian, the tracks of the Third Member are more widely distributed. Overall, the Third Member of the Tuchengzi Formation is dominated by saurischians and includes non-avian theropods (4 genera), birds (2 genera), and sauropods (1 genus). The Second Member mainly includes non-avian theropods (3 genera), sauropods (1 genus) and birds (1 genus). The First Member includes non-avian theropods (4 genera) and birds (2 genera). The absence of sauropods from the First Member may be due to preservation bias.

The Tuchengzi dinosaur ichnofauna is obviously dominated by saurischians, consistent with most Jurassic and Cretaceous track sites in China. Theropod tracks are highly diverse, including four ichnogenera. Three track sites recording deinonychosaurians, including two ichnogenera, showing weaker diversity. The trackmakers of these didactyl tracks may be closely related to the rich feathered dinosaurs of the Yanliao Biota and Jehol Biota. The bird tracks show a relative diversification, including three ichnogenera, which corresponds to the bird fossils of the Jehol Biota, particularly the 'shorebirds' records. The existence of ornithopod tracks is doubtful and awaits further discovery.

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