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Geological ages of dinosaur-track-bearing formations in China

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Abstract

In China more than 30 forms of dinosaur tracks at about 50 localities distributed in 16 provinces have been reported. These fossil footprints have been found in 25 Upper Triassic to Upper Cretaceous formations. They are the Xujiahe Formation (Upper Triassic), Zhenzhuchong and Ziliujing formations (Lower Jurassic), Xintiangou and Lower Shaximiao formations (Middle Jurassic), Penglaizhen Formation (Upper Jurassic), and Jiaguan and Daergun formations (Upper Cretaceous) in the Sichuan Basin; the Fengjiahe Formation (Lower Jurassic) and Jiangdihe Formation (Upper Cretaceous) in the central Yunnan Basin; the Zhiluo Formation (Middle Jurassic) and Fengjiashan Formation (Lower Cretaceous) in Shaanxi Province; the Jingchuan Formation (Lower Cretaceous) in Inner Mongolia; the Houcheng Formation (Upper Jurassic) and Jiufotang Formation (Lower Cretaceous) in northern Hebei; the Tuchengzi Formation (Upper Jurassic) and Fuxin Formation (Lower Cretaceous) in western Liaoning; the Laiyang Formation (Lower Cretaceous) in the Shandong Peninsula; the Tongfosi Formation (Cretaceous) in eastern Jilin Province; the Hekou Group (Lower Cretaceous) in Gansu; and the Xiaodong, Qiyunshan, and Nanxiong formations (Upper Cretaceous) in Hunan, Anhui, and Guangdong provinces, respectively. The invertebrate and vertebrate fossils including tetrapod footprints reported from some of these formations are outlined and their biostratigraphic significance and utility for correlation are discussed.

Keywords: Dinosaur tracks; Stratigraphy; Geologic age; China

1. Introduction

In China, the first dinosaur track was reported in 1929 from the Middle Jurassic in Shenmu County of Shaanxi Province (Teilhard de Chardin and Young, 1929); it was formally described and named *Sinoichnites youngi* almost 30 years later (Kuhn, 1958). In 1940, more than 4000 small dinosaur tracks were reported from red beds near Sijiazi village in the Yangshan Basin, 43 km south Chaoyang city, western Liaoning Province, within an area of 259 m^2. Recently Li Jianjun, M. Matsukawa, M. G. Lockley, and others studied this locality and the fossil bearing red beds of the ''Tuchengzi Formation'' recording more than 1170 tracks at two sites (Fig. 1). This formation is no older than Late Jurassic in age (Matsukawa et al., 2001), rather than Early Jurassic as reported by Zhen et al. (1989). This formation lies unconformably just below the well-known, feathered-dinosaur-bearing Yixian Formation. These dinosaur tracks were named *Jeholosauripus s-satoi* (Yabe et al., 1940), but the name was changed to *Anchisauripus s-satoi* (Baird, 1957), and later to *Grallator s-satoi* (Yabe, Inai, and Shikama) by Zhen et al. (1996).

So far, more than 30 forms of dinosaur tracks from about 35 localities (Figs. 2, 3) from the Upper Triassic to the Upper Cretaceous have been reported in China (Matsukawa et al., 1995; Zhen et al., 1996; Lockley et al., 2002). This shows that China is potentially rich in dinosaur footprints with

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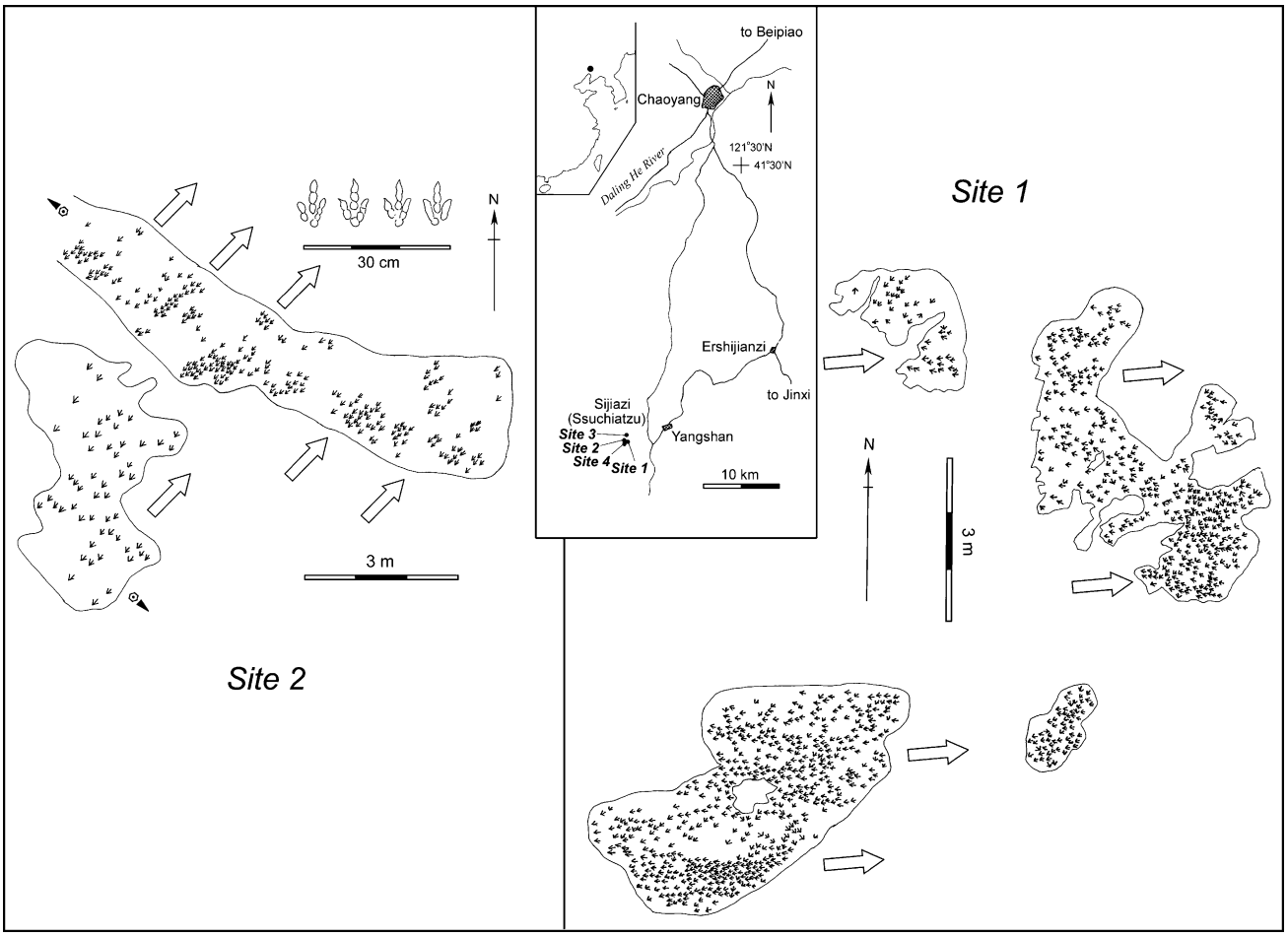

Fig. 1. The second discovery of dinosaur tracks in Liaoning Province, China, reveals more than 1170 tracks of *Grallator s-satoi*; parallel trackways of both sites suggest gregarious behavior.

wide distributions geographically and stratigraphically. However, the potential for discovering abundant track-bearing outcrops is undoubtedly greater in the arid north and northwest than in the humid, well-vegetated south.

2. Stratigraphic distribution of dinosaur tracks in China

2.1. Upper Triassic

Penxianpus cifengensis Yang and Yang was collected from the Xujiahe Formation at Panlong Bridge of the Cifeng region, Penxian County, Sichuan Basin, where the Upper Triassic can be divided into three formations in ascending order.

2.1.1. Ma'antang Formation (238 m)

Gray calcareous mudstone, siltstone, sandstone, and bioclastic limestone in the upper part (119 m), containing the ammonites *Trachyceras* sp., *Tropites* sp., and *Tibetites* sp.; bivalves *Halobia rugosa*, *H. convexa*, and *H. comatoides*; foraminifer *Aulotortus bronimanni*; conodont *Neogondolella polygnathiformis*; gray or light gray bioclastic limestone intercalated with gray calcareous mudstone in the lower part (119 m), containing the bivalves *Halobia subcomata* and *Halobia* cf. *H. kui* and the conodont *Neogondolella polygnathiformis*.

2.1.2. Xiaotangzi Formation (320 m)

Gray mudstone and sandy mudstone alternating with siltstone and fine-grained sandstone; clay and thin-bedded coal in the basal part, yielding the *Burmesia lirata-Costatoria napengensis* bivalve assemblage.

2.1.3. Xujiahe Formation (2211 m)

Alternating beds of gray or dark gray thick-bedded sandstone and black shale with coal for industrial use, yielding the *Dictyophyllum nathorsti-Clathropteris meniscioides* flora, the *Yunnanophorus boulei-Trigonadus keuperinus* bivalve assemblage, the ostracode *Darwinula* sp., the conchostracan *Euestheria minuta* Zietin, and the dinosaur tracks *Pengxianpus cifengensis* Yang and Yang.

The Ma'antang and Xiaotangzi formations are marine deposits and their ammonites, conodonts, and fossil bivalves such as *Trachyceras* sp., *Neogondolella polygnathiformis*, and *Burmesia lirata* indicate that the Ma'antang is Carnian in age and the Xiaotangzi is Norian in age.

The Xujiahe Formation was subdivided into six members. However, the first marine member has been separated and

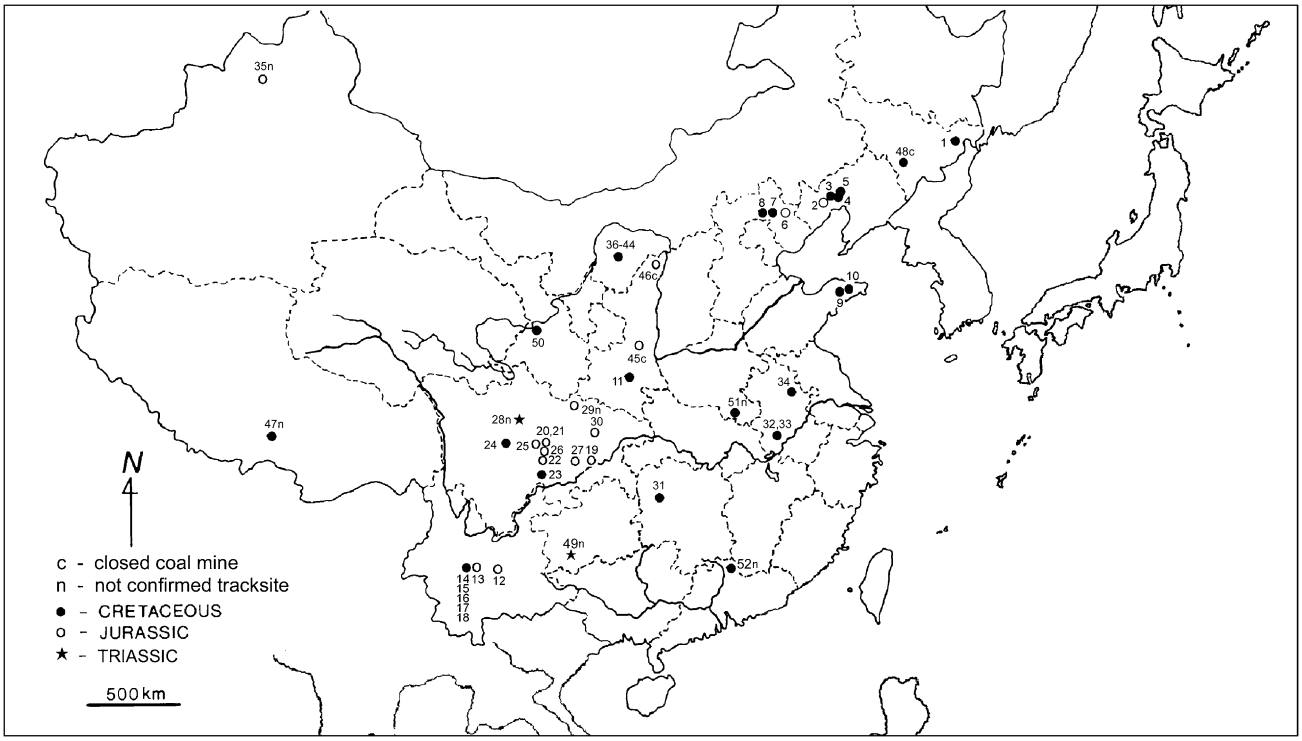

Fig. 2. Map showing dinosaur tracks in China. The locality numbers are the same as in table 1 in Matsukawa et al. (2006).

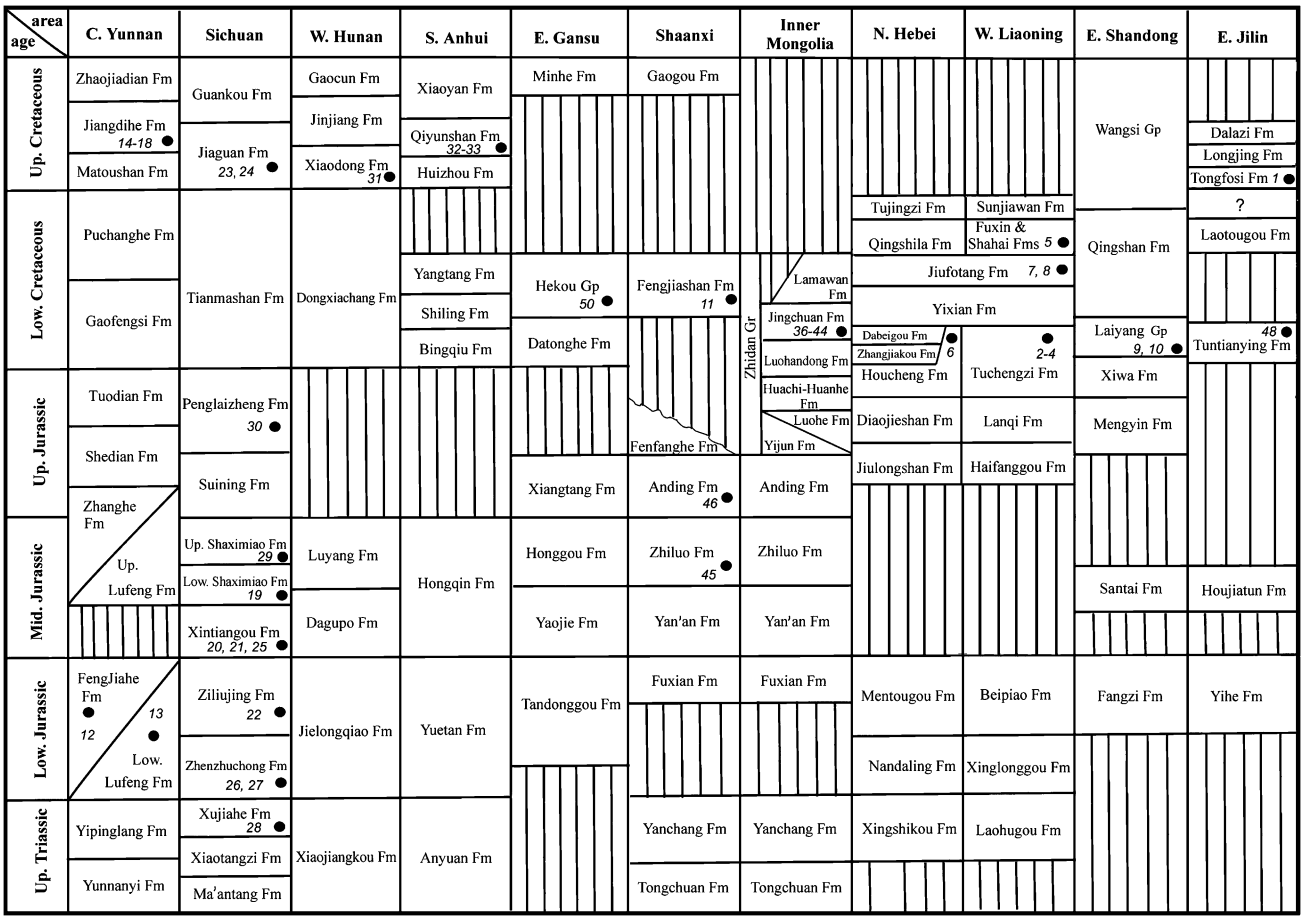

Fig. 3. Correlation of dinosaur track-bearing formations in China. Solid circles indicate dinosaur-track-bearing formations; numbers are locality numbers used in Fig. 1 and text.

established as the Xiaotangzi Formation at the Meeting on the Mesozoic of Southwest China held in Emei, Sichuan Province in 1974 (Bureau of Geology and Mineral Resources of Sichuan Province, 1991, p. 215), and the other five members are of nonmarine coal-bearing series. The dinosaur tracks were collected from the third member, which consists of dark and blackish gray mudstone and siltstone intercalated with coal beds and a few sandstone beds (Loc. 28 in Figs. 2 and 3). The Xujiahe Formation is generally considered as Norian to Rhaetian in age based on the *Dictyophyllum-Clathropteris* flora.

2.2. Lower Jurassic

2.2.1. Xiyang site

Xiyang is a small town 39 km southwest of the Jinning County seat, Yunnan Province. Dinosaur tracks are found on the surface of red beds of the Fengjiahe Formation 2 km north of the town (Loc. 12 in Figs. 2 and 3; 24° 27′ 49.5″ N, 102° 17′ 45.5″ E). They include *Grallator limnosus*, *Schizograllator xiaohebaensis*, *Paracoelurosaurichnus monax*, *Eubrontes platypus*, *Youngichnus xiyangensis*, and *Zhengichnus jinningensis* (Zhen et al., 1986).

The Fengjiahe Formation in the Xiyang Basin is composed of grayish purple, purplish red, and yellowish green sandstone, siltstone, mudstone and marl about 500 m in thickness yielding a few ostracodes such as *Darwinula* sp. and dinosaurs such as *Lufengosaurus*.

In some geological literature, the dinosaur-track-bearing rocks in this small basin are called the Lower Lufeng Formation (Compiling Group of the Regional Stratigraphic Table of Yunnan, 1978). This is a well-known stratigraphic unit characterized by the *Lufengosaurus* fauna (Young, 1951), and its type section is located in the Lufeng Basin (Loc. 13 in Figs. 2 and 3; 25° 10′ 4.14″ N, 102° 6′ 6″ E), where many dinosaurs have been found: *Lufengosaurus huenei*, *L. magnus*, *Sinosaurus triassicus*, *Chinshakiangosaurus* sp., *Lukousaurus yini*, *Gyposaurus sinensis*, *Yunnanosaurus huangi*, *Y. robustus*, *Microchampa scutata*, and *Pachysuchus imperfectus*. The fauna also includes the primitive mammals *Bienotherium elegans*, *Kunminia minia*, and *Lufengia delicata*. Bivalves include *Unio huangbogouensis*, *U. lufengensis*, and *Cuneopsis xiangyunensis*. Ostracodes include *Darwinula sarytirmenensis*, *D.* aff. *impudica*, *Metacypris* cf. *M. menglaensis*, and *Gomphocythere*? aff. *reticulata*. The 740-m-thick Lower Lufeng Formation mainly consists of purplish red, purplish gray, and grayish purple mudstone and silty mudstone intercalated with grayish green and yellowish green sandstone and siltstone. These rocks are very rich in dinosaur bones but lack footprints. The *Lufengosaurus* fauna was originally considered as Late Triassic in age (Young, 1951), but recent studies show that an Early Jurassic age is more likely (Dong, 1980, 1992; Lucas, 1996).

2.2.2. Youting site

The Youting site reveals the oldest footprints of sauropods in Asia. These dinosaur tracks are exposed on the surface of yellowish green siltstone in a cliff alongside a railway near Changhebian, Youting township, Dazu County, Chongqing city (Loc. 27 in Figs. 2 and 3; 29° 27′ 4.08″ N, 105° 47′ 3.9″ E). It belongs to the Zhenzhuchong Formation, which mainly consists of yellowish green silty and calcareous mudstone alternating with 5.7-m-thick purplish red mudstone. These beds yield the dinosaur *Lufengosaurus* sp., the bivalve *Qiyangia lilingensis*; and the plants *Coniopteris hymenophylloides*, *Ptilophyllum pecten*, and *Todites princeps*. The Zhenzhuchong Formation has produced six theropod tracks named *Weiyuanpus zigongensis* at Rongseng near Lianjie town, Weiyuan County (Loc. 26 in Figs. 2 and 3; 29° 45′ 6.96″ N, 104° 34′ 6.78″ E). The tracks form a trackway heading toward 65° NE. They are housed in the Zigong Museum.

2.2.3. Dongyuemiao site

The Dongyuemiao site is situated near Dongyuemiao (Loc. 22 in Figs. 2 and 3; 29° 21′ 20.28″ N, 104° 42′ 32.52″ E) in Gongjing township, Zigong, Sichuan Province. Dinosaur tracks are found in the Ziliujing Formation, which is a lacustrine deposit composed of the Dongyuemiao Limestone (lower part, 6–9 m), the Ma'anshan Mudstone (middle part, 120–140 m), and the Da'anzhai Limestone (upper part, 300–400 m). In the Sichuan Basin, the freshwater limestone and purplish red mudstone are rich in fossils such as *Apseudocardinia kweichouensis* and *Cuneopsis johannisboehmi* (bivalves); *Lioplacodes orientalis*, *Carinomphalus delicatus*, and *Amplovalvata mansueta* (gastropods); *Bulbilimnadia bullata*, *Palaeolimnadia baitianbaensis*, and *P. chuanbeiensis* (conchostracans); *Darwinula sarytirmenensis* and *Metacypris unibulla* (ostracodes); *Euaclistochara yunnanensis* and *Aclistochara minima* (charophytes); and *Bishanopliosaurus yaungi*, *Sinopliosaurus weiyuanensis*, and *Peipehsuchus teleorhinus* (reptiles).

The appearance of *Qiyangia lilingensis*, *Palaeolimnadia baitianbaensis*, and *Bishanopliosaurus* suggests that the Zhenzhuchong Formation may be early Early Jurassic in age. The Ziliujing Formation is probably late Early Jurassic in age (Compiling Group of Continental Mesozoic Strata and Fossils of the Sichuan Basin, 1982), because *Qiyangia lilingensis* is an important form for the early Lias Guanyintang Formation in southern Hunan Province (Zhou, 1984), whereas *Bishanoplliosaurus* is a plesiosaurid indicating a late Lias age (Dong et al., 1983).

2.3. Middle and Upper Jurassic

2.3.1. Sichuan Basin

Middle and Upper Jurassic rocks in this basin can be divided into five formations.

Xintiangou Formation (Middle Jurassic, 70–350 m). The Xintiangou Formation consists of variegated thick-bedded sandstone and mudstone in the lower and upper parts and black mudstone intercalated with thin-bedded limestone or marl in the middle part. The middle member is rich in fossils, including bivalves *Apseudocardinia triangulata*,

Pseudocardinia ovalis, *P. hupehensis*, *Psilunio chaoi*, *Eolamprotula cremerei*; ostracodes *Darwinula lufengensis* and *Metacypris triangular*; conchostracan *Euestheria ziliujingensis*; plants *Coniopteris hymenophylloides* and *Ptilophyllum* sp.; fishes *Lepidotes luchowensis* and *L. chungkingensis*; reptiles *Sinopliosaurus* sp., Plesiosauria indet., Cetiosaurinae indet., and Carnosauria indet.; and the dinosaur tracks *Zizhongpus wumaensis*, *Chongqinpus miceoiscus*, *Toujiangpus shuinanensis*, *Megaichnites jizhaoshiensis*, *Chonglongpus lei*, *Chuanchengpus wuhuangensis*, and *Jinlijingpus nianpanshanensis* (Yang and Yang, 1987).

Lower Shaximiao Formation (Middle Jurassic, 100–300 m). The Lower Shaximiao Formation also comprises flood plain and fluvial facies, but differs from the Upper Shaximiao Formation in the presence of lacustrine, grayish green, conchostracan-bearing shale at the top. Overall the formation is composed of interbedded purplish red mudstone and grayish green sandstone. It contains the *Shunosaurus* dinosaur fauna; the *Euestheria ziliujingensis* conchostracan fauna; bivalves *Psilunio chaoi* and *Eolamprotula cremeri*; ostracodes *Darwinula sarytirmenensis*, *D. impudica*, and *Metacypris hechuanensis*; and the plants *Coniopteris tatungensis*, *C. hymenophylloides*, *Neocalamites carrerei*, and *Equisetites yimaensis*.

Upper Shaximiao Formation (Middle Jurassic, 500–2000 m). The Upper Shaximiao Formation comprises flood plain and fluvial facies consisting mainly of purplish red and brownish yellow mudstone and siltstone interbedded with grayish white, thick-bedded sandstone. These beds contain the outstanding *Mamenchisaurus* dinosaur fauna; the conchostracan *Paleoleptestheria chinensis*; the ostracodes *Darwinula impudica* and *D. sarytirmenensis*; the fishes *Ceratodus szechuanensis* and *Lepidotus luchowensis*; the bivalves *Cuneopsis johannisboehmi*, *Psilunio* sp., *Eolamprotula guangyuanensis*, and *Undulatula sichuanensis*; and the charophytes *Euaclistochara lufengensis*, *E. yunnanensis*, *Mesochara* sp., *Obtusochara* sp., and *Sphaerochara* sp.

Suining Formation (Upper Jurassic, 150–500 m). The Suining Formation consists of bright red mudstone and siltstone yielding the charophytes *Aclistochara lata*, *A. yunnanensis*, *Obtusochara* sp., and *Porochara glypta*; the ostracodes *Cetacella inermis*, *C. ovata*, *C. triangular*, *C. isohypsos*, *Darwinula* spp., *Djungarica* spp., and *Metacypris* sp.; the conchostracans *Eosestheriopsis dianzhongensis* and *Suiningestheria rongxianensis*; the bivalves *Danlengiconcha* aff. *longata*, *D.* cf. *ovalis*, *D. carinata*, *Unio* sp., and *Psilunio suni*; the fish *Ceratodus szechuanensis*; and the reptile *Plesiochelus tatsuensis*.

Penglaizhen Formation (Upper Jurassic, 150–1200 m). The Penglaizhen Formation comprises grayish purple sandstone and brownish red mudstone intercalated with yellowish shale and grayish marl. These beds yield the charophytes *Aclistochara minima*, *A. rotunda*, *A. lata*, *A. yunnanensis*, *Sphaerochara hildesiensis*, *Porochara westerbeckensis*, and *P. kimmeridgensis*; the ostracodes *Damonella ovata*, *D. shuanbaiensis*, *Djungarica* spp., *Darwinula* spp., *Mantelliana* sp., and *Metaeypris* sp.; the conchostracans *Eosestheriopsis dianzhongensis*, *E. semiorbita*, *Migransia sichuanensis*, and *Huilongestheria rotunda*; the bivalves *Danlengiconcha longata*, *D. ovalis*, *D. sichuanensis*, *Martinsonella*? *cangshanensis*, and *M.*? *zhongjiangensis*; and the gastropods *Valvata* spp., *Gyraulus* sp., and *Cincinna penglaizhenensis*.

The Upper Jurassic dinosaur tracks *Jialingpus yuechiensis* and *Huanglongpus shengouensis* of the Sichuan Basin were collected from the Penglaizhen Formation at the Huanglong site of Yuechi County, north of Chongqing city (Zhen et al., 1983) (Loc. 30 in Figs. 2, 3).

The ostracode *Cetacella inermis* Martin from the Suining Formation is an important form of the Upper Jurassic of Europe, and the charophyte assemblage from the Penglaizhen Formation shows some similar characteristics to the Kimmeridgian in Germany (Liu and Zheng, 1992).

The well-known *Mamenchisaurus* dinosaur fauna from the Upper Shaximiao Formation includes *Mamenchisaurus constructus*, *M. hochuanensis*, *Omeisaurus changshouensis*, *Yangchuanosaurus shangyouensis*, *Y. magnus*, *Szechuanosaurus campi*, *Sinocoelurus fragiris*, *Gongbusaurus shiyii*, *Chialingosaurus kuani*, *Tuojiangosaurus multispinus*, and *Chungkiangosaurus jiangbeiensis*. It was referred to the Upper Jurassic because these large dinosaurs look very similar to the *Diplodocus* fauna from the Morrison Formation of United States (Young, 1958; Young and Zhao, 1972; Dong, 1980; Dong et al., 1983). However, most Chinese geologists considered that the Upper Shaximiao Formation should be late Middle Jurassic in age, based on invertebrate and plant fossils (Gu, 1962; Compiling Group of Continental Mesozoic Strata and Fossils of the Sichuan Basin, 1982; Chen, 1996). Recently, research on vertebrate biochronology is also changing the geological age of the *Mamenchisaurus* fauna to late Middle Jurassic (Lucas, 1996). So far, no dinosaur tracks have been found in this formation.

Middle Jurassic dinosaur footprints in the Sichuan Basin are found in the Xintiangou Formation, Wumacun village (Loc. 20 in Figs. 2 and 3; 29° 43′ 27.84″ N, 104° 47′ 31.98″ E; Loc. 21 in Figs. 2 and 3; 29° 43′ 19.92″ N, 104° 47′ 35.4″ E), Nianpanshan near Jinlijing township in Zizhong County (Loc. 25 in Figs. 2 and 3; 29° 47′ 39.12″ N, 104° 38′ 29.28″ E), and Rongshen village, in Weiyuan County. Crouching tracks occur at Loc. 20 that were described by Lockley et al. (2003). Middle Jurassic dinosaur footprints in this basin were also collected from the Lower Shaximiao Formation at Yemaoxi on the south bank of the Yangtze River at Chongqing city (Loc. 19 in Figs. 2 and 3). Concerning the Middle Jurassic age for both of the Lower Shaximiao and Xintiangou formations, there is no dispute in China. However, the tracks are very similar to Lower Jurassic ichnofaunas from North America, and certain forms resemble *Grallator*, *Eubrontes*, and *Anomoepus*.

2.3.2. Shaanxi Province

Two dinosaur tracks were reported from Shaanxi Province. One is *Shensipus tungchuanensis* (Young, 1966) attributed to

a coelurosaurid from the Zhiluo Formation at the Jiaoping open-cut coal mine of Tongchuan city (Loc. 45 in Figs. 2 and 3). Another is *Sinoichnites youngi* (Kuhn, 1958) referred to an iguanodontid, and probably from the Lower Upper Jurassic Anding Formation as in Shenmu County (Loc. 46 in Figs. 2 and 3). Unfortunately this track, which was the first found in China has been lost. It was described by one of China's most famous paleontologists in conjunction with one of Europe's most famous paleontologists (Teilhard de Chardin and Young, 1929).

The Zhiluo Formation is a coal-bearing series consisting of grayish green, yellowish green, and purplish red interbedded sandstone and mudstone in the upper part, and yellowish green massive sandstone in the lower part. It contains the fossil bivalves *Sibireconcha* spp., *Ferganoconcha* sp., and *Pseudocardinia* spp.; the plants *Coniopteris hymenophylloides*, *C. tatungensis*, *Phaenicopsis angustifolia*, *Ginkgoites* cf. *G. sibiricus*, *Czekanowskia* sp., and *Brachyphyllum* cf. *B. expansum*; gymnospermous pollen (70%) such as *Quadraeculina*, *Piceaepollenites*, *Pinuspollenites*, *Podocarpidites*, and *Classopollis*, and cyatheaceous spores (30%) including *Deltoidospora*, *Cyathidites*, *Concavissimisporites*, and *Klukisporites*. These fossils indicate a late Middle Jurassic age.

2.3.3. Western Liaoning and northern Hebei

In western Liaoning the sequence has been divided into eight formations, in ascending order: Haifanggou, Lanqi, Tuchengzi, Yixian, Jiufotang, Shahai, Fuxin, and Sunjiawan (Fig. 3). Thus, the age of the Tuchengzi Formation was generally inferred to be older: i.e., late Middle Jurassic to Late Jurassic (Zhang, 1985; Chen and Hudson, 1991; Wang et al., 2000; Chen, 2003). Fission track dates obtained from the upper part of Tuchengzi Formation during the course of this study suggest an age of about 145.9 Ma (Matsukawa et al., 2001; Lockley et al., 2006). This suggests a Tithonian age for the upper.

Tuchengzi Formation (2000 m). Grallator s-satoi (Yabe, Inai, and Shikama) was found from the upper part of Tuchengzi Formation in the Chaoyang and Beipiao areas, western Liaoning Province, northeastern China (Loc. 2 in Figs. 2 and 3; 41° 11′ 47.52″ N, 120° 18′ 36.36″ E). This formation consists of green sandstone with cross-bedding in the upper part, grayish purple conglomerate in the middle part, and red sandstone, siltstone, and shale in the lower part (320–1214 m total thickness). The lower part yields the *Pseudograpta* conchostracan fauna, which includes *P.* aff. *murchisoniae*, *P. orbita*, *Nestoria reticulata*, *N. pissovi*, *Mesolimnadia jinlingsiensis*, *M. recta*, *Monilestheria ovata*, *M. oblonga*, *Prolynceus beipiaoensis*, and *P. lineatus* (Shen and Chen, 1984); the palynomorphs *Classopollis* spp. (86.2%), *Psophosphaera* sp., *Araucariacites* sp., *Cycadopites nitidus*, and *Ephedripites* sp.; and the dinosaur *Chaoyangosaurus liaoxiensis.*

The important forms of the conchostracan fauna, *Pseudograpta murchisoniae* (Jones) and *P. orbita* Chen, have been found in the uppermost Middle Jurassic of Scotland (Chen and Hudson, 1991). *Nestoria pissovi* Krasinetz is an important element of the Upper Jurassic *Nestoria-Keratestheria* conchostracan fauna in northeastern China and Transbaikalia of Russia (Chen, 2003). It is possible that there was a migration of the *Pseudograpta* fauna from Europe in the late Middle Jurassic to East Asia, in Oxfordian time. However, other interpretations might be also possible.

In northern Hebei, similar dinosaur tracks and the same *Pseudograpta* conchostracan fauna have also been found in the Houcheng Formation, which is equivalent to the Tuchengzi Formation of western Liaoning. Both of these are red beds with massive conglomerate beds in their middle parts. The reddish purple, thin-bedded sandstone with small dinosaur footprints have been used to pave the courtyards of Temples in Chengde city. They were collected at Shibanwao (Loc. 6 in Figs. 2 and 3; 40° 54′ 58.08″ N, 118° 09′ 51.18″ E), a small mountain village near Madigou in Chengde County. We studied the tracks in this area in 2000.

2.4. Lower Cretaceous

2.4.1. Inner Mongolia

The small settlement of Chabu (Locs. 36-44 in Figs. 2 and 3; 38° 54′ 37.2″ N, 107° 17′ 43.8″ E) is called Bulun Temple on many Chinese geographical maps. It is situated about 650 km west of Beijing in the west part of the Inner Mongolian Autonomous Region, and belongs geologically to the Ordos Basin. In the past only theropod tracks had been found from this area (Zhen et al., 1989), but recently Lockley et al. (2002) reported abundant sauropod tracks from the same area. All the track sites are preserved in subhorizontal strata of the Jingchuan Formation, which is the upper part of the Zhidan Group. Bird tracks are also abundant at many sites.

Lower Cretaceous variegated deposits in the Ordos Basin can be divided into three units, in ascending order the Luohandong, Jingchuan, and Lamawan formations.

The Luohandong Formation (107–338 m) consists of purplish red, brownish red, light gray and orange-yellow siltstone, mudstone, and sandstone with large-scale cross-beds that are very characteristic. It contains the plant fossil *Cladophlebis* cf. *C. dunkeri*; ostracodes *Cypridea koskulensis*, *Clinocypris scolia*, *Lycopterocypris infantilis*, *Rhinocypris foveata*, *Djungarica stolida*, and *Darwinula simplus*; bivalves *Sphaerium* spp.; gastropod *Valvata* cf. *V. suturalis*; fish *Sinamia* sp.; and dinosaur *Psittacosaurus* sp.

The overlying Jingchuan Formation (114–557 m) is mainly composed of grayish green breccia and conglomerate, yellowish green sandstone, and variegated mudstone intercalated with blue-gray oolitic limestone and marl. This formation contains the plants *Zamiophyllum buchianum*, *Otozamites* sp., and *Pagiophyllum* sp.; ostracodes *Cypridea koskulensis*, *C. unicostata*, *Pseudocypridina* aff. *globra*, *Clinocypris scolia*, *Lycopterocypris infantilis*, *Jungarica stolida*, and *Rhinocypris foveata*; conchostracans *Yanjiestheria* cf. *Y. sinensis* and *Y.* cf. *yumenensis*; bivalves *Nakamuranaia chingshanensis* and *Sphaerium* spp.; gastropod *Valvata suturalis*; insects *Mesolygaesus rotundocephalus*; fish *Sinamia zdanskyi*; and dinosaur *Psittacosaurus youngi*.

The Lamawan Formation (226 m) only occurs in the northeastern margin of the Ordos Basin. It consists of grayish white and yellowish green massive sandstone, and red and dark gray silty mudstone with coal seams or coal intercalations in the upper part. It yields the plants *Acanthopteris gothani*, *Elatocladus* cf. *E. manchuricus*, *Coniopteris*? *nympharus*, *Sphenolepidum* sp., and *Brachyphyllum japonicum*. The Louhandong and Jingchuan formations are roughly correlative with the Jiufotang Formation, whereas the Lamawan Formation is equivalent to the Shahai or Fuxin Formation in northeastern China based on the *Cypridea koskulensis* ostracode fauna and the coal deposits respectively. The dinosaur-track-bearing Jingchuan Formation is composed of fluvio-lacustrine facies with some tuffaceous materials (Lockley et al., 2002); the Luohandong Formation may be composed of fluvio-lacustrine and aeolian facies (Jiang and Li, 1996). Both of them could be Valanginian–early Hauterivian in age instead of Barremian-early Aptian in age. Some late Hauterivian–Barremian marine dinoflagellates and bivalves have been recovered from Lower Cretaceous coal-bearing horizons such as the Chengzihe Formation in eastern Heilongjiang Province, northeastern China, and the Severosuchan Formation in the Russian Far East (He and Sun, 2000; Chen, 2003). The Lamawan Formation in the Ordos Basin could be correlated with these coal-bearing formations in northeastern Asia because they have the same *Acanthopteris gothani* flora.

2.4.2. Northern Hebei and Western Liaoning

Lower Cretaceous outcrops are widely distributed in western Liaoning and northern Hebei. They are divided into five formations in western Liaoning and four formations in northern Hebei (Fig. 3); the Yixian Formation and the overlying Jiufotang Formation are identified in both areas.

In western Liaoning, the sequence has been divided into five formations in ascending order: Yixian, Jiufotang, Shahai, Fuxin, and Sunjiawan. Older reports claimed that the Yixian Formation containing a middle ''Jehol'' fauna might be as old as Tithonian in age (Chen and Jin, 1999, p. 6). However, more recent isotopic and paleomagnetic interpretations of the age of the Yixian Formation suggest younger dates (124–123 Ma), suggesting a late Neocomian (Hauterivian–Barremian) age (Swisher et al., 1999; Zhu et al., 2002, 2004). Some Chinese biostratigraphic researchers are still believing that the Jurassic-Cretaceous boundary might be within the Yixian Formation (Zheng et al., 2003; Chen et al., 2005).

Jiufotang Formation (1000 m). This formation consists mainly of lacustrine variegated deposits including grayish green siltstone; sandy mudstone and shale intercalated with gray, grayish white, grayish purple, yellow, blackish gray and green sandstone; oil shale; and marl. It contains the insects *Ephemeropsis trisetalis*, *Coptoclava longipoda*, *Chironomaptera melanura*, and *Mesolygaus laiyangensis*; fish *Lycoptera* sp.; conchostracans *Yanjiestheria jiufotangensis*, *Eosestheria fuxinensis*, and *E. subroutunda*; ostracodes *Cypridea koskulensis*, *C. unicostata*, *C. vitimensis*, *C. pognasta*, *Pseudocypridina ellipselloides*, *Rhinocypris echinata*, *Limnocypridea obscondida*, *Djungarica stolida*, *Mongolianella palmosa*, *Clinocypris scolia*, *Lycopterocypris infantilis*, and *Damonella circulata*; birds *Sinornis*, *Chaoyangia*, *Cathayornis*, *Sonlingornis*, *Largirostrornis*, *Cuspirostrisornis*, *Longchengornis*, *Boluochia*, *Yanornis*, and *Yixianornis*; and dinosaur *Sinopterus dongi.* The dinosaur tracks are found mainly along the railway at Qiaomaigoumen (Locs. 7 and 8 in Figs. 2 and 3; 40° 54′ 29.28″ N, 117° 16′ 9.24″ E, and 40° 53′ 24.78″ N, 117° 07′ 56.22″ E) near the Pingfang station of Luanping County, northern Hebei Province. You and Azuma (1995) described dinosaur tracks from Loc. 7.

Fuxin Formation (434–1483 m). The Fuxin Formation is a coal-bearing sequence consisting mainly of grayish white thick-bedded sandstone intercalated with gray shale and four coal seams that are actively mined. It yields the *Acanthopteris gothani-Nilssonia sinensis* fossil plant assemblage; bivalves *Ferganoconcha quadrata* and *Sphaerium anderssoni*; gastropods *Campeloma tani*, *Bellamya fengtienensis*, and *Bithynia* cf. *B. mengyinensis*; and ostracodes *Cypridea tumidiuscula*, *C. unicostata*, *Pinnocypridea dictyotroma*, *Pseudocypridina globra*, and *Lycopterocypris infantilis*. Many ornithopod and some gracile-toed theropod dinosaur tracks have been found on the surface of grayish white thick-bedded sandstone in the Fuxin coal open-cut mine of western Liaoning (Loc. 5 in Figs. 2 and 3; 42° 00′ 5.4″ N, 121° 41′ 33.42″ E). *Changpeipus carbonicus* was first reported from this locality (Young, 1960).

2.4.3. Jilin

The Yanji Basin is situated in the eastern part of Jilin Province near North Korea. Here gracile-toed theropod and iguanodontid dinosaur tracks were found in the lower part of the Tongfosi Formation between Laotougou and Tongfosi towns (Loc. 1 in Figs. 2 and 3; 42° 53′ 37.9″ N, 129° 13′ 12.66″ E) near Yanji city (Matsukawa et al., 2006). The Lower Cretaceous rocks in the Yanji Basin can be divided into four stratigraphic units. They are, in ascending order, the Laotougou, Tongfosi, Longjing, and Dalazi formations. The Laotougou Formation is a coal-bearing series and can be correlated with the Fuxin Formation. Their ages may be late Barremian (Zhang et al., 2003). The Dalazi Formation is Albian in age based on the spore-pollen assemblage (Yu and Miao, 1984). The sequence including the Tongfosi, and Longjing formations was assigned to the Aptian and correlated with the Sunjiawan Formation of western Liaoning (Chen, 2000). However, recent research indicates that early Late Cretaceous (Cenomanian) age for the Tongfosi Formation is suggested by the presence of tricolporate angiosperm pollen (Nichols et al., in press).

Huinan is situated in the southern part of Jilin Province. The theropod track *Changpeipus carbonicus* Young was found in the Tuntainying Formation at Sungsankang coal mine (Loc. 48 in Figs. 2 and 3). The Tuntainying Formation is composed of volcanic rocks intercalated with clastic deposits and can be correlated with the Yixian Formation in western Liaoning.

2.4.4. Shandong

Laiyangpus liui, a theropod track, was named from the Laiyang Formation at Beibozi (formerly spelling Peiputze) of

Laiyang County, Shandong Peninsula (Young, 1960). The Laiyang Formation is lacustrine facies including four members.

1st (lowest) member. Grayish black and yellowish green calcareous siltstone, shale and sandy shale.
2nd member. Grayish brown silty marl, pelitic siltstone, and shale in the upper part; grayish green conglomerate and sandstone intercalated with a few sandy limestone beds in the lower part.
3rd member. Yellowish green siltstone and fine-grained sandstone, grayish green shale; gravel-bearing feldspathic quartz sandstone in the basal part.
4th (highest) member. Grayish green siltstone and fine-grained sandstone, yellowish or purplish red shale.

The total thickness of this formation is about 1277 m. It contains the fishes *Lycoptera sinensis*, and *Sinamia* sp.; conchostracans *Yanjiestheria sinensis*, *Y. chekingensis*, *Y. kyongsangensis*, and *Eosestheria* sp.; ostracodes *Cypridea* spp., *Damonella zhejiangensis*, and *D. ovata*; bivalve *Sphaerium anderssoni*; gastropods *Probaicalia* cf. *P. prinadae*, and *Valvata zhuchengensis*; insects *Mesolygaeus laiyangensis*, *M. rotundocephalus*, *Chironomaptera gregaria*, *Coptoclava longipoda*, *Sinoblatta laiyangensis*, and *Laiyangia paradoxiformis*; and the plants *Brachyphyllum obesum*, *Cupressinocladus elegans*, *C. gracilis*, *Onychiopsis elongata*, *Ruffordia* cf. *goepperti*, *Sphenobaiera longifolia*, *Elatocladus* sp., *Otozamites* sp., *Podozamites lanceolatus*, and *Schizolepis* sp.

The dinosaur tracks in the Laiyang area are found mainly in the third member of the Laiyang Formation and are associated with fish and insect fossils (Young, 1960). In 2000 we visited two new localities guided by Mr. Li Rihui. Small slender-toed theropod tracks and bird tracks are found at a quarry near Huangyandi village northeast of Beibozi (Loc. 10 in Figs. 2 and 3; 37° 02′ 36.84″ N, 120° 48′ 7.2″ E) and a small theropod (Li and Zhang, 2000) was reported from a small quarry near Shuinan village (Loc. 9 in Figs. 2 and 3; 36° 56′ 15.96″ N, 120° 48′ 41.16″ E).

2.4.5. Shangxian site

This site is near Shaojian in Shangxian County, southern Shaanxi Province (Loc. 11 in Figs. 2 and 3; 33° 55′ 17.04″ N, 109° 51′ 14.34″ E). There are two kinds of gracile-toed and large robust theropod dinosaur tracks found here. The largest one is 55 × 42 cm in size. Both are preserved on the same surface of grayish green siltstone, which is in the lower part of the Fengjiashan Formation. In the Shangxian Basin of the Qinling Mountain area, this formation is composed of two members. The lower member (522 m) comprises grayish green and yellowish green and grayish black mudstone and siltstone intercalated with grayish green sandstone, conglomerate, coal seams, and marl in the mid-upper part; grayish green and purplish conglomerate, sandstone, and pelitic siltstone in the lower part. It contains the ostracodes *Cypridea vitimensis*, *C. sancta*, *C. cruda*, *C. monstrosa*, *Ziziphocypris costata*, *Darwinula* cf. *D. contracta*, and *Rhinocypris* cf. *R. panosa*; the charophyte *Clypeator jiuquanensis*; the conchostracans *Yanjiestheria shouchangensis*, *Y. minor*, *Y. yumenensis*, *Diestheria* aff. *yixianensis*, *Neodiestheria cuneata*, *N. shangxianensis*, and *Eosestheria gouyuensis*, the insects *Ephemeropsis trisetalis* and *Shangxiania fengjiashanensis*, the bivalves *Sphaerium anderssoni*, *Neomiodonoides yumenensis*, and *Nakanuranaia chingshanensis*; the gastropods *Probaicalia gerassimovi*, *Zaphychius delicatus*, and *Viviparus matsumotoi*; and the plants *Radicites* sp., *Coniopteris* sp., *Acanthopteris alata*, *Ginkgoites orientalis*, *Baiera furcata*, *Pityophyllum staratschini*, *Sequoia*? *gracilis*, *Frenalopsis*? sp., *Podozamites macronatus*, *Brachyphyllum* sp., and *Pagiophyllum* sp. The lower member can be approximately correlated with the Shahai Formation in northeastern China and might be late Hauterivian to early Barremian age (Chen and Yuan, 1993; Yuan and Ma, 1993).

The upper member (409 m) comprises yellowish green, grayish green, and purplish red siltstone, mudstone, and sandstone intercalated with marl, conglomerate, and a few coal seams that yield the ostracodes *Cypridea coronata*, *Metacypris principalis*, *Clinocypris shanqingcunensis*, *Darwinula* cf. *D. contracta*, *Lycopterocypris infantilis*, *Limnocythere* sp., *Ilyocypris* sp., and *Candoniella* sp.; the charophytes *Aclistochara* spp., *Sungliaochara huadongensis*, and *Mesochara stipitata*; the bivalves *Sphaerium anderssoni*, *Limnocyrena tani*, *L. fuxinensis*, and *Neomiodonoides yumenensis*; the gastropods *Viviparus onogoensis*, *Lioplacodes* cf. *L. cholnokyi*, and *Amnicola meikiensis*; and the plants *Arctopteris tschumikanensis*, *Chiaohoella*? sp., *Ginkgoites* sp., *Pityophyllum lindstroemi*, and *Acanthopteris gothani*. This member can be correlated with the Fuxin Formation of western Liaoning Province, NE China and might be late Barremian to early Aptian age (Chen and Yuan, 1993).

2.4.6. Laohukou site

Recently, local geologists of the Gansu Geological Survey have found hundreds of dinosaur tracks on three surfaces of gray sandstone intercalated between purplish red mudstone of the Hekou Group at Laohukou, Yanguoxia town, near Lanzhou city, northwestern China (Loc. 50 in Figs. 2 and 3). They include large sauropod tracks, medium and small theropod tracks, and tracks of ornithopods and pterosaurs (Li et al., 2000, 2002). The Hekou Group is made up of fluvio-lacustrine sequences consisting of variegated (dominantly red and green) mudstone, shale, siltstone, and sandstone intercalated with conglomerate in the upper part, which yield the ostracodes *Cypridea koskulensis*, *C. vitimensis*, *C. unicostata*, *Lycopterocypris* aff. *infantilis*, *Ziziphocypris simakovi*, *Rhinocypris jurassica*, *Bisulcocypridea* cf. *B. skeeteri*, and *Latonia* sp.; the charophytes *Aclistochara huihuibaoensis*, *Flabellochara harrisi*, *F.* cf. *jurongica*, *Hornichara stipitata*, *Sphaerochara parvula*, and *S. verticillata*; the conchostracans *Yanjiestheria kyongsangensis* and *Orthestheria leduensis*; the bivalves *Nakamuranaia chingshanensis* and *Nippononaia tetoriensis*; the gastropods *Valvata* cf. *V. onogoensis*, *V.* cf. *helicoides*, and *Bithynia leachioides*; the fish *Sinamia* sp.; and the spores and pollen *Classopollis* (58.9%), *Inaperturopollenites* (24.1%), *Psophosphaera* (8.9%), *Schizaeoisporites* (1.1%), and some angiosperm pollen (Hao et al., 1986).

2.5. Upper Cretaceous

2.5.1. Chuxiong sites

Sauropod tracks were first reported by Chen and Huang (1993, 1994) from the lower part of the Jiangdihe Formation at Yuanjitun village near Cangling town, Chuxiong County, Yunnan Province, southwestern China (Locs. 14, 16–18 in Figs. 2 and 3; 25° 02′ 28.38″ N, 101° 40′ 31.8″ E for Loc. 14). These tracks were named *Chuxiongpus canglingensis* and *C. zheni* (Chen and Huang, 1993), but recently they have been reassigned to the ichnogenus *Brontopodus* (Lockley et al., 2002). *Yunnanpus huangcaoensis* also from the Jiangdihe Formation (Chen and Huang, 1993) was found near Fangjiahe, about 1.5 km to the west of Yuanjitun village (Loc. 15 in Figs. 2 and 3; 25° 02′ 44.46″ N, 101° 39′ 15.6″ E). It is probably a theropod track but is poorly preserved (a thus is a nomen dubium).

The Upper Cretaceous deposits are all red beds in the central Yunnan Basin. They contain three formations (Fig. 3). The Jiangdihe Formation is the middle and can be further subdivided into four members (Chen, 1996).

Dinosaur tracks are found in the Luozuomei Member of the lower part of the Jiangdihe Formation, associated with the ostracodes *Darwinula oblonga*, *D. lenguminella*, *Eucypris* cf. *anluensis*, and *E.* cf. *debiloides* (Lockley et al., 2002). In addition, some fish and conchostracan fossils (such as *Aglestheria separata*) were previously collected from this member in the same district.

Fossils recovered from the Yuanyongjin Member in the upper part of the Jiangdihe Formation include spores and pollen grains (*Cicatricosisporites minutaestriatus*, *Araucariacites incisus*, *Quercoidites henrici*, *Torosisporites* sp., *Echinatisporites* sp., *Monosulcocites minimus*, *Polypodiaceaesporites* sp., *Tricolpites* sp., and *Triporopollenites* spp.). A rock salt bed is also found in this member. These indicate an arid tropical or subtropical environment.

The Jiangdihe Formation is composed of lacustrine deposits. Its thickness varies from 939 to 2396 m in the central Yunnan Basin. Such a great sequence might be Turonian to Santonian age (Chen, 1996). At the Chuxiong sites the dinosaur tracks from the Luozuomei Member in the lower part of the Jiangdihe Formation are probably Turonian or Turonian-?Coniacian in age (Lockley et al., 2002).

2.5.2. Emei site

The Emei dinosaur track site is at Xingfuya near Chuanzhu town, Emei County, Sichuan Province (Loc. 24 in Figs. 2 and 3; 29° 36′ 12.72″ N, 103° 26′ 34.86″ E). Tracks include *Grallator emeiensis*, *Minisauripus chuanzhuensis*, *Velociraptorichnus sichuanensis*, and *Iguanodonopus xingfuensis* (Zhen et al., 1995, 1996). They were found in the Jiaguan Formation, which is distributed in the southwestern Sichuan Basin. It comprises brownish red and lateritic mudstone and siltstone intercalated with thin-bedded shale, marl, and gypsum in the upper part (894 m) and brownish red and lateritic sandstone and siltstone with shale and basal conglomerate in the lower part (391 m). It unconformably overlies the Lower Cretaceous Tianmashan Formation or Upper Jurassic Penglaizhen Formation, and it yields the ostracodes *Cypridea tera*, *C. gunzulingensis*, *C. enodata*, and *Kaitunia cuneata*. These fossils are also found in the Upper Cretaceous strata in northeastern China.

2.5.3. Jiuquwan site

The dinosaur tracks *Xiangxipus chenxiensis*, *X. youngi*, and *Hunanpus jiuquwanensis* were collected and named from the Xiaodong Formation (not the Jinjiang Formation as reported by Zeng, 1982, and Zhen et al., 1996) at Hongwei village near the Jiuquwan copper mine, Chenxi County, western Hunan Province (Loc. 31 in Figs. 2 and 3; 27° 55′ 41.28″ N, 110° 04′ 20.28″ E). The Xiaodong Formation in this area is mainly composed of lateritic and grayish green sandstone, siltstone, sandy mudstone, and basal conglomerate and is 494 m in thickness. In addition to the tracks, the formation yields a few ostracodes such as *Mongonianella* sp. and *Eucypris* sp. Local geologists prefer to assign it to the Upper Cretaceous (Bureau of Geology and Mineral Resources of Hunan Province, 1988).

2.5.4. Qiyunshan site

Qiyunshan is a famous mountain for Taoism temples in southern Anhui Province of southeastern China. The track site is located in the roof of Xiaohutian cave (Locs. 32 and 33 in Figs. 2 and 3; 29° 48′ 30.3″ N, 118° 01′ 48.54″ E for Loc. 32), near the top of this mountain. All together, there are 35 tracks outcropping on the under surface of a thick-bedded sandstone of the Qiyunshan Formation. This formation comprises brownish-gray and purplish red thick-bedded conglomerate, sandstone with sandy marl in the lower part (81 m), purplish gray and purplish red thick-bedded conglomerate, sandstone, and siltstone in the middle part (74 m), and purplish gray massive conglomerate and purplish red thick-bedded sandstone and siltstone in the upper part (52 m). In addition to the dinosaur tracks, fossil plants and palynomorphs including *Cladophlebis* cf. *C. exiliformis*, *Sphanopteris*? sp., *Schizaeoisporites*, *Cyathidites*, *Psophosphaera*, *Cicatricosisporites*, *Inaperturopollenites*, *Monosulcites*, and *Quercoidites* are found. These track-bearing rocks have been referred to the lower Upper Cretaceous chiefly based on regional stratigraphic correlation, although there is insufficient biostratigraphic evidence (Bureau of Geology and Mineral Resources of Anhui Province, 1987).

2.5.5. Yibien site

Yangtzepus yipingensis was reported from the Chiating Group at Guanyingchong near Guanying town, Yibien County, Sichuan Province (Young, 1960) (Loc. 23 in Figs. 2 and 3). This is an ornithopod track. The Chiating Group can be divided in ascending order into the Wuotoushan, Daergun, Sahe, and Gaokangba formations by local geologists. The former two formations can be correlated with the Jiaguan Formation, and the later two are equivalent to the Guankou Formation in the Emei area (Compiling Group of Continental Mesozoic Strata and Fossils of the Sichuan Basin, 1982). These tracks were probably collected from the Daergun Formation.

2.5.6. Nanxiong site

During the early 1980s, local geologists found some small theropod dinosaur tracks in the Nanxiong Formation in Nanxiong County, northern Guangdong Province (Loc. 52 in Fig. 2). These dinosaur-track-bearing rocks also yielded some dinosaur body fossils such as *Microhadrosaurus*, *Nanxiongosaurus*, and *Tarbosaurus* (Dong, 1980), and abundant microfossils, among them the *Talicypridea-Mongolocypris-Candona* ostracode assemblage and the *Porochara anluensis-Charites tenuis* charophyte assemblage. These indicate a Campanian age (Chen, 1996, 2003). This may be the stratigraphically highest dinosaur-track-bearing horizon discovered so far in China.

3. Conclusions

(1) China is rich in dinosaur tracks from the Upper Triassic to the Upper Cretaceous. They include not only tracks of theropods, ornithopods, and prosauropods but also sauropods often associated with bird tracks in the Cretaceous. So far there are more than 50 track sites known from 16 provinces in this country. The Jurassic localities are concentrated mostly in the Sichuan Basin.

(2) Geological ages of the majority of dinosaur track-bearing formations in China have been determined based on associated ostracodes, conchostracans, charophytes, palynomorphs, and other nonmarine fossils. Due to the lack of marine intercalations, in almost all cases dating is still difficult. These track-bearing formations might be assigned to epochs such as the Lower or Upper Cretaceous but cannot be correlated more precisely with international standard stages.

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