



Early Cretaceous dinosaur and other tetrapod tracks of southwestern China

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Abstract In recent years the Lower Cretaceous red beds of southwestern China have yielded more than 20 significant dinosaur-dominated tracksites. More than half occur in the Jiaguan Formation with the remainder in the Feitianshan and Xiaoba formations. Collectively these sites provide evidence of at least 13 distinct dinosaurian trackmaker morphotypes, in addition to two avian theropod (bird) morphotypes and pterosaur and turtle tracks. Together these total 17 morphotypes provide a data base of 479 potential trackmakers, probably representing the same number of individuals. Such an ichnological database provides a useful proxy paleoecological census of tetrapod communities in the area during the Early Cretaceous, and is especially significant given the complete absence or scarcity of skeletal remains reported from these formations. The composition of ichnofaunas in all three formations is heavily saurischian (theropod and sauropod) dominated with a high diversity of distinctive theropod morphotypes, mostly assignable to known ichnogenera. Moreover, ichnofaunal data from multiple sites are generally consistent between sites and an indication of the reliability and repeatability of track census data. Such regionally-

widespread data are rapidly superseding the information available from the skeletal record in the corresponding area, and must therefore be considered of high paleontological value.

Keywords Early Cretaceous · Dinosaur tracks · Southwestern China · Paleoecology

1 Introduction

A recent blitzkrieg in tracksite discoveries has brought on an ichnological renaissance in Chinese Mesozoic paleontology. Over 200 Mesozoic tetrapod tracksites were known in 2015 [1–3], compared with only 27 such sites in 1989 [4]. Most of the new sites were discovered and described by Sino-Japanese-American expeditions, between 1999 and 2006, and by Sino-American collaborative studies undertaken since 2012. The latter are characterized by strong international cooperation and multidisciplinary partnerships.

A great many of the newly discovered Chinese tracksites are Early Cretaceous in age, and have provided new insights into the fauna from this time. During the Early Cretaceous, the Earth experienced strong geologic and climactic changes, including the further separation and fragmentation of the continents, intense sea-floor spreading, abundant global volcanic activity [5], and a peak in the greenhouse climate [6]. Such environmental forces, fostered geographic isolation and drove organisms to evolve novel adaptations to the changing conditions, making the Early Cretaceous a key epoch in the study of Mesozoic biogeographic diversity [7].

Among China's Lower Cretaceous tracksites, those from Sichuan (with Chongqing, Northern Yunnan and Guizhou), Inner Mongolia, Gansu, and Shandong are among the

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richest, and record the greatest diversity. In particular, the track record of Gansu and Shandong, in the Sichuan-Yunnan Basin, have been critical in understanding the local palaeoecology, because equivalent-aged skeletal fossils have long been sparse or absent in the region [8].

2 Geological setting

In the Early Jurassic after coalification in terrestrial facies during Late Triassic, the studied areas experienced fluvio-lacustrine deposition under drier climatic conditions. Ultra-thick red clastic deposits constituted the framework of Sichuan Basin deposition and were widely distributed in Panxi (Panzhihua-Xichuang) area [8, 9]. Deposition in the study area lasted from the Late Triassic to the end of the Oligocene [9].

The Cretaceous strata of Sichuan Province are concentrated in the Sichuan Basin, where they can be divided into three areas: the northern area (Tongxi-Bazhong region), the western area (Chengdu-Ya'an region), and the southwestern area (Yibin-Xishui region) (Fig. 1) [8]. The Sichuan Basin was under the influence of a tectonic belt in the north-northwest and a fault-fold belt in the southeast from the Cretaceous to the Paleogene. Deposition was volumetrically quite limited during the Early Cretaceous in the northern part of the basin while it was more rapid and continuous in the western and southwest parts from the Early Cretaceous to the Paleogene [9].

Most of the Cretaceous tracks have been discovered in the Jiaguan Formation, in the west and southwestern areas of the Sichuan Basin. Based on sporopollen assemblages, Chen [10] suggested that the Jiaguan Formation was formed in Barremian–Albian times, as fluvial facies under a tropical, or subtropical, semiarid and semi-humid climates.

The Southwest part of Sichuan Province is named Panxi. Compared with the Sichuan Basin, the area indicates relatively poor sedimentary continuity and displays the sedimentary characteristics of intermountain basin [9]. Panxi's largest basin is the Mishi-Jiangzhou Basin. Lower Cretaceous tracks there are mainly preserved in the Feitianshan Formation and the Xiaoba Formation. Tamai et al. [11] proposed that the Feitianshan Formation is Berriasian–Barremian age, based on paleomagnetism evidence. Lithological correlation shows that the Jiaguan Formation, in the Sichuan Basin, is comparable to the lower part of the Xiaoba Formation [12].

3 Dinosaur fauna

Twelve tracksites have been found in the Jiaguan Formation since 1971, and six and five, respectively, have been found in the Feitianshan Formation and Xiaoba Formation

since 1991 (Table 1). The few dinosaur skeletal fragments found in the Jiaguan Formation, lack any description and discussion [8], and none is known from the Feitianshan Formation or Xiaoba Formation. All these tracksites, except Guanyuanchong [13] and Chuanzhu sites [14, 15], were found and described by the authors and colleagues since 2007 (Fig. 1) [16–33].

The Feitianshan Formation (Berriasian–Barremian) is older than the Jiaguan Formation (Barremian–Albian) [26]. Therefore, the known Cretaceous dinosaur records in the Mishi-Jiangzhou Basin begin in the Early Cretaceous and represent a greater span of time than presently known from the Sichuan Basin. Generally, the track record demonstrates a strong similarity between the dinosaur faunal assemblages from the Sichuan Basin and the Mishi-Jiangzhou Basin. Both include ornithopod, sauropod, non-avian theropod, and pterosaur tracks, while the Jiaguan Formation also yields thyreophora and bird tracks and the Feitianshan Formation yields possible turtle tracks (Table 1). The record from the Xiaoba Formation is far less diverse, and consists only of theropod and sauropod tracks. None of the formations has yielded crocodylian tracks.

Both the Sichuan and Mishi-Jiangzhou basins show a highly diversity of theropod tracks, including large, medium and small-sized tridactyl specimens, most of which are referred to *Grallator*-type and *Eubrontes*-type (Table 2). Both also yield significant didactyl tracks representing the Deinonychosauria: cf. *Dromaeopodus* from the Jiaguan and Feitianshan formations and *Velociraptorichnus* from the Jiaguan and Xiaoba formations. This indicates the success of deinonychosaurian trackmakers during the Early Cretaceous in the paleoenvironments represented by these deposits. In addition, the Jiaguan Formation has yielded unique specimens, including the world smallest theropod track *Minisauripus* and the bird tracks *Koreanaornis* and *Wupus*. The Feitianshan Formation also contains *Siamopodus*.

Brontopodus type tracks from the Feitianshan Formation are the first clearly described record of sauropod tracks in the Cretaceous strata of Sichuan Province. They are known from both the Jiaguan Formation and Xiaoba Formation. All sauropod tracks are referred to *Brontopodus* type, but the sauropods from the Jiaguan Formation appear to be more primitive than those in the Feitianshan Formation, as indicated by the consistently narrower trackway gauges seen in the Jiaguan Formation. Regarding the ornithischian track record, *Caririchnium* and *Ornithopodichnus* are represented by large and small ornithopod tracks in the Sichuan and Mishi-Jiangzhou basins. In many instances, the ornithopod trackways are parallel, suggesting gregarious behavior. The thyreophoran track *Tetrapodosaurus* has also been reported from the Sichuan Basin, but this is a rare occurrence based on limited material, and probably atypical. Pterosaur tracks, and probably atypical. Pterosaur

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