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A new *Minisauripus* site from the Lower Cretaceous of China: Tracks of small adults or juveniles?

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ABSTRACT

Because skeletal remains of very small theropods are delicate and rare, diminutive tracks provide valuable, additional evidence of body size. The distinctive Asian ichnogenus *Minisauripus* has assumed importance in this debate and has played a role in the challenging question about whether it represents a small trackmaker species or juveniles of a larger species. New discoveries of *Minisauripus* footprints from the Lower Cretaceous Feitianshan Formation at Yangmozu in Sichuan Province, China, support the conclusion that all known examples of this ichnotaxon are small. The main Yangmozu site reveals 65 theropod tracks (~20 trackways) of different-sized trackmakers. Three trackways, comprising 10 pes imprints of 2.5–2.6 cm length, are assigned to *Minisauripus*. The remaining 17 trackways represent small–medium-sized theropods (track lengths 9.9–19.6 cm), including one assigned to cf. *Jialingpus*. All unequivocally identified *Minisauripus* tracks from Korea (five sites) and China (three sites) fall in the size range of ~1.0–6.1 cm. Assuming a small adult trackmaker, and based on standard foot length, leg length and body length ratios, all *Minisauripus* tracks indicate trackmakers with hip heights of <~5.0 and ~28.0 cm and body lengths in the range of ~12.0–72.0 cm. Based on lack of large tracks (longer than 6.1 cm) at any known sites, and various precedents in the ichnological literature we infer that *Minisauripus* represents a small theropod species. However, we cannot completely exclude the possibility that such tracks represent juveniles of larger trackmaking species.

1. Introduction

Body size is an important parameter for understanding theropod biology, and a key factor in bird evolution. While skeletal remains are an obvious source of data on theropod size, very small species and juveniles are rare in most deposits, due to bias against the preservation of delicate bones. Tracks, therefore, are useful in indicating the size and frequency of small trackmakers. Although comparatively rare, well preserved assemblages of small or "diminutive" theropod tracks (length <~5.0 cm) include dune assemblages from the Jurassic of the western USA (Rainforth and Lockley 1996; Lockley, 2011), and several *Minisauripus* assemblages from the Cretaceous of China and Korea (Zhen et al., 1994; Lockley et al., 2008; Kim et al., 2012). Although small tracks might also be rare due to preservational bias (Leonardi, 1981), this explanation is weakened by the abundance of small bird tracks, particularly in the Cretaceous of China and Korea, in some cases at the same sites as *Minisauripus*.

Various Jurassic assemblages have been interpreted as evidence that desert faunas were characterized by diminutive species (Rainforth and Lockley, 1996). In the case of *Minisauripus* the debate has not been about palaeoenvironmental influences, but rather about whether the tracks represent a small species or juveniles of larger species (Kim et al., 2012). As new evidence accumulates, such as that from the Yangmozu site described here, it becomes easier to discuss this question. As noted below, both tracks and pes skeletons of small individuals are known and can be compared. Ideally it should be possible to identify likely trackmakers for known tracks, or tracks for known trackmakers, if not at the species level, then perhaps at the genus or family level.

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At present, the smallest known skeleton of an adult non-avialian theropod is *Anchiornis*, with a total skeletal length of between 34 and 40 cm (Xu et al., 2009; Hu et al., 2009). Others are *Epidexipteryx*, a non-avialian in some phylogenetic analyses, the dromaeosaurid *Microraptor*, the troodontid *Mei*, and several alvarezsauroids such as *Xixianykus* and *Parvicursor* (Karhu and Rautian, 1996; Xu et al., 2000, 2010; Xu and Norell, 2004; Zhang et al., 2008).This is not to imply any demonstrated correlation of these potential trackmakers with *Minisauripus*. For any such correlations to be convincing, in addition to correlation between foot and footprint morphology, feasible geographical and stratigraphic distribution of tracks and potential trackmakers should also be demonstrated.

Minisauripus, originally classified as an ornithopod track (Zhen et al., 1994), but later unequivocally recognized as a theropod track (Lockley et al., 2008) is the smallest known non-avialian theropod track ichnogenus. The smallest *Minisauripus* specimen is 1.05 cm long (CUE 08 1003, Kim et al., 2012). Small theropod hip height is generally estimated as 4.5 times foot length (Thulborn, 1990), and body length can be estimated at 2.63 times hip height (Xing et al., 2009). Based on this method, and assuming an adult trackmaker for the smallest *Minisauripus*, a hip height of 4.7 cm and a body length of just over 12 cm can be calculated. Assuming a juvenile trackmaker, values might be overestimates because of the relative larger pes length compared with the leg length that occurs in some juveniles and paedomorphic forms (Lockley, 2007). Even the largest (presumably adult) *Minisauripus* (foot length 6.0 cm) implies an estimated hip height and body length of ~27.0 and ~71.0 cm, respectively.

Unlike tracks of the *Grallator* type, which are widely distributed and variable in size (Lockley et al., 2013), *Minisauripus* has a unique morphology and is presently regarded as an Early Cretaceous ichnogenus endemic to East Asia (Kim et al., 2012; Lockley et al., 2013). Prior to this study ~82 *Minisauripus* tracks, representing at least 52 trackways, had been documented from two Chinese (Emei and Houzuoshan) and five Korean (Gain, Sinsu, Godu, Buyun, and Gae Je) localities (Kim et al., 2012). With the addition of the present report, a total of ~92 *Minisauripus* tracks, representing at least 55 trackways, are now recorded from a total of eight localities.

Investigations of Cretaceous tracksites in Zhaojue County, Sichuan Basin by L.X. and M.G.L. in 2013 and 2014 revealed three new tracksites with hundreds of footprints of sauropods, ornithopods, theropods, and pterosaurs (Xing et al., 2013, 2014a, 2015). Meanwhile, in June 2013, the Regional Geological Survey Team from the Sichuan Bureau of Geological Exploration and Development of Mineral Resources, reported middle-sized tridactyl tracks found during geological mapping along the western outskirts of Luowuyiti Village, Yangmozu Township, Zhaojue County (Fig. 1). Subsequently, L.X and M.G.L. investigated the tracksite and identified it as the third *Minisauripus* site known from China. In the following sections, we describe this assemblage in detail and discuss arguments supporting either small adult or juvenile trackmaking groups.

1.1. Institutional and location abbreviations

CU = University of Colorado, Denver, USA; IVPP = Institute of Vertebrate Paleontology and Paleoanthropology, Beijing, China; NIGP = Nanjing Institute of Geology and Palaeontology, Nanjing, China; UCM = University of Colorado Museum of Natural History, Boulder, USA.

1.2. Ichnological abbreviations

L/W = length/width; M = mesaxony; ML = maximum track length; MW = maximum track width; ML/MW = maximum length/maximum width; PL = step length; SL = stride length; PA = pace angulation.

2. Geological setting

The southwestern area of Sichuan Province, consisting of Liangshan autonomous prefecture and Panzhihua city, is commonly known as the Panxi (Panzhihua–Xichang) region. Here, Cretaceous formations are widely exposed, and the largest accumulations are in the Mishi (Xichang)–Jiangzhou Basin (Luo, 1999). Based on ostracods and charophytes, the Cretaceous sediments in the Mishi–Jiangzhou Basin can be divided into the Lower Cretaceous Feitianshan and Xiaoba formations, and the Upper Cretaceous–Palaeogene Leidashu Formation (Gu and Liu, 1997).

Rhythmic bedding in the Lower Cretaceous Feitianshan Formation consists of purplish red and brick-red medium-grained feldspathic quartzose sandstone, siltstone, and shale overlying silty mudstones of the Guanggou Formation, which is considered to be Jurassic in age. The Feitianshan Formation is Berriasian–Barremian in age (Tamai et al., 2004). The Lower Member of the Feitianshan Formation, 517 m thick, comprises fluvial and lacustrine delta facies. The Upper Member, 604 m thick, belongs to lacustrine delta facies (Xu et al., 1997). Dinosaur tracks from the Lower Member of the Feitianshan Formation are preserved in purplish red, medium-grained quartzose sandstone (Fig. 2). Diverse invertebrate trace fossils, ripple marks, mud cracks and raindrop imprints indicate a lakeshore environment (Lim et al., 2002).

3. Methods

Ladders, scaffolding and the help of a professional mountaineering team were used to gain access to most of the track-bearing portion of the surfaces. This permitted examination of the tracks at close quarters, and allowed us to make a chalk grid over the main body of the track-preserving surface. The grid was divided into 50 cm squares, which were photographed separately using a digital Canon 5D MKIII camera. The photographs were merged using Adobe Photoshop CS6, and the distribution pattern was mapped from the composite image. As a back-up, the surface was also mapped on graph paper using traditional methods. This allowed the map to be used to record information on individual tracks and plot the location of those tracks that were traced, moulded and replicated.

Individual tracks were also photographed and outlined with chalk prior to being traced on transparent acetate (CU tracing T 1653) and other plastic sheets. Once all the tracks in the uppermost sector of the outcrop had been outlined, a large sheet of transparent plastic was used to trace most of the trackway segments in this sector. Well-preserved tracks, which were moulded with latex, have been converted into plaster of Paris hard copies and are deposited at the CU and UCM in the series 214.286–214.293.

4. The Yangmozu tracksite

Almost all the tracks identified here are from the Yangmozu site I (YMZI) where they are preserved as natural casts on steeply inclined bare rock surfaces, which form a steep overhang dipping west at 45° (Fig. 1). This overhang represents a bedding surface about 5 m above the base of the thick sandstone-dominated sequence making up the Feitianshan Formation, in which there are only a few fine siltstone and mudstone intercalations. This contrasts with the underlying silty mudstones of the Guanggou Formation, which contain few sandy units. Poorly preserved tracks occur at the base of the Feitianshan sequence close to the interface with the underlying silty mudstone of the Guanggou Formation. The main track-bearing units described here are associated with the first, silty mudstone intercalation and the thin sandy units that immediately overly it. Other track-bearing surfaces occur higher in the section (Fig. 1), include the site here referred to as YMXII (Yangmozu II) which occurs a little more than 100 m above the main site (YMZI; Fig. 2).