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A POSSIBLE ANKYLOSAURIAN (THYREOPHORA) TRACKWAY FROM THE LOWER CRETACEOUS JIAGUAN FORMATION OF EMEI, SOUTHWEST CHINA: PALEOECOLOGICAL IMPLICATIONS

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Abstract—Ankylosaurian trackways are rare in the Cretaceous red beds of China, and in Asia, in general. Here we report on a possible thyreophoran (ankylosaurian) trackway from the Jiaguan Formation of Sichuan Province, China inferred from an important historical (1970s) report, the first dealing with tracks from this formation. The Jiaguan Formation has recently become well known for an abundance of saurischian-dominated tracksites, indicating that the 1970s report is anomalous. Nevertheless, the record describes a trackway, which represents a large animal with a wide pes up to ~41 cm and a transverse morphology (length/width ~0.8). The trackway is unusual because of the lack of visible manus tracks, perhaps due to preservational factors. The rarity of such trackway morphotypes in China is attributed to the facies preference of Cretaceous ankylosaurians for organic-rich coastal plain substrates, which abound in North America where ankylosaur dominated ichnofacies have been defined.

INTRODUCTION

The Lower Cretaceous Jiaguan Formation in the Sichuan Basin, China, preserves a relatively diverse dinosaur-pterosaur track assemblage, which has produced numerous specimens since 2007, such as the Lotus, Qijiang (Xing et al., 2007, 2013a, 2015a, b), Hanxi, and Gulin sites (Xing et al., 2015c). Xing et al. (2007) incorrectly described ankylosaur tracks from Qijiang, but they were subsequently reinterpreted as undertracks of hadrosaurs (Xing et al., 2015b). Therefore, no unequivocal record of ankylosaurian tracks has yet been found in the Jiaguan Formation.

Nevertheless, the Third Team of The Second Regional Geological Survey Team (TSRGST), Bureau of Geology of Sichuan Province, conducted a regional geological survey in the Emei area (Fig. 1) from May, 1967 to August, 1971 and produced the 1:200,000 Emei Map Sheet H-48-20 (TSRGST, 1971). The cartographer recorded an occurrence of dinosaur tracks from Chuanzhu in the Emei area (TSRGST, 1971: P. 60 and Fig. 48). In the 1980s, the Chongqing Natural History Museum and Beijing Natural History Museum, following the map, found some tracks on rock falls at Xinfu Cliff in the Chuanzhu area, including four types of dinosaur tracks and isolated bird tracks (Zhen et al., 1994). However, this investigation did not find the tracks mentioned in TSRGST (1971), possibly due to repeated maintenance of the Chuanzhu highway. The dinosaur tracks found by TSRGST (1971) were most likely destroyed by road repair or collapse.

Lu et al. (2013) briefly described six tetrapod natural deep casts from the Chuanzhu area. In July 2015, the first author found a small number of tracks from siltstone layers during investigations in the same area (Fig. 2). These tracks form the basis for this description.

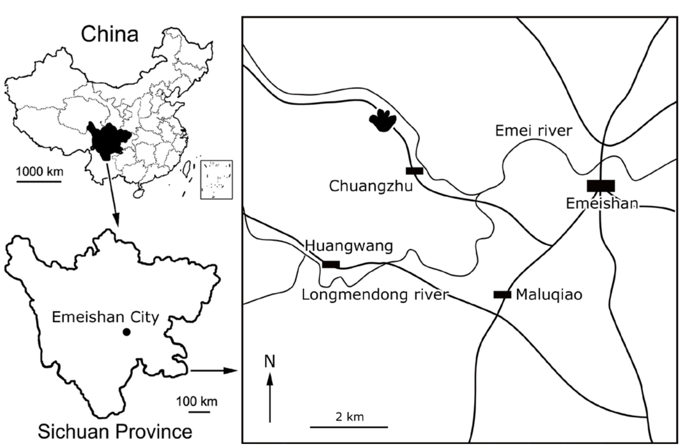

FIGURE 1. Geographic position of the Chuanzhu dinosaur tracksite, indicated by footprint icon.

Abbreviations: CZ = Chuanzhu tracksite, Sichuan Province, China; **I** = isolated tracks; **L** and **R** = left and right; **O**= ornithischian, **P**=pes impression

GEOLOGICAL SETTING

The Chuanzhu site (GPS: 29°36'12.75"N, 103°26'33.14"E) is positioned 6 km west of Emei City and belongs to the Lower Cretaceous Jiaguan Formation. The Jiaguan Formation consists of thick, brick-red, feldspathic, quartz-sandstone (Sichuan Provincial Bureau of Geology aviation regional Geological Survey Team, 1976) (Fig. 3). Below, it is in unconformable contact with the Upper Jurassic Penglaizhen Formation and, above, conformably contacts the sandy conglomerate and mudstone of the Upper Cretaceous Guankou Formation (Gu and Liu, 1997). According to recent palynological studies, the Jiaguan Formation was deposited in the Barremian–Albian stages (Chen, 2009).

Surveys conducted by the Sichuan Provincial Bureau of Geology aviation regional Geological Survey Team (1976) note that the Jiaguan Formation comprises an upper member and a lower member. The lower member is 211–405 m thick and consists of feldspathic quartz sandstone interbedded with layers of mudstone, with a conglomerate thinner than 10 cm at the bottom and 2–10 m thick mudstone at the top. The upper member is 345–1000 m thick and is made up of feldspathic quartz sandstone interbedded with thin layers of lenticular mudstone and siltstone. Other features, like cross-bedding, mud-cracks, rain-prints, and asymmetrical ripple marks, were also reported (Xing et al., 2015b).

PREVIOUS STUDIES

TSRGST (1971, p. 60) notes "no [body] fossil is preserved in Jiaguan Formation and only three westwards trackways are found on surface of brick-red fine sandstone in middle Jiaguan Formation beside Chuanzhu highway (1 km west of Chuanzhu Commune)." This constitutes one of the earliest reported record of dinosaur tracks from the Jiaguan Formation, which has yielded many tracksites. The report also provides a sketch of a trackway comprising eight tracks with a detailed outline for one of them (Fig. 4). The authors also point out the positions of the heels and the variation in track depths. The deepest track measures 6–7 cm in depth.

MATERIALS AND METHODS

In the following description we a base our analysis on the illustration (Fig. 4) preserved in the 1971 files (TSRGST, 1971, fig. 48). The unnumbered trackway from the *1971 files* composed of eight tracks at the Chuanzhu site by TSRGST (1971) is catalogued as CZ-O1-

FIGURE 2. The outcrop of the Chuanzhu dinosaur tracksite.

RP1–LP4. One isolated natural cast indentation is catalogued as CZ-I1.

The gauge (trackway width) of the quadruped trackway was calculated for pes and manus tracks using the ratios WAP/P'ML and WAM/M'ML (Marty, 2008; Marty et al., 2010). We here use the classification scheme of Marty (2008), in which a value of 1.0 arbitrarily distinguishes narrow gauge from medium gauge trackways: the ratio 1.2 distinguishes between medium gauge and wide gauge trackways, and a ratio above 2.0 indicates very wide gauge (Marty, 2008).

DINOSAUR TRACKS

Description

All tracks from the CZ-O1 trackway are similar in morphology. They are tetradactyl, and the trackway is very wide gauge (WAP/P'ML=2.4; Marty, 2008), with slight (~3–7°) outward rotation from the trackway axis. The trackway lacks manus impressions.

In the best preserved track (CZ-O1-LP3), sediment displacement rims are indicated both anteriorly and posteriorly (TSRGST, 1971). Based on the scale, this track is ~31 cm long and ~ 41 cm wide, with a L/W ratio of 0.8. Digit III is the most forward projected. The four digits are similar in length (11–12 cm). Digit II is the narrowest, digits I, III and IV are smaller in length and width. All digit impressions are terminally blunt. The heel region is the deepest, and is smoothly curved posteriorly, directly facing the boundary between digits I and II. The total divarication angle between digits I and IV is 91°. The average pace angulation is 79°.

CZ-I1 is 30 cm in length and 6 cm deep. CZ-I1 preserves one of the outer digits, either I or IV. Only one of the inner digits is complete. All digits impressions are terminally blunt. They are similar to the CZ-O1 tracks in both size and digit features. A morphologically distinct isolated track (Zhen et al., 1994) has been found at the Chuanzhu site, but is smaller (21 cm in length) with sharper claw marks (Xing et al., 2009), making it different from CZ-I1; this track is referable to the Grallatoridae ichnofamily (Lockley et al., 2013).

Discussion

We describe the CZ-O1 trackway in detail for the first time and determine that they are most likely referable to a thyreophoran (possibly an ankylosaurian). Such tracks are common in the earliest Cretaceous to early Late Cretaceous of Canada (McCrea et al., 2001, 2014) and the western USA (Lockley et al., 2014) and are also known from Germany (Nopsca, 1923; Hornung and Reich, 2014) and Australia (Lockley et al., 2012) but rarely reported from Asia (Fujita et al., 2003).

Whether the manus impressions from CZ-O1 trackway were shallow, and thus not recorded in TSRGST (1971), were overprinted, or not preserved is not determined. They could have been undertracks, although this is not likely if some were 6–7 cm deep.

The Chuanzhu tracks are morphologically consistent with the pes skeletons of some thyreophorans (e.g., Apesteguía and Gallina, 2011). Tetradactyl pes tracks with terminally round and blunt digits are present in the ichnogenera *Tetrapodosaurus* (Sternberg, 1932; McCrea et al., 2001) and *Ceratopsipes* (Lockley and Hunt, 1995). Traditionally, *Ceratopsipes* has been interpreted as a ceratopsian track (Lockley and Hunt, 1995), and *Tetrapodosaurus* as an ankylosaurian track due to their morphologies being similar to the pedal osteology of these two groups (McCrea et al., 2001). These referrals are also supported by comparison of the tetradactyl semiplantigrade and plantigrade ornithischian tracks to the foot skeletons of possible trackmakers (Lockley and Gierliński, 2014). Based on type specimens, *Tetrapodosaurus* isp. has more elongate well-demarcated pes digit traces than *Ceratopsipes* isp. (Lockley and Gierliński, 2014), although there are few prints identified as belonging to *Ceratopsipes* isp. versus *Tetrapodosaurus* isp.

The Chuanzhu tracks are similar to *Tetrapodosaurus* in the following morphological characters: medium–large size (FL = 33.8 cm in the type of *Tetrapodosaurus*), a tetradactyl pes with width greater than length; and a wide-gauge trackway. However, in the typical *Tetrapodosaurus*, pedal digit I is usually the smallest in length and width and points toward the midline of the trackway; digits II–IV are usually similar in length and width and cluster together with their long axes oriented more toward the direction of progression.

Tetrapodosaurus is common in the earliest Cretaceous to early Late Cretaceous, especially in the mid-Cretaceous (Aptian–Cenomanian) of the North American Cordillera (McCrea et al., 2014). In addition to the ankylosaur track occurrences catalogued by McCrea et al. (2001), *Tetrapodosaurus* isp. is abundant in the Dakota Sandstone (Albian–Cenomanian) of Colorado (Lockley et al., 2014) and has recently been identified from the Broome Sandstone (Lower Cretaceous (?Valanginian)) of western Australia (Lockley et al., 2012). The geological range of common North American *Tetrapodosaurus* isp. occurrences is similar to that of the Jiaguan Formation (Barremian–Albian).

Only one other site in China yields similar tetradactyl tracks: the Jishan sites of Shandong Province (Xing et al., 2013b). Nevertheless, the tetradactyl tracks at the Jishan site are small (19–27cm) and narrow-gauge. Xing et al. (2013b) indicate that they have an affinity to *Psittacosaurus*, for which the fossil record is rich in that area. Besides differences in overall size and gauge, digits III and IV of the Jishan specimens are longer than those of the Chuanzhu tracks.

Paleoecology

Tetrapodosaurus isp. and *Tetrapodosaurus*-like tracks are common in Cretaceous formations in North America (especially the Valanginian–Turonian of Canada: McCrea et al., 2001, 2014), and the Aptian-Cenomanian of Colorado (Kurtz et al., 2001; Lockley et al., 2006, 2014; Lockley and Gierliński, 2014). However, until now they were not reported from red bed facies in China. In fact the large number of recent reports of Jiaguan Formation tracksites consistently include a

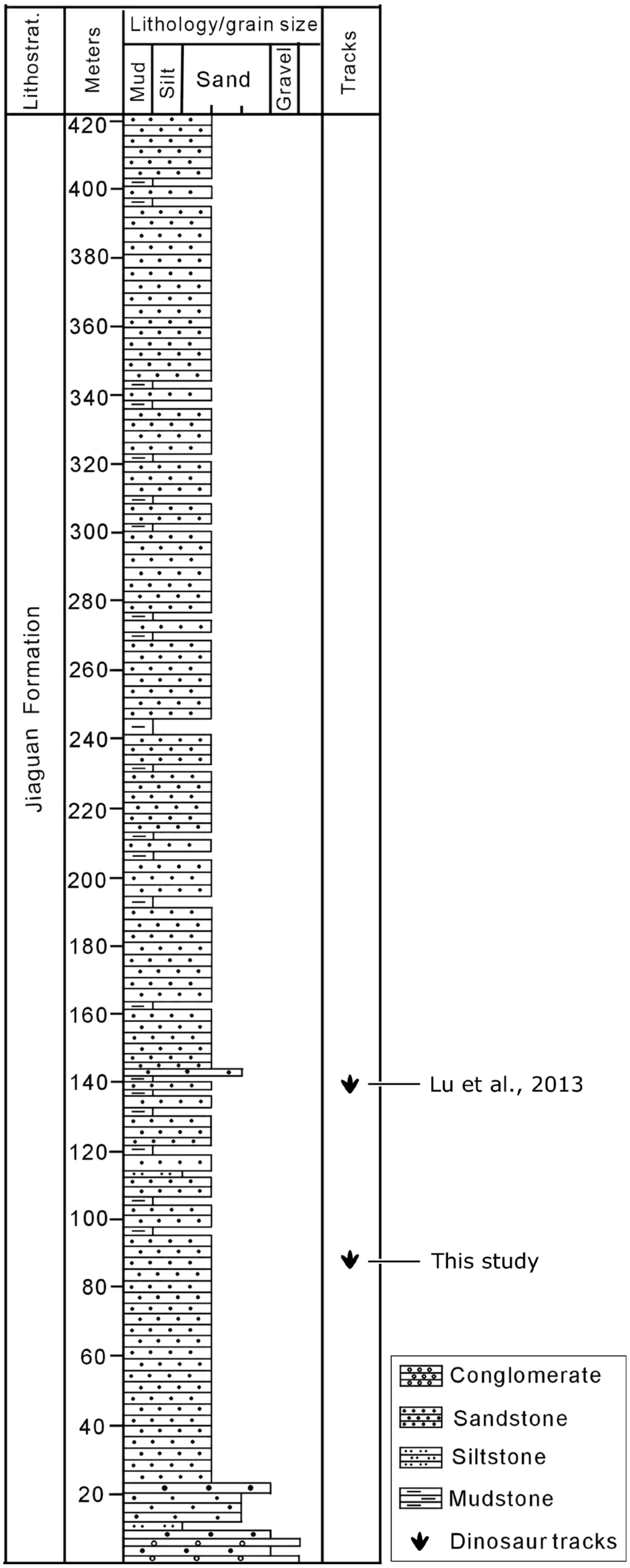

FIGURE 3. Stratigraphic section of the Chuanzhu dinosaur tracksite.

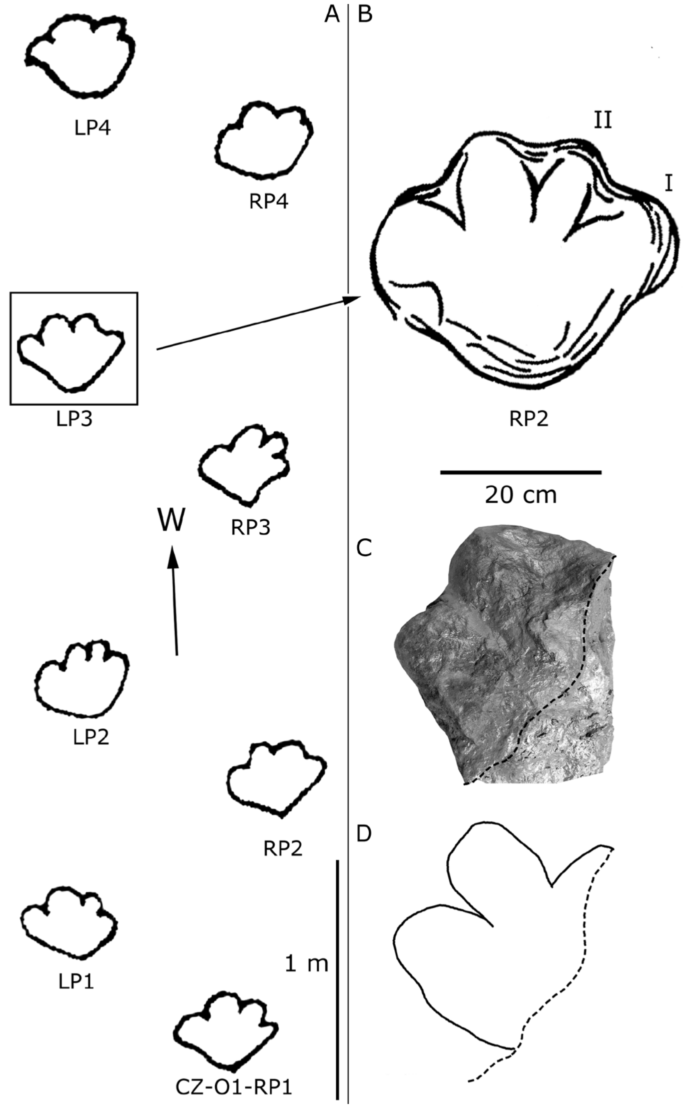

FIGURE 4. Outline drawings of ornithischian trackway CZ-O1 (**A**) and close-up of the best-preserved track (**B**) by TSRGST (1971), and the photograph (**C**) and outline drawing (**D**) of isolated natural cast CZ-I1 from the Chuanzhu dinosaur tracksite.

facies dominated by saurischian tracks (Lockley et al., 2015a; Xing et al., 2015d, 2016) with only relatively rare reports of ornithopod tracks (Xing et al., 2015b, 2016). These differences are likely facies-controlled, indicating that the Chuanzhu occurrence is anomalous. There are some similarities between Chinese and North American ichnofaunas. For example, *Irenesauripus* isp., from the Jiaguan Formation (Xing et al., 2011) resembles Canadian tracks (Sternberg, 1932; McCrea et al., 2014), and *Wupus agilis* from the Jiaguan Formation (Xing et al., 2015a) compares with Early Cretaceous (Albian) *Limiavipes curriei* (McCrea et al., 2014). However, other ichnofaunal signals are different. Crocodilian tracks are absent from Cretaceous facies in China, but common in North America (Lockley et al., 2015b). Likewise, it is becoming evident that deinonychosaur tracksites are far more common in the Cretaceous of China than in other regions (Lockley et al., in press), and the distinctive diminutive theropod track *Minisauripus* is also found only in Asia.

McCrea et al. (2001, 2014) erected the *Tetrapodosaurus* ochnofacies based on a large number of North American ichnocoenoses where ankylosaur tracks were associated with low energy, highly organic substrates and, according to the original definition, little evidence of bipedal trackmakers. These occurrences, also typical of coastal plain facies in Colorado (Lockley et al., 2006, 2014), are often ankylosaur-track dominated. Although ankylosaur tracks may occur in higher-energy deposits with lower organic contents, these surfaces,

TABLE 1. Measurements (in cm) of the ornithischian trackways from Chuanzhu tracksite, Sichuan Province, China.

Number.	ML	MW	ML /MW	PL	SL	PA	I-IV	WAP	WAP /P'ML
CZ-O1-RP1	32.6	43.1	0.8	80.6	108.5	70°	91°	73.4	2.3
CZ-O1-LP1	31.0	39.0	0.8	105.6	101.1	62°	87°	81.3	2.6
CZ-O1-RP2	32.5	38.5	0.8	89.3	131.6	79°	91°	76.6	2.4
CZ-O1-LP2	31.2	41.3	0.8	114.8	138.2	85°	75°	72.7	2.3
CZ-O1-RP3	34.3	38.1	0.9	87.5	135.9	80°	85°	76.3	2.2
CZ-O1-LP3	33.5	45.9	0.7	119.7	125.6	74°	87°	77.2	2.3
CZ-O1-RP4	33.2	42.0	0.8	84.7	—	—	90°	—	—
CZ-O1-LP4	35.1	45.6	0.8	—	—	—	82°	—	—
Mean	32.9	41.7	0.8	97.5	123.5	75°	86°	76.3	2.4

Abbreviations: **ML**: Maximum length; **MW**: Maximum width; **PL**: Pace length; **SL**: Stride length; **PA**: Pace angulation; **I-IV**: angle between digits I and IV; **WAP**: Width of the angulation pattern of the pes (calculated value); **ML/MW** and **WAP/P'ML** are dimensionless.

dominated by bipeds, are not considered part of the *Tetrapodosaurus* ochnofacies (McCrea et al., 2001, 2014). The track-bearing levels in Chuanzhu primarily consist of fluvial siltstone (Lu et al., 2013), indicating a depositional environment unlike the organic-rich coastal plain deposits of North America (Dai et al., 2015).

CONCLUSIONS

A trackway from the fluvial red beds of the Lower Cretaceous Jiaguan Formation at the Chaungzhu tracksite locality indicates a large tetradactyl trackmaker of probable ankylosaurian affinity. The trackway is unusual because it does not preserve manus tracks either due to overprinting or preservational factors. This report is significant due to the scarcity of ankylosaurian tracks in Asia. In contrast, ankylosaurian tracks are abundant in the Cretaceous of North America (Canada and the USA) where they are typically associated with organic rich, low energy coastal plain facies.

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