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# Tetrapod track assemblages from Lower Cretaceous desert facies in the Ordos Basin, Shaanxi Province, China, and their implications for Mesozoic paleoecology

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ABSTRACT

Tetrapod ichnofaunas are reported from desert, playa lake facies in the Lower Cretaceous Luohe Formation at Baodaoshili, Shaanxi Province, China, which represent the first Asian example of an ichnnofauna typical of the *Chelichnus* Ichnofacies (*Brasilichnium* sub-ichnofacies) characteristic of desert habitats. The mammaliomorph tracks, assigned to *Brasilichnium*, represent the first report of this ichnogenus from Asia. The assemblages also contain three different theropod trackway morphotypes: one very wide *Magnoavipes*-like morphotype, one relatively wide, broad-toed, small *Eubrontes*-like form with short steps and strides, and wide straddle, and an elongate morphotype (*Sarmientichnus*) with longer steps and narrower straddle representing a didactyl trackmaker, the latter being the first example of the enigmatic ichnogenus found outside its type area in Argentina. The *Sarmientichnus* occurrence, the first in Asia, has important implications, demonstrating that the trackmaker was not monodactyl, but didactyl with probable affinities to deinonychosaurians which are ichnologically well-represented in the Lower Cretaceous of Asia. Although morphologically distinctive, *Sarmientichnus* should be recognized as a "form" ichnotaxon compromised by suboptimal preservation. The combination of *Brasilichnium* isp., *Sarmientichnus* isp., and tridactyl theropod tracks, indicates mammaliomoprhs and small theropods, and is comparable to ichnofaunas from similar desert facies on other continents. Thus, Cretaceous desert ichnofaunas from China are consistent with global ichnofacies predictions.

## 1. Introduction

Most tetrapod track assemblages from desert deposits are highly distinctive and representative of dune ecology and paleoecology. However, desert sedimentary facies, sensu *lato*, are variable typically including both eolian, dune, and associated interdune or playa lake facies, which are typically associated with localized flooding and the deposition of ephemeral lake deposits. Krapovickas et al. (2016) for example recognized three "desert landscape units": i) eolian dunes, interdunes and sand sheets, ii) wet intedunes, and iii) playa lakes.

Late Paleozoic through Cenozoic dune deposits are generally dominated by tracks of arthropods (insects and arachnids), small reptiles and mammals or protomammals. Ichnologists have remarked on the similarities between Late Paleozoic, Mesozoic (Lockley et al., 1994; Lockley and Hunt, 1995; Hunt and Lucas, 2007) and even Cenozoic dune ichnofaunas (Lockley et al., 2007), which have been characterized as the *Chelichnus* ichnofacies (Hunt and Lucas, 2007; Krapovickas et al., 2016), and also as the *Octopodichnus* or *Octopodichnus-Entradichnus* ichnofacies (Krapovickas et al., 2016). These two ichnofacies are essentially synonymous (Lockley et al., 2007a, 2007b) and more or less co-extensive with desert sand dune (erg) deposits. Thus, differences are mainly semantic, the former using a label based on a vertebrate ichnogenus, the latter based on an invertebrate.

The generalized notion of desert, dune or eolian ichnofaunas and ichnofacies may implicitly include local interdune subfacies in which track assemblages may differ in composition: i.e., "interdune" implies

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within the larger dune or eolian systems (McKee, 1979). There are few formations of predominantly eolian origin that are comprised entirely of dune deposits, without some units of interdune origin (McKee, 1979).

Generally speaking Paleozoic expressions of the *Chelichnus* ichnofacies, well represented in the western USA, are dominated, by the tracks of small protomammals (synapsids) and arachnids (e.g., Lockley et al., 1994) with rare lizard-like (lacertiform) tracks (Haubold et al., 1995). Mesozoic examples of the *Chelichnus* ichnofacies, well represented in North and South America, are characterized by relatively abundant synapsid tracks (*Brasilichnium*), arachnid tracks and footprints of small theropod dinosaurs (Lockley and Hunt, 1995; Hunt and Lucas, 2007; Leonardi, 1981, 1994). These ichnofaunas have been characterized as the *Brasilichnium* ichnofacies, (Lockley et al., 1994, 2004a; Lockley, 2007) which Hunt and Lucas (2007) regard as a subset of the *Chelichnus* ichnofacies, labelled the *Brasilichnium* ichnocoenosis. Cenozoic "eolian" deposit ichnofaunas, also labelled as *Chelichnus* ichnofacies have also yielded abundant small mammal tracks in association with insect trails (Lockley et al., 2007). Krapovickas et al. (2016) proposed five phases of colonization of desert paleonevironments throughout the Phanerozoic of which the first two predate the colonization of continental interiors by tetrapods. This study, while important in recognizing "recurrent patterns" and the diversity of desert paleoenvironemts, focused mainly on invertebrate traces, many of which represent infauna. In contrast, with the exception of tetrapod burrows, most tetrapod traces are epifaunal trackways.

Here we describe tetrapod track assemblages reported from dune and interdune facies developed in the Lower Cretaceous (Barremian) Luohe Formation of Shaanxi province, China (Li, 2017). The assemblage, described here from the Cretaceous "eolianites" in Shaanxi Province China, provide only the second report of *Sarmientichnus*, which, as in Argentina, co-occurs with theropod and small mammal tracks. This makes the Shaanxi ichnofauna exceptional for several reasons. Not only is it a Cretaceous example of an assemblage most similar to ones previously known only from the Jurassic, it is also the first such association from Asia, and the first Asian ichnofauna to be compared closely with the eolian ichnofacies: i.e., the *Chelichnus* ichnofacies. Moreover, we present evidence that ichnogenus *Sarmientichnus* is attributable to a deinonychosaurid trackmaker. This interpretation has both ichnotaxonomic and paleobiological implications for our understanding of the distribution of deinonychosaurian trackmakers and track preservation potential in space and time.

## 2. Geological setting

The Ordos Basin, a large depositional basin in central and western China occupying an area up to 90,000 km$^2$, contains a relatively complete Phanerzoic stratigraphic sequence, with only Silurian and Devonian strata missing. In the center and western part of the basin, continental deposits more than 1000 thick formed in Early Cretaceous times (Xie et al., 2005). These rocks belongs to Zhidan Group and can be primarily divided into the Yijun, Luohe, Huachi, Huanhe, Luohandong and Jingchuan formations from bottom to top (Ma, 1998). The tracks described here come from the Luohe Formation, part of a large continental "red bed" sequence detailed below.

An important vertebrate fossil assemblage, known as the *Psittacosaurus* Fauna, occurs in the Jingchuan and Luohandong formations of the Ordos Basin. The following taxa are present:,chelonia *Ordosemys leios* (Brinkman and Peng, 1993a), *Sinemys gamera* (Brinkman and Peng, 1993b), *S. brevispinus* (Tong and Brinkman, 2013), choristoderes *Ikechosaurus sunailinae* (Brinkman and Dong, 1993), crocodyliformes *Shantungosuchus hangjinensis* (Wu et al., 1994), cf. *Theriosuchus* sp. (Wu et al., 1996), pterosaur Dsungaripteridae (Ji et al., 2017), Cerapoda *Psittacosaurus neimongoliensis*, *P. ordosensis* (Russell and Zhao, 1996), stegosaurs *Wuerhosaurus ordosensis* (Dong, 1993), ankylosaurs Ankylosauria indet. (Ji et al., 2016), sauropod cf. *Euhelopus* sp. (Hou et al., 2017), theropod *Sinornithoides youngi* (Russell and Dong, 1993; Currie and Dong, 2001), large size theropod teeth and Dromaeosauridae teeth (Ji et al., 2017), avian *Otogornis genghisi* (Hou, 1993), *Cathayornis chabuensis* (Li et al., 2008a), primitive mammal *Hangjinia chowi* (Godefroit and Guo, 1999).

Articulated or complete vertebrate fossils from the Ordos Basin are very rare, making species abundance and distribution difficult to determine for this Early Cretaceous fauna. Therefore, abundant trace fossils playing an important role in improving understanding of the ecology of the vertebrate record. There are about 17 tracksites located within the Luohandong and Jingchuan formations with over 1000 trackways reported, including saurischian tracks including the non-avian theropod tracks *Chapus* and *Asianopodus*, the sauropod track *Brontopodus* and the bird (avian theropod) track *Tatarornipes* (Li et al., 2009, 2011; Lockley et al., 2002; Lockley et al., 2011a; Lockley et al., 2014a, 2014b, 2014c). In addition, there are also non-avian theropod tracks, *Jialingpus*, reported from the Luohe Formation in Xunyi County at the southern margin of Ordos Basin (Xing et al., 2014).

Between September and November 2017 a survey of Danxia landforms terrain defined below (Peng, 2001), was undertaken in the study area in northern Shaanxi, by scientists from the Shaanxi Geological Survey Center. They found many dinosaur and other tetrapod tracks in the Luohe Formation near Zhongji Town, Shenmu City, at the northeast margin of Ordos Basin (Figs. 1, 2). These tetrapod tracks form assemblages (ichnofaunas) of a type never previously found in China, and therefore have important paleoecological and ichnofacies implications. Tang et al. (In press) briefly described these tracksites, but did not provide morphologic details of the ichnites.

## 3. Geological setting

The Luohe Group was established by Clapp and Fuller (1926) and originally called the Luohe Sandstone, being defined as a loose massive medium-grained cross-bedded sandstone, pink, pale yellow or bright red in color. The studied section is that of (Clapp and Fuller, 1926). The type section is beside the Luohe River, 40–55 km southeast of Yan'an City, and extends northwest to an area near the Great Wall (Clapp and Fuller, 1926). Ma (1998) redefined the Luohe Formation as a stratigraphic sequence above the Anding Formation (or Yijun Formation) and below the Huanhe Formation or Pleistocene strata. The unit comprises purple or gray purple thick-to-medium grained arkose interbedded with siltstone and mudstone with locally interbedded conglomerate and shale. Large cross bedding can be seen in the sandstone layers (Fig. 3), often indicating alternating paleowind directions (Jiang et al., 2001).

In the present study area in the northeast margins of the Ordos Basin, the Luohe Formation is ~63.8 m thick and generally shows an angular unconformity with the Middle Jurassic Anding Formation below (Fig. 3B). Locally such angular unconformity is not discernable and the contact appears conformable. The Luohe Formation primarily comprises medium-fine grained arkose interbedded with fine sandstone, siltstone or brick red silty mudstone which represent an alternation of eolian and playa lake deposits of the type described by Jiang et al. (2001, 2004), and discussed below.

In China such red bed sequences have been referred to as Danxia landforms and defined, geomorphologically, as "red-colored sandstones and steep cliffs… developed through long-term erosion [which have] in recent years… been receiving international attention, [where] six examples in China became [part of] a UNESCO World Natural Heritage [site] in 2010" (Zhang et al., 2011). According to Peng (2001), Huang and Chen (2003) and Qi et al. (2005) good examples of Danxia landforms exist in northwestern China (Gansu and Shaanxi provinces). Most represent Cretaceous deposits.

The geology of the Luohe Formation in the Danxia landform landscapes of northern Shaanxi Province (Fig. 1) has been described in some detail by Jiang et al. (2001) with attention to paleowind indicators. These authors measured more than 125 foreset orientations indicating