Palaeogeography, Palaeoclimatology, Palaeoecology 423 (2015) 62–79

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Tracking the yellow dragons: Implications of China's largest dinosaur tracksite (Cretaceous of the Zhucheng area, Shandong Province, China)

Martin G. Lockley [a,*], Rihui Li [b], Masaki Matsukawa [c], Lida Xing [d], Jianjun Li [e], Mingwei Liu [f], Xing Xu [g]

[a] Dinosaur Trackers Research Group, University of Colorado Denver, Denver, CO 80217, USA
[b] Qingdao Institute of Marine Geology, China Geological Survey, Qingdao 266071, China
[c] Department of Environmental Sciences, Tokyo Gakugei University, Koganei, Tokyo 184-8501, Japan
[d] School of the Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China
[e] Beijing Museum of Natural History, Beijing, China
[f] Shandong Provincial No.4 Institute of Geological and Mineral Resources, Weifang 261021, China
[g] Institute of Vertebrate Paleontology and Paleoanthropology, Beijing, China

ARTICLE INFO

Article history:
Received 6 September 2014
Received in revised form 15 January 2015
Accepted 24 January 2015
Available online 3 February 2015

Keywords:
Lower Cretaceous
Shandong Province
China
Footprints
Theropods
Sauropods
Turtles

ABSTRACT

Surfaces with more than 2200 dinosaur footprints from the Huanglonggou (Yellow Dragon Valley) site near Zhucheng, in Shandong Province, were excavated for scientific study and with a view to future development as an educational site suitable for further research and tourism. Although geographically close to spectacular and historically famous Upper Cretaceous sites yielding vast bone assemblages, representing giant hadrosaurs and other dinosaurs from the Wangshi Group, the tracksite is in the Lower Cretaceous Yangjiazhuang Formation (equivalent in part to the Longwangzhuang Formation), represents an entirely different dinosaurian fauna, dominated by small theropods. In contrast to a recent pre-excavation study of a localized outcrop which identified only three theropod track morphotypes, in a sample of 135 tracks, the present study has identified at least 2000 additional tracks including those of sauropods and turtles. It is therefore possible to present a more complete interpretation of the site based on the larger and more diverse track assemblage presently exposed. Three theropod track morphotypes are identified as grallatorid morphotypes A and B, with the latter assigned to *Grallator yangi* comb. nov., and *Corpulentapus lilasia*. Tracks have been identified from at least 5 levels, of which level 4 exhibits the vast majority in an excellent state of preservation. Other recent studies, which we re-evaluate, suggest the tracks help define an ENE–WSW shoreline with the lake center to the SSE. In terms of number of tracks documented the Huanglonggou site is one of the largest dinosaur tracksites in China, or indeed in the world.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

As noted by Li et al. 2011 tetrapod tracks were first reported from Shandong Province by Young (1960). He introduced the name *Laiyangpus liui* for multiple parallel scrape marks found in lacustrine deposits of the Shuinan Formation, underlying the Longwangzhuang Formation (Laiyang Group), in Muyudian Town, Laiyang, and attributed them to a coelurosaurian trackmaker. The holotype was subsequently thought lost and the coelurosaurian interpretation was challenged in favor of a possible crocodilian swim tracks origin (Lockley et al., 2010). Recently, the holotype has been relocated and examined by four of the present authors (MGL, JL, LX and XX) who infer a turtle swim tracks origin. Bird tracks (*cf. Tatarornipes*) and a few grallatorid tracks have also been reported from the Laiyang site. In total only a few dozen tracks have been recorded from this site.

The second Early Cretaceous ichnofauna reported from Shandong consists of theropod tracks named *Paragrallator yangi* by Li and Zhang (2000), also from the Longwangzhuang Formation (Laiyang Group), in Longwangzhuang Town, Laiyang. This site has yielded only a few tracks. As discussed below, Xing et al., 2010: p. 1111 consider "the theropod ichnotaxon *Paragrallator* …a *nomen dubium*" and Lockley et al., 2012a, 2013 also agree that this ichnotaxon is in need of revision.

A larger and more important Early Cretaceous ichnofauna is known from the Tianjialou Formation (Barremian–Albian) at Houzuoshan Dinosaur Park in Junan County. The site reveals more than 350 tracks from multiple levels and is the type locality for *Shandongornipes* (Li et al., 2005; Lockley et al., 2007) *Dromaeopodus shandongenis* (Li et al.,

Abbreviations: CU, University of Colorado at Denver, Dinosaur Tracks Museum; IVPP, Institute of Vertebrate Paleontology and Paleoanthropology (Beijing); LRH-ZC, Ri-Hui Li, Zhu-Cheng collection; QIMG, Qingdao Institute of Marine Geology; UCM, University of Colorado Museum of Natural History

* Corresponding author. Tel.: +1 303 5564884; fax: +1 303 5566197.
E-mail address: Martin.Lockley@UCDenver.edu (M.G. Lockley).

http://dx.doi.org/10.1016/j.palaeo.2015.01.028
0031-0182/© 2015 Elsevier B.V. All rights reserved.

2008) and *Minisauripus zhensohounani* (Lockley et al., 2008). A detailed description of ichnological assemblage from this site is given by Li et al., 2015.

As noted by Li et al., 2011, the Huanglonggou site, discovered in 2000 and studied by the three senior authors in 2006 through 2008, then represented the fourth major dinosaur tracksite reported from Shandong Province (Figs. 1–4). Li et al., 2011, p. 423 noted that "collectively these four ichnofaunas indicate that diverse vertebrate ichnofaunas are widely distributed in Shandong Province. The previously un-described Zhucheng… [Huanglonggou] …site reveals at least one distinctive theropod ichnotaxon (*Corpulentapus lilasia* ichnogen. et ichnosp. nov.) unknown from any other sites."

Since 2011 there has been a flurry of publications on additional dinosaur tracksites in Shandong Province. Li et al., 2015 list eight sites. Among these the Linshu site has been described independently by Xing et al., 2013 and Chen et al., 2013; Peng et al., 2013 and Xing et al., 2012 reported pterosaur tracks from the Wenxinyuan site. Other reports of dinosaur tracksites from Shandong Province include multiple sites from the Tancheng area (Kuang et al., 2013; Wang et al., 2013a) and the Tangdigezhuang site in northwest Zhucheng (Wang et al., 2013b).

2. Previous work at the Huanglonggou dinosaur tracksite

The Huanglonggou (Yellow Dragon Valley) site discovered in May 2000 by one of us (RL), is one of the largest and most significant dinosaur tracksites in China. For this reason alone it deserves much attention and careful study. A preliminary study (Li et al., 2011) established that a high density of tracks was exposed in a small stream bed outcrop ~35 m long and ~2 m wide (~70 m^2). This yielded 35 mappable tracks, including the distinctive new theropod ichnospecies *Corpulentapus lilasia* (Li et al., 2011). However, in 2010, soon after this initial study the Zhucheng Government decided to excavate the area so as to expose a total area of about ~1900 m^2 (~38 × 50 m), which was then enclosed with a wall which defines the present boundaries of the 'site' (Figs. 2–4). One of us (LX), was involved in this excavation phase while future plans for research and documentation were in the making. The Zhucheng Government also established an international advisory board to help with the development of the site and other bone-rich Upper Cretaceous dinosaur sites in the region. The senior author ML, and XX, were appointed as members of this board, and in October 2011 ML coordinated an effort to map the site in detail with the help of several of the present authors (RL, MM, JL). The result of this first step was the production of a colorful site map suitable as a template for interpretative signage (Fig. 4). A benefit of exposing this greatly enlarged area of bedding plane was the opportunity to study the huge assemblage of well-preserved dinosaur tracks and other traces in detail (Figs. 3 and 4), based on a much larger sample than was available for the previous study (Li et al., 2011). Allowing for the areas where outcrop is missing within the walled area the total bedding plane surface is on the order of 1400 m^2. Preliminary results of this phase of the work were presented at the 11th Mesozoic Terrestrial Ecosystems Symposium where the map was presented (Lockley et al., 2012b) and it was reported that the site was only one of three in China where turtle tracks had been discovered, in 2011, and simultaneously reported, with notice of those found that same year in Nei Mongol and Xinjiang (Xing et al., 2014) as the first described from China (Lockley et al., 2012c). The aforementioned, re-location of the lost *Liayangpus* holotype adds a fourth occurrence of Cretaceous turtle tracks to the three reported in 2012 though 2014.

After excavation of the site (*i.e.*, removal of the overburden) brief visits were made, in 2010, by several of the present authors and it was observed that sauropod and turtle tracks also occur at the site (Lockley et al., 2012c). It was also observed that tracks are distributed unevenly across the site, with a large concentration of small theropod tracks at the northern, down dip end of the site, and that the turtle tracks are found to the south, where there are few dinosaur tracks. Arrangements were made with the local authorities to remap the whole site. This project was undertaken in October 2011, leading to the results presented below.

Before 2010 the track-bearing outcrop was very localized along the bed of a small stream. However, it was evident that many of the tracks were well preserved, including a morphotype not previously described

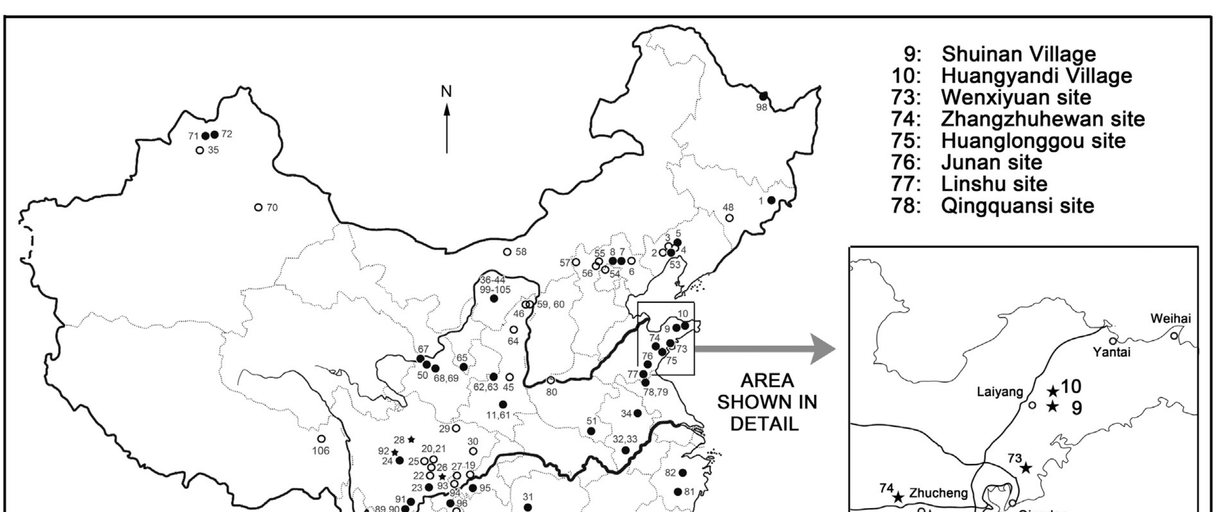

Fig. 1. Locality map. Modified after Li et al., 2014.

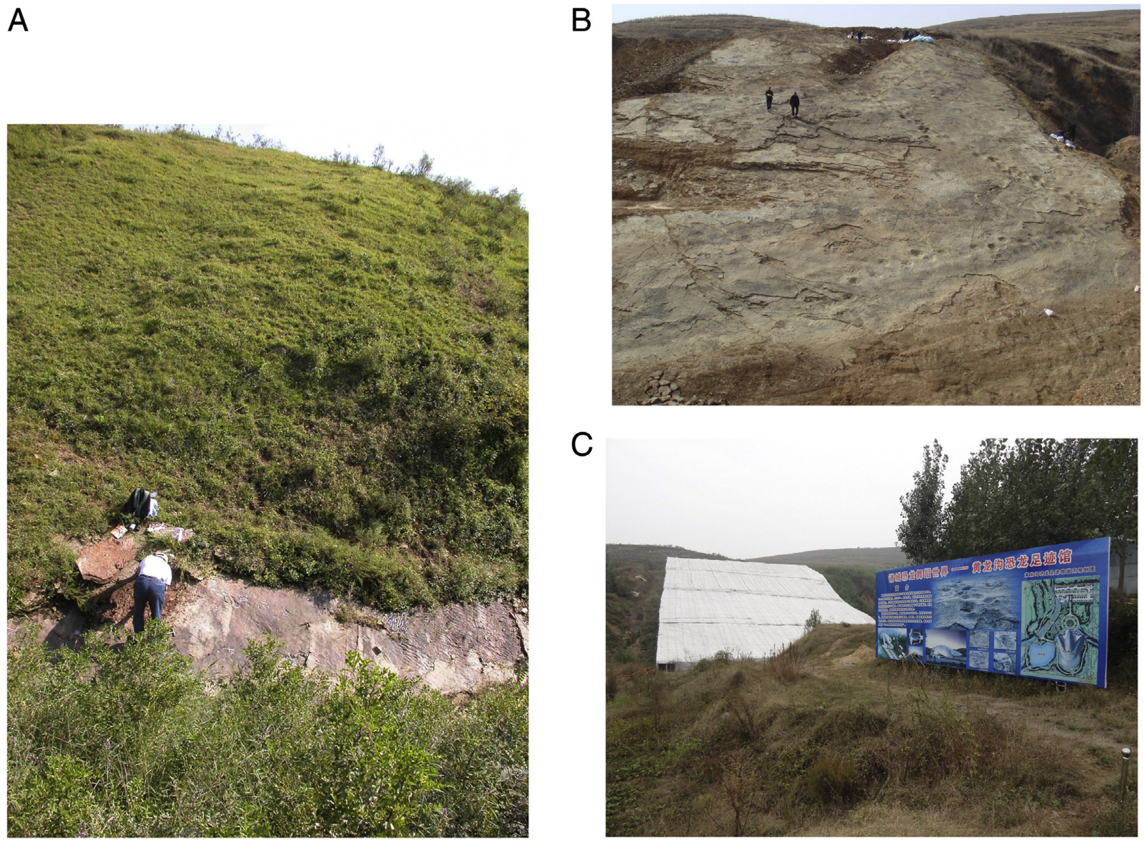

Fig. 2. Photos of Huanglonggou site: A: during field work in 2006–2008, prior to excavation in 2010. B: after excavation in 2010. C: after covering of site with protective roof in 2011.

(*C. lilasia*). Li et al., 2011 inferred that the tracks represent at least three theropod track morphotypes. These included a large unnamed morphotype (footprint length ~ 30 cm), designated as morphotype A, numerous smaller tracks, *cf. Grallator*, designated as morphotype B, that are potentially attributable to the problematic ichnogenus *Paragrallator* discussed by Xing et al., 2010 and Lockley et al., 2013. Prior to any revision of the ichnogenera *Grallator* and *Paragrallator* these are provisionally referred to as "grallatorid tracks." Most significantly the new ichnospecies *C. lilasia* (morphotype C) was described on the basis of distinctive trackways of a medium-sized biped with very short, wide, robust, 'lily-shaped' tracks, and long steps typical of theropods. Representative specimens, including original casts and molds and replicas made from impressions were collected in 2006 and 2008: see Li et al., 2011 for details. Many more *Corpulentapus* trackways were discovered after the 2010 excavation, and following mapping of the site in 2011 more molds were made.

Li et al., 2011 noted that the exposed stratigraphic section at Huanglonggou is very thin (~1.5 m: see Fig. 5) and inferred that the tracks occur in the lower part of the Longwangzhuang Formation which locally consists of track-bearing sandstones overlying mudstones interpreted as the upper part of the Shuinan Formation. Conspicuous ripple marks with a consistent crest trend of 120–300° occur in association with the main track-bearing layer as well as layers a few centimeters below. It was also noted that at least one large theropod trackmaker had created underprints on the main track-bearing surface as the result of having registered footprints on higher surfaces not exposed prior to 2010. Thus, Li et al., 2011 concluded that only theropod tracks were exposed at the site. It should be noted that subdivision and correlation of Cretaceous strata in Zhucheng area have been in dispute: in the Zhucheng area, the expressions of the Longwangzhuang Formation and underlying Shuinan Formation, which are chiefly distributed in the Laiyang area, should be combined under the name Yangjiazhuang Formation in the study area (Shandong Provincial No.4 Institute Of Geological and Mineral Resources, 2003).

In August 2013 Xu et al., 2013 published a moderately detailed description and interpretation of the site, in which they referred to some previous work (Li et al., 2011) but not other reports (Lockley et al., 2012b, 2012c). This study is interesting for several reasons. First, these authors referred to the site as being in the Yangjiazhuang Formation, not the broadly equivalent Longwangzhuang Formation (see explanation above). Second the study was conducted without collaboration with most of the authors of the present study. Third, such independent study has the benefit of allowing future researchers to compare two independent analyses of the same ichnological assemblage. On the other hand such independent work has, in this case, generated significantly different interpretations of the ichnological assemblage, and associated depositional environment evidence. These will ultimately need to be integrated if a reasonable consensus as to the most convincing interpretations is to be achieved.

For the reasons given above we briefly summarize the report of Xu et al., 2013 before presenting our own results. According to Xu et al., 2013, p. 468 they identified 63 trackways, of which 50 were well-preserved and measured. These authors refer to "upper and lower beds" with "abundant wavemarks and mud cracks" providing evidence of superimposition of tracks which indicate that all "tracks were not left at the same time." They inferred a lacustrine paleoshoreline with an EW orientation and a lake center to the S/SW (*i.e.* with the onshore direction to the N/NE: *i.e.* in the present down dip direction). They used these inferences to suggest that the *Corpulentapus* trackmakers "were living much closer to the shore" than the *Paragrallator* trackmakers.

Since the time the field photographs of Xu et al., 2013 (Fig. 2) were taken, the site was enclosed with a low, more or less rectangular cement wall which serves as footpath or walkway (Figs. 3–4). The walkway is about 1 m wide and is horizontal (along strike) along the northern

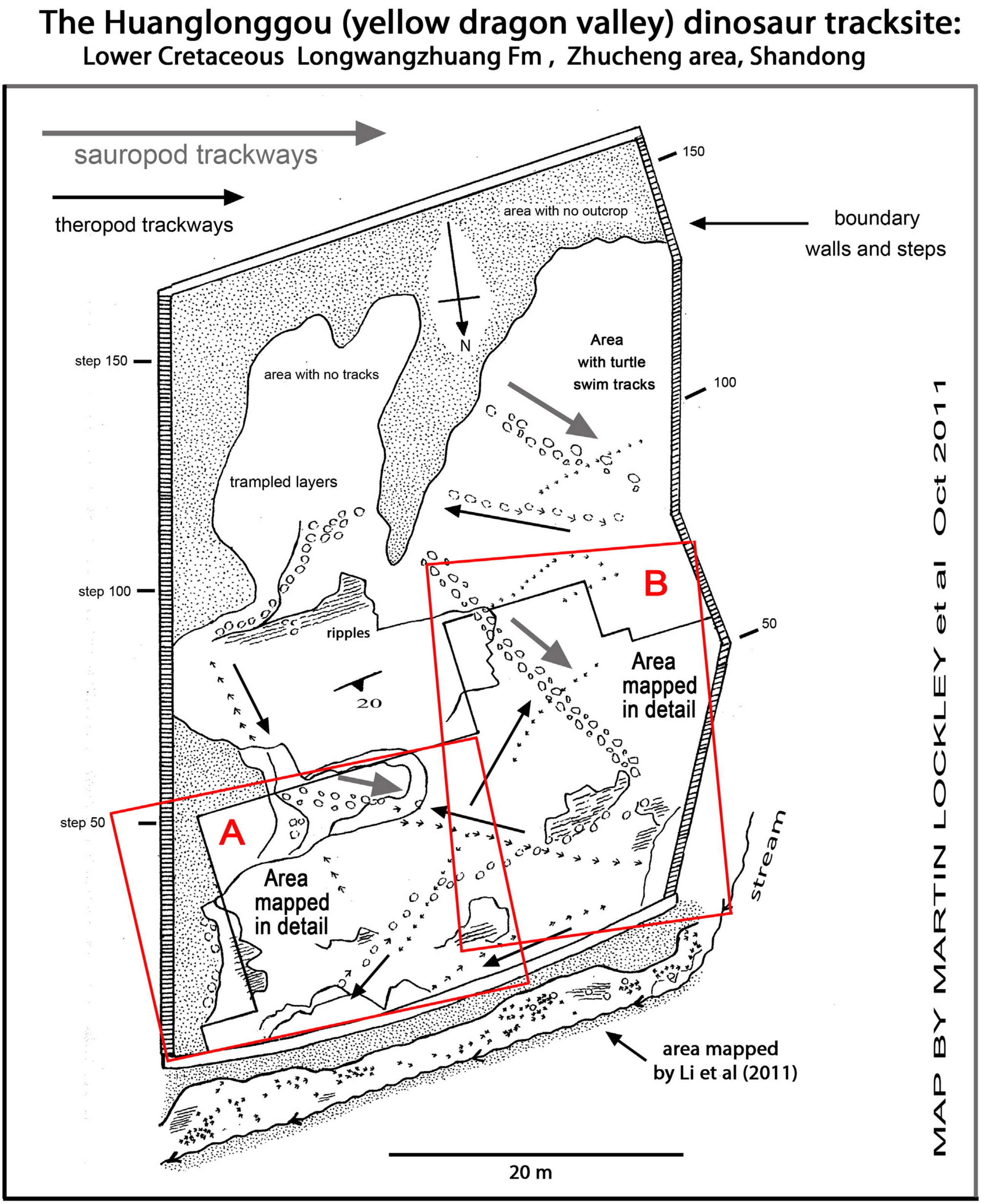

Fig. 3. General map of the Huanglonggou dinosaur tracksite (2011), showing four boundary walls marked by steps and walkways. Note that the site dips north at about 20°. The area mapped prior to excavation runs along the banks of the stream that flowed along strike just north of the present northern boundary walkway: see Li et al., 2011, and areas A and B which correspond to detailed maps presented here in Figs. 6 and 7 respectively.

(lower), and southern (upper) boundaries of the site. Along the eastern and western boundaries, the walkway is a series of steps that traverse the dip slope at an angle of about 20°. These developments were made to protect the site and as an initial step towards developing it as an educational and tourist resource. After excavation of the site, resin was poured and brushed over the surface, with various results noted below, and in 2010 a temporary roof was constructed. One of the results of the excavation was to fill in, at least temporarily, the very small

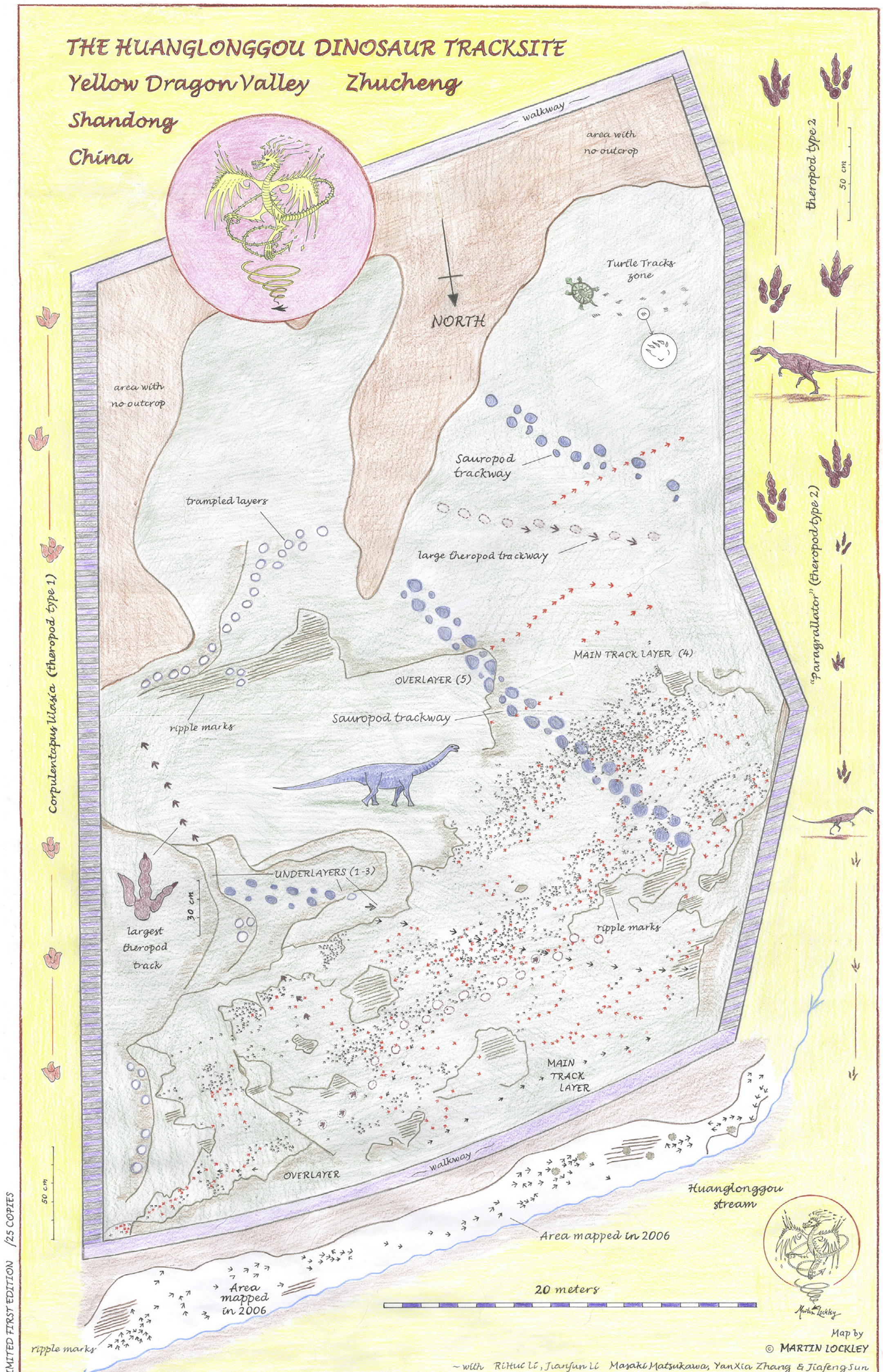

Fig. 4. Pictorial map of the Huanglonggou dinosaur tracksite designed for an interpretative sign. Compare with Figs. 6 and 7. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

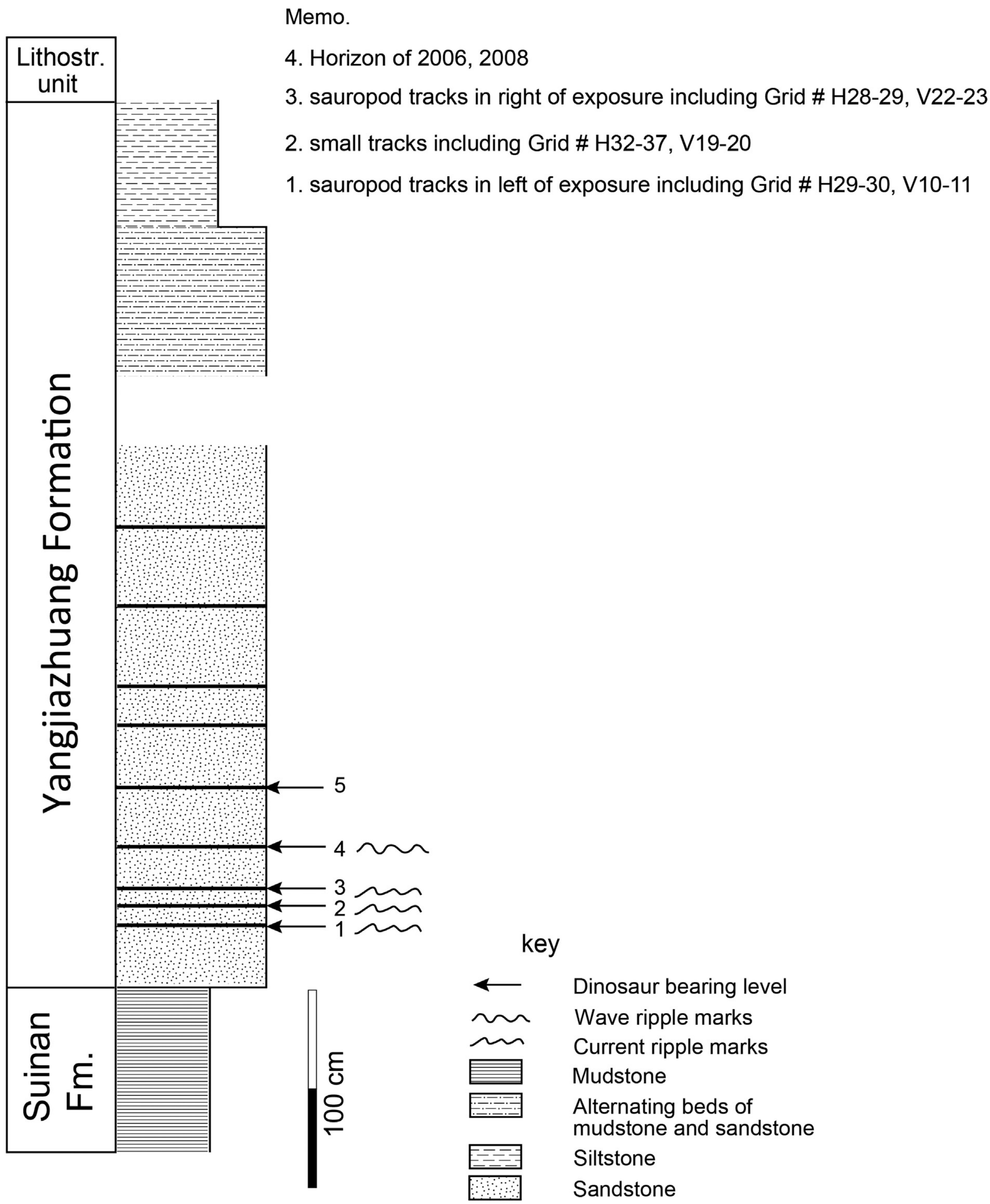

Fig. 5. Stratigraphy of the Huanglonggou site modified after Li et al., 2011, (Fig. 3).

stream that flowed along strike on the northern boundary of the site. The combination of this fill and the construction of the northern boundary walkway have covered the area that was originally mapped by Li et al., 2011. However, as noted below, the same track morphotypes have been identified in the enlarged area now exposed, and a number of specimens and replicas from that area were collected from the area that is now effectively inaccessible.

In this regard it is important to recognize that the map published by Xu et al., 2013 (Fig. 2) was made before the cement wall was constructed. Thus, they were able to show the relationship of the area mapped by Li et al., 2011 to the larger area that had just been exposed. In contrast, by necessity, our maps (Figs. 3–4) show the 2011 map as separate from the rest of the site due the installation of the lower walkway along the northern boundary and the accumulation of excavated debris in this area at the base of the dip slope. It is also worth noting that Xu et al., 2013 mapped the site before it was covered by low (2–3 m-high) scaffolding and heavy opaquely translucent polythene and synthetic canvas sheets (Fig. 1C). Thus, conditions of lighting and illumination were different during both studies. Moreover, as long as the site is covered the potential to obtain 3D images using Lidar or other similar technologies is postponed and compromised. In this regard the use of a resin coating on the track-bearing surface is also a factor which affects present and future results to various degrees.

3. Methods

After the site was excavated and enclosed in the boundary wall, and the surface coated with resin, it was covered with a canvas roof supported by scaffolding. These measures, while protecting the surface from the direct impact of precipitation, have certain drawbacks, including the masking of subtle features by resin, and the reduction and diffusion of natural light. It was therefore decided in October 2011 to map the site using traditional compass and tape methods. Four of the authors formed a team to lay out a chalk grid over the whole site covering an area of about 1900 m^2. The site was then mapped by one of us (ML) on two scales. General reference maps (Figs. 3–4) were made at a scale of 1:200 (0.5 cm = 1 m), and the northern part of the area, where there is a high concentration of small tracks in an area of ~625 m^2, was then mapped at a scale of 1:50 (2 cm = 1 m). While mapping at both scales it was possible to separate out *Corpulentapus* tracks from other morphotypes, based on their distinctive morphology. Due to the high density of grallatorid tracks they could only be mapped at the larger (1:50) scale. Given the large size and semi-pictorial nature of the interpretative color map (Fig. 4), it is not conducive to showing details of the small tracks. For this reason, two maps covering the high density of tracks in the northern area are presented here (Figs. 6 and 7) in order to show the track and trackway distributions more clearly.

After mapping was complete, measurements and tracings were collected for representative, trackways, in all cases choosing only trackway segments where consecutive right and left footprints were identified unambiguously. Measurements were made on site, from the actual tracks, of track length, track width, step and stride using steel tape graduated in millimeters. The tracings were made with transparent acetate film, and these are archived in the University of Colorado collections. The criteria for obtaining trackway measurements were as follows: trackways needed to be well preserved, and steps and, in most cases, also strides in trackways needed to be clearly seen. In general this was easy to do with *Corpulentapus* trackways, and some of the larger non-*Corpulentapus* theropod trackways, However, it was generally difficult to distinguish small theropod (grallatorid) trackway patterns and orientations due to the dense concentrations of tracks of similar size, that often show overlapping relationships. For this reason it has not been possible to estimate the number of grallatorid trackways found at the site, although a more or less accurate estimate of the total number of individual mapped tracks is possible. It is also possible to use the map to show orientations of many of the measured trackways. However, due to the limitations of plotting small footprints in densely tracked areas it is not possible to use the map to reliably measure the orientation of individual small grallatorid tracks (and trackways) other than those for which tracings were made or measurements collected directly (see tabulations herein). However it has been possible to estimate the speeds of dinosaurs using the formula of Alexander (1976) $V = 0.25\ g^{0.5} \cdot SL^{1.67} \cdot h^{-1.17}$ in which V = velocity, g = the acceleration due to gravity, SL = stride length and h = hip height (estimated at 4× footprint length).

Finally, a few sets of overlapping photographs of representative track areas were obtained in order to create 3D images using photogrammetric methods. We have future plans to obtain 3D images of the

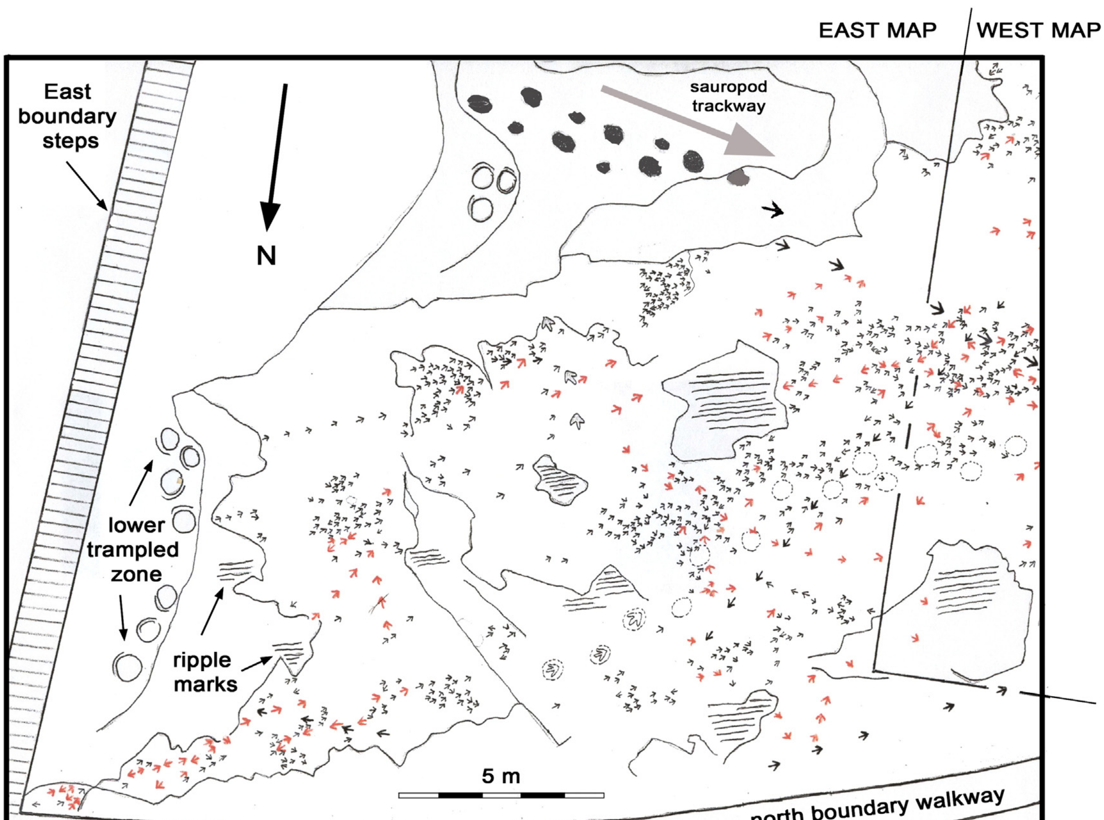

Fig. 6. Detailed map of the eastern sector of the northern portion of the Huanglonggou tracksite. Compare with Figs. 3, 4 and 7. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

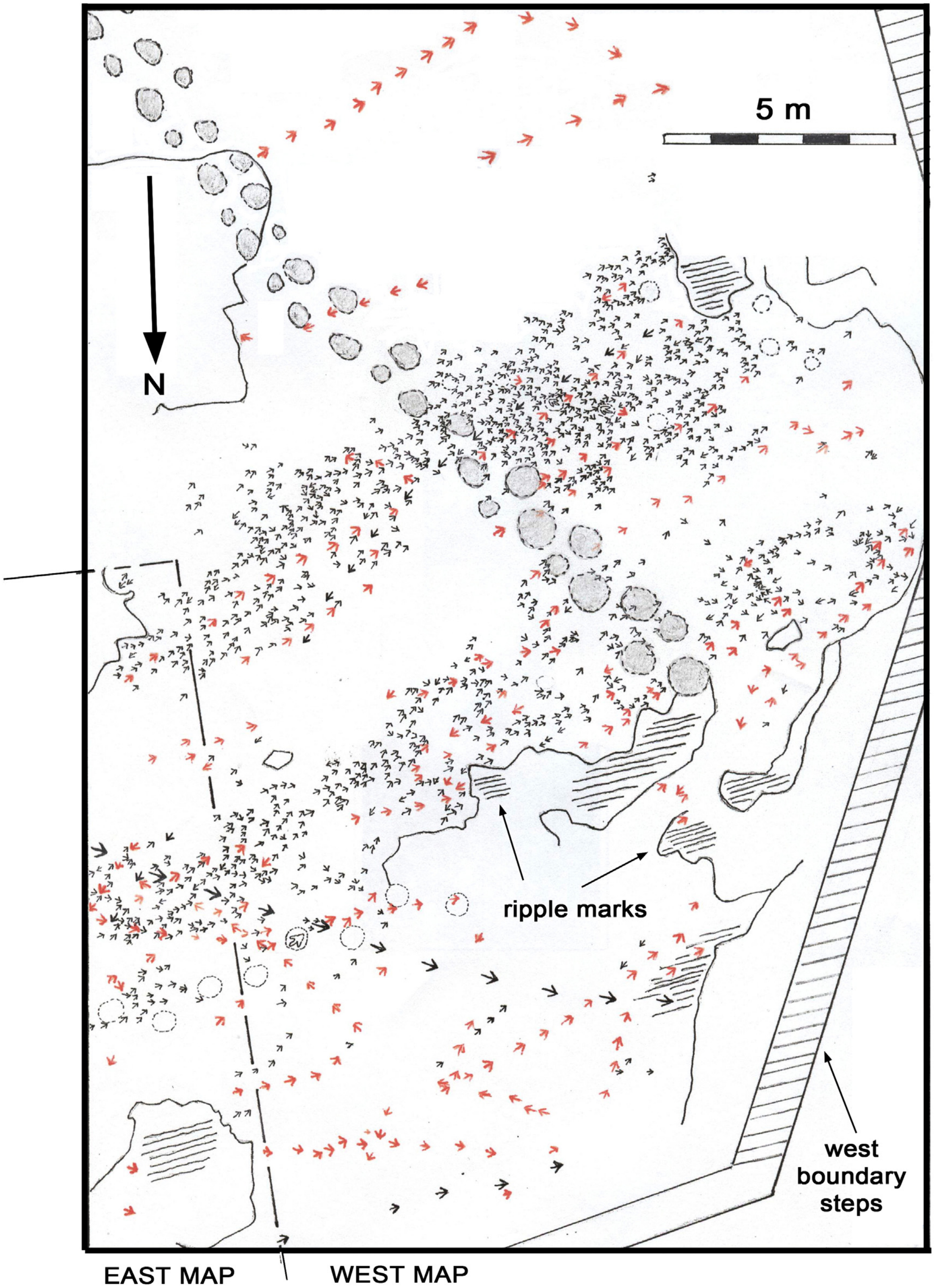

Fig. 7. Detailed map of the western sector of the northern portion of the Huanglonggou tracksite. Compare with Fig. 3, 4 and 6. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

whole site at such time as the requisite technology is available for our use, and the temporary covers are removed. Whether such images are obtained using photogrammetric methods, or Lidar scanning, we anticipate that at least locally, if not for the whole site, it may be possible to obtain more precise orientation data for the large number of grallatorid tracks, and perhaps to discriminate a larger number of reliably-measured grallatorid trackways.

Readers should note that while it is possible to compare the trackway measurements obtained by Xu et al., 2013, (Table 1) with those presented herein, our trackway numbers and measurements were compiled independent of those obtained by these authors, prior to the publication of their results. Thus, the trackway numbers in the two data sets are not the same. In short, the two data sets must be treated as independent samples of the better-preserved trackways from the assemblage.

Table 1
Theropod tracks: morphotype A, showing length (L), width (W), L/W, step stride and speed in m/s. Number (N) of each data set also given. Mean values indicated in bold.

Trackway #	Length (N)	Width (N)	L/W	Step (N)	Stride (N)	Speed (N)
T-1	36.0 (1)	26.0 (1)	1.38	110.0 (1)	–	
T0	34.0 (1)	32.0 (1)	1.06	128.0 (1)	233.0 (1)	2.24
T1	30.2 (3)	19.3 (3)	1.56	123.0 (3)	246.0 (3)	2.82
T2	24.7 (3)	16.0 (3)	1.54	105.0 (3)	211.0 (2)	2.76
T3	25.0 (2)	13.7 (3)	1.82	101.3 (3)	200.5 (2)	2.50
T6	26.2 (3)	16.2 (3)	1.62	110.5 (2)	221.5 (1)	2.80
Means	**29.35 (6)**	**20.53 (6)**	**1.43 (6)**	**112.96 (6)**	**222.40 (5)**	**2.625 (5)**

Thus, they provide a good test case for comparing independently-obtained results.

4. Results

The following results were obtained in the present study:

1) Complete site maps were created at a scale of 1:200 (Figs. 3–4). However, the northern part of the area was mapped at a scale of 1:50 owing to the high density of small tracks. The maps for this area are presented herein in two categories: a pictorial map for general, touristic, interpretative purposes (Fig. 4) and detailed maps for scientific evaluation (Figs. 6–7).
2) A stratigraphic section of the track-bearing area was obtained showing that there are at least 5 different track-bearing layers (Fig. 5).
3) Measurements and tracings were obtained for the best-preserved and most representative tracks and trackways.
4) Trackway orientations were recorded for *Corpulentapus* and sauropod trackways.
5) Molds of representative tracks and trackway segments were made with latex and converted into hard copies in plaster and fiberglass. These include 28 molds collected between 2008 and 2011 and cataloged as UCM 214.121, UCM 214.172 to 214.176, UCM 214.222 to 214.239, UCM 214.242 and UCM 214.249 to UCM 214.252.
6) Based on overlapping photographs of representative tracks, three dimensional photogrammetric images were generated.

4.1. General description of the tracksite

The Huanglonggou tracksite is much larger than any other currently known in Shandong province, in fact, as noted below, in terms of the total number of tracks mapped and recorded (illustrated) in any *bona fide* scientific publication, it is the largest tracksite in China, and one of the largest in the world. The total of about 2200 mapped tracks, is about ten times the number reported from multiple levels at the Houzuoshan Dinosaur Park site in Junan (Li et al., 2014). In comparison with the area (~70 m^2) mapped by Li et al., 2011 the present area is ~30 times larger and there are more than 15 times as many tracks recorded (Fig. 4).

As indicated in Figs. 4, 6 and 7 the tracks are not evenly distributed throughout the area, nor are the five track-bearing levels equally well exposed. Very few tracks associated with the lower three levels (1–3) are exposed, and some of these just show trampling. For this reason it is only level 4 that was mapped in detail. Level 5 appears to have registered only a small number of trackways of large animals that in some areas are transmitted through to level 4 as underprints. In order to present these trackway distribution patterns with graphic clarity, the general site map (Fig. 3) shows only the trackways of the three sauropods and the six largest theropods. All but one sauropod and one large theropod trackway occur within, or cross into, the northern area which was mapped in detail. In the southern area, which was not mapped in detail, many tracks are faint and difficult to interpret, and the outcrop is also more broken up (Figs. 3 and 4).

There are significant ichnological and sedimentological differences between the northern and southern parts of the site (*cf*., Xu et al., 2013), particularly in relation to level 4. As described below, the northern part of the site has a high density of tridactyl dinosaur tracks that are well preserved, and many surfaces show well developed ripple marks. In contrast the southern area has a lower density of tracks in most areas, and those attributed to dinosaurs are mostly undertracks that have been transmitted through from a higher layer, presumably level 5. There are many conspicuous, non-biogenic sedimentary structures such as ripple marks associated with level 4 but less associated with level 5. There are many small tetrapod swim tracks associated with the southern sector of the main surface: these we attribute to turtles (Lockley et al., 2012c). Clearly these differences in the distribution of tracks and other non-biogenic sedimentary structures have a bearing on the interpretations of the local paleogeography as inferred by Xu et al., 2013 and as discussed below.

It is also striking that in the northern area the highest densities of *Grallator* tracks occur in two more or less parallel zones oriented ENE–WSW. As discussed below this pattern appears in some way related to the paleogeography and its influence on sediment consistency in the vicinity of a shoreline.

4.2. Local stratigraphy

The track-bearing surfaces (levels 1–5) constitute the major part of the local outcrop. Most of the exposed surface is here designated as level 4. Although there are some poorly-exposed outcrops of the succession below the main tracksite, there is not much vertical section that is well-exposed above and below the surface of level 4 which constitutes the main part of the whole site. Moreover, it is not possible to unambiguously trace these five levels continuously across the whole area to establish whether or not they pinch out locally or continue as planar units of consistent thickness. For example the surfaces of units 1–3 are mostly overlain by level 4. Nevertheless with a vertical section of only ~1.50 m we have identified at least five track bearing levels, each with significantly different track assemblages and style of preservation. The lowest layers exposed on the eastern side of the site, appear to be trampled zones caused by the registration of sauropod footprints. As there is little areal exposure of these bedding planes little information is available for level 1. Likewise there is limited exposure of level 2. At level 3 however, there is at least one recognizable sauropod trackway. As noted below, the vast majority of tracks occur on the level 4 surface, which has by far the largest exposed area of any of the five track-bearing levels. A small number of tracks found on level 4 are demonstrably undertracks transmitted from level 5. The level 5 track-bearing surface is the second largest in areal extent, exposed mostly in the middle part of the site towards the eastern boundary. As discussed below the impact of level 5 trackmakers on the level 4 surface is of sedimentological and ichnological interest.

4.3. Mapping of the northern area

There are ~2000 tracks in the northern area of ~625 m^2. This is an average density of 3.2 tracks/m^2, although in some areas (Figs. 6 and 7) the density is as high as 30–40 tracks/m^2. Such an abundance of tracks in such a small area makes it difficult to present a single map at a scale suitable for publication. Thus, we present the northern area maps in two sections, suitable for visual inspection, for comparison with the overall site maps (Figs 3 and 4), which shows some of the larger tracks in the southern sector of the site where track density is low.

4.4. Identification and measurement of theropod trackways

It is well established that the majority of tracks from the Huanglonggou site are attributable to theropods. According to Li et al., 2011 there are three theropod track morphotypes referred to as A, B and C. The first is a large theropod morphotype which is easily distinguished from the grallatorid morphotype (type B) and the distinctive ichnospecies *C. lilasia* (morphotype).

4.4.1. Morphotype A

Morphotype A is a typical theropod track, that is easily distinguished from morphotype B on the basis of size and length/width ratio. The average size of morphotype A is three times the size of morphotype B, and the average length/width ratio of the larger morphotype (A) is only 77% that of the smaller morphotype (B). Moreover, morphotype A is uncommon being represented by only six well preserved trackways, whereas morphotype B is extremely abundant.

At least five specimens were molded from the footprints we assigned to morphotype A. These are UCM 214.172, UCM 214.176, UCM 214.229-230 and UCM 214.249 (Fig. 8). UCM 214.250 is also provisionally included in this category. We provisionally label these tracks as large grallatorids in the general sense used by Olsen (1980) when he used the term *Grallator–Anchisauripus–Eubrontes* plexus (GAE) suggesting that all three ichnogenera could be considered sub-ichnogenera in the super ichnogenus *Grallator*. Although this ichnotaxonomy was never formally established by the revision of the type material, and in fact is contradicted by Olsen et al., 1998 in a study which retains the three ichnogenera as separate ichnotaxa, the suggested synonymy has been cited by various workers as a general acknowledgment that the three morphotypes are difficult to separate. The main difference appears to be that larger forms are less elongate (with lower L/W ratios) and weaker mesaxony as measured by the height (or anterior apex) of the anterior triangle defined by Olsen (1980) and used by Weems (1992); Lockley (2009) to analyze differences in theropod track proportions.

The mean length (L), width (W), and L/W measurements obtained for morphotype A from Huanglonggou are 29.35 cm, 20.53 cm and 1.43 respectively based on six trackways of trackmakers with a foot length of 25 cm or more. This footprint length is based on the categories used by Thulborn (1990) and includes footprints from one trackway with a mean footprint length of 24.7 cm (Table 1): the mean step and stride for this sample are 112.96 cm and 224.00 cm respectively. Thus, the mean step length is 3.84 times the mean foot length (L).

We note that with the exception of two trackways, here designated as T4 and T5 (Table 2) with lengths between 18.2 and 20.5 cm, there are few tracks in our measured sample with lengths between about 15 and 25 cm. Thus there is a distinct grouping based on size between a small number of large grallatorids (morphotype A) and abundant small grallatorids (morphotype B). As discussed in the next section the difference between these two morphotypes is not only in size but also in L/W proportions (compare Table 1 and 2) and the degree of weak *versus* strong mesaxony.

As noted above estimates of the speeds of the theropods represented by the trackways included in this categories, defined here, were made using the formula of Alexander (1976): $V = 0.25\ g^{0.5} \cdot SL^{1.67} \cdot h^{-1.17}$. Speed estimates for morphotype A range from 2.24 to 2.80 m/s ($N = 6$). These values translate into between ~8 and 10 km/hr.

4.4.2. Grallatorid morphotype B Grallator yangi comb. nov.

As noted above the small grallatorid morphotype resembling *Grallator* (*sensu lato*) that is so abundant at the Huanglonggou site is similar if not indistinguishable from the problematic morphotype assigned to ichnospecies *P. yangi* (*sensu* Li and Zhang, 2000), originally named from the coeval Lower Cretaceous Longwangzhuang Formation of Shandong Province, and also referred to as *Paragrallator* by Xu et al., 2013: see Xing et al., 2010; Lockley et al., 2013 for further comment on the argument against using this ichnogenus, originally proposed for a Lower Jurassic ichnite from South Africa (Ellenberger, 1972), to name Shandong tracks. Thus, since *P. yangi* is indistinguishable from *Grallator sensu lato*, here we use the combination *G. yangi* as the most appropriate label for the small grallatorid tracks from Huanglonggou (Fig. 9). However, we recognize that careful analysis of various *Grallator* (*sensu lato*) tracks from the Cretaceous of China, and comparison with Jurassic assemblages (Hitchcock, 1858; Olsen et al., 1998) may result in further ichnotaxonomic results. As shown in Table 2 the majority of

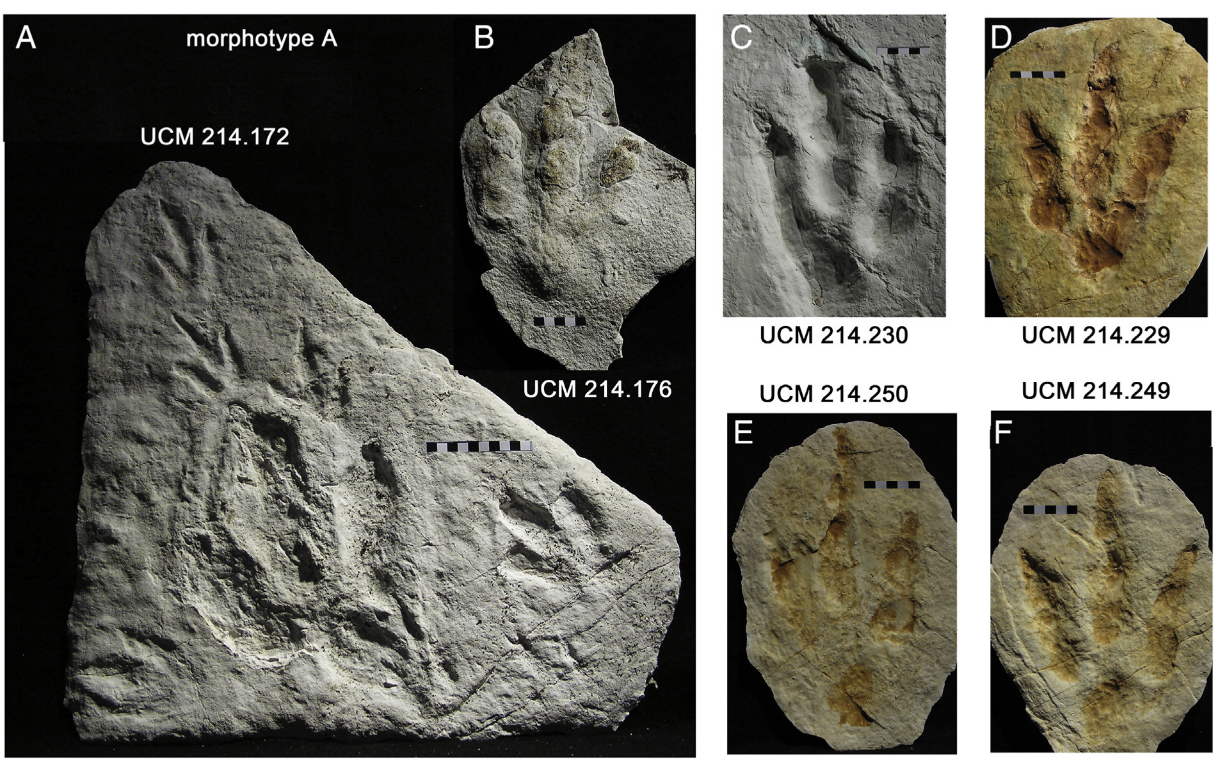

Fig. 8. Theropod tracks designated as morphotype A and represented by replicas in the UCM collections by UCM 214. 172, 214.176, 214.229-230 and UCM 214.249-250. Scale bar 10 cm in A and 5 cm in B–F.

Table 2
Theropod tracks: morphotype B, showing length (L), width (W), L/W, step stride and speed in m/s. Number (N) of each data set also given, with mean values in bold.

Trackway #	Length (N)	Width (N)	L/W	Step (N)	Stride (N)	Speed (N)
T4	20.5 (3)	12.3 (3)	1.67	80.0 (2)	160.0 (1)	2.16
T5	18.2 (3)	10.3 (3)	1.77	84.0 (3)	168.5 (2)	2.71
T7	12.5 (3)	7.0 (3)	1.79	60.8 (2)	121.5 (1)	2.44
T8	14.8 (3)	8.0 (3)	1.85	59.7 (3)	119.2 (3)	1.94
T9	13.0 (3)	7.3 (3)	1.78	63.8 (3)	127.5 (2)	2.52
T10	11.3 (2)	6.2 (3)	1.82	62.0 (2)	124.0 (1)	2.84
T11	11.3 (2)	6.5 (3)	1.74	53.3 (3)	107.0 (2)	2.22
T12	11.8 (3)	6.2 (3)	1.90	61.8 (2)	124.0 (1)	2.70
T13	10.5 (3)	6.0 (3)	1.75	46.0 (2)	92.0 (1)	1.88
T14	8.0 (2)	4.5 (2)	1.78	57.5 (2)	–	
T15	13.2 (3)	6.5 (2)	2.03	61.3 (3)	123.0 (2)	2.33
T16	13.5 (3)	7.0 (3)	1.93	54.8 (3)	109.5 (2)	1.87
T17	10.8 (2)	5.5 (3)	1.96	62.3 (3)	123.0 (2)	2.95
T18	12.2 (3)	6.8 (3)	1.79	54.5 (3)	106.3 (2)	2.01
T19	11.5 (3)	5.7 (3)	2.02	51.3 (2)	102.0 (1)	2.01
T20	13.2 (3)	6.7 (3)	1.97	52.0 (1)	107.0 (1)	1.85
T21	12.5 (30)	6.0 (3)	2.08	68.0 (2)	136.0 (1)	2.94
Means	**12.87 (17)**	**6.97 (17)**	**1.86 (17)**	**60.77 (17)**	**114.15 (16)**	**2.336 (16)**

these tracks fall in the footprint length size range of 8.0–14.8 cm (mean foot length 12.9 cm, footprint width 7.0 and L/W 1.86). Note that compared with morphotype A the difference in L/W ratio is about 30% (*i.e.*, 1.86/1.43 = 1.3/1.00). The mean step length of 60.8 cm is 4.72 times the mean footprint length (L) and thus proportionally longer than the L-step ratio recorded for morphotype A.

Estimates of the speeds of the theropods represented by the trackways included in the morphotype B category, and provisionally labeled as *G. yangi* again were made using the aforementioned formula of Alexander (1976). Speed estimates range from 1.85 to 2.94 m/s (N = 16). These values translate into between ~6.7 and 8.8 km/hr.

4.4.3. *C. lilasia*

C. lilasia is a highly distinctive theropod track morphotype described by Li et al., 2011 on the basis of a small number of trackway segments available for study on the small surface exposed prior to 2010. During the present study 19 *Corpulentapus* trackways (C1–C19) were measured (Table 1), and we herein illustrate several representative replicas in the UCM collections (Fig. 10). In addition, other trackways producing less-precise measurements are identified and shown on the site maps. As noted in Table 3, *Corpulentapus* tracks are relatively wide (L/W = 1.24 compared with 1.43 and 1.86 for morphotypes A and B). As previously noted by Li et al., 2011 a *Corpulentapus* track in the IVPP collections (IVPP 17903) was labeled, incorrectly as *Liayangpus*.

Due to the distinctive morphology of *C. lilasia* (Li et al., 2011) it has been possible to discriminate between this morphotype and the grallatorids assigned to morphotypes A and B. As a result 25 *Corpulentapus* trackways are shown in the maps presented here (Figs. 6 and 7) making it possible to measure their orientations (Fig. 11). The orientations show a strong ENE trend which is parallel to the inferred shoreline orientation.

Estimates of the speeds of the theropods represented by the trackways included in ichnogenus *Corpulentapus* were made using the aforementioned formula of Alexander (1976). Speed estimates range from 1.7 to 3.2 m/s (N = 25). These values translate into between ~6.2 and 11.4 km/hr. Based on these estimates the mean speeds of *Corpulentapus* were closer to those of the large grallatorid morphotype (A) than to the smaller *Grallator* (morphotype B), even though based on track lengths *Corpulentapus* and morphotype B were very similar in size.

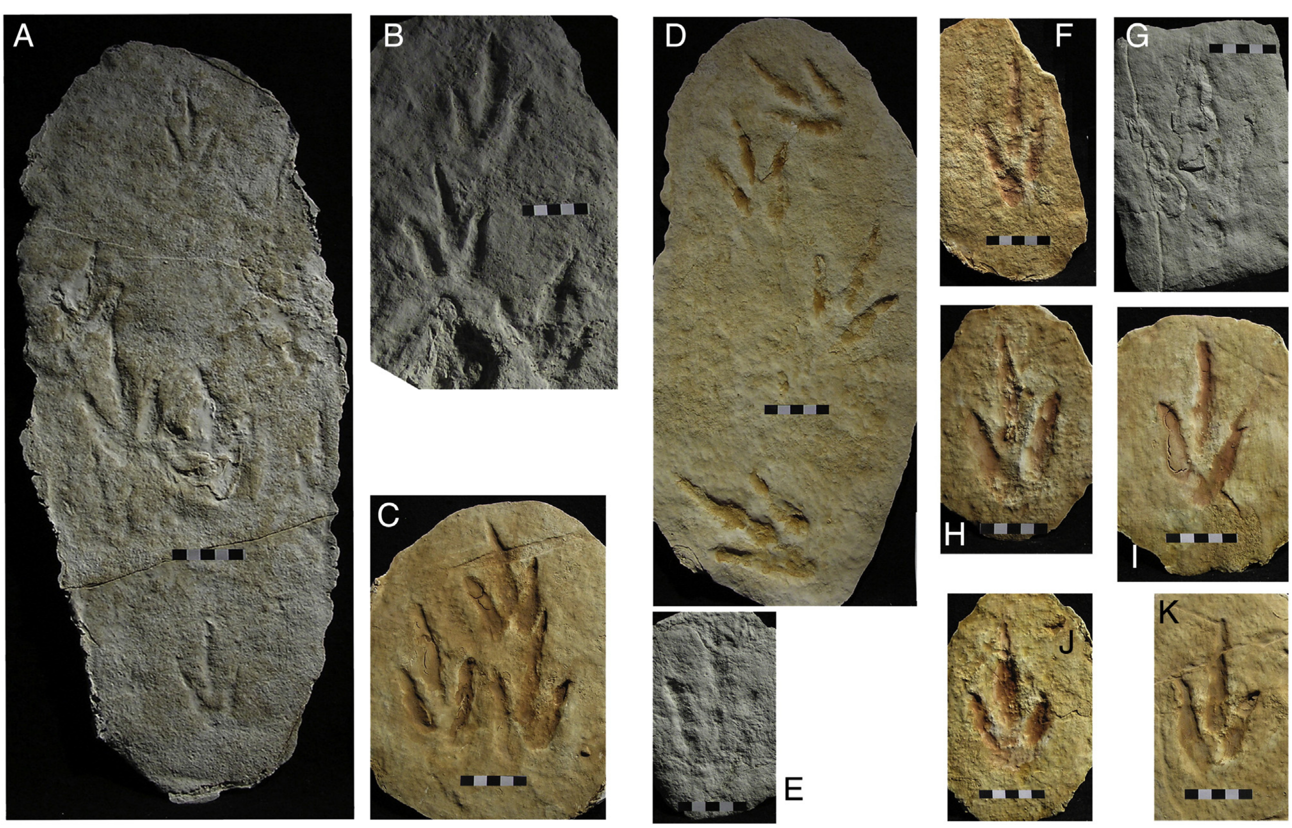

Fig. 9. Grallatorid theropod tracks (morphotype B) represented by replicas in the UCM collections: A: UCM 214.228, B: UCM 214.172, C: UCM 214.227, D: UCM 214.251, E. UCM 214.173, F: UCM 214.225, G: UCM 214.175, H: UCM 214.223, I: UCM 214.226, J: UCM 214.224 and K: UCM 214.222. All scale bars of 5 cm.

Fig. 10. *Corpulentapus lilasia* track replicas represented in the UCM collections. A: UCM 214.172, B: UCM 214.121, C: UCM 214.174 and D: UCM 214.230.

4.4.4. Sauropod trackways

We have identified three unequivocal sauropod trackways that show both manus and pes impressions, and therefore the direction of progression of the trackmakers. The longest trackway segment, oriented towards the NW (Figs. 3, 4, 7 & 11) was evidently registered on level 5 and transmitted through to level 4 as underprints, resulting in track superposition, or strictly what should be referred to as underprint overprinting on pre-formed prints on buried underlayers. The same interpretation of transmission from a higher level onto level 4 is possible for a second, shorter, sauropod trackway segment exposed in the south-western sector of the site. Both trackways have very similar orientations towards the NW (Fig. 11). A third sauropod trackway with a WNW orientation is associated with level 3 (Figs. 3, 4 and 6). The identification of these three trackways as sauropodan is based on three diagnostic factors. The rounded/oval morphology of pes and manus tracks, with the manus tracks being much smaller, the low pace angulation (~100°) and the trackway width, which is much greater than the underprints of large bipeds (theropods) which also occur at the site. As noted below, in our opinion (Xu et al., 2013) misidentified the orientation of both the upper level (level 5) sauropod trackways, and were uncertain about their identification. They also, in some cases misinterpreted sub-oval theropod undertracks in narrow trackways with much higher pace angulations (~160°).

Table 3
Corpulentapus tracks, showing length (L), width (W), L/W, step stride and speed in m/s. Number (N) of each data set also given, with mean values in bold.

Trackway #	Length (N)	Width (N)	L/W	Step (N)	Stride (N)	Speed
C1	13.0 (3)	11.2 (3)	1.16	62.7 (3)	123.5 (2)	2.39
C2	12.2 (3)	9.0 (3)	1.35	60.2 (3)	121.0 (2)	2.49
C3	12.2 (3)	10.0 (3)	1.22	58.0 (3)	115.0 (2)	2.29
C4	11.7 (3)	10.3 (3)	1.14	70.3 (2)	140.0 (1)	3.34
C5	12.3 (3)	10.3 (3)	1.19	62.3 (2)	126.0 (2)	2.64
C6	11.7 (3)	9.2 (3)	1.27	59.8 (2)	120.0 (1)	2.58
C7	13.3 (3)	9.8 (3)	1.36	74.8 (3)	148.5 (2)	3.17
C8	12.5 (3)	10.3 (3)	1.21	66.0 (2)	132 (1)	2.80
C9	12.5 (3)	10.7 (3)	1.17	68.5 (2)	137 (1)	2.98
C10	13.3 (2)	10.5 (2)	1.27	74.0 (1)	–	
C11	11.0 (2)	8.3 (2)	1.32	71.0 (1)	–	
C12	11.7 (3)	9.8 (3)	1.19	47.0 (2)	94.0 (1)	1.72
C13	12.3 (3)	10.3 (3)	1.19	58.2 (3)	117.0 (2)	2.33
C14	12.7 (3)	9.7 (3)	1.31	60.5 (2)	121.0 (1)	2.38
C15	13.8 (2)	10.3 (2)	1.34	71.0 (1)	–	
C16	10.3 (3)	8.2 (3)	1.25	51.5 (2)	103.0 (1)	2.32
C17	13.2 (3)	10.7 (3)	1.23	72.5 (2)	145.0 (1)	3.07
C18	11.0 (3)	10.2 (3)	1.08	58.5 (2)	117 (1)	2.66
C19	12.0 (1)	9.0 (1)	1.33	57.0 (1)	–	
Mean	**12.24 (19)**	**9.92 (19)**	**1.24 (19)**	**63.36 (19)**	**124.00 (15)**	**2.61**

4.4.5. Other tetrapod tracks

As reported by Lockley et al., 2012c there are a large number of small tetrapod tracks that were registered on the southern part of the bed 4 surface. These authors have inferred the trackmakers to have been turtles. The tracks, represented in the UCM collections

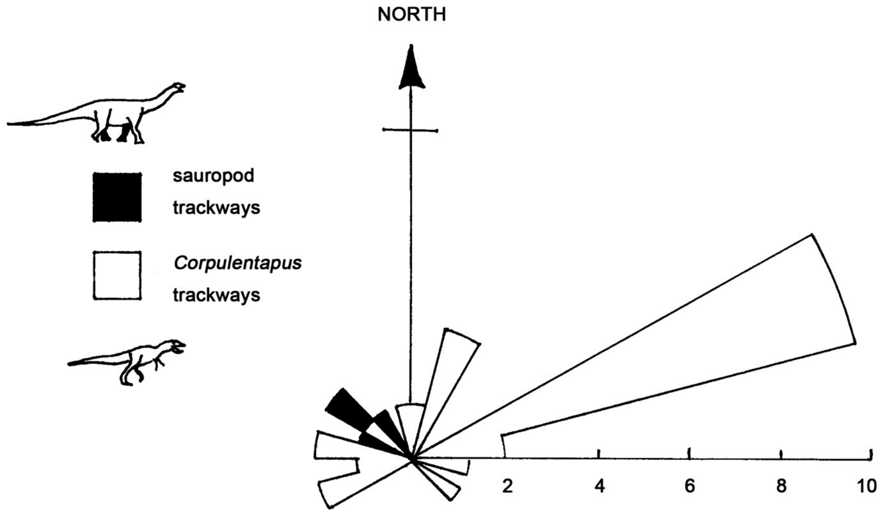

Fig. 11. Rose diagram showing trackway orientations of 25 *Corpulentapus* trackways (white) and three sauropod trackways (black). Note strong ENE trend.

by replicas UCM 214.231-239 and UCM 214. 252 (Fig. 12) are very variable in shape, but generally all are quite small (2–5 cm). Many show at least four parallel toe traces, sometimes short but in other cases extended into elongate scratch marks. The more or less equal lengths of the toe traces are characteristic of both the manus and pes tracks of turtles (although they also characterize pterosaur pes swim traces) (Lockley et al., 2014). One set of tracks (Fig. 11H, I) appears to represent a walking animal that left small circular footprints with a more or less regular spacing pattern. Although various names like *Hatcherichus* and *Characichnos* (Foster and Lockley, 1997; Whyte and Romano, 2001 respectively), which also lend their ichnogenus names to ichnofacies (Hunt and Lucas, 2007; Lockley, 2007) have been applied to tetrapod swim tracks, we consider it premature to name these inferred turtle swim tracks prior to a more detailed study. Moreover, neither of these names could be appropriately applied to the set of tracks inferred to represent walking (Fig. 11H, I). The recent re-location of the holotype of *Liayangpus*, noted above, highlights similarities between this important specimen and those from Huanglonggou. This suggests

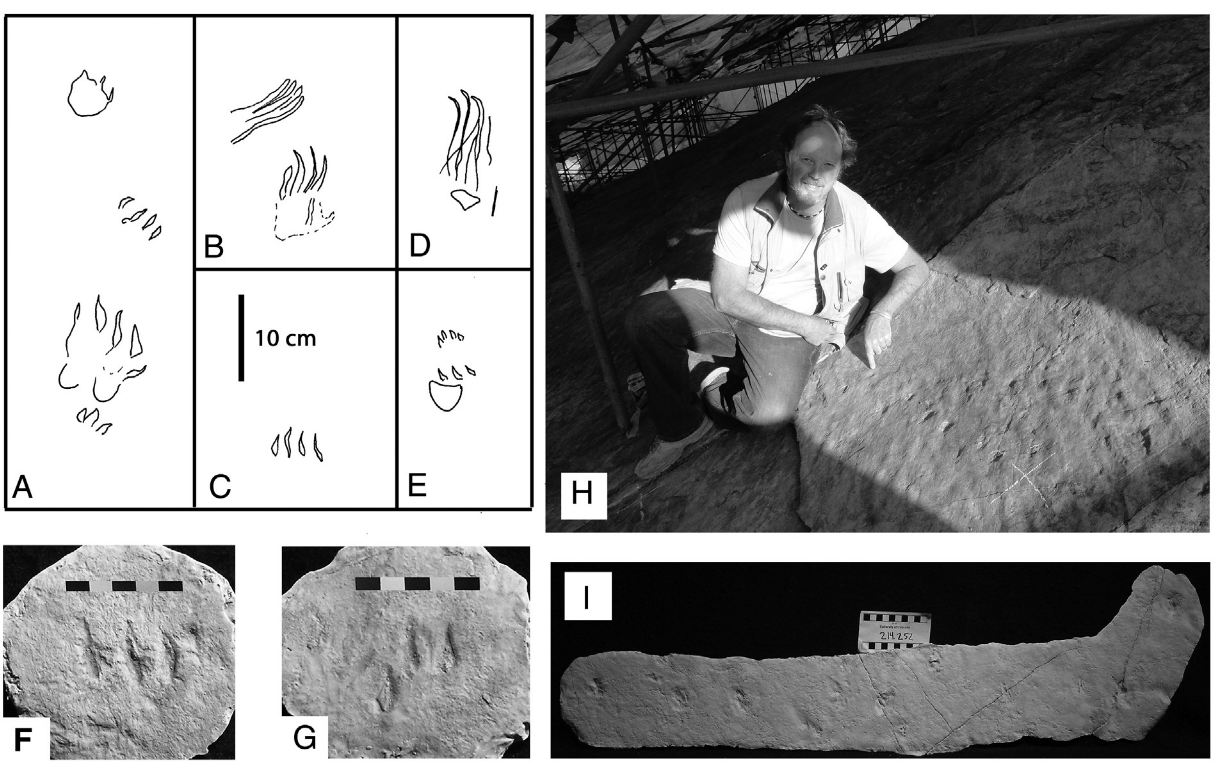

Fig. 12. Turtle tracks from the Huanglonggou site. A–E represent line drawings of turtle track replicas in the UCM collections A: UCM 214. 239, B: UCM 214.236, C: UCM 214.233, D: UCM 214.238, and E: UCM. 214.235. F: photograph of UCM 214.233 (compare with C) and G: photograph of UCM 214.231. H and I outcrop photograph (H) and replica (I) of turtle trackway UCM 214.252. Note scaffolding and plastic roof over site in background of photograph H.

that the ichnogenus label *Liayangpus* must be considered as potentially applicable in any further study of turtle tracks, especially those reported from the Cretaceous of China.

5. Discussion

5.1. General observations

The Huanglonggou dinosaur tracksite is very important for various reasons discussed below. Obviously with such an abundance of consistently well-preserved tracks, occurring at multiple levels in association with various non-biogenic sedimentary structures there is great potential for further detailed study in a number of different directions including: track morphology and ichnotaxonomy, detailed photogrammetric/3D imaging, paleoecological census, track preservation, and local and regional paleoenvironmental analysis. Added to these areas of interest we may also include the potential to develop the site for tourism, and related issues such as comparison of the site with others of global significance (ranking of the sites' importance: *sensu* Alcalá et al., 1972), and long term protection and management.

Clearly we cannot address all these issues in detail in a single paper, and for this reason we consider this paper only a preliminary contribution to the growing literature on the Huanglonggou site (Li et al., 2011; Xu et al., 2013). However, it is important to address previous work, especially in cases where distinctive trackways have been given questionable labels and interpretations (Xu et al., 2013) which we need to re-evaluate. Therefore, for the purposes of clarity, we focus on the following topics:

1) Challenges of mapping and interpreting the whole site.
2) Aspects of track preservation.
3) Comparison of the Huanglonggou tracksite with other large tracksites.

5.2. Challenges of mapping and interpreting the whole site

As noted above we have mapped the whole site (Figs. 3,4, 6 & 7) at two scales. The level of resolution adopted allowed us to plot every track we were able to recognize under two constraints: 1) the low level of illumination available under the plastic and scaffolding roofing in place in 2011, and 2) the covering of the surface by resin. These latter two constraints were not problems facing previous investigators, when the small northern area was mapped in 2006 and 2008 (Li et al., 2011) or when the whole site was first exposed in 2010 at which time there was no roof to affect the illumination (Xu et al., 2013; Fig. 13 herein).

The map produced by Xu et al., 2013, here reproduced with modification, is of a different style from ours (Figs. 3, 4, 6 & 7) because it shows only selected trackways as arrows, not individual tracks. One useful aspect of this map is that it shows the relationship of the whole site to the area mapped by Li et al., 2011. This could not be shown precisely in our study because between the opening of the site in 2010 and the mapping we undertook in 2011, a concrete walkway was constructed more or less in the area of the original exposure (see Figs. 3 and 4). However, the mapping by Xu et al., 2013 suffers several drawbacks: first it does not adequately show the distribution of tracks across the site, second it incorrectly identifies many track types, and third it often incorrectly identifies the direction of progression registered by the trackmakers. We address each of these issues in turn.

First, as shown in Figs. 3, 6 and 7 the highest densities of small theropod tracks clearly occur in two sub parallel zones in the northern part of the area, shown in detail in Figs. 6 and 7. Each of these zones is about 4–5 m wide from north to south and both zones extend more or less continuously, for about 40 m across the whole site from ENE to WSW. The two zones have their centers about 6–7 m apart: *i.e.* with a lightly tracked zone about three meters wide between them. These patterns give insight into the small meter- or micro-scale paleogeography of a Cretaceous shoreline. Two possible explanations for these concentrations are given below. The map of Xu et al., 2013 has a very vague suggestion of concentrations of trackways in the northern sector, but the pattern is not mapped or described in any detail as done here. In addition, there is no reference by Xu et al., 2013 to the many small tetrapod (turtle tracks) found in the southern (southwestern) sector.

Second, regarding trackway and trackmaker identification, Xu et al., 2013 labeled certain large trackways as sauropod/ornithopod, and identified all others as theropodan. In our analysis we recognize no ornithopod trackways, and consider that several of the trackways referred to as sauropod/ornithopod (especially E: see Fig. 13) are in fact undertracks of large theropods: compare with Figs. 6 and 7. In our analysis of the small theropod tracks we were able to distinguish between the wide, ‘fleshy’ track morphotype *Corpulentapus* (shown in red in Figs. 4, 6 and 7) and the elongate tracks here referred provisionally to *G. yangi* (shown in black) in these same figures. The differences between these two morphotypes are quite striking and obvious. For example *Grallator* consistently has very strong mesaxony, well defined pad impressions and sharp distal claw traces, whereas *Corpulentapus* is almost the polar opposite with weak mesaxony, a lack of clear digital pad traces and sharp distal claw traces (Lockley, 2009).

Third the problem of discerning trackway orientations is evident from a comparison of our mapping with that of Xu et al., 2013. In the case of two the large trackways (B and D) of Xu et al., 2013, referred to as sauropod/ornithopod, (Fig. 13 herein) we are able to clearly identity that they are sauropod trackways oriented to the NW, and not to the SE. In the case of the *Corpulentapus* trackways, orientations are very clear and shown in our maps (see Fig. 11 for summary). The orientations of the *Grallator* trackways are more difficult to discern due to the high densities. It is outside the scope of this study to comment in detail on the orientations (purportedly dominantly to the WSW) of theropod tracks and trackways reported by Xu et al., 2013 except as follows. Firstly, Xu et al., 2013 do not discriminate between the two theropod ichnogenera which we differentiate in our maps, and secondly, if their rose diagrams have the same orientation as their maps they appear to show a strong WSW orientation for tracks and trackways. (Alternately they have the north arrow in the correct direction for their rose diagrams but at 180° to the correct orientation of their map). As shown in Fig. 11, the predominant orientation of *Corpulentapus* trackways is ENE, in the opposite direction. Simple inspection of our maps shows that this is the predominant direction of the grallatorid tracks. Why the trackway orientations are unimodal, rather than bimodal as is sometimes the case in shore-parallel trackways (Lockley, 1986, 1991) is a matter of conjecture.

5.3. Aspects of track preservation

In the previous section we noted that Xu et al., 2013 have made what we consider to be some incorrect trackway identifications, in part because of misinterpretation of undertracks. In this section we draw attention to the fact that some of the trackways of the larger animals, notably sauropod trackway B (Fig. 13) are clearly transmitted prints (underprints) when they appear on surface 4. Because they are underprints they appear as large bowl-shaped indentations indenting surface 4 on which many well preserved *Grallator* tracks were registered prior to the deposition of layer 5. For this reason it appears that the *Grallator* tracks are superimposed on the large bowl-shaped indentations when in fact the reverse is the case (Fig. 14). The underprints are the result of the layer above level 4 (*i.e.*, layer 5) which is about 10 cm thick and topped by surface 5, being impacted so as to transmit underprints to surface 4. Because surface 4 was already buried, the small *Grallator* prints were not obliterated as they never came in contact with the sauropod foot. However, in many cases, where the walls of the underprints are steep, the *Grallator* tracks occur on very steep surfaces that have been pushed to inclinations of ~30° or more from the original horizontal orientations (Fig. 14). Tracks in their undisturbed positions (inclinations) relative to the original surface (4) on which they were

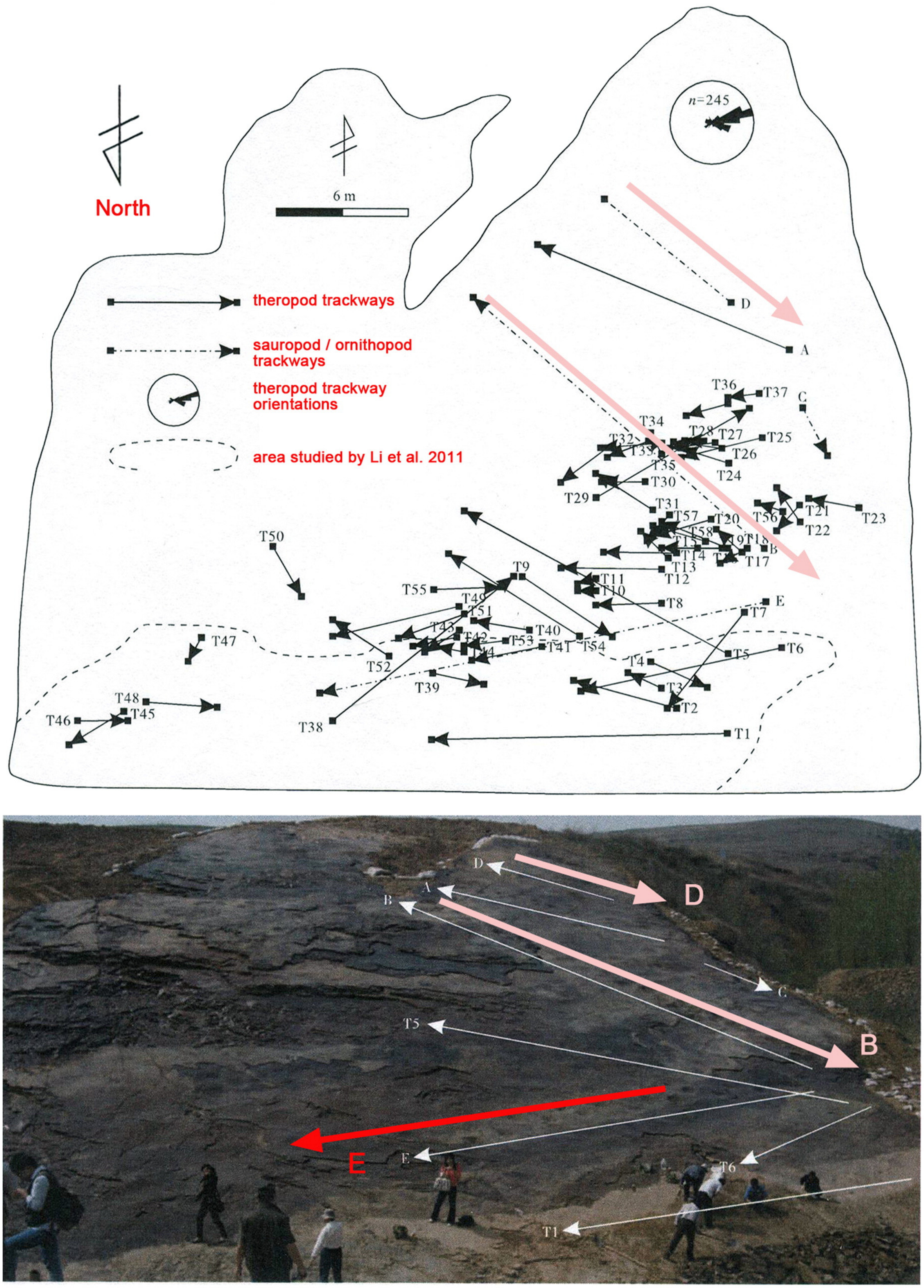

图 2　诸城皇华镇黄龙沟恐龙足迹化石点行迹分布

Fig. 13. Amended version of the Huanglonggou map of Xu et al., 2013, (Fig. 2), showing amendments and translations in red and pink. Note north arrow, and translated labels for arrows on upper map, showing area mapped by Li et al., 2011. Pink arrows for trackways B and D show correct directions of sauropod progression. Red arrow indicates a theropod track (not sauropod). See text for details. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

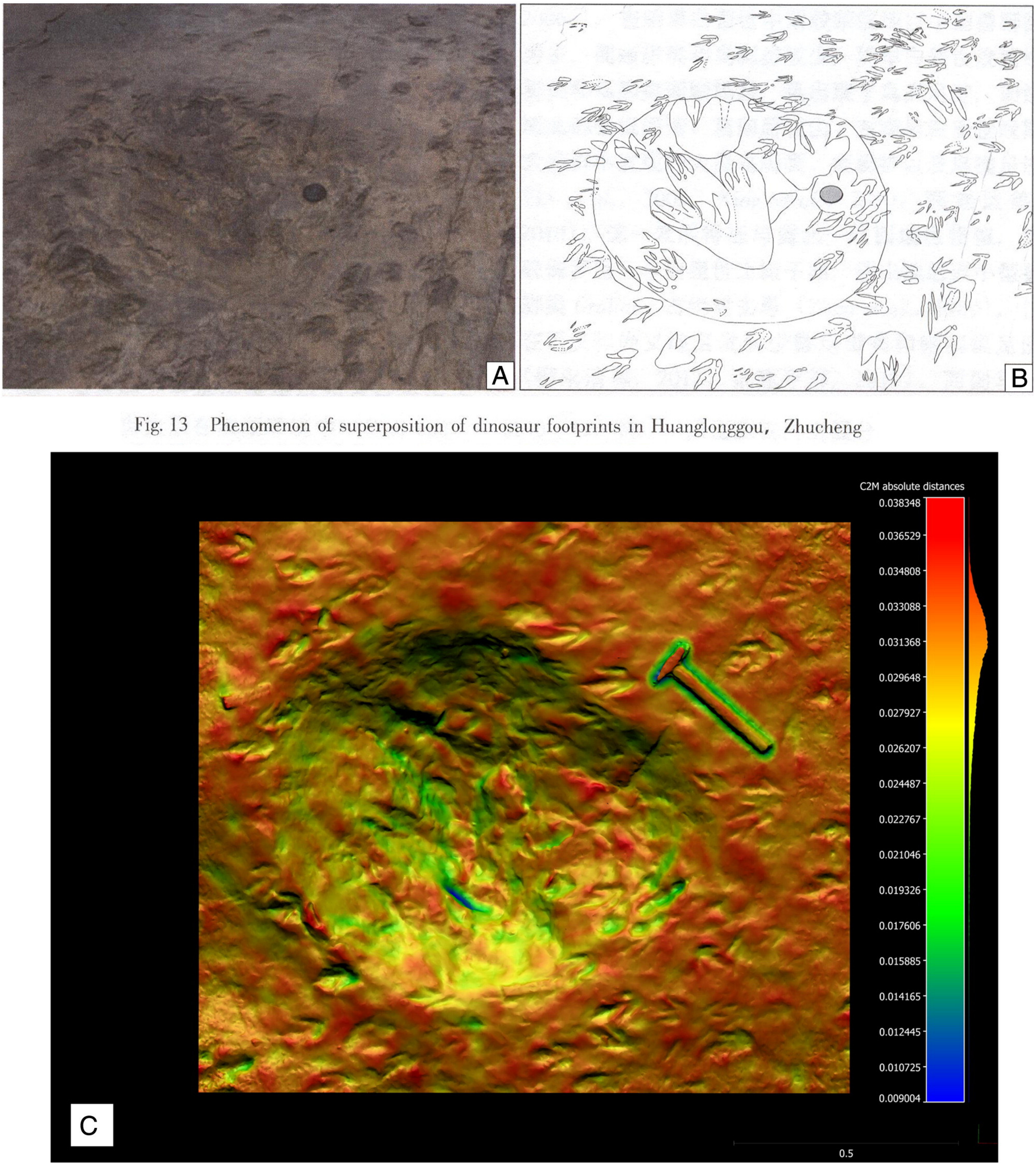

Fig. 14. Interpreting track superposition. A (photo) and B (line drawing), after Xu et al., 2013, (Fig. 13A, B) show apparent superposition of large and small theropod tracks on a large bowl shaped track. However, the large tridactyl tracks inferred by Xu et al., 2013 are artifacts that we could not verify. C shows a photogrammetric image of the same area, from the present study. Note the clear *Grallator* tracks just left of the hammer head on the originally horizontal surface, and the very similar *Grallator* tracks just below with the same orientation, but a quite different inclination, where they now appear on the steep wall of the large track. These large rounded tracks are interpreted as underprints that indented the level 4 surface after the deposition of the overlying bed. See text for details.

registered, are still evident on the Level 4 surface where it was not impacted by transmitted prints from large animals.

To the best of our knowledge this is the first case it can be unambiguously shown that small tracks situated inside large tracks, therefore appearing to have been made later, were in fact made earlier on a surface already buried at the time the large undertracks were superimposed on them. The reverse pattern, *i.e.*, small tracks inside large tracks, has been reported in a few cases (Lockley et al., 1997; Hwang et al., 2002). This suggests caution is necessary in interpreting the sequence of events represented where tracks are superimposed.

A more general aspect of track preservation pertains to the distribution of tracks across the whole site. As noted above Xu et al., 2013 inferred that the distribution of tracks suggested an E–W lake shoreline with the lake center to the south. We have observed two zones of small *Grallator* tracks with a dominantly ENE orientations. These small tracks are very bird-like and so reminiscent of shorebird and the shorebird ichnofacies (Lockley et al., 1994; Hunt and Lucas, 2007; Lockley, 2007; Kim et al., 2012). The occurrence of two narrow zones a few meters apart suggests either that the shoreline shifted a few meters perpendicular to the ENE–WSW trend in order to create conditions ideal for good preservation of small tracks, or that there may have been two zones ideal for preservation separated by a drier, perhaps slightly elevated zone a few meters wide. The former interpretation requires that the first formed zone preserve the tracks without significant deterioration (dissolution) while the shoreline shifted. If the shift was the result of falling water levels towards the lake center to the south then the more northerly zone was likely the first formed.

It is noteworthy that there is a low density of tracks to the south, towards the inferred lake center (*sensu* Xu et al., 2013). Explicitly, this means a low density of dinosaur tracks, because many small and inconspicuous tetrapod tracks occur in this area (Fig. 10). These which have been identified as turtle tracks, were evidently not noted or interpreted by Xu et al., 2013. The presence of abundant turtle tracks towards the south supports this inference as turtles are aquatic. Of equal significance is the striking similarity between the meter-scale, micro-paleogeography, inferred from shoreline track distributions at both the Huanglonggou site in Shandong, and the Gajin site from the Cretaceous Haman Formation in Korea (Kim et al., 2012, Fig. 2). At the Korean site a high density of small bird tracks occurs in a narrow 3–4 m-wide zone, flanked on one side by a zone with larger bird tracks that show evidence of feeding. This evidence strongly supports the inference that high density track zones only a few meters wide are small scale, or micro-paleogeographical shoreline indicators and that much lower densities of tracks may occur only a few meters away from these high density zones.

Thus we agree with the general interpretation of Xu et al., 2013 that the lake center was to the south with a shoreline towards the north. However, we offer much more detailed corroborating evidence based on a careful analysis of the track evidence. We note also that there are many small wavelength ripple marks with crest orientations from ENE to WSW to help corroborate this shoreline trend, implying that waves broke shore-parallel. Xu et al., 2013 also discuss ripple mark evidence.

5.4. Comparison of the Huanglonggou tracksite with other large tracksites

Clearly the Huanglonggou tracksite is exceptional in many respects, and has already been the subject of several studies. It is the largest tracksite currently known in Shandong Province and indeed in all of China, especially with respect to the number of tracks mapped and recorded. Recently, significant tracksites from various regions around the world have been compared using various criteria including area of tracksite, number of tracks and trackways, number of track types (including holotypes), preservation quality and other factors such as accessibility, educational and scientific value (Alcalá et al., 1972). There are a relatively small number of large tracksites, with more than 1000 tracks corroborated by published maps. For example, among sites that have been mapped in detail Thulborn and Wade (1984) mapped and reported >4000 tracks from the mid-Cretaceous of Australia. Lockley et al., 1986 reported more than 1300 tracks from the Upper Jurassic of Colorado, and Lockley and Hunt (1995) presented a map of ~2000 tracks from the Middle-Upper Jurassic of Utah (Lockley and Gillette, 1989). Kim et al., 2012 reported more than 2500 tracks, mostly of birds (avian theropods) mapped at the Lower Cretaceous Gajin tracksite in South Korea. Various other sites with more than 1000 tracks are known (Lockley and Gillette, 1989) but not all have accessible published maps.

6. Conclusions

1) The Huanglonggou tracksite is one of the largest concentrations of dinosaur tracks ever reported from the Cretaceous of China, indeed from anywhere in the world. With more than 2000 footprints it is presently among the largest concentrations of tetrapod tracks known from anywhere in the world. This large number does not include numerous small turtle tracks.
2) Due to the site's importance the site has already been the subject of several previous preliminary studies notably by Li et al., 2011; Xu et al., 2013. However, the former study was preliminary based on a small area exposed prior to large scale excavation of the site. The latter study is flawed by sketchy, schematic mapping, misidentification of trackway orientations, lack of discrimination between trackway morphotypes and a lack of appropriate ichnotaxonomic labeling.
3) The quality of preservation of the tracks is generally very good, especially at level 4. Tracks at four other levels (1–3 and 5) are not well exposed. They nevertheless indicate repeated tetrapod activity in the area for some time.
4) The layer 4 assemblage is dominated by small to medium-sized theropod tracks assigned to two grallatorid morphotypes (A and B) and *C. lilasia* (Li et al., 2011).
5) A few large sauropod trackways also occur in association with levels 3 and 5.
6) Abundant small tetrapod tracks of presumed turtle affinity occur but have not been mapped.
7) The distribution of tracks and associated sedimentary structures, notably ripple marks, indicates that most of the tracks were made close to a lacustrine shoreline, with evidence of land to the north or NNW and the lake center to the south or SSE.
8) Dominant trackway orientation trends to the ENE coincide with the main wave ripple crest trends thereby supporting an ENE–WSW shoreline orientation.
9) Plans for the site are to develop it as a tourist attraction, which is situated close to other historically important and well-exposed bone-bed sites of Cretaceous age.
10) The mapping component of this study was completed with the objective of providing interpretative material to aid in the development of the site.

Acknowledgments

This study was supported financially by National Natural Science Foundation of China (grant nos.: 40972005 and 40572011 to R. Li), and partly supported by China Geological Survey (Nos. GZH200800501, 1212011220113). The study was also supported, in part, by the offices of the University of Colorado Denver, Dinosaur Tracks Museum and Dinosaur Trackers Research Group. All specimens with the prefix CU have were transferred, in 2012, to the University of Colorado Museum of Natural History (UCM) and will in future have the replacement prefix UCM, without change to the numbers. We thank Yanxia Zhang and Kebai Wang of the Zhucheng Municipal Bureau of Tourism, Zhucheng, Shandong for their help with field work. We thank Neffra Matthews, National Operations Center, USDOI-Bureau of Land Management, Federal Center, Denver, Colorado, for help producing the image used in Figure 14C. We thank Richard McCrea of the Peace Region Palaeontological Research Center, British Columbia, and Spencer Lucas, New Mexico Museum of Natural History and Science for their helpful reviews of the first draft of this manuscript.

References

Alcalá, L. Lockley, M. Cobos, A. Mampel, L and Royo-Torres, R. 1972. Evaluating the Dinosaur Track record: an integrative quantitative approach to understanding the regional and global distribution, scientific importance, preservation and management of fossil footprint sites *In* Richter, A. and Marty, D. (eds) *Dinosaur Tracks, Next Steps*, Indiana University Press.
Alexander, R. McN, 1976. Estimates of speeds of dinosaurs. Nature 261, 129–130.
Chen, J., Kuang, H., Liu, Y., Wu, Q., Cheng, G., Xu, K., Peng, N., Xu, H., Liu, H., Xu, H., Wang, M., Wang, B., Zhang, P., 2013. Characteristics of dinosaur footprints of the late Early Cretaceous in Linshu area Shandong Province. J. Palaeogeogr. 15 (4), 505–512.

Ellenberger, P., 1972. Contribution à la classification des Pistes de Vertébrés du Trias: Les types du Stormberg d'Afrique du Sud (I). Palaeovertebrata, Memoire Extraordinaire, Montpellier (104 pp.).
Foster, J.R., Lockley, M.G., 1997. Probable crocodilian tracks and traces from the Morrison Formation (Upper Jurassic) of eastern Utah. Ichnos 5, 121–129.
Hitchcock, E., 1858. Ichnology of New England. A Report on the Sandstone of the Connecticut Valley, Especially Its Fossil Footmarks. W. White, Boston (reprinted 1974 by Arno Press, New York).
Hunt, A.P., Lucas, S.G., 2007. Tetrapod ichnofacies: a new paradigm. Ichnos 14, 59–68.
Hwang, K.G., Huh, M., Lockley, M.G., Unwin, D.M., Wright, J.L., 2002. New pterosaur tracks (Pteraichnidae) from the Late Cretaceous Uhangri Formation, S. W. Korea. Geol. Mag. 139 (4), 421–435.
Kim, J.-Y., Kim, J.-Y., Seo, S.J., Kim, K.S., Lockley, M.G., Kim, S.H., Baek, K.S., 2012. A paradise of Mesozoic birds: the world's richest and most diverse Cretaceous bird track assemblage from the Early Cretaceous Haman Formation of the Gajin tracksite, Jinju, Korea. Ichnos 19, 28–42.
Kuang, H., Liu, Y., Wu, Q., Cheng, G., Xu, K., Liu, H., Peng, N., Xu, H., Chen, J., Wang, B., Xu, J., Wang, M., Zhang, P., 2013. Dinosaur track sites and palaeogeography of the late Early Cretaceous in Shuhe Rifting Zone of Shandong Province. J. Palaeogeogr. 15 (4), 435–453.
Li, R., Zhang, G., 2000. New dinosaur ichnotaxon from the early Cretaceous Laiyang Group, in the Laiyang Basin, Shandong Province. Geol. Rev. 46, 605–610.
Li, R., Lockley, M.G., Liu, M., 2005. A new ichnotaxon of fossil bird track from the Early Cretaceous Tianjialou Formation (Barremian–Albian), Shandong Province, China. Chin. Sci. Bull. 50, 1149–1154.
Li, R., Lockley, M.G., Makovicky, P., Matsukawa, M., Norell, M., Harris, J., 2008. Behavioral and faunal implications of deinonychosaurian trackways from the Lower Cretaceous of China. Naturwissenschaften 95, 185–191.
Li, R., Lockley, M.G., Matsukawa, M., Wang, K., Liu, M., 2011. An unusual theropod track assemblage from the Cretaceous of the Zhucheng area, Shandong Province, China. Cretac. Res. 32 (4), 422–432.
Li, R., Lockley, M.G., Matsukawa, Liu, M., 2015. Important dinosaur-dominated footprint assemblages from the Lower Cretaceous Tianjialou Formation at the Houzuoshan Dinosaur Park, Junan County, Shandong Province, China. Cretac. Res 52, 83–100.
Lockley, M.G., 1986. The paleobiological and paleoenvironmental importance of dinosaur footprints. Palaios 1 (1), 37–47.
Lockley, M.G., 1991. Tracking Dinosaurs: A New Look at an Ancient World. Cambridge University Press (238 p.).
Lockley, M.G., 2007. A tale of two ichnologies: the different goals and missions of vertebrate and invertebrate ichnology and how they relate in ichnofacies analysis. Ichnos 14, 39–57.
Lockley, M.G., 2009. New perspectives on morphological variation in tridactyl footprints: clues to widespread convergence in developmental dynamics. Geol. Q. 53, 415–432.
Lockley, M.G., Gillette, D.D., 1989. Dinosaur tracks and traces: an overview. In: Gillette, D.D., Lockley, M.G. (Eds.), Dinosaur Tracks and Traces. Cambridge University Press, pp. 3–10 (454 p.).
Lockley, M.G., Hunt, A.P., 1995. Dinosaur Tracks and Other Fossil Footprints of the Western United States. Columbia University Press (338 p.).
Lockley, M.G., Houck, K., Prince, N.K., 1986. North America's largest dinosaur tracksite: implications for Morrison Formation paleoecology. Geol. Soc. Am. Bull. 97 (10), 1163–1176.
Lockley, M.G., Hunt, A.P., Meyer, C., 1994. Vertebrate tracks and the ichnofacies concept: implications for paleoecology and palichnostratigraphy. In: Donovan, S. (Ed.), The Paleobiology of Trace Fossils. Wiley and Sons, Inc., pp. 241–268 (vi + 308 p.).
Lockley, M.G., Huh, M., Lim, S.-K., Yang, S.-Y., Chun, S.S., Unwin, D., 1997. First report of pterosaur tracks from Asia, Chollanam Province Korea. J. Paleontol. Soc. Korea 2, 17–32 (Special Publication).
Lockley, M.G., Li, R., Harris, J., Matsukawa, M., Mingwei, L., 2007. Earliest zygodactyl bird feet: evidence from Early Cretaceous Road Runner-like traces. Naturwissenschaften 94, 657–665.
Lockley, M.G., Kim, S.H., Kim, J.-Y., Kim, K.S., Matsukawa, M., Li, R., Li, J., Yang, S.-Y., 2008. *Minisauripus* — the track of a diminutive dinosaur from the Cretaceous of China and Korea: implications for stratigraphic correlation and theropod foot morphodynamics. Cretac. Res. 29, 115–130.
Lockley, M.G., Li, R., Matsukawa, M., Li, J., 2010. Tracking Chinese crocodilians: *Kuangyuanpus*, *Laiyangpus* and implications for naming crocodylian and crocodylian-like tracks and associated ichnofacies. N. M. Mus. Nat. Hist. Sci. Bull. 51, 99–108.
Lockley, M.G., Lucas, S.G., Matsukawa, M., Harris, J.D., 2012a. Cretaceous tetrapod footprint biostratigraphy, biochronology and ichnofacies. J. Stratigr. 36, 503–550.
Lockley, M.G., Li, R., Matsukawa, M., Li, J., Liu, M., Wang, K., Zhang, X.X., Xing, X., 2012b. The importance of the Huanglonggou or "Yellow Dragon Valley" dinosaur tracksite (Early Creatceous) of the Zhucheng area, Shandong Province China. In: Huh, M., Kim, H.-J., Park, J.Y. (Eds.), The 11th Mesozoic Terrestrial Ecosystems Abstracts Volume (August 15–18), Korea Dinosaur Research Center, Chonnam National University, pp. 315–317 (461 p.).
Lockley, M.G., Xing, L., Li, J., Li, R., Matsukawa, M., 2012c. First records of turtle tracks in the Cretaceous of China. In: Huh, M., Kim, H.-J., Park, J.Y. (Eds.), The 11th Mesozoic Terrestrial Ecosystems Abstracts Volume (August 15–18), Korea Dinosaur Research Center, Chonnam National University, pp. 311–313 (461 p.).
Lockley, M.G., Li, J., Li, R.H., Matsukawa, M., Harris, J.D., Xing, L., 2013. A review of the tetrapod track record in China, with special reference to type ichnospecies: implications for ichnotaxonomy and paleobiology. Acta Geol. Sin. 87, 1–20.
Lockley, M.G., Cart, K., Martin, J., Prunty, R., Houck, K., Hups, K., Lim, J.-D., Kim, K.-S., Houck, K., Gierlinski, G., 2014. A bonanza of new tetrapod tracksites from the Cretaceous Dakota Group, western Colorado: implications for paleoecology. N. M. Mus. Nat. Hist.Sci. Bull. 62, 393–409.
Olsen, P.E., 1980. Fossil great lakes of the Newark Supergroup in New Jersey. In: Manspeizer, W. (Ed.), Field Studies of New Jersey Geology and Guide to Field Trips. New York State Geological Association, 52nd Annual Meeting., Rutgers University, pp. 352–398.
Olsen, P.E., Smith, J.B., McDonald, N.G., 1998. Type material of the type species of the classic theropod footprint genera *Eubrontes*, *Anchisauripus* and *Grallator* (Early Jurassic, Hartford and Deerfield basins, Connecticut and Massachusetts, USA). J. Vertebr. Paleontol. 18, 586–601.
Peng, N., Liu, Y., Kuang, H., Wu, Q., Liu, H., Chen, J., Xu, H., Xu, J., Wang, M., Wang, B., Wang, K., Chen, S., Zhang, Y., 2013. Differences in characteristics of dinosaur footprints in the late Early Cretaceous, Yishu Rifting Zone, Shandong Province. J. Palaeogeogr. 15 (4), 517–528.
Shandong Provincial No.4 Institute Of Geological and Mineral Resources, 2003. In: Song, M., Wang, P. (Eds.), Regional Geology of Shandong Province. Map Publishing House of Shandong Province, Jinan (in Chinese).
Thulborn, R.A., 1990. Dinosaur Tracks. Chapman Hall London (410 p.).
Thulborn, R.A., Wade, M., 1984. Dinosaur trackways in the Winton Formation (Mid-Cretaceous) of Queensland. Mem. Queensland Mus. 21, 413–517.
Wang, M., Kuang, H., Liu, Y., Peng, N., Liu, H., Wu, Q., Xu, J., Chen, J., Xu, H., Wang, B., Zhang, P., 2013a. New discovery of dinosaur footprint fossils and palaeoenvironment in the late Early Cretaceous at Tancheng County, Shandong Province and Donghai County, Jiangsu Province. J. Palaeogeogr. 15 (4), 489–504.
Wang, B., Liu, Y., Kuang, H., Wang, K., Chen, S., Zhang, Y., Peng, N., Xu, H., Chen, J., Hai, Liu, Xu, J., Wang, M., 2013b. New discovery and its significance of dinosaur footprint fossils in the late Early Cretaceous at Tangdigezhuang Village of Zhucheng County, Shandong Province. J. Palaeogeogr. 15 (4), 454–466.
Weems, R.E., 1992. A re-evaluation of the taxonomy of Newark Supergroup saurischian dinosaur tracks, using extensive statistical data from a recently exposed tracksite near Culpeper Virginia. In: Sweet, P.C. (Ed.), Proceedings of the 26th Forum on the Geology of Industrial Minerals: Virginia, Division of Mineral Resources, pp. 113–127.
Whyte, M.A., Romano, M., 2001. A dinosaur ichnocoenosis from the Middle Jurassic of Yorkshire, UK. Ichnos 8, 233–234.
Xing, L., Harris, J.D., Wang, K-B, Li, R.-H., 2010. An Early Cretaceous non-avian dinosaur and bird footprint assemblage from the Laiyang Group in the Zhucheng Basin, Shandong Province, China. Geol. Bull. Chin. 29 (8), 1105–1112.
Xing, L., Harris, J.D., Gierlinski, G.D., Gingras, M.D., Divay, J.D., Tang, Y.-G., Currie, P., 2012. Early Cretaceous pterosaur tracks from a "buried" dinosaur tracksite in Shandong Province, China. Palaeoworld 21, 50–58.
Xing, L., Lockley, M.G., Marty, D., Klein, H., Buckley, R.T., McCrea, R.T., Zhang, J., Gierlinski, G.D., Divay, J.D., Wu, Q., 2013. Diverse dinosaur ichnoassemblages from the Lower Cretaceous Dasheng Group in the Yishi fault zone, Shandong Province, China. Cretac. Res. 45, 114–134.
Xing, L., Avanzini, M., Lockley, M.G., Miyashita, T., Klein, H., Zhang, J., He, Q., Qi, L., Divay, J.D., Jia, C., 2014. Early Cretaceous turtle tracks and skeletons from the Junggar Basin, Xinjiang, China. Palaois 29, 137–144.
Xu, H., Liu, Y., Kuang, H., Wang, K., Chen, S., Zhang, Y., Peng, N., Chen, J., Wang, M., Wang, B., 2013. Middle Early Cretaceous super-large scale dinosaur tracks in Zhucheng area, Shandong Province, and their palaeogeography and palaeoecology. J. Palaeogeogr. 15 (4), 467–488.
Young, C.C., 1960. Fossil footprints in China. Vertebr. Palasiatica 4, 53–66.