SPANISH JOURNAL OF PALAEONTOLOGY

Ichnology and sedimentary environment of Cretaceous redbeds in the Ruyang Basin, western Henan Province, China

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Bin H., Changzheng W., Yuanyaun W. & Huibo S. 2014. Ichnology and sedimentary environment of Cretaceous redbeds in the Ruyang Basin, western Henan Province, China. [Icnología y ambiente sedimentario de las capas rojas del Cretácico de la cuenca de Ruyang, Oeste de la provincia de Henan, China]. *Spanish Journal of Palaeontology*, 29 (2), 151-164.

Manuscript received 31 March 2013
Manuscript accepted 03 October 2014

ABSTRACT

A sequence of terrestrial clastic redbeds of Cretaceous age is exposed in the Ruyang Basin of western Henan Province in China. The rocks consist of conglomerate, sandstone, siltstone and mudstone containing the ichnofossils *Psilonichnus*, *Arenicolites*, *Palaeophycus*, *Scoyenia*, *Planolites*, *Skolithos* and other burrows and rhizoliths. The beds also contain the dinosaur fossils *Huanghetitan ruyangensis* and *Zhongyuansaurus luoyangensis*. On the basis of the lithology, sedimentary structures and ichnofossils, it is suggested that the sedimentary environments of the Ruyang Basin during the Cretaceous were primarily alluvial fan in character, including middle fan and fan edge subfacies. In this sedimentary setting, eight lithofacies types are distinguished, and two ichnoassemblages are recognized: (1) *Scoyenia-Skolithos* ichnoassemblage occurring in braided fluvial deposits of an alluvial fan system, and (2) *Psilonichnus-Palaeophycus* ichnoassemblage occurring in shallow pond or lake deposits at the fan edge.

Keywords: Ruyang Basin, alluvial fan, Cretaceous, trace fossils, China.

RESUMEN

En la cuenca de Ruyang, al oeste de la provincia china de Henan, aflora una secuencia de capas rojas clásticas terrestres de edad cretácica. Se trata de conglomerados, areniscas, limolitas y lutitas que contienen los icnofósiles *Psilonichnus*, *Arenicolites*, *Palaeophycus*, *Scoyenia*, *Planolites*, *Skolithos,* otras trazas y rizolitos. Las capas también engloban fósiles de los dinosaurios *Huanghetitan ryuangensis* y *Zhongyuansaurus luoyangensis*. En base a la litología, las estructuras sedimentarias y los icnofósiles, se sugiere que los ambientes sedimentarios de la cuenca de Ruyang durante el Cretácico fueron primordialmente de tipo abanico aluvial, incluyendo subfacies de abanico medio y de borde de abanico. En este contexto sedimentario, se distinguen ocho tipos de litofacies y se reconocen dos icnoasociaciones: (1) Icnoasociación de *Scoyenia-Skolitos* en depósitos fluviales anastomosados de un sistema de abanico aluvial, e (2) icnoasociación de *Psilonichnus-Palaeophycus* en charcas someras o depósitos lacustres en el borde del abanico.

Palabras clave: Cuenca de Ruyang, abanico aluvial, Cretácico, icnofósiles, China.

http://doi.org/10.7203/sjp.29.2.17684

1. INTRODUCTION

The Ruyang Basin is located in Ruyang County of Henan Province, China (Fig. 1), and it is situated in the area between the southern margin of the North China Plate and the Qinling Orogenic Belt. It is a rifted basin controlled by northwest and northeast-trending faults. In the Early Cretaceous, the rift basin formed with a northwest strike, inclined to the east and south. This basin is rhomb-shaped (Huang *et al.*, 2005; Lv *et al.*, 2005; Yu *et al.*, 2007; Zhang *et al.*, 2007). Body fossils of the dinosaurs *Huanghetitan ruyangensis* and *Zhongyuansaurus luoyangensis* have been found in this basin (Xu *et al.*, 2010). However, the trace fossils have not been studied in detail. The aim of this paper is to describe the ichnologic and sedimentary features and to interpret the palaeoenvironment of the Cretaceous dinosaur-bearing strata.

2. GEOLOGIC SETTING

Based on lithology and fossils, the Cretaceous strata of this basin are divided into the Lower Cretaceous Jiudian, Xiahedong and Haoling Formations and the Upper Cretaceous Shangdonggou Formation (Fig. 2). The lower part of the Jiudian Formation is conglomerate, and the middle-upper part is crystalline tuff. The thickness of the formation ranges from 354 to 1,806 m, and it unconformably overlies the Mesoproterozoic Ruyang Group or Xionger Group. The lower part of the Xiahedong Formation is composed of conglomerate mixed with sandy conglomerate, lithic sandstone, and muddy siltstone with conglomerate. The upper part is composed of conglomerate interbedded with muddy siltstone. The thickness ranges from 79 to 363 m, and it conformably overlies the Jiudian Formation, which underlies the

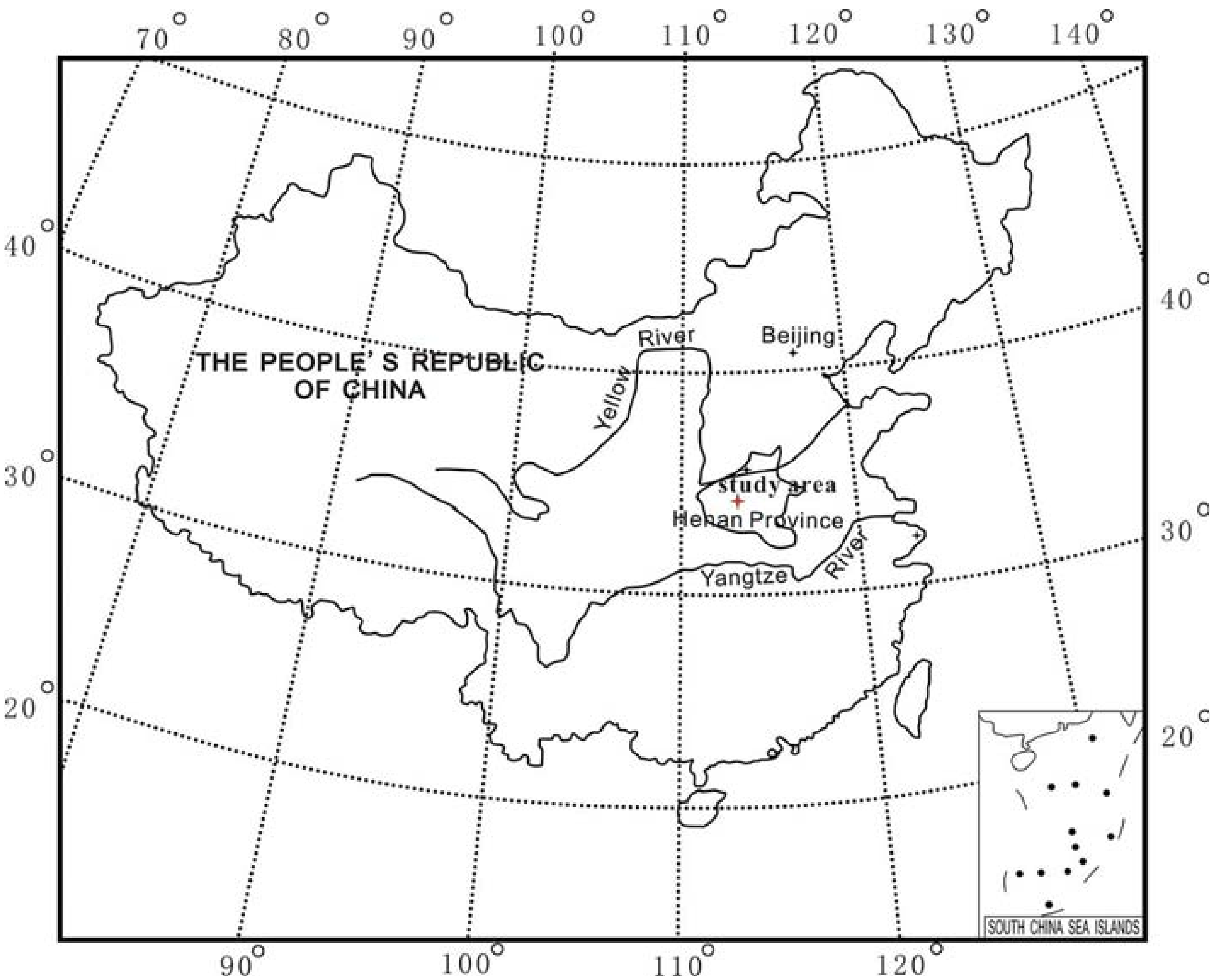

Figure 1. Location of the study area in Henan Province, China.

Haoling Formation. The Haoling Formation is composed of conglomerate interbedded with muddy siltstone and silty mudstone, mixed with sandy conglomerate containing calcareous concretions. The body fossils include dinosaurs, bivalves and ostracodes. The age is Early Cretaceous. The thickness ranges from 418 to 625 m, and it conformably overlies the Xiahedong Formation and underlies the Shangdonggou Formation. The Shangdonggou Formation is composed of brownish red siltstone, off-white sandy conglomerate, mixed with conglomerate, and it contains body fossils of the dinosaurs *Huanghetitan ruyangensis* and *Zhongyuansaurus luoyangensis*. The thickness ranges

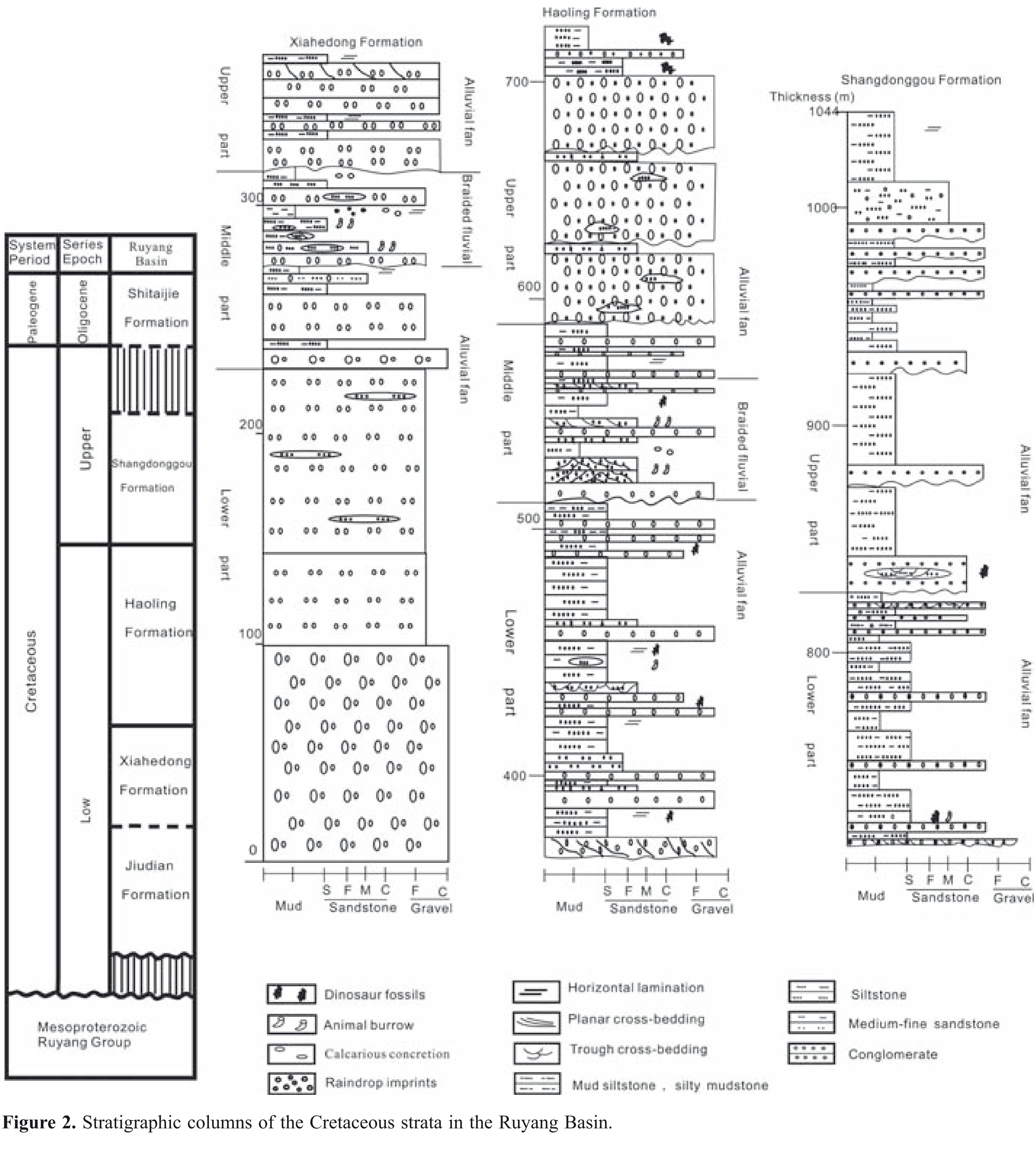

Figure 2. Stratigraphic columns of the Cretaceous strata in the Ruyang Basin.

from 331 to 341m. The age is Late Cretaceous. Facies types, lithologic composition, depositional sequence and sedimentary structures of the Cretaceous redbeds in the Ruyang Basin are analyzed in detail (Fig. 2).

3. LITHOFACIES DESCRIPTION

Eight lithofacies are distinguished on the basis of lithology, sediment texture, primary sedimentary structures and fossil content. A summary of the description and interpretation of the sedimentary facies is offered in Table 1.

Table 1. Description and interpretation of the lithofacies.

Lithofacies	Lithology and texture	Sedimentary structures	Bioturbation	Interpretation
Gmm	Matrix-supported, massive conglomerate	No grading or weak graded, scour structures	None	Subaerial rapidly plastic debris flow high-strength, viscous
Gcm	Clast-supported massive conglomerate, sandy conglomerate	Weak grading to ungraded	None	Subaerial pseudoclastic debris flow
Gm	Massive conglomerate	Weak imbricate structure	None	Channel lag deposits
Gt	Clast-supported conglomerate	Tabular cross-bedding, trough cross-bedding, scour structures	None	Small channel lag deposits
St	Medium-fine grained lithic sandstone, mixed with pebbly sandstone	Trough and wedge cross-bedding	*Palaeophycus*, *Skolithos*, dinosaur fossils	Channel fills
Sm	Medium-fine grained sandstone	Massive	None	Gravity current
Fm	Silty mudstone, intercalated grayish fine grained sandstones	Massive	Dinosaur fossils, *Psilonichnus*, *Arenicolites*, other burrows	Shallow pond or lake within fan edge
Fsm	Brownish red muddy siltstone and silty mudstone	Horizontal lamination, massive, raindrop imprints	Dinosaur fossils, *Scoyenia*, *Planolites*, *Palaeophycus*, *Skolithos*, rhizoliths, other burrows	Sheet flood deposition or flood plain

3.1. Lithofacies Gmm/Gcm

This lithofacies consists of matrix-supported massive conglomerate (Gmm) and clast-supported massive conglomerate (Gcm). It occurs in the Cretaceous sections throughout the whole study area. These massive conglomerate beds are dozens of centimeters to several meters thick. The size of the clasts is mostly 3 to 20 cm, but the largest clasts may be up to dozens of centimeters. The texture and fabric of the conglomerate beds are unsorted and disorganized, and the clasts do not show any significant stratification. The conglomerate clasts are subangular to rounded. The matrix is composed of sand and mud, as in lithofacies Gcm (Fig. 3b). The conglomerate beds are capped by either fine- to medium-grained sandstone or by purplish red laminated silty mudstone beds. The capping beds usually contain small pebbles that are composed of the same material as the conglomerate clasts.

The massive and disorganized nature of the beds indicates episodes of rapid debris flow sedimentation, where sediment concentration was high. The basal erosional scour, lack of graded bedding, lack of stratification, and poor grain sorting indicates debris flow deposition. The matrix-supported massive conglomerate lithofacies (Gmm) (Fig. 3a) is interpreted to represent a rapidly deposited subaerial debris flow (Nemec *et al.*, 1980). Their interbedded occurrence with alluvial channel-fill sandstones indicates reworking and winnowing of earlier deposited debris flows (lithofacies Gcm) by alluvial currents. The lithofacies Gcm is interpreted to represent a subaerial debris flow.

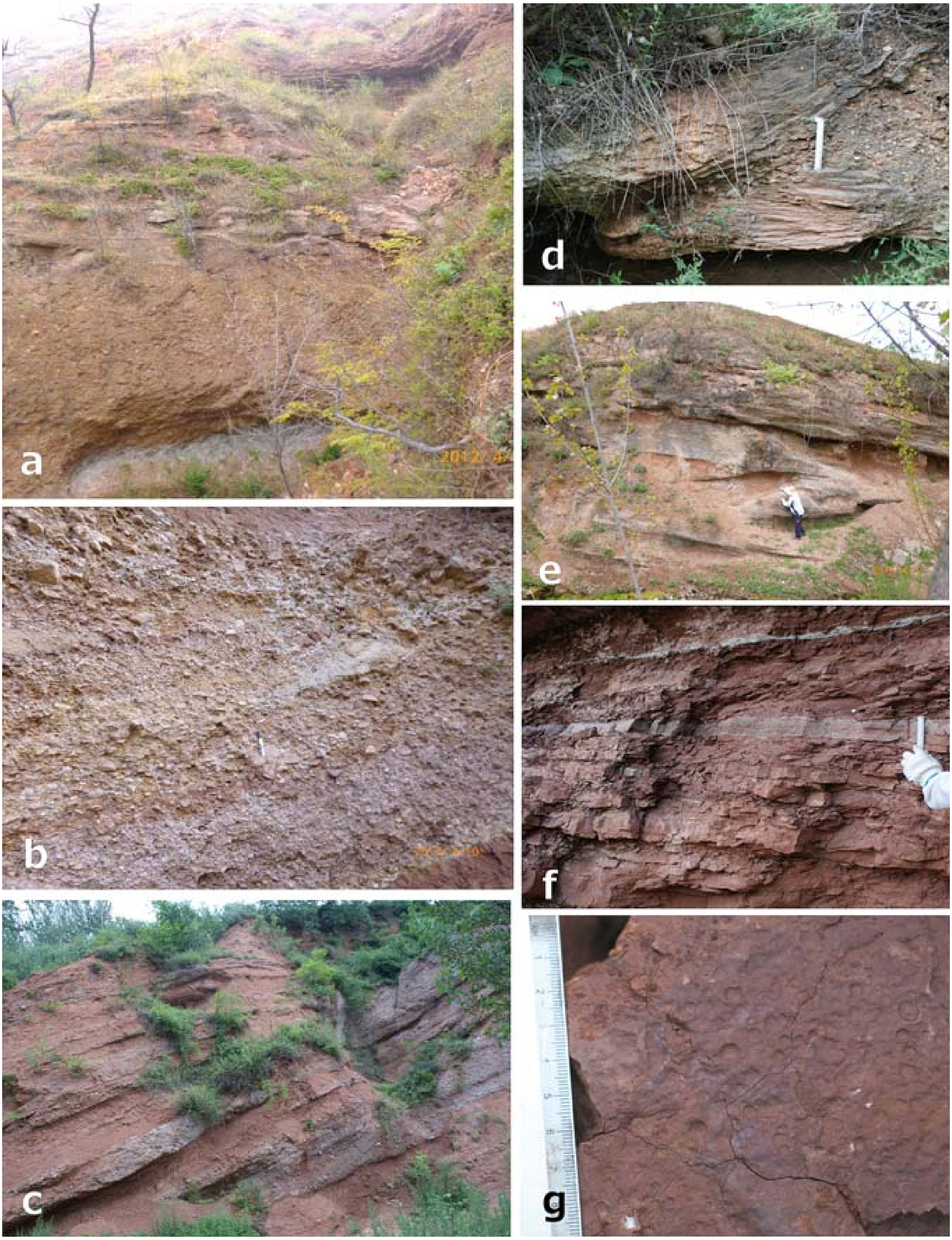

Figure 3. Outcrop characteristics of sedimentary structures in the Cretaceous strata of the Ruyang basin. **a)** Outcrop of the Haoling Formation, showing matrix-supported massive conglomerate at the bottom. **b)** Clast-supported massive conglomerate. **c)** Massive conglomerate. **d)** Trough cross-bedding sandstone and trough crossbedding conglomerate. **e)** Wedge cross-bedding in sandstone. **f)** Brownish red siltstone and silty mudstone. **g)** Raindrop imprints.

3.2. Lithofacies Gm/Gt

This facies association consists of massive conglomerate (Gm) and trough crossbedded conglomerate (Gt), and it occurs in the Xiahedong and Haoling Formations. The Facies Gm consists of purplish red, gray and purple conglomerate, and it is overlain by fine to medium-grained, crossbedded sandstone. The conglomerate clasts are subangular to subrounded, and they exhibit an imbricated arrangement. Conglomerate beds exhibit inverse grading and concave-down lenticular structures (scour and fill structures), which suggests reworking in an alluvial channel. Large channel lag deposits form large tabular crossbedding, as in Gm (Fig. 3c). Facies Gt with trough cross-bedding apparently formed in small channel lag deposits (Fig. 3d).

3.3. Lithofacies St

This lithofacies consists of gray to grayish green lithic sandstone with large-scale, trough and wedge crossbedding, containing fine gravel, abundant trace fossils and well developed erosive structures (Figs 3d-3e). Bed thickness of the sandstone ranges from 1 to 7.6 m, sometimes changing laterally to siltstone or mudstone, and the sandstone beds in this lithofacies are thinner than the conglomerate and siltstone beds. These sedimentary characteristics indicate that the lithofacies St formed in the channel fills. This lithofacies can be found in the Lower Cretaceous Xiahedong and Haoling Formations and the Upper Cretaceous Shangdongou Formation.

3.4. Lithofacies Sm

This lithofacies is composed of massive, gray to grayish green, fine to coarse-grained pebbly sandstone. It is commonly found in the Lower Cretaceous Haoling Formation and the Upper Cretaceous Shangdongou Formation. This lithofacies is not well exposed, and its lateral continuity is uncertain. The massive sandstone beds are overlain by silty mudstone or conglomerate beds, sometimes in an upward fining sequence, i.e., conglomerate to massive sandstone to mudstone beds, or occurring as an interlayer within the conglomerate beds. This lithofacies formed in a mid-fan or fan-edge position within the alluvial fan system.

3.5. Lithofacies Fm/Fsm

Lithofacies Fm is characterized by massive silty mudstone intercalated with gray fine-grained sandstone, and lithofacies Fsm is dominated by muddy siltstone and silty mudstone. The mudstone and siltstone can be traced laterally for dozens of meters, and the individual layer thickness of Fm and Fsm ranges from 1.0 to 12.0 m, but they may change locally to sandstone and conglomerate.

Lithofacies Fm appears only in the Haoling Formation, where it is characterized by silty mudstone and intercalated gray fine-grained sandstone. In outcrop section, the lithofacies Fm changes laterally to fine-grained sandstone and silty mudstone, in which the trace fossils are mostly “U”, “W”, “J” and “Y”-shaped burrows. Calcareous concretions occur in isolation within the mudstones. This lithofacies is interpreted as a deposit in a seasonally or climatically controlled intra-fan pond within a foodplain.

Commonly, brownish red siltstone and silty mudstone alternate in the lithofacies Fsm (Fig. 3f). Sometimes siltstone also is mixed with sandy conglomerate and conglomerate. The silty mudstone beds are disturbed by root traces. On weathered outcrops, calcareous concretions commonly are encased in mudstone, and their distribution is either isolated or stratified.

Some raindrop imprints occur irregularly on the surfaces of mudstone beds (Fig. 3g). The trace fossils *Scoyenia*, *Planolites*, *Palaeophycus*, *Skolithos* and other burrows, as well as vertebrate fossils, also are common. This lithofacies Fsm is interpreted as representing foodplain deposits between fluvial fan channels and braided river channels.

4. DEPOSITIONAL ENVIRONMENTS

Based on lithology, physical sedimentary structures, sedimentary sequences, bed boundaries and fossil contents, two kinds of depositional environment were recognized in the succession studied (Figs 2, 4): (1) alluvial fan environment and (2) braided fluvial environment.

4.1. Alluvial fan environment

Alluvial fan deposits are well developed in the Cretaceous sequences in this basin. The base of the Xiahedong Formation is a matrix-supported tuff conglomerate. The lower part is a conglomerate mixed with brownish red muddy siltstone containing gravel and off-white lithic sandstone. The pebble grains range from round to subangular. The composition of the pebbles is mainly volcanic rock derived from the middle Proterozoic Xionger Group. The grain size decreases upward in the sedimentary sequence. Lateral continuity of bedding is poor. Generally, outcrop profiles display a sequence of graded beds that become thinner and finer upwards in the alluvial fan (Fig. 4B). The upper part of the Xiahedong Formation is brownish red, grayish-green sandy conglomerate interbedded with purplish red silty mudstone containing

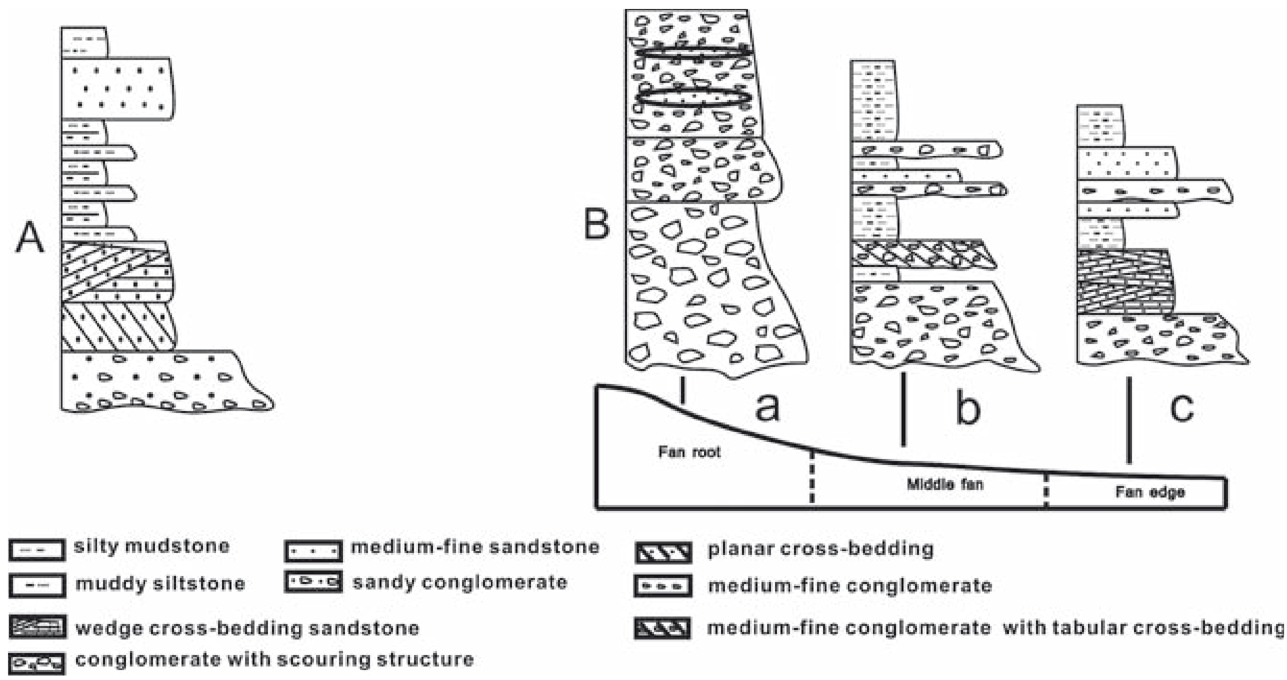

Figure 4. Sedimentary sequences of an alluvial fan system in the Ruyang Basin.

calcareous concretions. The sedimentary features include horizontal bedding, tabular crossbedding and erosional scour structures. The sedimentary system is mainly debris flow and channel fill deposits in a mid-fan (Fig. 4B-b) and edge-fan position (Fig. 4B-c) within the alluvial fan system (Fig. 4B).

The sedimentary characteristics of the Haoling and Shangdonggou Formations are similar to those in the Xiahedong Formation, except for no development of plant roots in the depositional environment. The principal difference is that the lower member of Haoling Formation displays lithofacies Fm, which formed in a fan edge environment.

4.2. Braided fluvial environment

The braided fluvial system developed is represented by lithofacies St and Fsm. Lithofacies St is characterized by medium to fine-grained lithic sandstones with trough and wedge crossbedding (Table 1), mixed with pebble-bearing sandstone. The lower part of this sedimentary sequence contains the conglomerate bed, and the upper part contains alternating layers of brownish red siltstone and silty mudstone (Fig. 4A), in which the silty mudstone beds are commonly thicker than the siltstone beds. Many trace fossils were found in the sandstone, siltstone and mudstone. The braided fluvial deposits are present mainly in the middle member of the Xiahedong Formation and middle member of the Haoling Formation (Fig. 2).

5. TRACE FOSSIL DESCRIPTIONS

Trace fossils are abundant in the sandstone, siltstone and mudstone beds of the Xiahedong, Haoling and Shangdonggou Formations. Common ichnotaxa include *Psilonichnus* ichnosp., *Arenicolites* ichnosp., *Palaeophycus tubularis*, *Scoyenia* ichnosp., *Planolites montanus*, *Planolites* ichnosp., *Skolithos* ichnosp., and other burrows and rhizoliths.

5.1. *Palaeophycus tubularis* (de Saporta, 1872)

This ichnospecies is a simple, unbranched or sparsely branched, straight to curved burrow with a distinct lining, having identical infill to the host rock. These burrows are parallel or inclined to the bedding plane (Figs 5a-5d). Overcrossing of different specimens is common. The burrow diameter is 5 to 30 mm, visible length is 8 to 15 cm. Preserved on the bedding plane and bottom of fine-grained sandstone or in muddy siltstone. Generally, this kind of burrow is thought to represent dwelling traces of suspension feeders or predators (Pemberton & Frey, 1982). The trace fossils occur mostly in the Cretaceous sandstones of the Ruyang Basin and are interpreted as having formed in a channel fill sedimentary environment.

5.2. *Psilonichnus* ichnosp.

The ichnofossils are "Y" or "J"-shaped burrows (Figs 6a-6b), which are vertical or steeply inclined to the bedding

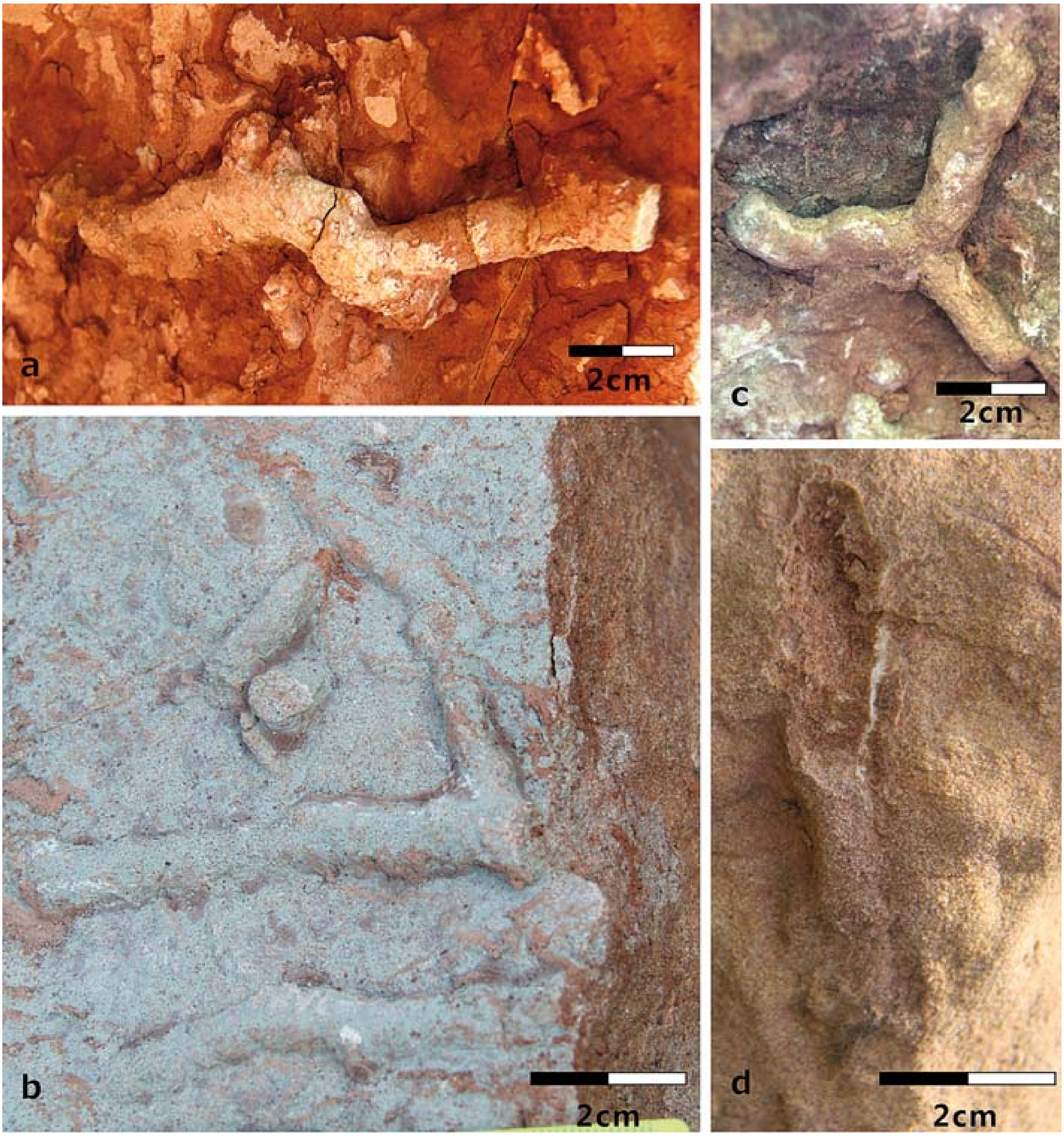

Figure 5. *Palaeophycus tubularis* in the Cretaceous of the Ruyang Basin. **a-b)** From the middle part of the Xiahedong Formation. **c-d**) From the middle part of the Haoling Formation.

plane. The diameter of burrows is 6 to 46 mm, and the length is 15 to 60 mm. Burrow fill is identical to the overlying sediments. These burrows occur with dinosaur fossils in fine-grained sandstone in the middle part of the Lower Cretaceous Haoling Formation.

In the geologic record, *Psilonichnus* has been found mostly in backshore environments along marine coastlines (Nesbitt & Campbell, 2002, 2006). However, it also has been found in some terrestrial environments (Frey & Pemberton, 1987). The trace makers are mainly suspension feeders or mud eaters, such as decapod crustaceans (e.g., crabs, shrimps and crayfish). These trace fossils have been reported in several different types of continental environments (Fürsich, 1981; Frey *et al.*, 1984; Hasiotis

& Mitchell, 1993; Bedatou *et al.*, 2008). Sedimentary characteristics suggest that these burrows were produced in a setting of moderate water energy in a seasonally or climatically controlled intra-fan pond in a foodplain.

5.3. *Arenicolites* ichnosp.

The ichnofossils are "U" or "W"-shaped burrows (Fig. 6a), which are vertical or steeply inclined to the bedding plane. A spreite is not observed. The single pipe diameter of burrows is 10 to 32 mm, width between two pipes is 18 to 25 mm, and the length (or vertical depth) is 26 to 35 mm. Burrow fill is identical to the overlying sediments. These burrows occur with dinosaur fossils and *Psilonichnus* in fine-grained sandstone in the middle part of the Lower Cretaceous Haoling Formation.

5.4. *Skolithos* ichnosp.

This ichnospecies is based on several specimens in field occurrences (Figs 7a-7c). It is an unwalled vertical burrow that is oriented nearly perpendicular to bedding and showing a circular cross-section with a diameter of 5 to 10 mm and a length of 3 to 13.5 cm. Burrow fill is similar to the overlying red silty mudstone. These burrows were observed mostly in fine-grained sandstone of channel fill deposits in the Lower Cretaceous Xiahedong and Haoling Formations.

5.5. *Scoyenia* ichnosp.

Scoyenia is very common in the Lower Cretaceous alluvial and lacustrine deposits of western Henan Province, but the burrow is not well preserved in the Xiahedong and Haoling Formation. It a slightly curved tubular burrow with a crescent backfill structure, up to 9 cm in length and 9 mm in width, and wall scratchings can be observed (Fig. 8). The burrows occur in red muddy siltstone with horizontal laminae, and they are oriented parallel to the bedding plane. Based on sedimentary characteristics of the host rock, these burrows probably were formed in an overbank or floodplain environment.

5.6. *Planolites montanus* (Richter, 1937)

The specimen is a simple, unbranched, straight to slightly curved, cylindrical to subcylindrical burrow, having infill same as that of the host rock (Fig. 9a). Diameter is 1 to 2 mm and observed length is 8.5 cm. It was preserved in semirelief in silty sandstone with horizontal laminae, and it was oriented more or less horizontal or oblique to the bedding plane. This trace fossil was produced in floodplain deposits in the Lower Cretaceous Xiahedong Formation.

5.7. *Planolites* ichnosp.

This specimen was found in the middle member of the Lower Cretaceous Xiahedong Formation. It is a smooth,

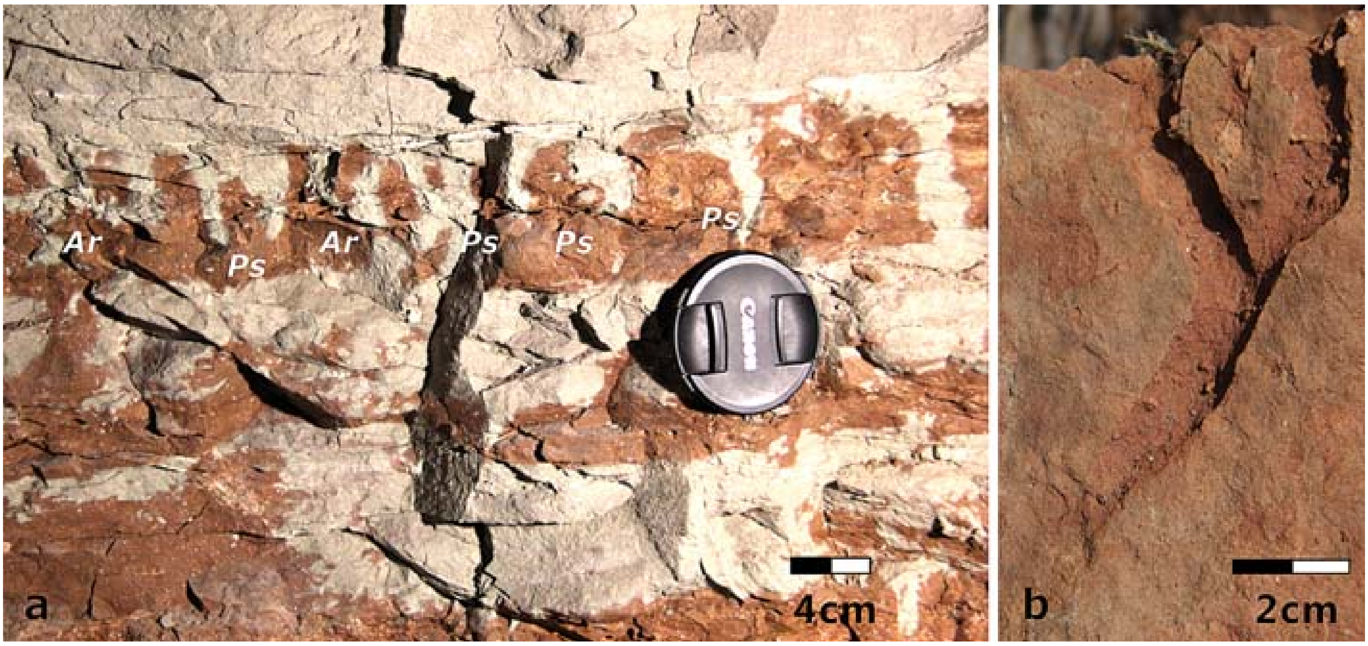

Figure 6. *Psilonichnus (Ps)* and *Arenicolites (Ar)* in the Cretaceous of Ruyang Basin. **a)** *Psilonichnus* ichnosp. and *Arenicolites* ichnosp. from the lower part of the Haoling Formation. **b)** *Psilonichnus* ichnosp. from the middle part of the Xiahedong Formation.

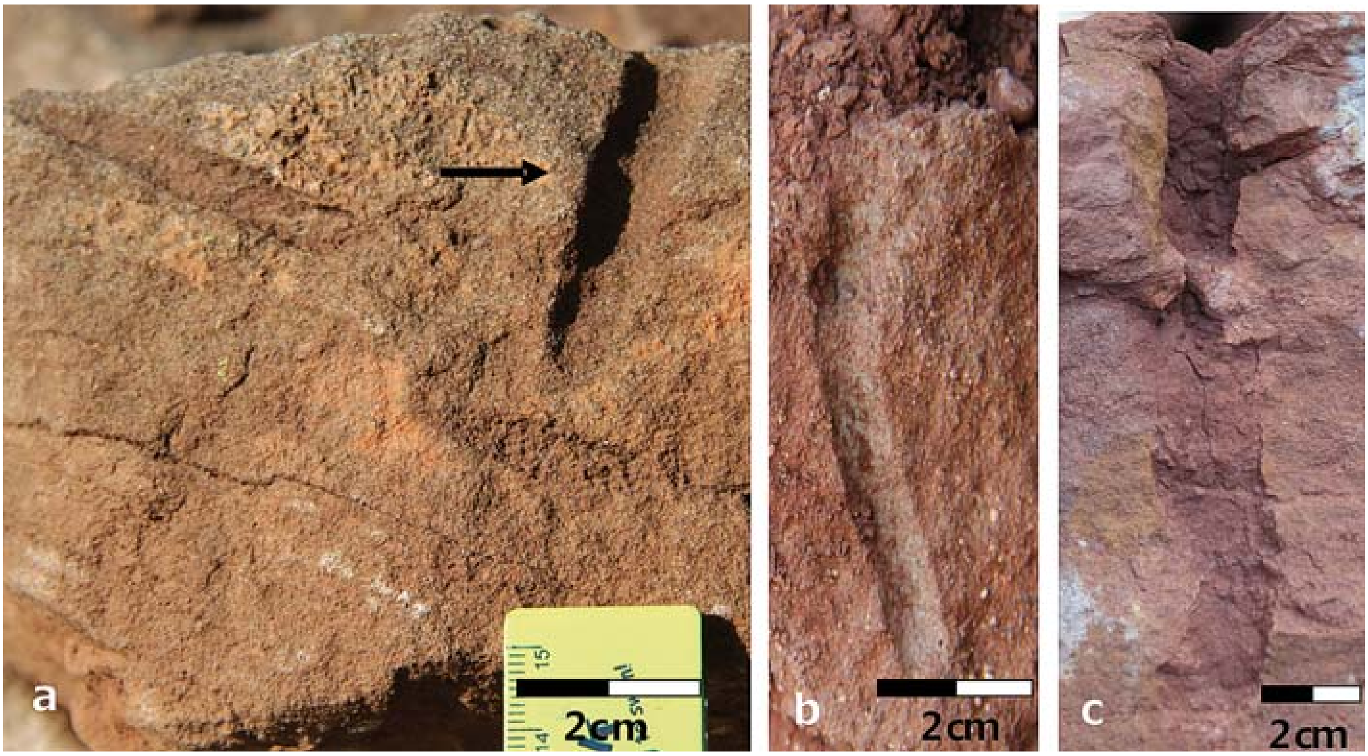

Figure 7. *Skolithos* in the Lower Cretaceous of the Ruyang Basin. **a-c)** *Skolithos* ichnosp. from the middle part of the Xiahedong Formation.

Figure 8. *Scoyenia* from the middle part of the Xiahedong Formation in the Ruyang Basin.

straight to gently curved, unbranched burrow that is parallel to bedding. The burrow is 5 to 11 mm in diameter and up to 16 cm in visible length. The burrow appears to become wider toward both ends, where it is about twice as wide as in the narrow middle part. Burrow fill is preserved in hyporelief in fine-grained sandstone (Fig. 9b).

5.8. Other bioturbation structures

Other bioturbation structures refer to unidentified vertical or inclined burrows in the muddy siltstones (Figs 10a-10b). Commonly, they appear singly or in groups, but it is difficult to identify their ichnogenus or ichnospecies. These burrows are mostly 2 to 20 cm long and 1.5 to 2 cm wide, and they are passively filled. Depositional characteristics show that they are mainly present in a floodplain environment.

5.9. Rhizoliths

Root traces are preserved at the contact between the red interbedded fine-grained siltstone and mudstone (Figs 10c-10d). They are oriented vertically or slightly inclined to bedding. The root traces are 2 to 15.8 cm long and 2 to 19 mm wide. They are filled with fine-grained oxidized sediments, and they were produced in floodplain environments.

6. ICHNOFOSSIL ASSEMBLAGES AND THEIR SEDIMENTARY ENVIRONMENTS

Ichnofossils in the Cretaceous terrestrial deposits of the Ruyang Basin include six ichnospecies, together with unidentified burrows and root traces. Based on their composition, distribution, occurrence and sedimentary environments, two ichnoassemblages are recognized (Fig. 11).

6.1. *Scoyenia- Skolithos* ichnoassemblage

This assemblage mainly consists of *Scoyenia*, *Skolithos*, *Planolites*, *Palaeophycus* and rhizoliths. *Palaeophycus* and *Skolithos* are preserved in medium to fine-grained lithic sandstone intercalated with red silty mudstone. *Planolites*, *Scoyenia* and rhizoliths occur in alternating layers of siltstone and brownish red silty mudstone. Dinosaur skeletal elements belonging to several different taxa (Xu *et al.*, 2010) were found in the silty mudstone and siltstone containing the ichnofossils. The ichnoassemblage was produced in the lithofacies Fsm and St, so it is interpreted as having formed in a braided fluvial environment of an alluvial fan system (Fig. 11a).

Figure 9. *Planolites* from the middle part of the Xiahedong Formation in the Ruyang Basin. **a)** *Planolites montanus.* **b)** *Planolites* ichnosp.

Figure 10. Cretaceous ichnofossils in the Ruyang Basin. **a-b)** Bioturbation from the lower part of the Shangdonggou Formation. **c-d)** Rhizoliths from the middle part of the Haoling Formation.

6.2. *Psilonichnus-Palaeophycus* ichnoassemblage

This ichnoassemblage is characterized by abundant *Psilonichnus*, *Palaeophycus* and *Arenicolites*, plus lesser numbers of *Skolithos*. *Palaeophycus* occurs in alternating layers of sandy conglomerate and brownish red muddy siltstone or sandy mudstone in the Haoling Formation, and it was formed in a middle fan to fan edge sedimentary environment (Fig. 11b).

Psilonichnus and *Arenicolites* are present in lithofacies Fm. It is interpreted as having formed in a shallow pond or lake within the fan edge subfacies. It is noteworthy that the associated dinosaur fossils, such as *Zhongyuansaurus* *luoyangensis,* were discovered in the same layer along with *Psilonichnus*, *Arenicolites* and *Skolithos*. Because this was an extremely shallow pond or lake environment at the edge of an alluvial fan, the preservation of dinosaur fossils in this setting suggests that it may be a flood event deposit.

As mentioned above, the lithofacies and ichnoassemblages indicate that the Cretaceous Xiahedong, Haoling and Shangdonggou Formations in Ruyang basin of western Henan were generated in a depositional environment of alluvial fans in association with braided rivers (Fig. 11).

7. CONCLUSIONS

Based on the study of lithology, sediment texture, primary sedimentary structures and trace fossils, eight lithofacies (Gmm, Gcm, Gm, Gt, St, Sm, Fm and Fsm) are distinguished in the Cretaceous Xiahedong, Haoling and Shangdonggou Formations in the Ruyang Basin of western Henan Province. Two distinct ichnoassemblages are recognized in these sequences (*Scoyenia-Skolithos* ichnoassemblage and *Psilonichnus-Palaeophycus* ichnoassemblage). They were produced in a braided fluvial environment of an alluvial fan system and in a shallow pond or lake at the edge of the alluvial fan system, respectively.

ACKNOWLEDGMENTS

This research was supported by the National Science Foundation of China (Grant No. 41272117), the Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20094116110002), and the Developing Projects of Science and Technology of Henan Province (Grant No. 124300510039, 092300410167). Special thanks to A.A. Ekdale for suggestions to modify the paper.

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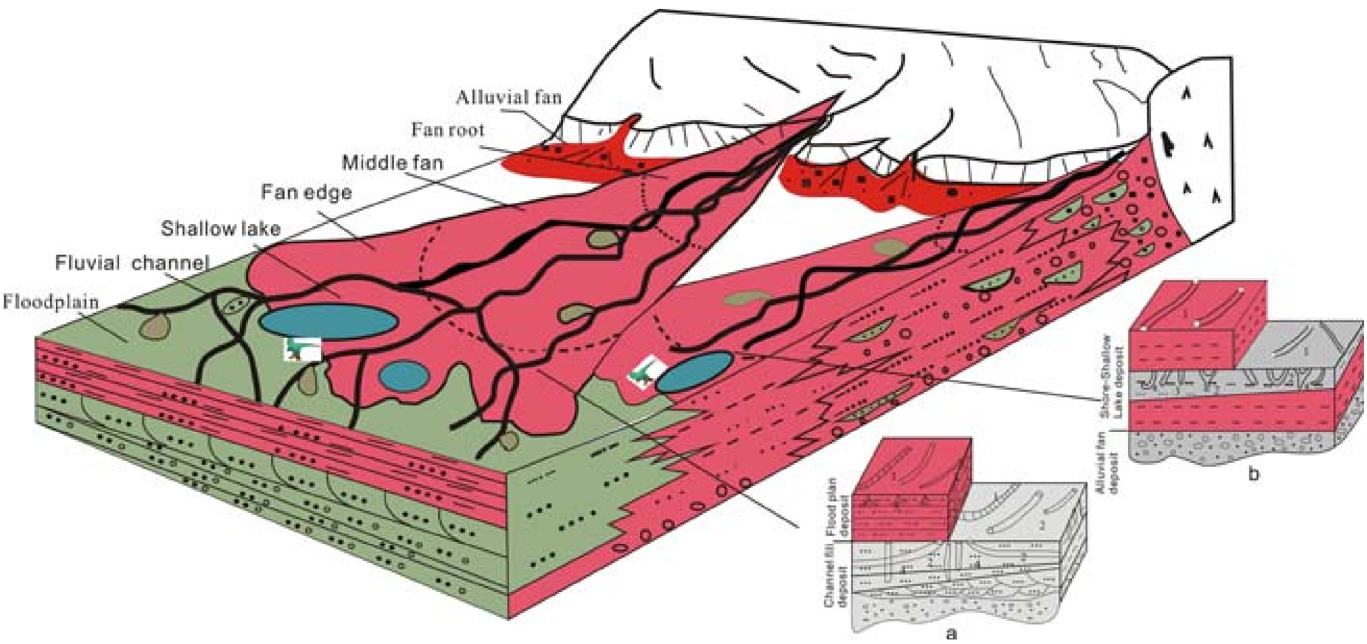

Figure 11. Model of the Cretaceous sedimentary setting and associated ichnofossils in the Ruyang Basin. **a)** *Scoyenia-Skolithos* assemblage: 1-*Scoyenia*, 2-*Palaeophycus*, 3-*Planolites*, 4-*Skolithos*, 5-rhizoliths. **b)** *Psilonichnus-Palaeophycus* assemblage: 1-*Palaeophycus*, 2-*Areniocolites*, 3-*Skolithos*, *4-Psilonichnus*.

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