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Paleosols in an outcrop of red beds from the Upper Cretaceous Yaojia Formation, southern Songliao Basin, Jilin Province, NE China

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Abstract

Paleosols in an outcrop of fluvial–lacustrine red beds have been recognized in the Upper Cretaceous Yaojia Formation in southern Songliao Basin, Songyuan City, Jilin Province, NE China. They are recognized in the field by pedogenic features, including root traces and burrows, soil horizons and soil structures. Root traces are remnants of small herbaceous plants, elongating and branching downwards in the red paleosols. They are filled by calcite, analcime, and clay minerals in spaces created by the decay of the plant roots. Burrows are found near the root traces with backfilled cells made by soil-dwelling insects. Soil horizons include calcic horizons (Bk horizon) with continuous calcareous layers, argillic horizons (Bt horizon) with clay films and dark brown to black iron-manganese cutans, vertic horizons (Bw horizon) with slickensided claystone, and deformed soil structure and gleyed horizons (Bg horizon) with mottles and reticulate mottles. Soil structures of the paleosols include pseudo-anticlinal structures, subangular blocky structures, and angular blocky structures. The micro-pedogenesis characteristics are also observed, including micrite pedogenic minerals and clay skins. Based on the pedogenic features above, paleosols types including Aridisol, Alfisol, and Vertisol are interpreted in the red beds of the Yaojia Formation. Forming in the Late Cretaceous, the paleosols can provide more details about the seasonal climate conditions and terrestrial sedimentary system in lacustrine basin.

Keywords: Late cretaceous, Paleosol, Red bed, Palaeoclimate, Songliao Basin

1 Introduction

Paleosols are products of pedogenesis from sediments and rocks in geological time (Retallack 1997; Therrien 2005; Kraus and Hasiotis 2006; Smith et al. 2008a). They are potentially very powerful tools for research on palaeoclimate, palaeogeomorphology and even the evolution of early life on Earth (Wright 1992; Shao et al. 2008; Xue et al. 2016; Jones et al. 2018; Retallack 2018; Varela et al. 2018). In recent years, the Cretaceous paleosols have been recognized and studied from terrestrial deposits in China (Huang et al. 2010; Du et al. 2011; Gao et al. 2015; Li et al. 2016; Zhang et al. 2018a). The paleosols can provide reliable proxies of the terrestrial palaeoclimate reconstruction during the Cretaceous greenhouse climate period (Skelton et al. 2003; Bice et al. 2006). The Cretaceous terrestrial sedimentary records are well preserved in many ancient basins of China (Li et al. 2016; Wang et al. 2013a). However, the Cretaceous red paleosols sequences from outcrops are still poorly studied. The reconstruction of the mid-latitude terrestrial climate in the Late Cretaceous has been significantly challenged.

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This study introduces a newly discovered record of the Late Cretaceous paleosols from the Yaojia Formation of the southern Songliao Basin in Jilin Province, NE China (Fig. 1). The Songliao Basin is a large lake basin that contains well-preserved Late Cretaceous sediment records (Wang et al. 2013b; Gao et al. 2015). This Cretaceous basin in northeast China provides a good opportunity for reconstructing mid-latitude terrestrial palaeoclimate. Some important studies have been carried out targeting recognition and palaeoclimate interpretation of paleosols in the Songliao Basin. Most of the research is based on cores from drilling wells. Palaeopedology is fundamentally a field science (Retallack 1988), and the newly found red paleosols in the outcrops offer a good analog for the understanding of soil development in the Late Cretaceous terrestrial sedimentary records.

In this study, field characteristics of the paleosols in the southern Songliao Basin were used: (1) to assess whether the deposits are paleosols or not by evidence of root traces, soil horizons and soil structures; and (2) to infer origin and interpretation of the palaeoclimate based on recognition and classification of the red paleosols.

2 Geological setting

The Songliao Basin is a large Meso-Cenozoic sedimentary basin located in northeastern China, which covers an area of approximately 2.6×10^5 km^2 (Feng et al. 2010). Continuous sedimentary records during the Late Cretaceous are well-preserved in the basin. The outcrop section in this study is 27 km southeast of the Songyuan City, Jilin Province, China (Fig. 1). This area belongs to the southeastern uplift (Song et al. 2014) of the Songliao Basin. The Upper Cretaceous stratigraphy includes: the Quantou Formation (K_2q), the Qingshankou Formation (K_2qn), the Yaojia Formation (K_2y) and the Nenjiang Formation (K_2n) from bottom to top (Wu et al. 2013).

The Yaojia Formation overlies the Qingshankou Formation with a parallel unconformity (T_{11}) (Song et al. 2014), which consisted of the red claystones and greyish green interlayers of claystones (Fig. 2). The Yaojia Formation is composed of red and green mottled claystones with interbedded fine-grained sandstones and greyish green claystones. The Yaojia Formation is divided into three members from the bottom upwards, and is mainly composed of fluvial to lacustrine deposits in the southern Songliao Basin (Zhang et al. 2017).

In recent years, red paleosols formed in semi-arid palaeoclimate are found in fluvial, delta, and lakeshore deposits in cores of the Yaojia Formation from drilling wells in oilfields (Du et al. 2011; Zhang et al. 2017). The paleosols can provide important evidence for palaeoclimate research (e.g. the International Continental Scientific Drilling Project) in the Songliao Basin (Wang et al. 2013b). Although rare, several outcrops of the Yaojia Formation were recognized and studied from the perspectives of stratigraphy and sedimentology (Zhai 1989). However, the outcrops of the K_2y^1 were not studied in palaeopedology until recent years (Zhang et al. 2018a).

3 Methods

This research was conducted using observational and measurement data collected from field outcrop of the

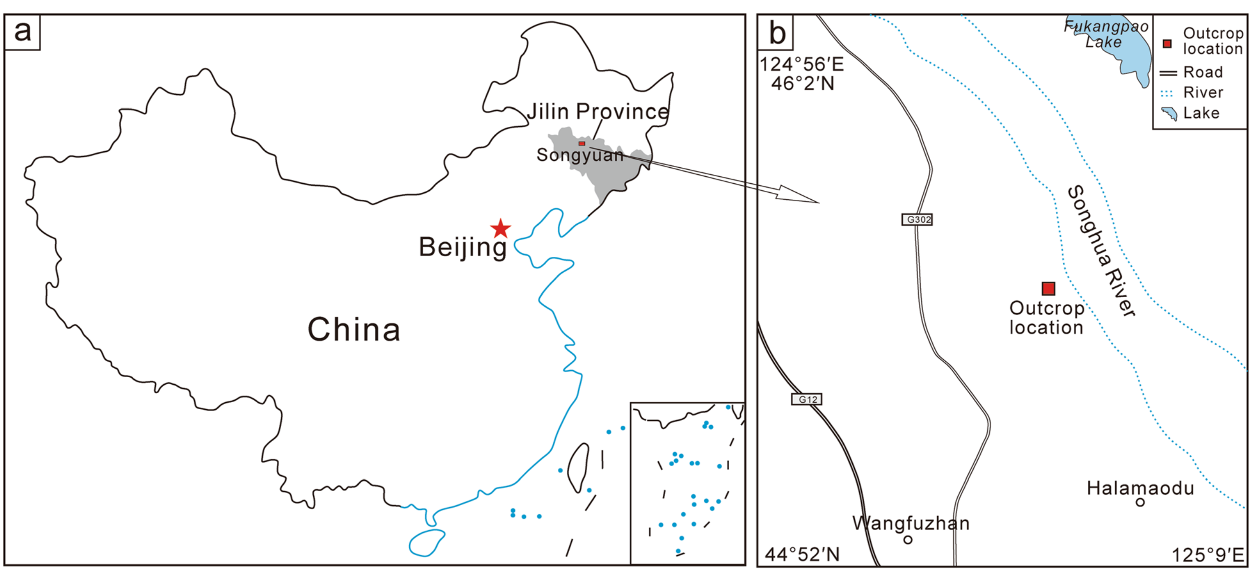

Fig. 1 Location of the field outcrop in Jilin Province, NE China. Base map of China is modified after the Standard Map Service of the National Administration of Surveying, Mapping and Geoinformation of China (http://bzdt.ch.mnr.gov.cn/) (No. GS(2016)1603)

Yaojia Formation of southern Songliao Basin in Songyuan City, Jilin Province, China (Fig. 1). Color, lithology and morphologic features of root traces, soil horizons and soil structures of the paleosols are described in the field, using the scheme of Retallack (1988). Photographs were taken to support the description of paleosols in the field. In addition to field measurement, samples of the paleosols were collected to analyze microscopic features in thin sections using a polarizing optical microscope. Type and microscopic features of the minerals in the root traces were analyzed using a field emission scanning electron microscope. The paleosols were then interpreted following the classification proposed by the Soil Survey Staff (2014).

4 Results

The Yaojia Formation in this section consists of a succession of brick-red and green mottled claystones with interbedded purple-red claystones, grey-green claystones, and grey-green siltstones. A variety of pedogenic features can be recognized in the B horizons of the paleosols. The most notable paleosol features in the outcrop of the Yaojia Formation are drab-colored root traces, burrows, pedogenic carbonates, and soil peds in the profile.

4.1 Root traces and burrows

As the most diagnostic evidence of paleosols, the root traces in the Yaojia Formation occur primarily in the red silty mudstone with mud clasts and burrows (Fig. 3a). The paleosol bed with root traces is approximately 1 m thick in the field. The root traces are mainly in the form of white rhizotubules (Kraus and Hasiotis 2006; Catena et al. 2016). They are distinguished by their color and loose texture from the surrounding paleosol matrix (Fig. 3b, c). The white color of the root traces differs greatly

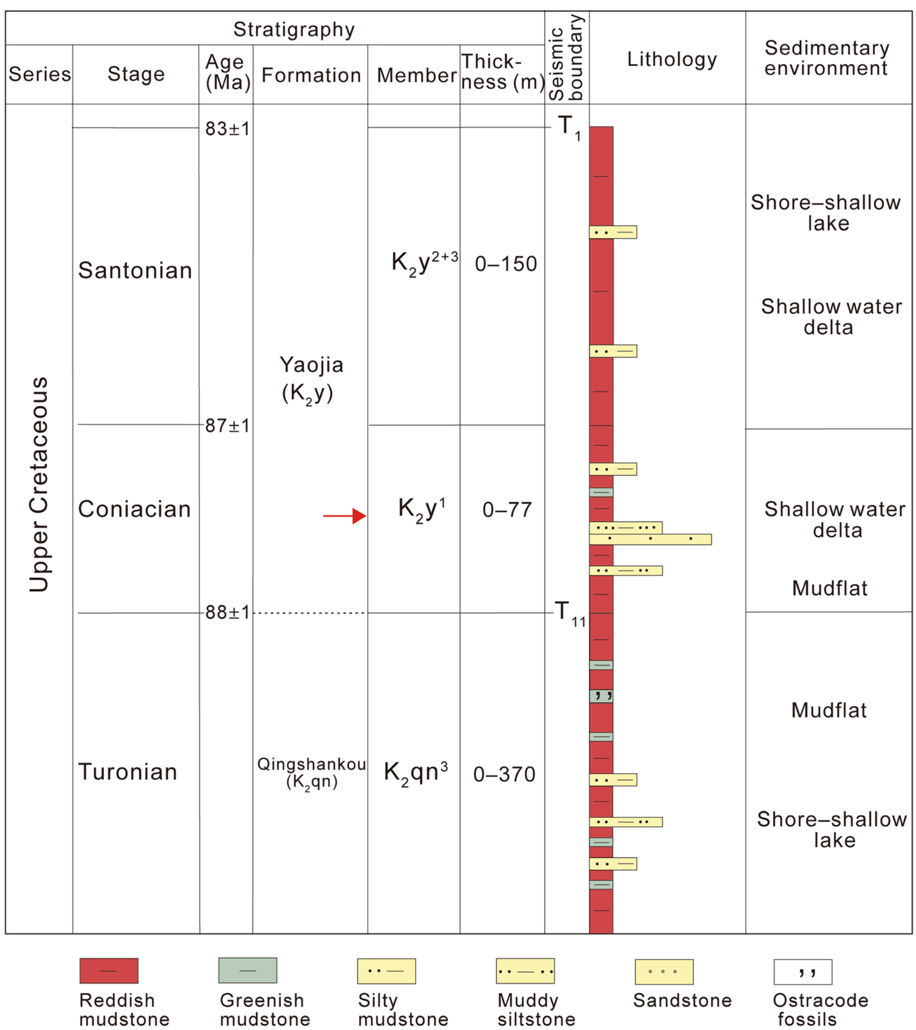

Fig. 2 Comprehensive column of the Yaojia Formation in the southern Songliao Basin (the main research target, the K_2y^1 in this study, is marked by a red arrow)

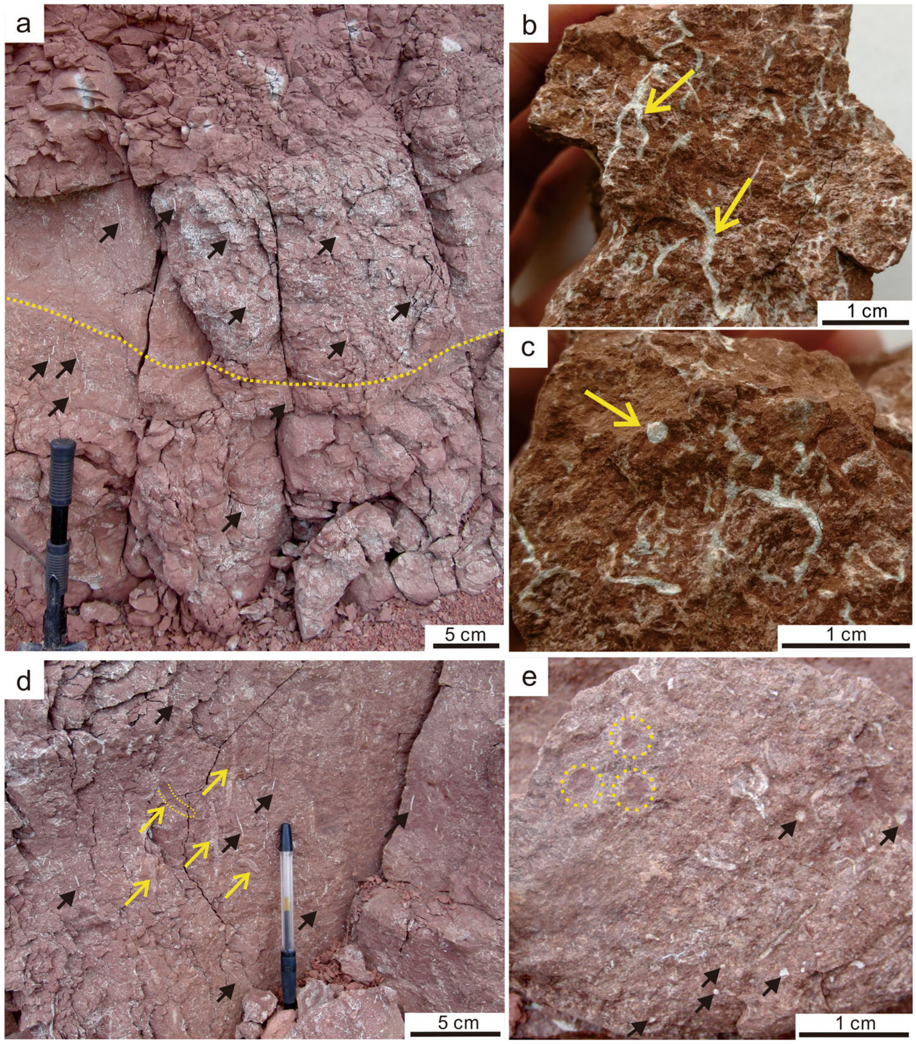

Fig. 3 Photographs showing field characteristics of the root traces and burrows in paleosols of the Yaojia Formation. **a** Root traces marked with black arrows in red paleosols with prismatic structure; the flood scouring surfaces are marked with a yellow dotted line; **b** Vertically-oriented root traces marked with yellow arrows in longitudinal section, showing morphological characteristics of the plant root growth; **c** Root traces in transverse cross-section; note the horizontal branches and circular sections marked with a yellow arrow; **d** Abundant burrows in longitudinal section (marked with yellow arrows) developing with root traces (marked with black arrows); **e** Burrows (marked with yellow dotted line) and root traces (marked with black arrows) in transverse cross-section in the red paleosols

from the surrounding matrix (Fig. 3a). They are 1–5 mm in diameter and can reach 10–20 mm in length. They elongate and branch downwards in the red paleosol with a circular cross-section, indicating plant root growth morphology (Fig. 3b, c). According to patterns of branching (Retallack 1988), they appear to be small herbaceous plants in the Late Cretaceous (Zhang et al. 2018a). The growth space of minerals in the root traces was created by the decay process of roots from the small herbaceous plants.

The burrows are subvertically oriented in the paleosol profile with cylindrical vertical sections (Fig. 3d). They are 4–8 cm in length and 0.6–1 cm in diameter. The burrows are found (Fig. 3e) around the root traces in the field. Backfilled cells (Fig. 3d) are recognized in the burrows filled with paleosol matrix. The trace maker of the burrows in the paleosols are most like soil-dwelling insects. The insects excavate and occupy a moving cell that is backfilled as they burrow through the soil (Smith et al. 2008b).

4.2 Soil horizons

Soil horizons in the paleosols have been recognized in the field. In this study, four types of B horizons are recognized in the paleosols of the Yaojia Formation. That is, calcic horizons (Bk) with thin calcareous layers (Fig. 4a), gleyed horizons (Bg) recognized by mottles and redoximorphic features (Fig. 4b, c), vertic horizons (Bw) of claystone with slickensides (Fig. 4d) and deformation structure, and argillic horizons (Bt) of claystone with clay films (Fig. 4b) and iron-manganese coatings (Fig. 4e, f). They are characterized by vertical repetition in the profile. In some positions of the outcrop, the horizons are truncated sharply by overlying thin cross-bedded very-fine sandstone and siltstone (Fig. 4a, d).

The calcic horizons (Bk) are marked by calcareous layers in the paleosols. The calcareous layers are laterally discontinuous, usually 5–15 cm thick (Fig. 4a). The calcareous layers effervesce strongly when treated with dilute hydrochloric acid. This indicates a high content of carbonate in the paleosols. The calcareous layers have high resistance to weathering in the profile. Laterally equivalent exposure of calcareous layers is observed in the field. The vertical distance between different calcareous layers is generally less than 1 m. This indicates shallow depth of the calcic horizons during the pedogenesis process. The calcic horizons indicate seasonal precipitation that facilitated a leaching and subsequent illuviation process of calcium from the paleosol matrix

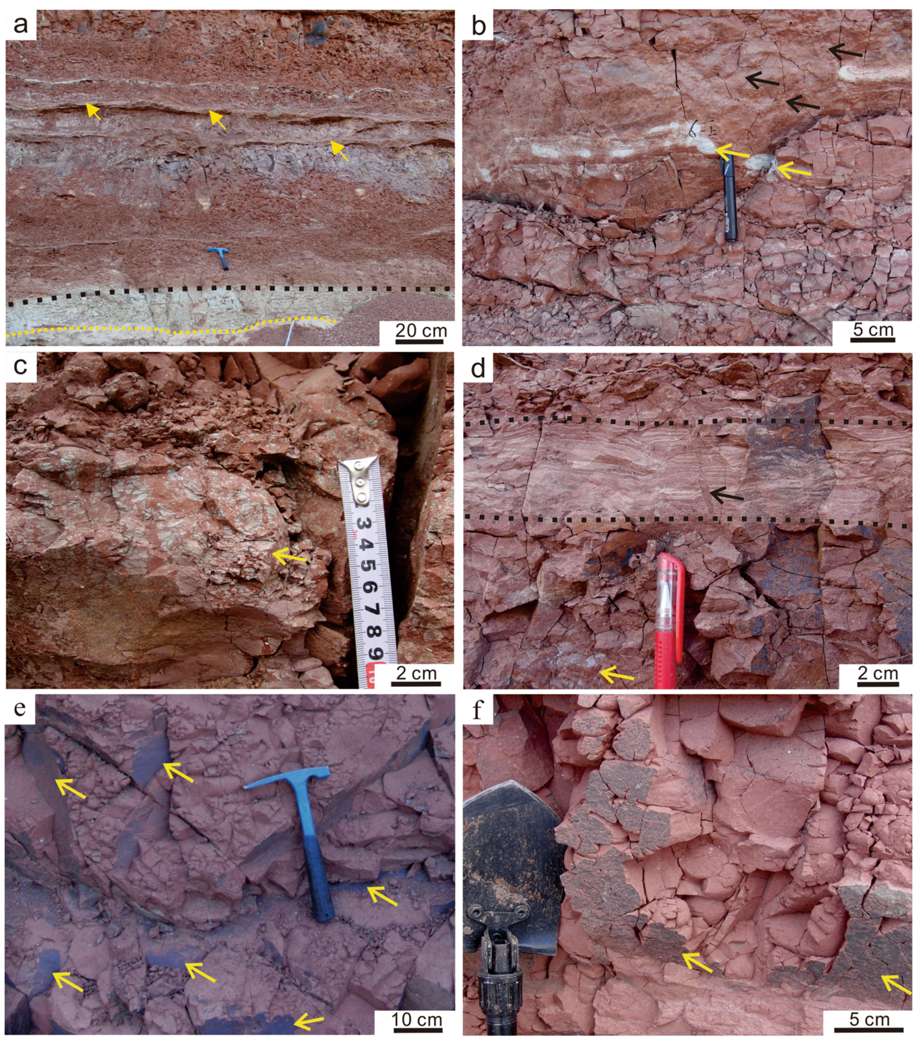

Fig. 4 Photographs showing field characteristics of the soil horizons in paleosols of the Yaojia Formation. **a** Calcic horizon (Bk) recognized by calcareous layers (marked with yellow arrows); note the greyish green claystone (under the black dotted line) and greyish white very-fine sandstone (under the yellow dotted line) indicating discontinuity of the petrogenesis process; **b** Greyish green mottles in gleyed horizon (Bg) of the paleosols (marked with yellow arrows); note the shiny clay films in the argillic horizons (Bt) marked with black arrows; **c** Reticular, mottled red paleosols in gleyed horizon (Bg) (marked with yellow arrow); **d** Slickensides recognized by polished and striated stress surface in the vertic horizon (Bw) of paleosols (marked with a yellow arrow); burrows are found in the overlying cross-bedded red siltstone (marked by the dotted line), indicating the pedogenesis interrupted by deposition of the siltstone; **e** Cutans on inclined planes in the argillic horizon (Bt) marked with yellow arrows; **f** Cutans on vertical planes (marked with yellow arrows) in the argillic horizon (Bt) with subangular blocky structure

in an arid and semi-arid climate (Brewer 1976; Zhao 2000; Retallack 2005; Huang et al. 2010).

The gleyed horizons (Bg) are characterized by red paleosols developed with mottles. Gradational boundaries can be observed between the rounded mottles and the surrounding paleosol matrix. The mottles are circular to ellipsoidal with diameters of 2–5 cm in cross section (Fig. 4b). Also, reticular, mottled red paleosols can also be found. They are marked by small plates of greyish green claystone and surrounding reddish claystone (Fig. 4c). The plates generally have a uniformly greyish green color, having sharp boundaries with surrounding reddish matrix. They are equivalent to the net-type structure of Du et al. (2011). The mottles in paleosols indicate iron mobilization in palaeosol during the gleying process, with alternating saturated and better-drained conditions controlled by falling water tables (Zhu 1988; Kraus and Hasiotis 2006).

Vertic horizons (Bw) are recognized by slickensides and deformation structure in the red paleosols. The slickensides are marked by shiny surfaces that are polished and striated (Fig. 4d). The surfaces are produced by soils sliding over another and the process is controlled by variation of moisture during pedogenesis (Soil Survey Staff 2014). The deformation structures are marked by pseudo-anticlinal structures (see Section 4.3). The genesis of these structures is related to the variation of moisture during pedogenesis.

Clay films and iron-manganese cutans are common in the argillic horizons (Bt). The clay films are recognized by shiny surfaces with waxy luster on faces of peds (Fig. 4b). They are formed by layers of oriented clay grains removed and illuviated in the argillic horizon (Zhao et al. 2006). The cutans in the field are marked by dark brown to black iron-manganese oxides on faces of peds (Fig. 4e, f). These cutans are easily distinguished by their color in the field, indicating frequent and intensive migration and deposition of soil-forming materials with Fe-Mn oxides (Gillman 1984; Liu et al. 2002; Huang et al. 2003).

4.3 Soil structures

Soil structures are characterized by complex organized structural units in paleosols. Pseudo-anticlinal structures in the vertic horizon (Bw) of paleosols are identified in the field (Fig. 5a). These small pseudo-anticlinal structures are marked by gently sloping synclines (Fig. 5b) and steep cuspate anticlines. The synclines and anticlines are recognized by the arrangement of parallel slip-planes which are commonly filled by calcite with millimeter thickness (Fig. 5c, d). The wave lengths of the pseudo-anticlinal structures range from 0.5 m to 1 m, and the amplitudes of the individual sets are less than 0.5 m. The pseudo-anticlinal structures in paleosols indicate a high swelling-clay content in the original soil in dry-wet alternate pedogenesis condition (Ahmad 1983; Wright 1992; Yang et al. 2002).

As cohesion within these units is greater than the adhesion among units, planes or zones are formed under stress as the boundary of the structural units (Soil Survey Staff 2014; Guo et al. 2018). In this study, blocky structures (Fig. 4 f, Fig. 5 d) and prismatic structures (Fig. 3 a, Fig. 5 a) are found in the paleosols. The blocky structures are moderate to strong in degree and medium to very coarse in size (Soil Survey Staff 2014), with the structural units defined by planes of slickensided clay skins and Fe–Mn curtans in the red claystones. In an angular blocky structure, the planes intersect at relatively sharp angles; while in a subangular blocky structure, edges and corners of the faces are mostly rounded. The structural units of prismatic structures are defined by flat to rounded vertical faces. The blocky and prismatic structures indicate swelling and shrinking process of clay minerals in pedogenesis process (Retallack 1988).

4.4 Petrographic observations (micropedogenisis)

Evidence of petrogenesis are gained from observations of thin sections of the paleosols in the Yaojia Formation. Micritic pedogenic minerals are found in root traces. As shown by thin sections and SEM analyses, the color of the root traces differs greatly from the surrounding matrix (Fig. 6a). They are filled with calcite (Fig. 6b), analcime, and clay minerals (Fig. 6c) (Zhang et al. 2018a). The analcime in root traces is characterized by euhedral and subhedral icositetrahedron (Fig. 6c). Root trace mineralogy (i.e., calcite and analcime), indicates an evaporative concentration process from evaporating soil water after roots decayed under dry climatic conditions (Klappa 1980; Owen et al. 2008). Details of clay skins are also revealed from the sections of paleosol matrix. The clay skins are marked by diffusion ferri around claystone clasts (Fig. 6d). The diffusion ferran are recognized by their reddish-brown color. Besides, microlite calcite and hematite diffusion are also found in the paleosol matrix. The clay skins indicate diffusion of oxygen during early diagenesis in the soil matrix (Brewer 1976; Retallack 1988).

5 Discussion

Fluvial, delta and lacustrine deposits of the Yaojia Formation were studied in the southern Songliao Basin (Zhang et al. 2018b). Compared to previous studies related to paleosols from drilling-well cores, this investigation studied the red deposits of the Yaojia Formation from the perspective of palaeopedology in the Songliao

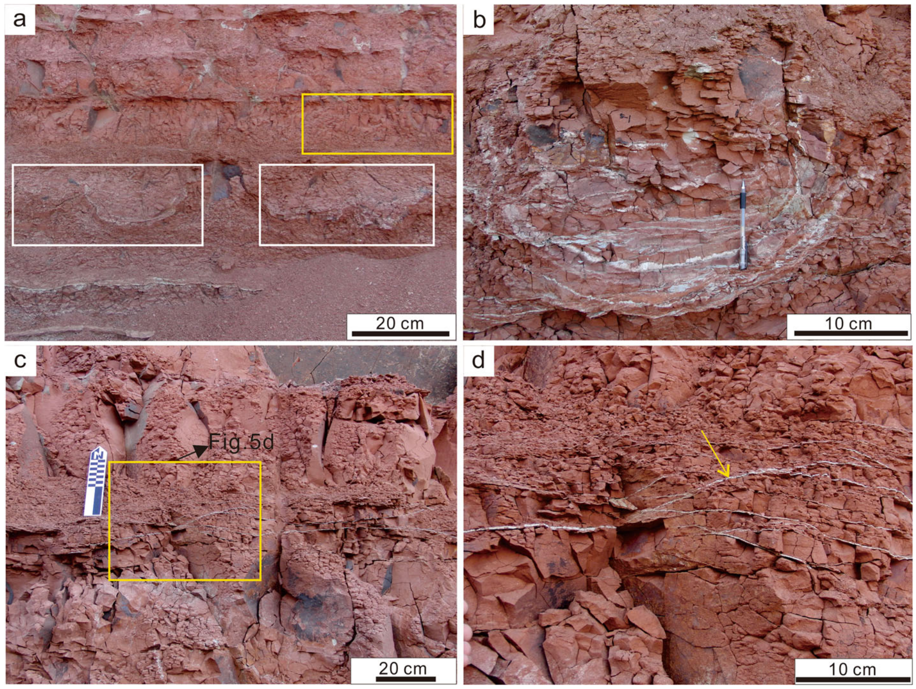

Fig. 5 Photographs showing field characteristics of the soil structures in paleosols of the Yaojia Formation. **a** Pseudo-anticlinal structures in the vertic horizon (Bw) (marked with white rectangles), and prismatic soil structure (marked with a yellow rectangle) in the paleosols; **b** Gently sloping synclines in pseudo-anticlinal structures in the vertic horizon (Bw); **c** Small pseudo-anticlines in the vertic horizon (Bw); **d** Close-up of the small pseudo-anticlines (Fig. 5c) in the vertic horizon (Bw) of the paleosols with angular blocky structure; the fracture surfaces are infilled by calcite

Basin. In this study, we discovered paleosols in outcrop developed in the fluvial–lacustrine succession by evidence of root traces, soil horizons, and soil structures. The original deposits of the Yaojia Formation experienced a prolonged exposure and were transformed to red paleosols. The paleosols with thick calcic horizons are moderately to strongly developed and can be related to modern soils.

The paleosols with Bk horizons are interpreted as Aridisols (Soil Survey Staff 2014). These paleosols in the Yaojia Formation commonly have blocky soil peds in field. The abundance of pedogenic carbonate are strong indicators of Aridisols. They indicate the lack of wetting season influenced by occasional rainfall in arid and semi-arid climates (Retallack 1997).

The paleosols with Bt horizons and Bg horizons are interpreted as Alfisols (Soil Survey Staff 2014). These paleosols in the Yaojia Formation commonly have blocky and prismatic soil peds in the field. The presence of the mottles, clay films, and iron-manganese cutans indicate migration and illuviation of soil materials. This process is influenced by seasonal moisture change during the pedogenesis (Soil Survey Staff 2014). Alfisols have a more humid soil moisture regime than that of the Aridisols.

The paleosols with Bw horizons are interpreted as Vertisols (Soil Survey Staff 2014). The presence of slickensides and pseudo-anticlinal structures are considered as the diagnostic features of Vertisols in the Yaojia Formation. These features in the Bw horizons indicate a shrinking and swelling process (Mack et al. 1993) of the clay in Vertisol. The shrinking and swelling process is controlled by variation of moisture in seasonal climate.

During the sedimentary period of the Yaojia Formation, the palaeo lacustrine area decreased and reached a minimum range (less than 10,000 km^2) (Zhang et al. 2011). The paleosols in the Yaojia Formation suggest exposure and pedogenetic processes influenced by tectonic uplift (Song et al. 2014). The red beds and calcic horizon in the Aridisols are evidence of warm and dry season influenced by seasonal fluctuations in climate (Zhao 2000; Retallack 2005; Catena et al. 2016; Basilici et al. 2016). The Alfisols and the Vertisols indicate pedogenesis process in seasonally wet-and-dry climates (Retallack 2005; Huang et al. 2010; Guo et al. 2018). Thus, these paleosol types support the interpretation of a generally semi-arid seasonal climate. The newly found paleosols in the field can provide important implications and supplement to the Late Cretaceous terrestrial deep-

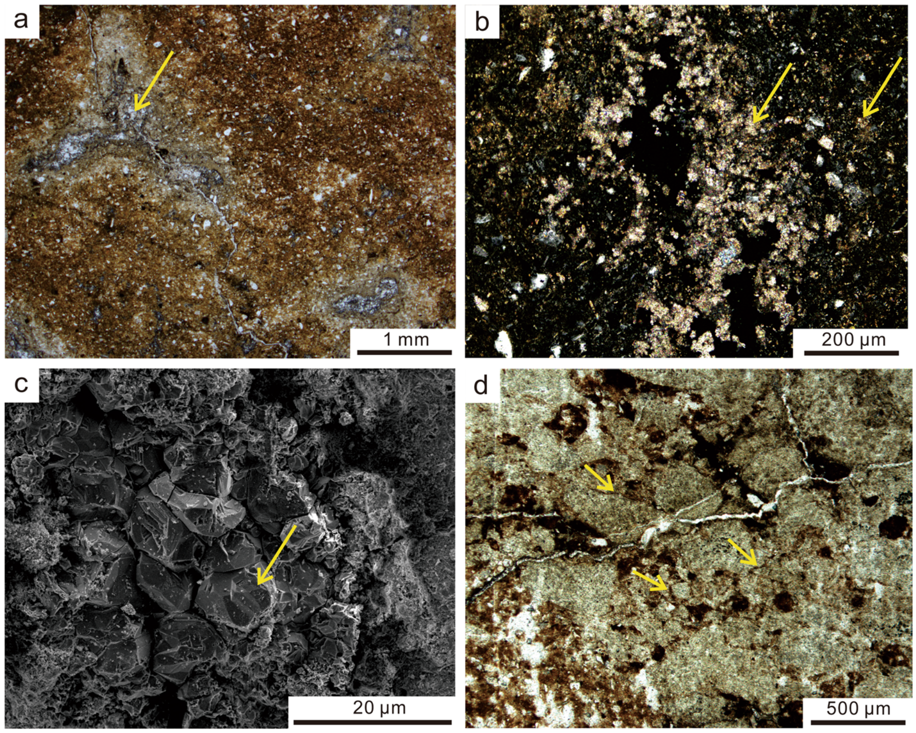

Fig. 6 Micro pedogenesis observed in thin sections and SEM. **a** Root traces marked with a yellow arrow in plane-polarized light; note the color difference between root traces and hematite bearing surrounding paleosol matrix; **b** Calcite filling root traces marked with yellow arrows in perpendicular polarized light; **c** Analcime filled root traces observed in SEM, the analcime are approximately 50–200 μm in diameter; **d** Clay skins with diffusion ferran around clay clasts in the paleosols

time palaeoclimate research based on pollen and ostracods fossils from drilling cores in the Late Cretaceous period (Wang et al. 2013b). Investigations of modern rivers and deltas have revealed that the seasonal climate has a significant controlling effect on the fluvial-delta sedimentary architecture (Fielding et al. 2018). The seasonal climate interpreted from the paleosols can give implication to the sedimentary architecture research of the fluvial-lacustrine deposits.

6 Conclusions

In this study, we confirm the development of paleosols in the red beds of Yaojia Formation through field observations and laboratory analyses. The pedogenic features of paleosols include root traces, burrows, soil horizons, and soil structures. The root traces are mainly in form of rhizotubules, indicating plant growth in alternating wetting and drying conditions. Developing with the root traces, the burrows are found in the paleosols made by insects. There are four types of B horizons in the paleosols of the Yaojia Formation, respectively as the calcic horizon (Bk), the gleyed horizon (Bg), the argillic horizon (Bt) and vertic horizon (Bw). The B horizons are thick and locally interrupted by deposits as upper A horizon. The pedogenic features are also confirmed based on the micro pedogenesis characteristics. Aridisol, Alfisols, and Vertisols are interpreted from the paleosols in Yaojia Formation. The paleosols indicate brief episodes of humid climate and arid climate in the Late Cretaceous highly seasonal climate.

Abbreviation

SEM: Scanning electron microscope

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Authors' contributions

Collection and analysis of the data from outcrop was through collaboration among all authors. The writing of the final manuscript was also through collaboration among all authors. The authors read and approved the final manuscript.

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Availability of data and materials

Information of data and materials was in figures of the manuscript.

Competing interests

The authors declared that they have no competing interests.

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References

Ahmad, N. 1983. Vertisols. In *Pedogenesis and soil taxonomy II. The soil orders*, ed. L.P. Wilding, N.E. Smeck, and G.F. Hall, 91–123. Amsterdam: Elsevier.

Basilici, G., P.F.D. Bo, and E.F. De Oliveira. 2016. Distribution of palaeosols and deposits in the temporal evolution of a semiarid fluvial distributary system (Bauru Group, Upper Cretaceous, SE Brazil). *Sedimentary Geology* 341: 245–264.

Bice, K.L., D. Birgel, P.A. Meyers, K.A. Dahl, K.U. Hinrichs, and R.D. Norris. 2006. A multiple proxy and model study of Cretaceous upper ocean temperatures and atmospheric CO_2 concentrations. *Paleoceanography* 21 (2): PA2002.

Brewer, R. 1976. *Fabric and mineral analysis of soils*, 434–444. New York: Krieger Publishing Company.

Catena, A.M., D.I. Hembree, B.Z. Saylor, F. Anaya, and D.A. Croft. 2016. Paleoenvironmental analysis of the neotropical fossil mammal site of cerdas, Bolivia (middle Miocene) based on ichnofossils and paleopedology. *Palaeogeography, Palaeoclimatology, Palaeoecology* 459: 423–439.

Du, X.B., X.N. Xie, Y.C. Lu, J.Y. Ren, S. Zhang, P. Lang, T. Chen, M. Su, and C. Zhang. 2011. Distribution of continental red paleosols and their forming mechanisms in the Late Cretaceous Yaojia Formation of the Songliao Basin, NE China. *Cretaceous Research* 32 (2): 244–257.

Feng, Z.Q., C.Z. Jia, and X.N. Xie. 2010. Tectonostratigraphic units and stratigraphic sequences of the nonmarine Songliao Basin, Northeast China. *Basin Research* 22 (1): 79–95.

Fielding, C.R., J. Alexander, and J.P. Allen. 2018. The role of discharge variability in the formation and preservation of alluvial sediment bodies. *Sedimentary Geology* 365: 1–20.

Gao, Y., D.E. Ibarra, C. Wang, J.K. Caves, C.P. Chamberlain, S.A. Graham, and H.C. Wu. 2015. Mid-latitude terrestrial climate of East Asia linked to global climate in the Late Cretaceous. *Geology* 43 (4): 287–290.

Gillman, G.P. 1984. Using variable charge characteristics to understand the exchangeable cation of oxic soils. *Australian Journal of Soil Research* 22 (1): 71–80.

Guo, X., G.J. Retallack, B. Lü, L. He, R. Wang, and H. Song. 2018. Paleosols in Devonian red-beds from Northwest China and their paleoclimatic characteristics. *Sedimentary Geology* 379: 16–24.

Huang, C.M., G.J. Retallack, and C.S. Wang. 2010. Cretaceous calcareous paleosols: Pedogenetic characteristics and paleoenvironmental implications. *Acta Pedologica Sinica* 47 (6): 1029–1038 (in Chinese with English abstract).

Huang, L., F. Liu, W.F. Tan, and Y.J. Wang. 2003. The progress of soil cutan study. *Chinese Journal of Soil Science* 34 (2): 143–147 (in Chinese with English abstract).

Jones, M.M., D.E. Ibarra, Y. Gao, B.B. Sageman, D. Selby, C.P. Chamberlain, and S.A. Graham. 2018. Evaluating Late Cretaceous OAES and the influence of marine incursions on organic carbon burial in an expansive east Asian paleo-lake. *Earth and Planetary Science Letters* 484: 41–52.

Klappa, C.F. 1980. Rhizoliths in terrestrial carbonates: Classification, recognition, genesis, and significance. *Sedimentology* 27: 613–629.

Kraus, M.J., and S.T. Hasiotis. 2006. Significance of different modes of rhizolith preservation to interpreting paleoenvironmental and paleohydrologic settings: Examples from Paleogene paleosols, Bighorn Basin, Wyoming, U.S.a. *Journal of Sedimentary Research* 76 (4): 633–646.

Li, J., X.Y. Wen, and C.M. Huang. 2016. Lower Cretaceous paleosols and paleoclimate in Sichuan Basin, China. *Cretaceous Research* 62: 154–171.

Liu, F., R.J. Gilkes, R.D. Hart, and A. Bruand. 2002. Differences in potassium forms between cutans and adjacent soil matrix in a grey clay soil. *Geoderma* 106 (3): 289–303.

Mack, G.H., W.C. James, and H.C. Monger. 1993. Classification of paleosols. *GSA Bulletin* 105: 129–136.

Owen, R.A., R.B. Owen, R.W. Renaut, J.J. Scott, B. Jones, and G.M. Ashley. 2008. Mineralogy and origin of rhizoliths on the margins of saline, alkaline lake Bogoria, Kenya rift valley. *Sedimentary Geology* 203 (1): 143–163.

Retallack, G.J. 1988. Field recognition of paleosols. In *Paleosols and weathering through geologic time: Principles and applications*, ed. J. Reinhardt and W.R. Sigleo, vol. 216, 1–19 Geological Society of America, Special Paper.

Retallack, G.J. 1997. Early forest soils and their role in Devonian global change. *Science* 276 (5312): 583–585.

Retallack, G.J. 2005. Pedogenic carbonate proxies for amount and seasonality of precipitation in paleosols. *Geology* 33 (4): 333–336.

Retallack, G.J. 2018. The oldest known paleosol profiles on Earth: 3.46 Ga Panorama Formation, western Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 489: 230–248.

Shao, L.Y., Z.P. He, and J. Lu. 2008. *Sequence stratigraphy and coal accumulation of the carboniferous and Permian in the Western Peri-Bohai Bay Area of the northern China*, 124–158. Beijing: Geological Publishing House (in Chinese with English abstract).

Skelton, P.W., R.A. Spicer, S.P. Kelley, and I. Gilmour. 2003. *The Cretaceous World*, 1–12. Cambridge: Cambridge University Press.

Smith, J.J., S.T. Hasiotis, M.J. Kraus, and D.T. Woody. 2008a. Relationship of floodplain ichnocoenoses to paleopedology, paleohydrology, and paleoclimate in the Willwood Formation, Wyoming, during the Paleocene–Eocene thermal maximum. *Palaios* 23 (9–10): 683–699.

Smith, J.J., S.T. Hasiotis, M.J. Kraus, and D.T. Woody. 2008b. Naktodemasis bowni: New ichnogenus and ichnospecies for adhesive meniscate burrows (amb), and paleoenvironmental implications, Paleogene Willwood Formation, Bighorn Basin, Wyoming. *Journal of Paleontology* 82 (2): 267–278.

Soil Survey Staff. 2014. *Kellogg Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42. 372*. Nebraska: U.S. Department of Agriculture.

Song, Y., J. Ren, A.A. Stepashko, and J. Li. 2014. Post-rift geodynamics of the Songliao Basin, NE China: Origin and significance of T11 (Coniacian) unconformity. *Tectonophysics* 634: 1–18.

Therrien, F. 2005. Palaeoenvironments of the latest Cretaceous (Maastrichtian) dinosaurs of Romania: Insights from fluvial deposits and paleosols of the Transylvanian and Hateg basins. *Palaeogeography, Palaeoclimatology, Palaeoecology* 218 (1): 15–56.

Varela, A.N., M.S. Raigemborn, S. Richiano, T. White, D.G. Poiré, and S. Lizzoli. 2018. Late Cretaceous paleosols as paleoclimate proxies of high–latitude southern hemisphere: Mata Amarilla Formation, Patagonia, Argentina. *Sedimentary Geology* 363: 83–95.

Wang, C.S., Z.Q. Feng, L.M. Zhang, Y. Huang, K. Cao, P. Wang, and B. Zhao. 2013b. Cretaceous paleogeography and paleoclimate and the setting of SKI borehole sites in Songliao Basin, Northeast China. *Palaeogeography, Palaeoclimatology, Palaeoecology* 385 (3): 17–30.

Wang, C.S., R.W. Scott, X.Q. Wan, S.A. Graham, Y.J. Huang, P.J. Wang, H.C. Wu, W.E. Dean, and L.M. Zhang. 2013a. Late Cretaceous climate changes recorded in eastern Asian lacustrine deposits and north American epieric sea strata. *Earth-Science Reviews* 126 (126): 275–299.

Wright, V.P. 1992. Paleosol recongnition: A guide to early diagensis in terrestrial settings. In *Diagenesis, III, developments in sedimentology*, ed. K. H. Wolf and G.V. Chilingarian, vol. 47, 591–619. Amsterdam: Elsevier.

Wu, H.C., S.H. Zhang, G.Q. Jiang, L. Hinnov, T. Yang, H. Li, X. Wan, and C. Wang. 2013. Astrochronology of the early Turonian–early Campanian terrestrial succession in the Songliao Basin, northeastern China and its implication for long-period behavior of the solar system. *Palaeogeography, Palaeoclimatology, Palaeoecology* 385 (3): 55–70.

Xue, J., Z. Deng, P. Huang, K. Huang, M.J. Benton, Y. Cui, D.M. Wang, J. Liu, B. Shen, J.F. Basinger, and S. Hao. 2016. Belowground rhizomes in

paleosols: The hidden half of an early Devonian vascular plant. *Proceedings of the National Academy of Sciences of the United States of America* 113 (34): 9451–9456.
Yang, L.J., L.Y. Shao, and P.F. Zhang. 2002. Palaeosols: Types and recognition. *Coal Geology of China* 14 (3): 1–3 (in Chinese with English abstract).
Zhai, G.M. 1989. *Petroleum geology of China (Volume2. Daqing, Jilin oil field)*, 41–76. Beijing: Petroleum Industry Press (in Chinese).
Zhang, L., Z.D. Bao, L. Dou, H. Wang, and Y. Ji. 2018a. New discovery of red paleosols with calcite and zeolitic rhizoliths in the Late Cretaceous Yaojia Formation, southern Songliao Basin, NE China. *Acta Geologica Sinica (English Edition)* 92 (6): 2462–2463.
Zhang, L., Z.D. Bao, L.X. Dou, D.S. Zang, S.W. Mao, J. Song, and Z.C. Wang. 2018b. Sedimentary characteristics and pattern of distributary channels in shallow water deltaic red bed succession: A case from the Late Cretaceous Yaojia Formation, southern Songliao Basin, NE China. *Journal of Petroleum Science and Engineering* 171: 1171–1190.
Zhang, L., Z.D. Bao, Y. Lin, Y. Chen, L.X. Dou, and B. Kong. 2017. Genetic types and sedimentary model of sandbodies in a shallow-water delta: A case study of the first member of Cretaceous Yaojia Formation in Qian'an area, south of Songliao Basin, NE China. *Petroleum Exploration and Development* 44 (5): 770–779.
Zhang, S., X.L. Fu, and C.C. Zhang. 2011. Stratigraphic sequences and sedimentary evolution in the Yaojia and Nenjiang formations, Songliao Basin. *Sedimentary Geology and Tethyan Geology* 31 (2): 34–42 (in Chinese with English abstract).
Zhao, J.B. 2000. A new geological theory about eluvial zone: Theory illuvial on depth of $CaCO_3$. *Acta Sedimentologica Sinica* 18 (1): 29–35 (in Chinese with English abstract).
Zhao, J.B., Y.F. Hao, and Y.L. Yue. 2006. Change of paleosol and climate during middle Holocene in Luochuan area of Shaanxi Province. *Quaternary Sciences* 26 (6): 969–975 (in Chinese with English abstract).
Zhu, J.J. 1988. Genisis and research significance of the plinthitic horizon. *Geographical Research* 20 (7): 12–20 (in Chinese with English abstract).

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