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The first report of terrestrial *Petroxestes* from the Lower Cretaceous Yixian Formation, western Liaoning, China

Jiang Xu, En-Pu Gong*, Tie-Hui Wang and Xiao-Hong Chen

Abstract

Abundant aggregated, elongate, shallow borings have been discovered from the Lower Cretaceous Yixian Formation in western Liaoning, China. By contrast with several similarly-shaped trace fossils, such as *Asthenopodichnium*, *Teredolites*, *Rogerella*, *Cubiculum* and *Petroxestes*, their appearance, size, arranged modes, distribution density and substrate types are most similar with traces of *Petroxestes* that was discovered from Southern Ohio, USA (J. Paleontol. 62: 306–08, 1988). This is the first report of *Petroxestes* from China, and also the first report of these traces from a terrestrial environment.

Keywords: Trace fossils, Jehol biota, Carbonate rocks, Terrestrial *Petroxestes*

1 Introduction

A large number of well-preserved Jehol Biota fossils have been discovered in the Lower Cretaceous deposits in western Liaoning, China, consisting of macroplants, palynomorphs, charophytes, protistans, conchostracans, ostracods, shrimps, insects, bivalves, gastropods, fish, turtles, lizards, pterosaurs, crocodiles, dinosaurs, birds, and mammals (Sha 2007; Pan et al. 2012; Pan et al. 2013; Ding et al. 2016). However, reported trace fossils are relatively scarce (Xing et al. 2009). Nevertheless, trace fossils are irreplaceable evidences for some palaeontological behavior studying, for example, burrowing. Nowadays, ichnology not only has important applications in classical palaeobiology, but also is of great value in the more applied disciplines of palaeoenvironmental and stratigraphical analysis (McIlroy 2004).

Petroxestes pera is an ichnospecies erected by Wilson and Palmer (1988) from the Ordovician of Ohio (USA), and interpreted to have been produced by boring bivalves. It is a bioerosional ichnotaxon, occurring within lithic substrates, and is characterized by a shallow to deep elongate outline, broadly parallel sides, and a rounded bottom in longitudinal and transverse section (Pickerill et al. 2001). It is densely distributed on the surface of carbonate rocks from the Lower Cretaceous Yixian Formation in western Liaoning, China. This paper aims to give a detailed description of the morphology of these trace fossils and point out their differences with other similarly-shaped traces.

2 Geological setting

Since the Early Cretaceous, the stress state in northeastern China changed from tension to extension (Zhu et al. 2008), resulting in the formation of several Mesozoic basins (Jiang et al. 2007; Huang 2015; Zhang et al. 2016). Jin–Yang Basin and Yixian Basin are two of these basins in western Liaoning (Fig. 1), and are characterized by producing numerous Jehol Biota fossils (e.g. Hou et al. 1995; Ji and Ji 1996, 1997; Hu et al. 1997; Chen et al. 1998; Sun et al. 1998; Ji et al. 1998; Chang et al. 2003; Ding et al. 2003; Ji 2004). In both basins, fossils were mainly discovered from the Yixian Formation. However, the sedimentary characteristics of the Yixian Formation in these two basins are different. Firstly, in Yixian Basin, Yixian Formation is comprised of many discontinuous members that are cut off by igneous rocks (e.g. Laogonggou, Yenangou, Zhuanchengzi, Dakangpu and Jingangshan Members), each of which has limited thickness. However, in the Jin–Yang Basin, the Yixian Formation is relatively continuous with a great thickness of about 135 m (Wang et al. 1998, 2004). Secondly, lithologically, in the Jin–Yang Basin, except for one carbonate rock stratum and several limestone lenses, the Yixian

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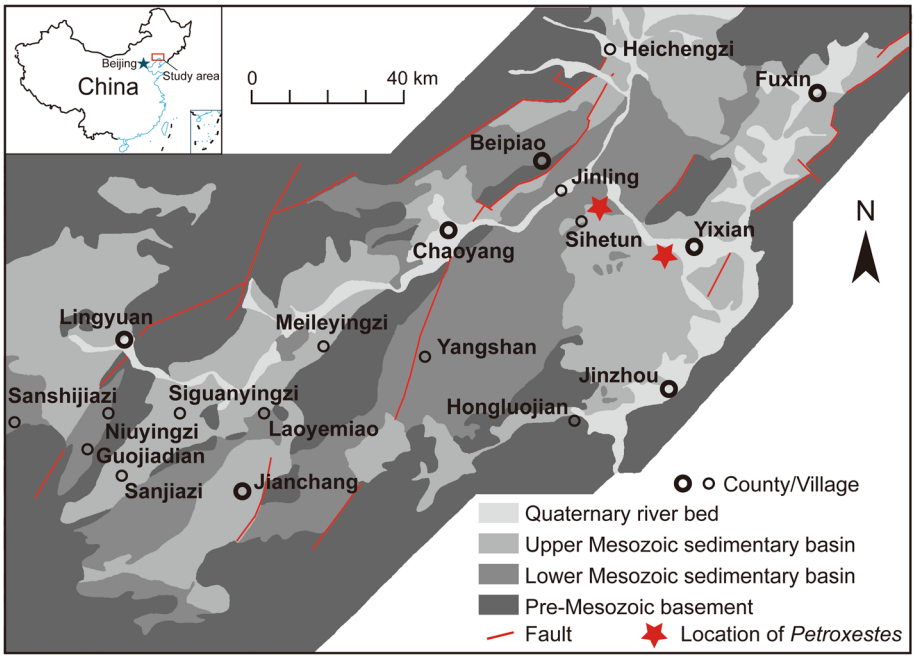


Fig. 1 Distribution of Mesozoic basins and distribution of *Petroxestes* in western Liaoning, NE China (modified from Gong et al. 2017). The insert map is modified after the State Bureau of Surveying and Mapping, China (No. GS(2016)1603)

Formation is mainly composed of sedimentary tuff, tuffaceous mudstone and tuffaceous shales, where fossils were mainly preserved (Guo et al. 2001; Jiang and Sha 2007; Wang et al. 1998). Nevertheless, there are many carbonate strata occurring in the Yixian Basin (Wang et al. 2004; Zhang et al. 2006), which are generally formed under hot and arid palaeoclimates (Chen et al. 2009, 2010, 2011; Gong et al. 2007, 2011).

Petroxestes fossils have been found from two sites (Fig. 1). One (GPS coordinates 41°36′15.7″N/120°51′44.8″E) is located 4.8 km northeast of Sihetun village (Fig. 1), and trace fossils were discovered in the lowermost portion of the Yixian Formation. The other (GPS coordinates 41°32′37.8″N/120°7′41.8″E) is located 9 km west of Yixian county, and trace fossils were preserved in the middle portion of the Yixian Formation. The former one belongs to the Jin–Yang Basin, and the latter one belongs to Yixian Basin. All *Petroxestes* were discovered in situ, on the surface of carbonate rocks from the Yixian Formation.

3 Materials and methods

Petroxestes from these two sites are vertical shallow borings with similar morphology (Fig. 2). In plan view, they are elongate with straight or slightly-curved parallel sides and rounded ends. They show no preferred orientation. These borings have a round bottom in both longitudinal and transversal sections (Fig. 3c, d). Except for a very few traces, most are close to each other. No intersecting structures have been observed. These traces have a high density, up to 50 counts per square meter. There are no bioglyphs distributed on the inside surface of these traces. The producers were not preserved inside the traces.

There is a slight difference in the size of *Petroxestes* between the two areas. *Petroxestes* from the Jin–Yang Basin is 9–21 mm long and 1–3 mm wide. The proportion of 12–14-mm-long traces is more than 50%, and 10–18-mm-long ones are exceeding 90%. More than 56% of traces are 2 mm wide. In the Yixian Basin, the length and width of *Petroxestes* are 11–20 mm and 2–4 mm, respectively. The proportion of 14–15-mm-long traces is more than 50%, and 11–15 mm long ones more than 80%. About 42% of traces are 2 mm wide. However, in the two areas, the depth of traces is similar, both varying from 1.5 mm to 3 mm. Generally, the width/length ratio of these *Petroxestes* is less than 0.2.

The main bases for the identification of these traces as borings rather than burrows are as follows. Firstly, borings are produced by physical and/or chemical erosion (usually acidic substances formed by organisms), so they usually have relatively-smooth inside surfaces (McIlroy 2004). Traces from the Yixian Formation have such surfaces (Fig. 2b–e; Fig. 3b, c). Secondly, these traces are straight in outline (Fig. 2a, b, d–e; Fig. 3b), which means they have no obvious extrusion deformation occurred during the process of diagenesis. If these traces were burrows that formed in soft sediments, it is

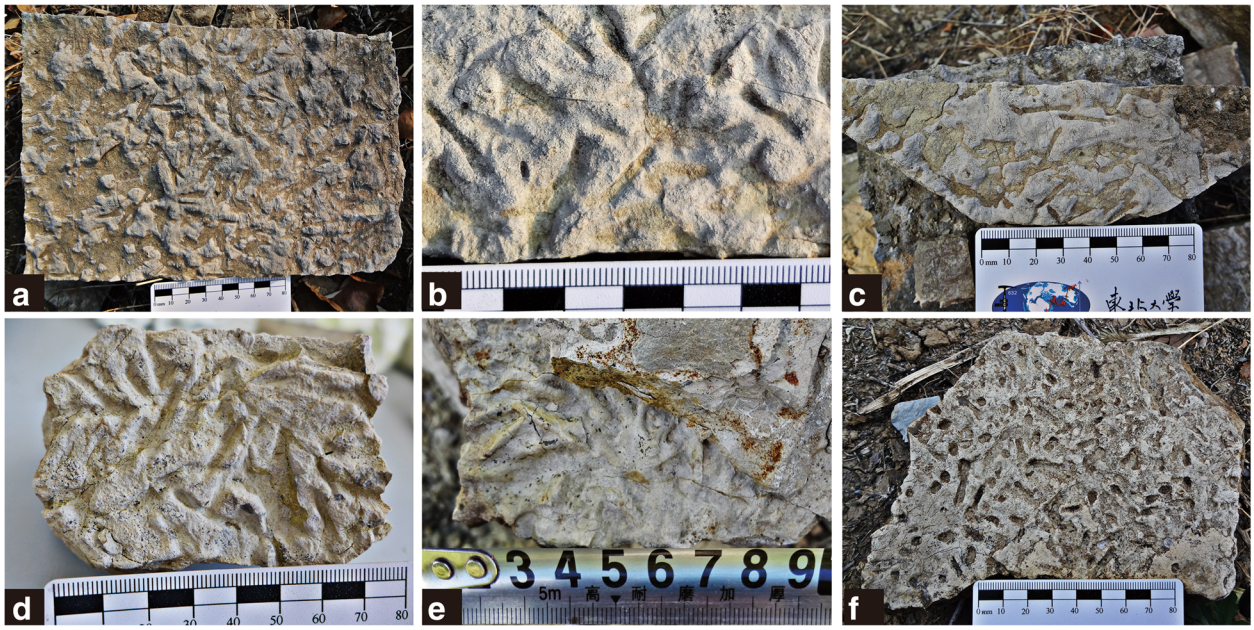


Fig. 2 *Petroxestes* (the elongate borings) from the Lower Cretaceous Yixian Formation, western Liaoning, China. **a**–**c** Aggregated traces of *Petroxestes* discovered from the Jin–Yang Basin; **d**–**f** *Petroxestes* from the Yixian Basin; in **e** fossil casts are shown, and in **f** some *Petroxestes* are preserved together with *Trypanites* (the rounded borings)

very difficult to achieve (Miller 2007). Thirdly, these traces were preserved on surface of carbonate rocks. In a continental environment, these strata generally indicate discontinuity of sedimentation by recurrent exposure to the air and were hard when they were formed (Barrell 1917). Lastly, the following lithostratigraphic characteristics of these traces-bearing carbonate rock strata also support the identification of borings. In the Jin–Yang Basin, carbonate stratum that bear traces is distributed in a limited area (the northeast–southwest span is about 200 m). The interface between the carbonate stratum and the overlying yellowish–green siltstone is clear and there are no sand grains squeezed into the carbonate rocks (Fig. 2c). It can be inferred that before the siltstone was deposited the carbonate sediments had been consolidated. In the Yixian Basin,

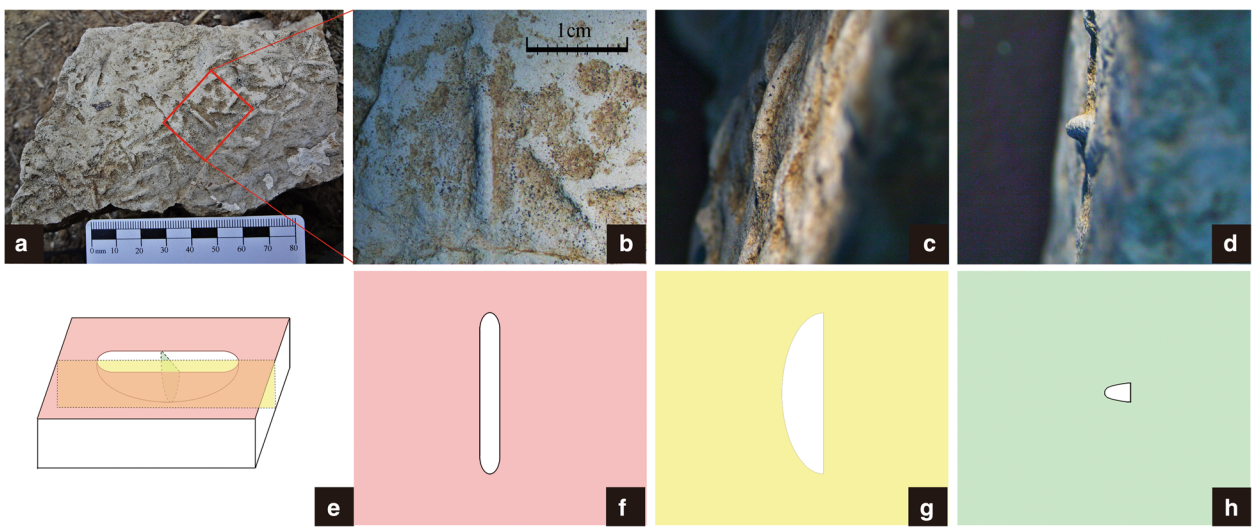


Fig. 3 Morphological features of monomer *Petroxestes* from the Lower Cretaceous Yixian Formation. **a**–**d** Fossil cast of one *Petroxestes* from the Yixian Formation and its appearance in plan view (**b**), side view (**c**) and front view (**d**); **e**–**h** – Monomer *Petroxestes* form and its appearance in plan view (**f**), side view (**g**) and front view (**h**)

carbonate stratum that contains traces is distributed in a smaller area (the northwest–southeast span is no more than 20 m). The carbonate rock, as well as other mudstone and shale, are all covered by a clastic marlstone that contains debris of sandstone, bivalve shells, three-dimensionally preserved caddisfly larval cases and so on (Gong et al. 2017). It can be speculated that the overlying clastic marlstone should be the product of gravity flows and the traces were formed after the diagenetic progress of the carbonate stratum.

4 Discussion

4.1 Differences with other similarly-shaped trace fossils

Petroxestes shows a round bottom in both longitudinal and transverse sections, which is obviously different from other trace fossils. Ignoring this feature, trace fossils with similar morphology include *Asthenopodichnium*, *Teredolites*, *Rogerella*, and *Cubiculum*.

4.1.1 Asthenopodichnium

Asthenopodichnium are small, U-shaped spreiten or pouch-like structures in wooden, organic-rich or bone substrates (Uchman et al. 2007). Traditionally, four ichnospecies have been described, from different substrates: *A. xylobiontum* (Thenius and Klaus 1979) and *A. lignorum* (Genise et al. 2012) occur on wood; *A. ossibiontum* (Thenius 1988) occurs on bone (which has been reinterpreted by Höpner and Bertling 2017, as belonging to a different ichnogenus: *Osteichnus ossibiontum*); whereas *A. lithuanicum* (Uchman et al. 2007) occurs on the surface of coal seams (Francischini et al. 2016) (Table 1). *A. lithuanicum* and *A. ossibiontum* are randomly arranged, as are the traces described in this paper, while all reported *A. xylobiontum* and *A. lignorum* are generally arranged with their long axis parallel to the wood fiber. *A. lithuanicum* is obviously different from *Petroxestes* from the Yixian Formation by its smaller size (length: 4–7.5 mm) and J-shaped outline. Morphologically, *A. ossibiontum* is most similar to *Petroxestes*, nevertheless, they have only been discovered on fossil bones from Austria (Thenius 1988).

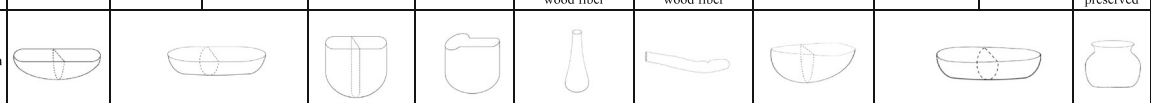
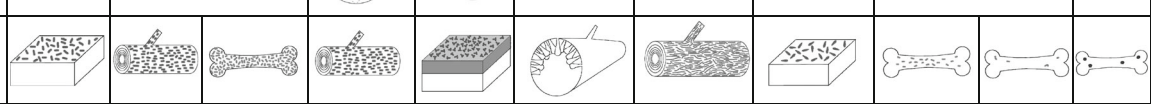
Francischini et al. (2016) reported a new species of *Asthenopodichnium*, *A. fallax*, that occurs on clasts of calcrete from the Upper Cretaceous Marília Formation of Brazil. Apart from the smooth and nearly-straight outline in longitudinal section, they are different from *Petroxestes* in having a higher width/length ratio (0.29).

4.1.2 Teredolites

Teredolites are characterized by their single aperture with a more-or-less circular cross-section, their hemispherical distal termination and thin calcite linings (Plint and Pickerill 1985) (Table 1). They have been discovered from nonmarine (e.g., Arua 1991; Plint and Pickerill 1985), marginal or shallow marine (e.g., Chamberlain 1976; Crampton 1990; Dewey and Keady 1987; Dott Jr. and Bourgeois 1982; Francis 1986; Howard and Frey 1984; Kiteley and Field 1984; Lindqvist 1986), and quiet deep marine deposits (e.g., Andersen 1983; Frey 1972; Turner 1973; Wolff 1979). Two different ichnospecies usually occur, a shorter or clavate form, *T. clavatus* Leymerie 1842, and an elongate form *T. longissimus* Kelly and Bromley 1984 (Monaco et al. 2011).

The long axis of *T. clavatus* is usually perpendicular to the substrate (Kelly and Bromley 1984), which is different from *Petroxestes* from the Yixian Formation. Additionally, its nearly-circular cross-section and hemispherical distal termination make it more distinctive. *T. longissimus* is primarily parallel (e.g., Monaco et al. 2011; Plint and Pickerill 1985; Savrda et al. 1993) or perpendicular (e.g., Arua 1991; Pickerill et al. 2003) to the grain of the substrate. It differs from *Petroxestes* in size (length greater than 20 mm), shapes (tortuous, circular cross-section), arrangement mode (close and parallel with each other), and substrate types (generally in xylic substrates), though having a similar width/length ratio.

Table 1 Comparison of main features of *Petroxestes* from the Yixian Formation with other similarly-shaped trace fossils

Ichnogenus	*Petroxestes*	*Asthenopodichnium*				*Teredolites*		*Rogerella*	*Cubiculum*		
Ichnospecies		*A. lignorum*	*A. ossibiontum*	*A. xylobiontum*	*A. lithuanicum*	*T. clavatus*	*T. longissimus*		*C. ornatus*	*C. inornatus*	*C. levis*
Length (mm)	9–21	15–18	10–15	8–12	4–7.5	6–7	20–130	1.2–2.5	7–20	12–47.6	Bowl shape
Width (mm)	1–4	5–6	3–5	2.5–3	1.5–4.5	2–6	2–12	0.2–0.42	2–6	4.9–9.6	
W/L	0.1–0.25	0.3–0.4	0.2–0.5	0.2–0.4	0.2–1.1	>0.2	<0.2	0.1–0.2	0.2–0.3	0.2–0.5	
Substrate	Carbonate rock	Wood	Bone	Wood	Coal	Wood and lignite		Rock, fossil sponge, echinoidea, and so on	Compact spongy bones	Fossil dinosaur bone	
Arrange mode	Randomly arraned	Parallel to wood fiber	Randomly arranged	Parallel to wood fiber	Randomly arranged	Generally perpendicular to wood fiber	Roughly parallel or perpendicular to wood fiber	Randomly arranged	Subparallel to each other	Singly preserved	Singly or gregariously preserved
Monomer form											
Aggregative form											

4.1.3 Rogerella

Rogerella (Saint-Seine 1951) presents holes with an elliptical contour and an elongate distal portion, as well as, sometimes, a slight curvature and a circular or conical proximal portion (Brezina et al. 2017) (Table 1). The traces can be found alone or in groups. When grouped, these holes are arranged randomly (e.g., Baird et al. 1990; Brezina et al. 2017) or parallel with each other (e.g., Seilacher 1968, 1969; Donovan and Jagt 2013; Donovan et al. 2016), and in a roughly equidistant, perpendicular or oblique to the substrate surface. They have been discovered on various types of substrates from Devonian to Holocene marine environments (Taylor and Wilson 2003), including carbonate hardgrounds (Brezina et al. 2017), echinoid skeletons (Saint-Seine 1951; Donovan and Jagt 2013; Donovan et al. 2016), belemnite rostra (Seilacher 1968, 1969), gastropods shells (Baird et al. 1990), and so on. *Rogerella* is most similar in shape to *Petroxestes*, but significantly smaller (length: 1.2–2.5 mm, and diameter: 0.2–0.42 mm).

4.1.4 Cubiculum

Cubiculum are regarded as traces of necrophagous or osteophagous insects (Ibrahim et al. 2014). Three species of *Cubiculum* have been reported, i.e., *C. ornatus* (Roberts et al. 2007), *C. inornatus* (Xing et al. 2016) and *C. levis* (Pirrone et al. 2014). In appearance, *C. levis* are bowl-shaped, while *C. ornatus* and *C. inornatus* are club-shaped (Table 1). The main difference between *C. ornatus* and *C. inornatus* is that the medial wall of the former has shallow grooves ornamentation, whereas the latter does not. Additionally, *C. inornatus* were discovered singly, while *C. ornatus* were observed more commonly in dense numbers. Except for morphology, the main difference between *Cubiculum* and *Petroxestes* is that the former is only found from fossil biogenic bones.

According to the summation above, it can be seen that traces from the Yixian Formation, in morphology, size, arrange mode and substrate types, are distinguished from *Asthenopodichnium*, *Teredolites*, *Rogerella*, *Cubiculum*, and other trace fossils. They are more in line with the definition of *Petroxestes*.

4.2 Contrast of reported *Petroxestes*

Since the first reported *Petroxestes* from the USA (Wilson and Palmer 1988), they have been found from the Lower Silurian Jupiter Formation from Canada (Tapanila 2001; Tapanila and Copper 2002), the Upper Cretaceous Maastricht Formation from Belgium (Jagt et al. 2009) and the Middle Miocene Grand Bay Formation from Lesser Antilles (Pickerill et al. 2001) (Table 2). *Petroxestes* from the USA were gregariously distributed in carbonate lithic substrates. The length and width of these traces vary little, while the depth varies greatly. About 20 specimens of *Petroxestes* were found from the surface of fossils stromatoporoid skeletons in Canada (Tapanila 2001). Except for a larger size, they were morphologically similar with the ones from the USA. There is only one sample from both Belgium and Lesser Antilles, which were produced in a hemipneustid echinoid and a valve of *Ostrea*, respectively. The Belgium sample has a quite high width/length ratio, and the Lesser Antilles fossil is much smaller in size than others. *Petroxestes* fossils from the Yixian Formation are very similar with those from the USA in appearance, arranged mode, distribution density and substrate types (Table 2). The main difference of these traces is that *Petroxestes* from China have a slightly smaller size. All reported *Petroxestes* fossils were from marine environments, thus, the samples from China were the first report from a terrestrial environment, which broadened their palaeoenvironmental range.

4.3 Producer analysis

Pojeta and Palmer (1976) were of the opinion that a facultative rock-boring modiomorphid bivalve, *Corallidomus scobina*, produced such traces, based on the presence of a specimen preserved in situ with the borings. Except for this documentation, there are no builder fossils in all the other reported *Petroxestes* borings. However, it is very clear that *Corallidomus scobina* are definitely not the builders of all the *Petroxestes*, because of the large span in geological time (from Late Ordovician to Middle Miocene) and palaeoenvironment types (from marine to terrestrial environments) of these trace fossils.

In ichnology, it is only under exceptional circumstances that the producer of an ichnotaxon can be identified with confidence, because unrelated groups are sometimes morphologically very similar and can therefore produce similar traces, or groups are morphologically very different but behave in a similar manner due to physical or biological parameters and again produce similar traces (Plint and Pickerill 1985; Seilacher 1960). Hence, only potential builders of *Petroxestes* from the Yixian Formation could be speculated.

There are only 13 species belonging to seven genera of bivalves in the Jehol Group (Jiang and Sha 2007). Only three species belonging to two genera were discovered in the Yixian Formation. They are *Arguniella yanshanensis* (Gu et al. 1976), *A. lingyuanensis* (Gu et al. 1976) and *Sphaerium anderssoni* (Grabau 1923). *Sphaerium* must have the ability to burrow, crawl and short-distance jump. *Arguniella* are able to crawl or swim, possibly to burrow, based on their physiological structure characteristics (Private communication with Prof. Sha. in 2017). The substrate was still plastic because some of the burrows were slightly compactionally deformed, which reduced the difficulty of burrowing. The length and height of their fossil records are as follows: *A. yanshanensis*, 15–21 mm

Table 2 A list of main features of reported *Petroxestes*

Location	Ohio and Kentucky, USA		Liaoning Province, China		Anticosti Island, Canada	Liège, Belgium	Carriacou, Lesser Antilles
	Gunpowder Greek	Manchester	Yixian county	Sihetun village			
Length (mm)	14.2–26.1	15.5–24.9	11–20	9–21	13.29–48.11	14	3.8
Width (mm)	2.9–4.7	2.5–4.4	2–4	1–3	3.01–6.62	4	1.4
W/L	0.21	0.18	0.13–0.25	0.1–0.23	0.05–0.3	0.29	0.37
Depth (mm)	1.7–11.0	4.5–20.1	1.5–3.0	1.5–3.0	< 14.53	3.0–3.5	0.5
Quantity	Mass		Mass	Mass	~ 20	1	1
Formation	Kope Formation		Yixian Formation		Jupiter Formation	Maastricht Formation	Grand Bay Formation
Series	Upper Ordovician		Lower Cretaceous		Lower Silurian	Upper Cretaceous	Middle Miocene
Substrate	Lithic substrates		Lithic substrates		Clathrodictyon stromatoporoids	Hemipneustid echinoid	Incomplete valve of *Ostrea*
Literature	Pojeta and Palmer 1976; Wilson and Palmer 1988; Taylor and Wilson 2003; Wilson and Palmer 2006		This study		Tapanila 2001; Tapanila and Copper 2002	Jagt et al. 2009	Pickerill et al. 2001

and 10–15 mm; *A. lingyuanensis*, 8–17 mm and 4–12 mm; *Sphaerium anderssoni*, 8–12 mm and 5–9 mm (Jiang and Sha 2007). The two former species are more likely to be the builders for their suitable size for these traces. However, it does not rule out the possibilities of other organisms to produce these traces.

5 Conclusions

1) *Petroxestes* have been discovered from the Lower Cretaceous Yixian Formation of western Liaoning, China. This is the first report of *Petroxestes* from China; meanwhile it is the first report of *Petroxestes* from a terrestrial environment.
2) *Petroxestes* from China are very similar with the ones from the USA in appearance, size, arranged mode, distribution density and substrate types, but are different from *Asthenopodichnium*, *Teredolites*, *Rogerella*, *Cubiculum* and other trace fossils.
3) *Petroxestes* fossils cannot be produced by the same fabricator, because the large span in geological time and paleoenvironment types of these trace fossils. *Petroxestes* from the Yixian Formation may be built by some bivalves of *Arguniella yanshanensis*, *A. lingyuanensis* and *Sphaerium anderssoni*, or other organisms.

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Authors' contributions
All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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