Tian et al. Journal of Palaeogeography (2018) 7:8
https://doi.org/10.1186/s42501-018-0008-0

Journal of Palaeogeography

RESEARCH Open Access

Occurrence of *Brachyoxylon* Hollick et Jeffrey from the Lower Cretaceous of Zhejiang Province, southeastern China

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Abstract

The Lower Cretaceous Guantou Formation is known as an important horizon for the Cretaceous petrified woods in southern China. Though abundant Cretaceous wood remains have been found in this formation, only one species has been recognized. A new coniferous wood, *Brachyoxylon zhejiangense* sp. nov. is described from the Lower Cretaceous Guantou Formation in Xinchang of Zhejiang Province, southeastern China. Anatomically, the new species is characterized by obscure annual rings, mixed type of radial pitting, araucarioid cross-field pits and uniseriate xylem rays. The finding of *Brachyoxylon zhejiangense* sp. nov. represents the first well-defined record of *Brachyoxylon* in southeastern China, and enriches the diversity of the Early Cretaceous petrified wood in southern China. Additionally, the new finding sheds new light on further understanding the floral composition, especially the forest vegetation type of the southern phytoprovince in the late Early Cretaceous. Diverse compressed leaf fossils of Cheirolepidiaceae have been described from the Guantou Formation in the fossil locality of the present petrified wood. The co-occurrence of *Brachyoxylon zhejiangense* sp. nov. and those cheirolepidiaceous leaf fossils provide additional evidences to support that *Brachyoxylon* may be systematically related to the Cheirolepidiaceae.

Keywords: *Brachyoxylon*, Cheirolepidiaceae, Lower Cretaceous, Guantou Formation, Zhejiang Province

1 Introduction

Anatomically-preserved petrified woods play significant roles in revealing the floristic composition and evolution of plant kingdom in geological history (Zhang et al. 2006). China is one of the most significant fossil localities for petrified woods with a remarkable high diversity. Until 2006, totally 181 species referred to 106 genera of petrified woods have been reported in China, ranging from Late Paleozoic to Cenozoic in time (Zhang et al. 2006). Xylofloras of China received progressively greater attention over the past decades. An increasing number of Mesozoic petrified woods have been reported from series of horizons in all over China (e.g., Jiang et al. 2008; Wang et al. 2009, 2017; Jiang et al. 2012, 2016; Yang et al. 2013; Feng et al. 2015; Shi et al. 2015; Tian et al. 2015, 2016; Zhang et al. 2015, 2016; Ding et al. 2016; Wan et al. 2016). For the Cretaceous records of petrified woods in China, the spatial-temporal distribution pattern is notably unbalanced. It is noted that 52 species have been described from the Early Cretaceous deposits in China (Yang et al. 2013); whereas, only five species were reported from the Late Cretaceous deposits (Sze 1951; Du 1982; Wang et al. 1996; Terada et al. 2011). Palaeogeographically, most of the Cretaceous petrified woods were described from northern China (especially Northeast China), whereas they are very scarce and limited in southern China (Yang et al. 1990; Duan et al. 2002).

The Lower Cretaceous Guantou Formation is known as an important horizon for the Cretaceous petrified woods in southern China. A large number of petrified woods have been found in this formation; however, only one species has been recognized, i.e., *Araucarioxylon xinchangense* Duan (Duan et al. 2002). In this paper, a new species of coniferous wood, *Brachyoxylon zhejiangense* sp. nov. is described based on a fossil wood fragment collected from the Lower Cretaceous Guantou Formation in Xinchang County of Zhejiang Province,

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southeastern China. This new finding enriches the diversity of Early Cretaceous petrified woods in southern China, and sheds new light on further understanding the floral composition, especially the forest vegetation type of the southern phytoprovince in the late Early Cretaceous.

2 Geological setting, material and methods

The new fossil material consists of a well-preserved silicified wood fragment found from Lower Cretaceous Guantou Formation in Suqin Village of northwestern Xinchang Basin of Zhejiang Province, southeastern China (29°30′20″N, 120°47′37″E) (Fig. 1). In the Xinchang Basin, the Early Cretaceous strata are well-developed and widely distributed, and can be sub-divided into the Guantou Formation and Chaochuan Formation, ascendingly (Dong et al. 2002). The Guantou Formation mainly crops out in the western edge of the basin (Dong et al. 2002). In the Xinchang Basin, the Guantou Formation is conformably overlain by the Chaochuan Formation, and unconformably overlies on the Upper Jurassic Jiuliping Formation (Fig. 2). Lithologically, the lower part of the Guantou Formation consists of purple pebbly sandstone and conglomerate, and then ascendingly consists of interbeds of variegated sandstones, siltstones, silty mudstones, and shales. The whole Guantou Formation can be divided into six layers, and the present fossil wood specimen was collected from the layer 4 (Fig. 2). Isotopic dating data of volcanic rock (110–103 Ma) suggest the age of the Guantou Formation to be Early Cretaceous (Albian) (Han et al. 1992; Yu and Xu 1999).

The petrified wood specimen was cut transversely, longitudinally and tangentially into several thin sections. These sections were prepared by standard methods, including cutting, grinding and polishing preparations (Hass and Rowe 1999). Photographs were taken with Scope Image 9.0 (H3D) Software adapted to a Yongxin BM2000 Microscope. The fossil wood specimen and six correlated thin slides described in this paper are housed in the Palaeontological Museum of Liaoning, Shenyang, China, with a registration on number PMOL-B-01476. Fossil wood description follows the standardized terminologies of IAWA Committee (2004) and Philippe and Bamford (2008).

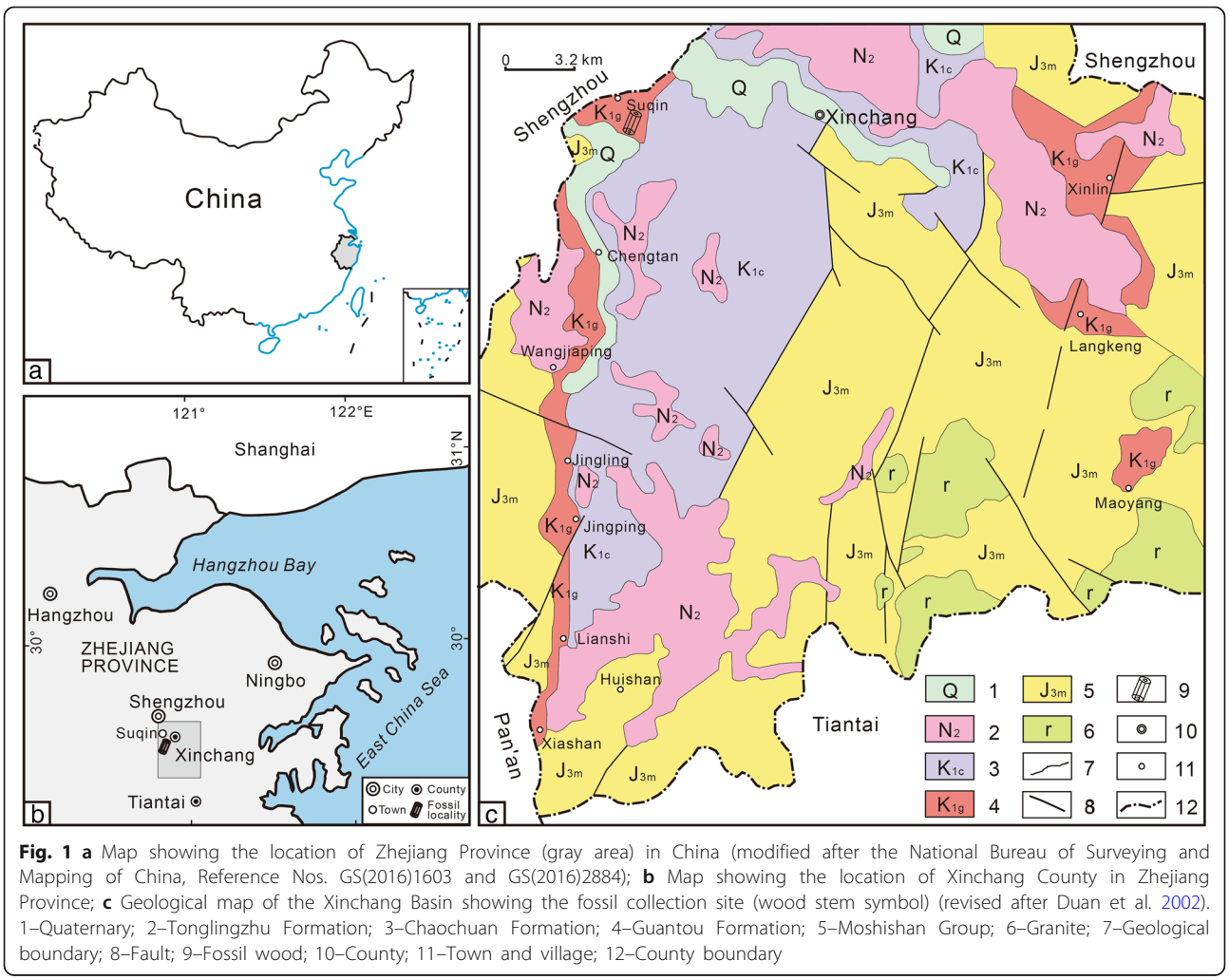

Fig. 1 **a** Map showing the location of Zhejiang Province (gray area) in China (modified after the National Bureau of Surveying and Mapping of China, Reference Nos. GS(2016)1603 and GS(2016)2884); **b** Map showing the location of Xinchang County in Zhejiang Province; **c** Geological map of the Xinchang Basin showing the fossil collection site (wood stem symbol) (revised after Duan et al. 2002). 1–Quaternary; 2–Tonglingzhu Formation; 3–Chaochuan Formation; 4–Guantou Formation; 5–Moshishan Group; 6–Granite; 7–Geological boundary; 8–Fault; 9–Fossil wood; 10–County; 11–Town and village; 12–County boundary

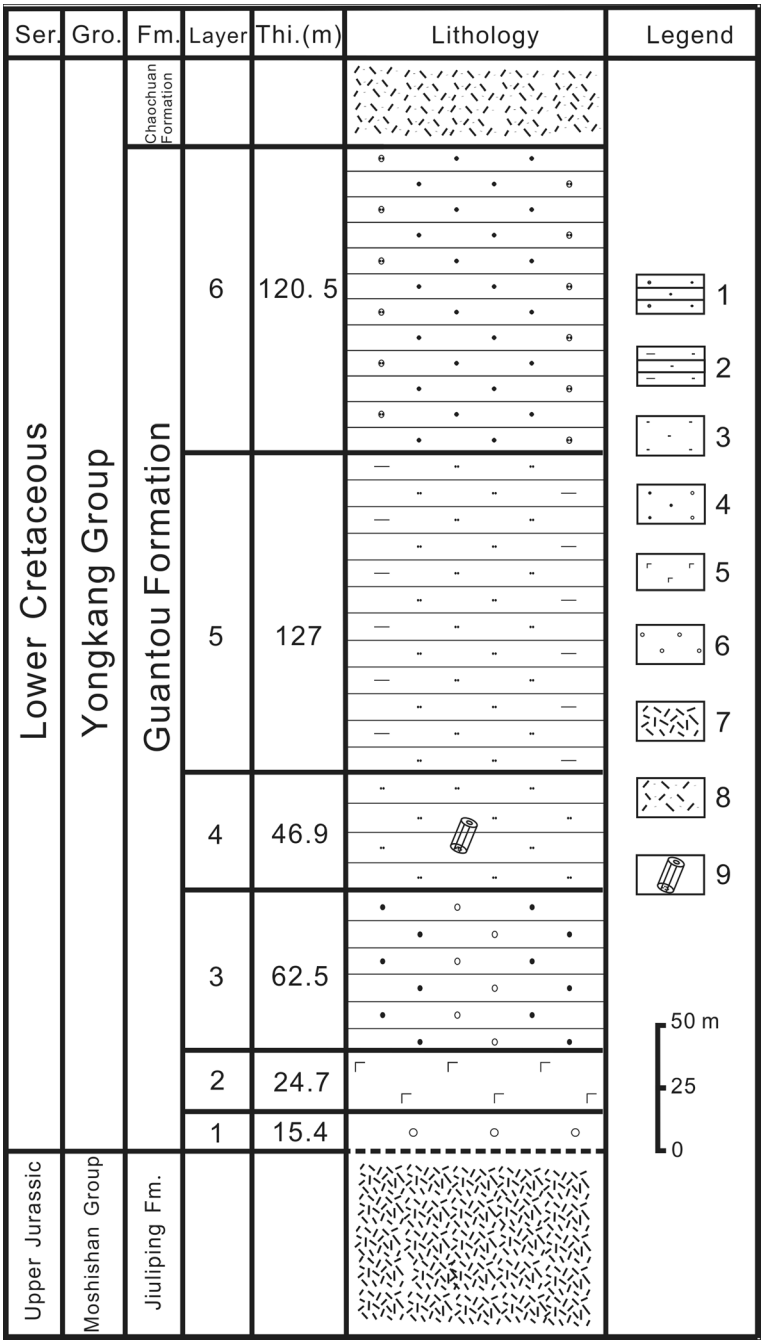

Fig. 2 Stratigraphic column of the Guantou Formation in Xinchang County, Zhejiang Province, SE China (drawn based on lithological description of Duan et al. 2002). 1–Pebbly sandstone; 2–Argillaceous siltstone; 3–Siltstone; 4–Coarse pebbly sandstone; 5–Basalt; 6–Conglomerate; 7–Rhyolite; 8–Tuff; 9–Fossil wood. Ser. = Series; Gro. = Group; Fm. = Formation; Thi. = Thickness

3 Results

Class: Coniferopsida
Order: Coniferales
Genus: *Brachyoxylon* Hollick and Jeffrey 1909
Type species: *Brachyoxylon notabile* Hollick and Jeffrey 1909
Species: *Brachyoxylon zhejiangense* sp. nov. Tian, Zhu et Wang

3.1 Holotype

PMOL-B-01476 with six sides numbered PMOL-B-01476-(a-f).

3.2 Type locality
Xinchang County, Zhejiang Province.

3.3 Horizon and age
Guantou Formation, Early Cretaceous.

3.4 Repository
The specimen and slides are housed in the Palaeontological Museum of Liaoning, Shenyang, China.

3.5 Etymology
The specific epithet *zhejiangense* refers the fossil locality Zhejiang Province, southeastern China.

3.6 Specific diagnosis
Homoxylous secondary xylem with obscure growth rings. Tracheid pitting in radial walls belonging to the mixed type, mostly uniseriate continuous or biseriate alternated, partly uniseriate distant, and rarely biseriate opposite; early wood cross-fields usually with 2–7 cupressoid oculipores, contiguous and alternately arranged in 1–3 rows; horizontal and end walls of ray cells smooth and unpitted; axial parenchyma and resin canals absent. Rays homogeneous, mostly uniseriate and rarely partially biseriate, 1–16 (mostly 2–7) cells high.

3.7 Description
The present fossil wood specimen (PMOL-B-01476) is preserved as a fragment of secondary xylem. No anatomical details of the pith and primary xylem are preserved. In the transverse section, the growth rings are weakly defined (Fig. 3a). The transition from the early to late wood is abrupt (Fig. 3a). The late wood zone is very narrow with only 3–5 layers of tracheids. Tracheids of the early wood are large and polygonal and thin-walled, while those of the late wood are rectangular and relatively thick-walled (Fig. 3a).

In the longitudinal radial section, the bordered pits on the tracheid walls belong to the mixed type. Most of them are uniseriate continuous (Fig. 3b–c) or biseriate alternated (Fig. 3f), partly uniseriate distant (Fig. 3d-e), and very rarely biseriate opposite or sub-opposite (Fig. 3g). In order to give a clear explanation of the radial pitting type, we counted the percentages of different type of radial pits. We assign each tracheid to a specific type of radial pitting, according to its predominant pitting. Considering that the biseriate opposite pits are rare and only occupy part of a tracheid, as long as biseriate opposite pits are observed in one tracheid, we define the tracheid having biseriate opposite pits. The results show that the uniseriate continuous and biseriate alternated pits are dominant (84.4% of the total number of tracheids, $n = 141$), the uniseriate distant ones account for 11.3%, the biseriate opposite and sub-opposite ones account for 4.3%. If only the typical biseriate opposite pits with a square outline is considered, they are with a percentage of 2.1%. Such a result shows that the present fossil wood meets the definition of mixed type of radial pitting defined by Philippe and Bamford (2008). The bordered pits are mostly rounded or slightly flattened, 13–17 μm in diameter (Fig. 3b–g). The pit-apertures are oval or rounded, ca. 4.5 μm in diameter (Fig. 3b–g). Rays are homogeneous, with both the horizontal and end walls smooth and unpitted (Fig. 3i–k). Cross-field pit arrangement is of the araucarioid type sensu IAWA Committee (2004) (Fig. 4a–c). Each cross-field bears 2–7 bordered pits with circular or oval outline, 23–28 μm in diameter, contiguous and arranged in 1–3 rows (Fig. 4a–c). Individual pits are of cupressoid type sensu IAWA Committee (2004). Pit aperture is horizontal or oblique, 6–11 μm in diameter (Fig. 4a–c).

In the longitudinal tangential section, rays are homocellular, mostly uniseriate and rarely partially biseriate, 1–16 (mostly 2–7) cells high (Figs. 4d–e, 5). Generally ca. 35 rays per mm^2 are observed. No axial parenchyma and tangential pits were identified in the studied specimen.

3.8 Taxonomic assignment and comparisons
For the identification of Mesozoic conifer-like woods, palaeoxylologists have paid much attention to the spacing of pits on tracheid radial walls and cross-field pits. According to Philippe and Bamford (2008), four major types of radial pitting are recognized for Mesozoic conifer-like woods, i.e., araucarian type, abietinean type, mixed type and xenoxylean type. Then, a new type of homoxylous wood radial pitting, the "*japonicum* type", was recognized based on a revision of the Mesozoic fossil wood from East Asia (Philippe et al. 2014). The current fossil wood is anatomically characterized by having mixed type of radial pitting and araucarioid cross-field pits (oculipores of cupressoid type). Among the morphogenera of Mesozoic conifer-like woods, although the *Agathoxylon* Hartig and *Shimakuroxylon* Philippe, Boura, Oh et Pons also have araucarioid cross-field pits, they distinguish from the present studied fossil wood by having araucarian and "*japonicum*" type of radial tracheid pitting, respectively (Philippe et al. 2004a, 2014; Philippe 2011). Although biseriate opposite and sub-opposite radial pits also occur in the present wood specimen, they are quite rare and account for only 4.3%. Since Philippe et al. (2014) proposed that a wood specimen which has "*japonicum*" type of radial tracheid pitting should display at least 10% of its radial tracheid pit total number being biseriate-opposite, the radial tracheid pitting of the wood studied in this paper does not belong to the "*japonicum*" type. Only three morphogenera of petrified wood have been defined to have mixed radial tracheid pitting and cross-fields with cupressoid oculipores, i.e., *Brachyoxylon* Hollick et Jeffrey, *Zonaloxylon*

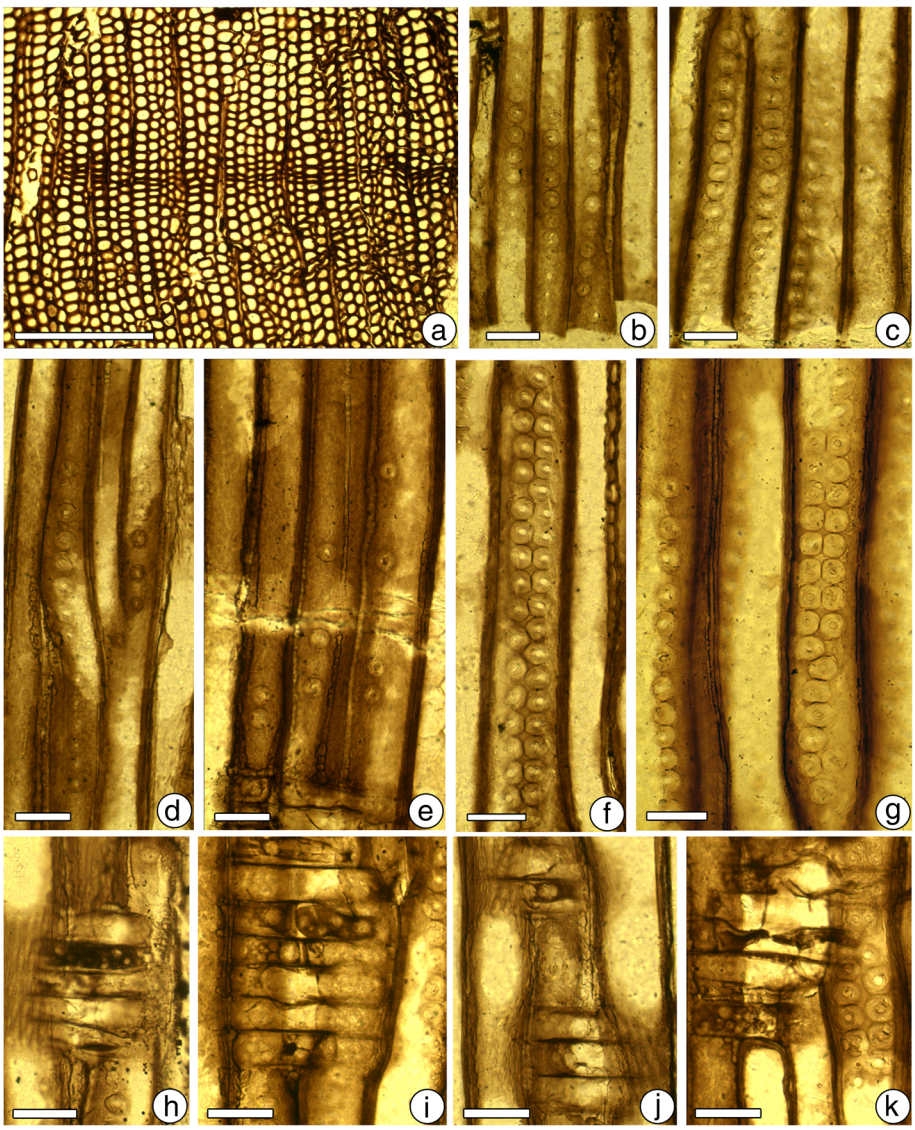

Fig. 3 *Brachyoxylon zhejiangense* sp. nov. Tian, Zhu et Wang (PMOL-B-01476-a, b) from the Lower Cretaceous Guantou Formation in Xinchang of Zhejiang Province, SE China. **a** Transverse section, showing the obscure annual ring, scale bar = 0.5 mm; **b–c** Longitudinal section, showing uniseriate, rounded and contiguous bordered pits, scale bar = 0.05 mm; **d–e** Longitudinal section, showing uniseriate and distant bordered pits, scale bar = 0.05 mm; **f** Longitudinal section, showing biseriate alternate bordered pits, scale bar = 0.05 mm; **g** Longitudinal section, showing biseriate opposite bordered pits, scale bar = 0.05 mm; **h–k** Longitudinal section, showing the cross-field and smooth horizontal wall of ray cells, scale bar = 0.05 mm

Grauvogel-Stamm et al. and *Protocupressinoxylon* Eckhold (Philippe and Bamford 2008; Bodnar et al. 2013). However, only *Brachyoxylon* is characterized by having araucarioid cross-field pits, which are contiguous and/or compressed and alternately arranged oculipores. Therefore, it is reasonable to assign the current fossil wood from China to the genus *Brachyoxylon*.

Brachyoxylon was originally established for petrified wood from the Upper Cretaceous of the United States (Hollick and Jeffrey 1909). Thereafter, this generic name was employed by many authors for Mesozoic fossil wood remains (Eckhold 1923; Torrey 1923; Kräusel 1949). Though widely used, different authors have different perceptions on how to define *Brachyoxylon*. Some authors put particular emphasis on the presence of traumatic resiniferous canals (Torrey 1923), while some others focus on the presence of typically araucarian radial pitting (Eckhold 1923). Bamford and Philippe (2001) proposed that *Brachyoxylon* should be used for tracheidoxyls with mixed tracheid pitting, araucarian cross-fields and with or without traumatic resin canals. During the past century, diverse petrified woods have been referred to this genus.

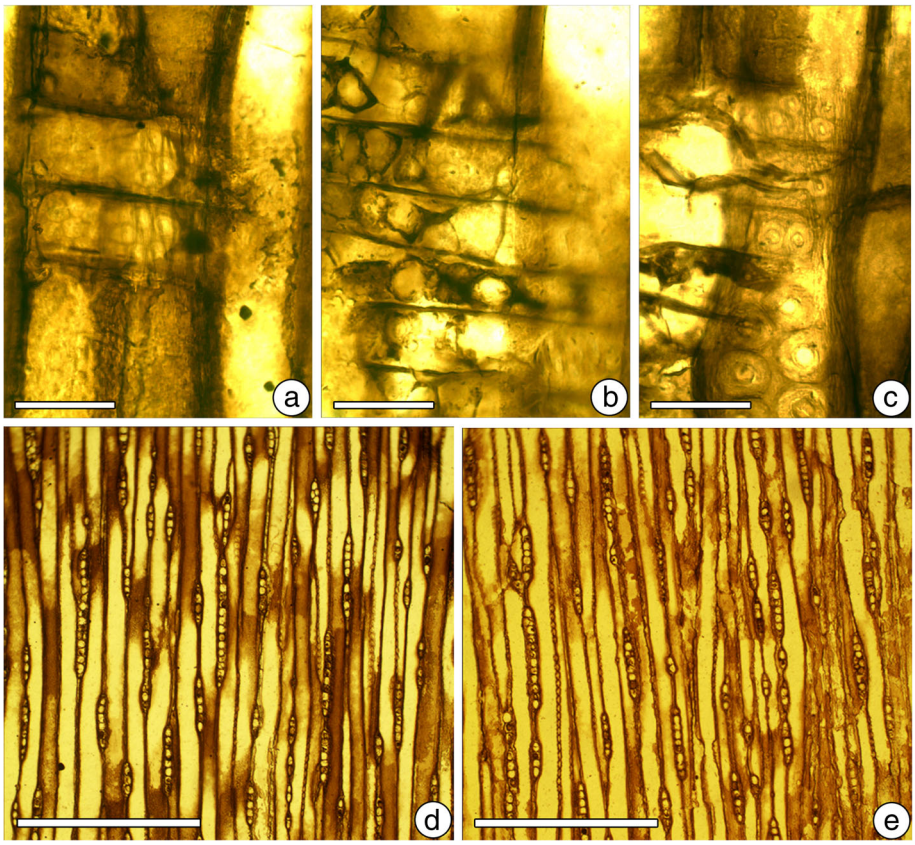

Fig. 4 *Brachyoxylon zhejiangense* sp. nov. Tian, Zhu et Wang (PMOL-B-01476-b, c) from the Lower Cretaceous Guantou Formation in Xinchang of Zhejiang Province, SE China. **a–c** Longitudinal section, showing details of the cross-field with 2–7 contiguous, compressed and alternately arranged oculipores, scale bar = 0.1 mm; **d–e** Tangential section, showing details of xylem ray cells, mostly uniseriate and occasionally partially biseriate, scale bar = 0.5 mm

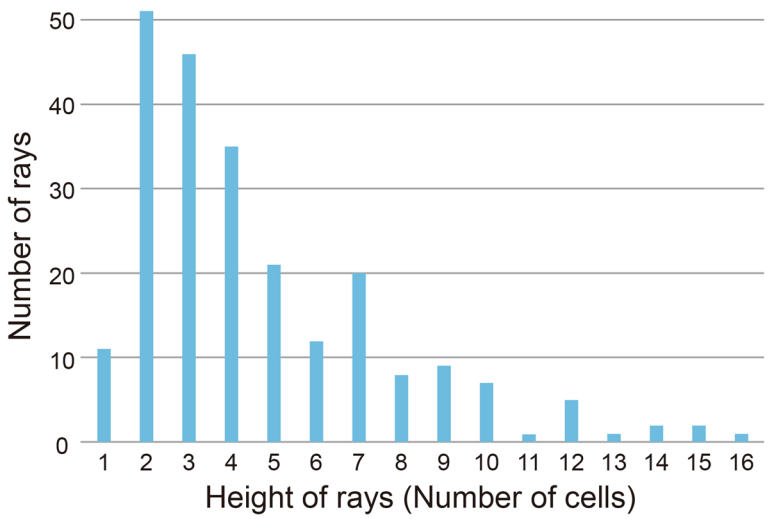

Fig. 5 The height frequency distribution of ray cells in a tangential section of *Brachyoxylon zhejiangense* sp. nov.

Even recently, a new species *Brachyoxylon baqueroensis* Vera et Césari was described from the Lower Cretaceous in Patagonia (Vera and Césari 2015). A comprehensive and detailed comparison between 17 species of *Brachyoxylon* was given in Bodnar et al. (2013). It is noted that among those listed *Brachyoxylon* species, five species (i.e., *B. brachyphylloides* (Torrey) Kräusel, *B. japonicum* (Shimakura) Kräusel, *B. saurinii* Boureau et Serra, *B. boureauii* Serra, and *B. orientale* (Serra) Philippe et al.) were later reassigned to *Shimakuroxylon* by Philippe et al. (2014). An updated comparative table of *Brachyoxylon* species is given (Table 1). Since there is no previously published species of this genus comparable with the present fossil wood from China, a new species *Brachyoxylon zhejiangense* sp. nov. is proposed.

It is noted that, including the type species *Brachyoxylon notabile* Hollick et Jeffrey, many *Brachyoxylon* species (e.g., *B. trautii* (Barale) Philippe, *B. liebermanii* Philippe, *B. avramii* Iamandei et Iamandei, *B. dobrogiacum* Iamandei et Iamandei, *B. semibiseriatum* (Pant et Singh) Kurzawe et Merlotti, and *B. serrae* Philippe et al.) are characterized by having tangential tracheid pitting and/or traumatic resin ducts (Table 1). Nevertheless, neither tangential tracheid pitting nor traumatic resin ducts are observed in *Brachyoxylon zhejiangense* sp. nov. Being different from the new species from China, *Brachyoxylon currumilii* from the Lower–Middle Jurassic of Argentina bears scanty and diffuse axial parenchyma (Bodnar et al. 2013). Another Argentina species, *Brachyoxylon baqueroensis* differs from the new species by having distinct annual rings, triseriate radial pits, and a higher number of cross-field pits (Vera and Césari 2015). Generally, *Brachyoxylon zhejiangense* sp. nov. seems to be more comparable to *B. woodworthianum* Torrey (mid-Cretaceous,

Table 1 Comparative table of species of the genus *Brachyoxylon* (modified after Bodnar et al. 2013)

Species	Age	Distribution	False GR	Resin ducts	Tg TP	Rd TP	Ax Pa	Cr	Rays (height)	CFP
Brachyoxylon zhejiangense sp. nov. Tian, Zhu et Wang	Early Cretaceous	China	A	A	A	mixed 1–2 seriate	A	A	mostly 1 seriate (1–16 cells)	2–7 cupressoid
B. notabile Hollick and Jeffrey 1909	Late Cretaceous	USA	A	**T**	**P**	mixed 1–2 seriate	A	**P**	1 seriate (1–8 cells)	5–11 cupressoid
B. woodworthianum Torrey 1923	Early Cretaceous	USA	A	**T**	A	mixed	A	A	1–2 seriate (2–20) cells	cupressoid
B. saurinii Boureau and Serra 1961	Jurassic (?)	Cambodia	A	**T**	A	mixed 1–2 seriate	A	A	1 seriate (1–31 cells)	2–12 cupressoid
B. lagonense (Laudouéneix 1973) Dupéron-Laudouéneix 1991	Cretaceous	Chad	A	**T**	A	mixed 2–3 seriate	A	A	1 seriate (low)	cupressoid
B. trautii (Barale 1981) Philippe 1995	Middle Jurassic	France	**P**	A	**P**	mixed 1–2 seriate	A	A	1 seriate (low)	4–9 cupressoid
B. liebermanii Philippe 1995	Jurassic	France	**P**	A	**P**	mixed 1 seriate	A	A	1 seriate (low)	5–12 **cupressoid to podocarpoid**
B. eboracense (Holden 1913) Philippe 2002	Jurassic	England	A	A	A	mixed 1–2 seriate	A	A	1 seriate, (low)	numerous cupressoid
***Brachyoxylon* sp.** Philippe et al. 2004b	Late Jurassic	Thailand	**P**	A	**P**	mixed 1–2 seriate	A	A	1 seriate, (low)	up to 12 cupressoid
B. avramii Iamandei and Iamandei 2005	Early Cretaceous	Romania	A	**T**	R	mixed, 1–2 seriate	A	A	1 seriate (1–21 cells)	1–8 cupressoid
B. dobrogiacum Iamandei and Iamandei 2005	Early Cretaceous	Romania	A	A	**P**	mixed 1–3 seriate	**P**	**P**	1 seriate (1–10 cells)	1–6 cupressoid
B. semibiseriatum (Pant and Singh 1987) Kurzawe and Merlotti 2010	Permian	Brazil	A	**P**	**P**	mixed 1–5 seriate	A	A	1 seriate (1–38 cells)	4–16 cupressoid
B. serrae Philippe et al. 2011	Early Cretaceous	Thailand	A	**T**	**P**	mixed 1–2 seriate	A	A	1 seriate (1–15 cells)	5–16 cupressoid
B. currumilii Bodnar et al. 2013	Early–Middle Jurassic	Argentina	A	A	R	mixed 1–2 seriate	**R**	A	1 seriate (1–10 cells)	4–11 cupressoid
B. baqueroensis Vera and Césari 2015	Late Cretaceous	Argentina	A	A	A	mixed 1–3 seriate	A	A	1 seriate (1–9 cells)	**8–26 cupressoid**

Note: Anatomical characters that differ from those of the new species *Brachyoxylon zhejiangense* sp. nov. are bolded
GR Growth rings, *Tg TP* Tangential tracheid pitting, *Rd TP* Radial tracheid pitting, *Ax Pa* Axial parenchyma, *Cr* Crassulae, *CFP* Cross-field pits, *P* Present, *A* Absent, *T* Traumatic, *R* Rare

North America) in ray height, obscure annual rings, and the absence of tangential tracheid pitting and parenchyma; however, original description of *B. woodworthianum* shows that it has traumatic resin canals and abietan pitting in traumatic ray cells (Torrey 1923).

4 Discussion

As a fossil wood morphogenus, the systematic affinity of *Brachyoxylon* is still undetermined. It has been linked to various coniferous families, such as Araucariaceae (Hollick and Jeffrey 1909), and Cupressaceae (Seward 1919). However, *Brachyoxylon* has been more frequently related to the distinct family Cheirolepidiaceae (e.g., Alvin et al. 1981; Alvin 1982; Machhour and Pons 1992; Limarino et al. 2012). The finding of *Brachyoxylon* woods in association with conifer leaves and *Classopollis*-bearing cones (Zhou 1983) suggests that at least some *Brachyoxylon* woods may be representatives of the Cheirolepidiaceae. In fact, the type species *B. notabile* Hollick et Jeffrey was related to *Brachyphyllum macrocarpum* Newberry 1896, a possible Cheirolepidiaceae (Alvin 1982). It is of interest that compressed leaf fossils of possible Cheirolepidiaceae, e.g., *Pseudofrenelopsis parceramosa* (Fontaine) Watson, *Pagiophyllum delicatum* Cao, *P. obtosior* Cao, and *P. xinchangense* Cao, have also been described from the Lower Cretaceous Guantou Formation in the same fossil locality (Suqin Village of Xinchang County, Zhejiang Province) with *Brachyoxylon zhejiangense* sp. nov. (Cao 1989, 1991). Additionally, *Pseudofrenelopsis papillosa* Chow et Tsao and *P. parceramosa* have also been found from the Guantou Formation in adjacent Jingling Village of Xinchang County (Ren et al. 2008). Generally, the co-occurrence of *Brachyoxylon* wood and leaf fossils of Cheirolepidiaceae in the Lower Cretaceous Guantou Formation further implies that the fossil wood genus *Brachyoxylon* may be systematically referable to the conifer family Cheirolepidiaceae.

Fossils of *Brachyoxylon* have been widely documented from both the boreal and Gondwana regions range from the Permian to the Late Cretaceous (Philippe et al. 2004a; Bodnar et al. 2013). Palaeogeographically, *Brachyoxylon* is much more common in boreal areas (e.g., the United States, Tunisia, Japan, Cambodia, Thailand, France and Romania) than in Gondwana region (Philippe et al. 2004a; Bodnar et al. 2013). Though abundant and diverse Mesozoic wood remains have been described, fossil records of *Brachyoxylon* are very scarce in China. Vozenin-Serra and Pons (1990) assigned a wood sample from the Lower Cretaceous in Lhunzhub of Tibet, southwestern China to *Protopodocarpoxylon orientale* Serra. However, due to its araucarioid cross-field pits, Philippe et al. (2004a) proposed it as a new combination *Brachyoxylon orientale* (Serra) Philippe et al. Then recently, this specimen is reassigned to *Shimakuroxylon japonicum* (Shimakura) Philippe et al. for having radial pitting of "*japonicum*-type" (Philippe et al. 2014). Additionally, *Brachyoxylon* sp. has been reported from the Lower Cretaceous in Lhasa of Tibet (Vozenin-Serra and Pons 1990; Zhang et al. 2006). Generally, the new finding of *Brachyoxylon zhejiangense* sp. nov. enriches the diversity of the Early Cretaceous petrified wood in southern China, and contributes to further understanding the floral composition, especially the forest composition of the southern phytoprovince in the late Early Cretaceous.

5 Conclusions

A new coniferous wood, *Brachyoxylon zhejiangense* sp. nov. was is described from the Lower Cretaceous Guantou Formation of Zhejiang Province, southeastern China, which represents the first record of *Brachyoxylon* wood in southeastern China. The new finding provides new clues for understanding the palaeogeographical distribution of this genus, as well as the forest composition of the Early Cretaceous flora in southeastern China. Additionally, the co-occurrence of *Brachyoxylon* wood and cheirolepidiaceous leaf fossils in the Guantou Formation further implies that *Brachyoxylon* may be systematically referable to the Cheirolepidiaceae.

Acknowledgements

We thank Dr. Zi-Kun Jiang (Beijing, China) for her helpful discussion. Special appreciations are due to Prof. Mihai E. Popa (Bucharest, Romania) and Marc Philippe (Lyon, France) for their detailed comments and valuable suggestions that improved this paper. This study was jointly supported by the Strategic Priority Research Program (B) of the Chinese Academy of Sciences (Grant Nos. XDB18000000 and XDB26010302), the State Key Program of Research and Development of Ministry of Science and Technology, China (Grant No. 2016YFC0600406), the National Natural Science Foundation of China (Grant Nos. 41302004, 41688103, and 41790454), the State Key Laboratory of Palaeobiology and Stratigraphy (NIGPAS, CAS) (Grant Nos. 133113 and 173124), and the Special Fund of Liaoning Provincial Universities' Fundamental Scientific Research Project (Grant No. LQN201718).

Authors' contributions

NT and YW designed and performed research; NT, YW, ZZ and SW analyzed the data. NT and ZZ made the figures; NT, YW, ZZ and SW wrote the paper. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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Received: 6 July 2017 Accepted: 13 October 2017
Published online: 20 September 2018

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