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Biodiversity and palaeoclimatic implications of fossil wood from the non-marine Jurassic of China

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Fossil woods are widely recorded in the non-marine Jurassic deposits of China from nine provinces and 18 localities. About 33 species referred to 17 genera have been documented, which are mainly ascribed to coniferales, cycadales and bennettitales. Stratigraphically, the fossil woods vary between a variety of horizons in the Lower, Middle and Upper Jurassic; the occurrences predominate in the Aalenian-Bajocian, Bathonian-Callovian and Oxfordian-Tithonian intervals. Jurassic woods are mainly distributed in the Northern Floristic Province in China, whereas they are rare in the Southern Floristic Province. Diversity and anatomical characteristics, especially the growth ring feature analysis implies climatic conditions with distinct seasonal variation in the Northern Floristic Province during the Early, Middle and Late Jurassic periods.

Introduction

Fossil wood materials are crucial because they represent an important archive of data for palaeoenvironmental reconstructions. They occur in either marine or non-marine strata preserved in all major depositional facies and palaeoecosystems. Systematic studies of fossil wood improve our knowledge of the composition of past vegetation. The growth ring patterns of fossil wood may provide key information regarding regional palaeoclimate as well as a tree palaeoecology and phenology in deep time (Falcon-Lang, 2005). Fossil wood is very abundant in China ranging from Late Palaeozoic to Cenozoic. Over 180 species of fossil wood referred to 106 genera have been recorded in China from several hundreds of localities (Zhang et al., 2006). Here we report fossil wood from the non-marine Jurassic deposits of China with special reference to their biodiversity and palaeoclimatic implications.

The research history of fossil wood in China can be dated back to the 1920s when C.Y. Chang (1929) described fossil wood from the Jurassic in Hebei, northern China. Later, Shimakura (1935–36) reported some Jurassic wood material from Jilin in northeast China. In 1951, H.C. Sze investigated fossil wood from northeastern China, including one taxon from Upper Jurassic volcanic rocks. Over 10 years later, H.C. Sze et al. (1963) published a monograph entitled “Mesozoic Fossil Plants of China”, in which a special chapter, “Fossil Gymnospermous Wood” summarized the Jurassic and Cretaceous wood materials.

Since the 1980s, an increasing number of works regarding the Jurassic wood floras have been published in China. Du (1982) described two wood fossils from the Late Jurassic in Jiayin, Heilongjiang Province, including *Xenoxylon latiporosum* (Cramer) Gothan and *Protopiceoxylon amurense* Du. When studying Late Mesozoic plants from eastern Heilongjiang, Zheng and Zhang (1982) reported two taxa of Jurassic wood, including *Protocupressinoxylon mishanense* and *Xenoxylon peidense*. Duan (1986) documented the wood species *Xenoxylon latiporosum* from Jurassic deposits in Yanqing, near Beijing. Zhang and Cao (1986) recorded *Cupressinoxylon hanshanense* from the Late Jurassic in Anhui, which represents an important find for Jurassic wood in southern China. Subsequently, Zhou and Zhang (1989) reported a fossil wood taxon *Protocupressinoxylon* sp. from the Yima Formation in Henan Province.

In recent decades, the study of Jurassic wood has become more active with an increasing number of publications. New specimens of Jurassic wood have been reported from northeastern China (Philippe et al., 1999; Ding et al., 2000; Duan, 2000; Zhang et al., 2000a; Zheng et al., 2001, 2005; Zheng, 2004). Additionally, He and Zhang (1993) described fossil wood from Jurassic coals in Henan and Ningxia. Duan and Peng (1998) recorded a fossil wood *Araucarioxylon zigongensis* from the Middle Jurassic in Zigong, Sichuan Province. The first record of *Scotoxylon* in China was reported from the Middle Jurassic of Yanqing (Zhang et al., 2000b). Wang et al. (2000) studied fossil woods from the Late Jurassic fossil forest in Qitai, Xinjiang, northwestern China. A fossil cycad-like stem, *Lioxylon liaoningense* was identified from the Middle Jurassic in western Liaoning, which shows a close systematic relationship to cycads (Wang et al., 2005; Zhang et al., 2006). Moreover, a rich and diverse silicified wood assemblage has recently been discovered from Shehong in Sichuan Province. These fossil woods are preserved in the Upper Jurassic Penglaizhen Formation and show good preservation of xylem structures (Wang et al., 2005, 2006). More results are expected in the coming years along with further research on Jurassic fossil woods in China.

The Non-marine Jurassic system and fossil wood horizons

The Jurassic system is well developed and widely distributed in China. Marine Jurassic strata are distributed mainly in the Qinghai-Tibetan Plateau (especially well exposed in the central part of the northern Himalayas, i.e., Tingri-Nyalam area), bear abundant fossils such as ammonites that are widespread in the Tethyan Realm (Chen, 2003; Shi et al., 2006; Yin et al., 2007). In contrast, non-marine Jurassic strata are developed extensively in the large areas of China.

Figure 1. Geographical distribution and major localities of Jurassic woods in China. 1 Jiayin of Heilongjiang; 2. Mishan of Heilongjiang; 3. Yingcheng of Jilin; 4. Fuxin of Liaoning; 5. Beipiao of Liaoning; 6. Chaoyang of Liaoning; 7. Yixian of Liaoning; 8. Liaoyuan of Liaoning; 9. Kazuo of Liaoning; 10. Tieling of Liaoning; 11. Zhuolu of Hebei; 12. Yanqing of Beijing; 13. Qitai of Xinjiang; 14. Lingwu of Ningxia; 15. Yima of Henan; 16. Shehong of Sichuan; 17. Zigong of Sichuan; 18. Hanshan of Anhui. N-Northern Floristic Province; S- Southern Floristic Province.

In the western part of China there are large inland basins, such as the Ordos, Sichuan, Qaidam, Junggar and Tarim basins. In this region the Jurassic is generally characterized by fluvial to lacustrine sediments, intercalated with a few carbonates of non-marine origin. In the eastern part, the Jurassic is characterized by the development of thick volcanic rock successions (Chen, 2003; Shi et al., 2006). Fossil woods are recorded mainly from the non-marine Jurassic deposits in China. Available data indicate that northern China is a major source of fossil wood with diverse and well-preserved specimens (Fig. 1).

Stratigraphically, fossil wood specimens are reported from a variety of horizons ranging from Lower, Middle and Late Jurassic intervals with different types of depositional sequences (Figs. 2, 3). The Early Jurassic timespan is only recorded in the Beipiao Formation in western Liaoning, corresponding to the Pliensbachian to Toarcian. During the Middle Jurassic, more horizons occur over a wider region, ranging from the Aalenian to the Bajocian and Bathonian to Callovian, such as the Haifanggou and Tiaojiashan Formations in western Liaoning, the Nankangzhuan Formation of Tieling in Liaoning, the Yima Formation in Henan, the Lower Shaximiao and Xintiangou Formations in Zigong, Sichuan. Late Jurassic woods show increased diversity of taxa and distribution by regions and horizons, ranging from Oxfordian to Tithonian. The major horizons include: the Chaoyangtun Formation in Baoqing, the Ningyuancun Formation in Jiayin, the Dongshengcun Formation of Mishan in Heilongjiang Province; the Huoshiling Formation of Yingcheng in Jilin; the Tuchengzi Formation in Liaoning; the Houcheng Formation of

Yanqing near Beijing; the Shishugou Formation in Qitai, Xinjiang; and the Penglaizhen Formation of Shehong in Sichuan.

Biodiversity of Jurassic fossil wood

The Jurassic woods documented from China are mainly found at 18 localities in nine provinces, most of them in northern China. The main localities are: Beipiao, Fuxin, Chaoyang, Yixian, Lingyuan, Kazuo, Tieling of Liaoning, Jiayin, Baoqing, Mishan of Heilongjiang, Yingcheng of Jilin, Zhuolu of Hebei, Yanqing of Beijing, Yima of Henan, Lingwu of Ningxia, Qitai of Xinjiang, Zigong and Shehong of Sichuan, and Hanshan of Anhui (Fig. 1).

To date about 33 species belonging to 17 genera of fossil wood have been recorded from the Jurassic in China (Fig. 3, Table 1). They are mainly preserved as silicified type, which is predominant group of fossil preservation. Some fossil woods are preserved as siderite and a few as coalified woods. Anatomically, most specimens of the taxa have only secondary xylem preserved, and about four genera have been reported with pith structures, including *Lioxylon*,

Formation \ Area		Northern China		Southern China	
		Junggar Basin (Northwest type)	North Hebei & Western Liaoning (Northeast type)	Sichuan Basin (Southwest type)	Jiangsu and Anhui (Southeast type)
Early Cretaceous		Tugulu Gr.	Yixian Fm.	Cangxi Fm.	Xihengshan Fm.
Late Jurassic	Tithonian		Dabeigou Fm. Zhangjiakou Fm.	Penglaizhen Fm.	
	Kimmeridgian	Kalaza Fm.	Tuchengzi Fm.		Hanshan Fm.
	Oxfordian	▲ Qigu Fm.	▲	Suining Fm.	
Middle Jurassic	Callovian	Shishugou Group	Tiaojiashan Fm. = Lanqi Fm.	Upper Shaximiao Fm.	
	Bathonian	Toutunhe Fm.	▲	Lower Shaximiao Fm.	
	Bajocian	Xishanyao Fm.	Haifanggou Fm.	Xintiangou Fm.	
	Aalenian		▲		
Early Jurassic	Toarcian	Sangonghe Fm.	Beipiao Fm.	Ziliujing Fm.	
	Pliensbachian		▲		
	Sinemurian	Badaowan Fm.	Xinglonggou Fm.	Zhengzhuchong Fm.	
	Hettangian				
Upper Triassic		Haojiagou Fm.	Laohugou Fm.	Xujiahe Fm.	Fanjiaian Fm. Lalijian Fm.

Figure 2. Representative non-marine Jurassic sequences from different regions of China and the major fossil wood horizons. The stratigraphical subdivision and general correlation between stages and formations are based on schemes proposed by Chen (2003) and Shi et al. (2006), with modification. Black triangles indicate the major fossil wood horizons.

Figure 3. Stratigraphical ranges of major fossil wood genera and the numbers of fossil wood horizons from the non-marine Jurassic of China. The numbers of dark bars (left part) indicate the number of species for each fossil wood genus; and bar with dots (right part) represents a fossil wood horizon. 1. *Sciadopityoxylon*; 2. *Protosciadopityoxylon*; 3. *Protophyllocladoxylon*; 4. *Xenoxylon*; 5. *Protocupressinoxylon*; 6. *Haplomyeloxylon*; 7. *Lioxylon*; 8. *Protocedroxylon*; 9. *Perisemoxylon*; 10. *Sahnioxylon*; 11. *Araucarioxylon*; 12. *Protopiceoxylon*; 13. *Cupressinoxylon*; 14. *Protocarpoxylon*; 15. *Prototaxodioxylon*; 16. *Scotoxylon*; 17. *Phyllocladoxylon*.

Scotoxylon, *Haplomyeloxylon* and *Sahnioxylon*. Based on anatomical features and comparisons with living wood anatomy, the Jurassic fossil woods from China may be taxonomically ascribed to the following four plant groups (Table 1).

1) Cycadales: only one fossil genus has been ascribed to this clade, i.e., *Lioxylon*. This genus is a structurally preserved stem composed of large pith seen in transverse section with a xylem cylinder, and many petioles and cortices. Detailed anatomical evidence indicates a close systematic affinity of *Lioxylon* to fossil and living cycads (Wang et al., 2005; Zhang et al., 2006).

2) Bennettitales: two species can possibly be referred to this group, i.e. *Perisemoxylon bispirale* and *Perisemoxylon* sp. *P. bispirale* was reported from the Middle Jurassic in Henan and Ningxia (He and Zhang, 1993). The inner and outer walls of the tracheids display spiral thickenings. The trunk surface cuticles are strongly waved with short ray cells. *Perisemoxylon* sp. was collected from the Middle Jurassic in Ningxia (He and Zhang, 1993). The tracheids of this species are very small and the morphology of the pits varies considerably; the stomata in the trunk epidermis are syndetochelic. Although these features are indicative of bennettitalean affinity, nevertheless, because of the type of preservation of specimens, further work is needed to confirm the systematic position of this species.

3) Coniferales: this is the dominant fossil wood group in the Jurassic of China ranging in age from Early to Late Jurassic. The fossils are distributed in Liaoning, Heilongjiang, Jilin, Beijing, Hebei, Xinjiang, Henan, Anhui, and Sichuan provinces, including 29 species ascribed to 14 genera. The major taxa include: *Araucarioxylon* (2 species), *Cupressinoxylon* (3 species), *Protocupressinoxylon* (1 species), *Haplomyeloxylon* (1 species), *Protopiceoxylon* (5 species), *Protocedroxylon* (1 species), *Phyllocladoxylon* (1 species), *Protophyllocladoxylon* (2 species), *Protopodocarpoxylon* (1 species), *Prototaxodioxylon* (1 species), *Sciadopityoxylon* (1 species), *Protosciadopityoxylon* (3 species), *Xenoxylon* (6 species) and *Scotoxylon* (1 species) (Figs. 3, 4).

4) Other plant groups: only one genus in this category, *Sahnioxylon* was recently reported from China. This is a Mesozoic wood

morphogenus, its affinity has long been debated as bennettitales or angiosperm. Recent investigation indicates that *Sahnioxylon* is neither bennettitalean nor true angiosperm wood (Zheng et al., 2005). It mostly represents an evolutionary transition link between the Paleozoic wood *Guizhouxylon* and the Late Triassic genus *Paradoxoxylon*, and is an ancestral plant type of angiosperms without vessels.

It is noted that there are some discrepancies for taxonomical status of some genera. For example, *Araucarioxylon* Kraus has been used repeatedly, although it is illegitimate and superfluous, most of the wood species referred to this genus should actually be transferred to *Agathoxylon* (Vogellehner, 1964; Philippe, 1993; Bamford and Phillipe, 2001). *Pinoxylon* is suggested to be the correct name for *Protopiceoxylon* Gothan (Medlyn and Tidwell, 1979; Bamford and Phillipe, 2001). For *Scotoxylon*, it should be made clearer that some of these names are for isolated secondary xylem pieces (tracheidoxyls) and some others for specimens with pith plus secondary xylem. According to recent considerations, from secondary xylem point of view, *Scotoxylon* is a synonym of *Protopiceoxylon*. *Sciadopityoxylon* is probably a taxonomical synonym of *Xenoxylon* Gothan (Bamford and Phillipe, 2001). The use of these genera name in China has a long history and it is therefore necessary to make a revision for all the above mentioned type species described in China, not only for the Jurassic taxa, but also for the taxa of other episodes. This is, however, out of focus of the present account.

Discussion on palaeoclimatic implications

The Jurassic phytogeography of the Euro-Asian Continent was proposed to be subdivided into a Continental Floristic Province and a Maritime Floristic Province. In China, these two provinces are generally called the Northern Floristic Province and the Southern Floristic Province (Zhou, 1984, 1995). They are bordered by the mountain ranges of the Kunlun Mt. – Qinling Mt. and Dabie Mt.

Table 1. Diversity of taxa and distribution of Jurassic fossil wood in China.

Plant group	Genera	Number of species	Name of species	Locality & Horizon	References
Cycadales	<i>Lioxylon</i>	1	<i>Lioxylon liaoningense</i> Zhang, Wang, Zheng, Saiki et Li	Beipiao of Liaoning, J ₂	Zhang et al., 2006
Bennettitales	<i>Perisemoxylon</i>	2	<i>Perisemoxylon bispirale</i> He et Zhang <i>Perisemoxylon</i> sp.	Yima of Henan, J ₂	He and Zhang, 1993
Coniferales	<i>Araucarioxylon</i>	2	<i>Araucarioxylon zigongensis</i> Duan <i>Araucarioxylon batuense</i> Duan	Zigong of Sichuan, J ₂ Chaoyang and Yixian, J ₂ Liaoning, J ₂	Duan and Peng, 1998 Duan, 2000
	<i>Cupressinoxylon</i>	3	<i>Cupressinoxylon hanshanense</i> Zhang and Cao <i>Cupressinoxylon baomiaqiaoense</i> Zheng et Zhang <i>Cupressinoxylon fujeni</i> Mathews et Ho	Hanshan of Anhui, J ₃ Baoqing of Heilongjiang, J ₃ Zhuolu of Hebei, J ₃	Zhang and Cao, 1986 Zheng and Zhang, 1982 Sze et al., 1963
	<i>Protocupressinoxylon</i>	1	<i>Protocupressinoxylon</i> sp.	Yima of Henan, J ₂	Zhou and Zhang, 1989
	<i>Haplomyeloxylon</i>	1	<i>Haplomyeloxylon tiaojishanense</i> Zhang et Wang	Beipiao of Liaoning, J ₂	Wang et al., 2006
	<i>Protopiceoxylon</i>	5	<i>Protopiceoxylon amurense</i> Du <i>Protopiceoxylon extinctum</i> Gothan <i>Protopiceoxylon xinjiangense</i> Wang, Zhang et Saiki <i>Protopiceoxylon chaoyangense</i> Duan <i>Protopiceoxylon yabei</i> (Shimakura) Sze	Jiayin of Heilongjiang, J ₃ Zhuolu of Hebei, J ₃ Qitai of Xinjiang, J ₃ Chaoyang and Yixian, J ₂ Huoshiling of Jilin, J ₂	Du, 1982 Sze et al., 1963 Wang, Zhang and Saiki, 2000 Duan, 2000 Sze et al., 1963
	<i>Protocedroxylon</i>	1	<i>Protocedroxylon lingwuense</i> He et Zhang	Lingwu of Ningxia, J ₂	He and Zhang, 1993
	<i>Phyllocladoxylon</i>	1	<i>Phyllocladoxylon</i> cf. <i>eboracense</i> (Holden) Kräusel	Yingcheng of Jilin, J ₃	Shimakura, 1935-36
	<i>Protophyllocladoxylon</i>	2	<i>Protophyllocladoxylon chaoyangense</i> Zhang et Zheng <i>Protophyllocladoxylon franconicum</i> Vogellehner	Chaoyang of Liaoning, J ₁ Beipiao of Liaoning, J ₃	Zhang, Zheng and Ding, 2000a Zhang, Zheng and Ding, 2001
	<i>Protopodocarpoxylo</i>	1	<i>Protopodocarpoxylo batuyingziense</i> Zheng et Zhang	Beipiao of Liaoning, J ₃	Zheng, 2004
	<i>Prototaxodioxylo</i>	1	<i>Prototaxodioxylo romanense</i> Philippe	Beipiao of Liaoning, J ₃	Zheng, 2004
	<i>Sciadopityoxylo</i>	1	<i>Sciadopityoxylo heizyoense</i> (Shimakura) Zhang et Zheng	Lingyuan of Liaoning, J ₁	Zhang, Zheng and Ding, 2000a
	<i>Protosciadopityoxylo</i>	3	<i>Protosciadopityoxylo liaoiense</i> Zhang et Zheng <i>Protosciadopityoxylo jeholense</i> (Ogura) Zhang et Zheng <i>Protosciadopityoxylo liaoningense</i> Zhang, Zheng et Ding	Chaoyang, Lingyuan and Kazuo, Liaoning, J ₁ Beipiao of Liaoning, J ₁ Beipiao of Liaoning, J ₁	Zhang, Zheng and Ding, 2001 Zhang, Zheng and Ding, 2000a Zhang, Zheng and Ding, 1999; Wang et al., 2006
	<i>Xenoxylon</i>	6	<i>Xenoxylon latiporosum</i> (Cramer) Gothan <i>Xenoxylon ellipticum</i> Schultze-Motel ex. Vogellehner <i>Xenoxylon hopeiense</i> Chang <i>Xenoxylon peideense</i> Zheng et Zhang <i>Xenoxylon japonicum</i> Vogellehner <i>Xenoxylon conchylanium</i> Fliche	Beipiao of Liaoning, J ₁ Yanqing of Beijing, J ₂ , J ₃ Jiayin of Heilongjiang, J ₃ Qitai of Xinjiang, J ₃ Beipiao of Liaoning, J ₃ Zhuolu of Hebei, J ₃ Beipiao and Chaoyang of Liaoning, J ₁ , J ₂ Mishan of Heilongjiang, J ₃ Kazuo and Tieling, Liaoning, J ₁ , J ₃ Chaoyang of Liaoning, J ₁ Hebei, J ₂	Duan, 1986; Du, 1982; Sze, 1951; Ding, Zheng and Zhang, 2000; Zheng, 2004; Wang, Zhang and Saiki, 2000 Ding, Zheng and Zhang, 2000; Zheng, Zhang and Ding, 2001 Chang, C.Y., 1929; Ding, Zheng et Zhang, 2000 Zheng and Zhang, 1982 Ding, Zheng and Zhang, 2000 Ding, Zheng and Zhang, 2000 Li and Cui, 1995
	<i>Scotoxylon</i>	1	<i>Scotoxylon yanqingense</i> Zhang et Zheng	Lingyuan of Liaoning, J ₃	Zhang, Zheng and Ding, 2000b
Incertae sedis	<i>Sahnioxylon</i>	2	<i>Sahnioxylon rajmahalense</i> (Sahni) Bose et Sah <i>Sahnioxylon</i> sp.	Beipiao of Liaoning, J ₂	Zhang et al., 2005; Philippe et al., 1999;

Notes: J₁ = Lower Jurassic; J₂ = Middle Jurassic; J₃ = Upper Jurassic

Available data clearly demonstrate that the Jurassic wood specimens are mainly recorded in the Northern Floristic Province; whereas in the Southern Floristic Province, fossil wood records are rare (Figs. 1, 3). The possible reason for this phenomenon may be because of insufficient specimen collection and investigation. Further work is therefore needed in the Southern province to improve the records of Jurassic fossil wood.

It is noteworthy that Jurassic wood and growth ring features in China provide informative evidence for palaeoclimatic reconstruction. Tree rings preserve a continuous record of environmental factors present during the life of a tree. Fossil tree rings are a unique source of detailed information about growth factors such as seasonality, annual growing conditions, water availability, limiting temperatures

or forest productivity in the geological past (Creber and Francis, 1999). The occurrence of growth rings in nearly all of the woods analyzed indicates that the trees grew under a distinctly seasonal climate (e.g. Creber, 1977; Creber and Chaloner, 1984, 1985; Francis, 1984, 1986; Keller and Hendrix, 1997; Falcon-Lang, 2005).

Jurassic wood from Northern Floristic Province

As noted above, fossil woods are abundant in the Northern Floristic Province, ranging from the Early to Late Jurassic periods,

Figure 4. Selected fossil wood taxa from the Jurassic deposits of China. 1-4. *Araucarioxylon batuense* Duan, from the Middle Jurassic Tiaojishan Formation, Chaoyang, Liaoning Province. 1. Transverse section, showing growth rings, bar=125 μ m; 2-3. Radial section, showing the cross-fields and radial tracheids, bar=50 μ m; 4. Tangential section, showing the height of rays, bar=50 μ m. 5-8. *Xenoxylon hopeiense* Chang, 5, 6, 8 from the Middle Jurassic Tiaojishan Formation, Beipiao, Liaoning Province; 7 from the Upper Jurassic Houcheng Formation, Hebei Province. 5. Transverse section, showing the distinct growth rings, bar=312.5 μ m; 6. Transverse section, showing the variations of the tracheid, bar=167 μ m; 7. Radial section, showing the radial wall pits and cross-field pits, bar=43 μ m; 8. Tangential section, showing changes of the height of rays, bar=31 μ m. 9-12. *Protosciadopityoxylon liaoningense* Zhang, Zheng et Ding, from the Lower Jurassic Beipiao Formation, Beipiao, Liaoning Province. 9. Transverse section, showing the growth rings, bar=312.5 μ m; 10. Transverse section, showing the tracheids, bar=167 μ m; 11. Radial section, showing the cross-field and radial tracheids, bar=31 μ m; 12. Tangential section, showing the height of rays, bar=31 μ m. 13-16. *Sahnioxylon rajmahalense* (Sahni) Bose et Sah, from the Middle Jurassic Tiaojishan Formation, Beipiao, Liaoning Province. 13. Transverse section showing xylem cylinder, over 12 growth rings. Note the central empty pore is the space after pith decayed, bar=286 μ m; 14. Transverse section, showing distinct tracheids and growth rings, bar=286 μ m; 15. Radial section, showing radial wall scalariform pits and cross-field pits, 16. Tangential section, showing uniseriate rays and the variation of ray height, bar=57 μ m.

and are especially well documented in the horizons of the Middle and Late Jurassic (Fig. 3).

Lower Jurassic: The Lower Jurassic wood is reported only from the Beipiao Formation in Western Liaoning Province, corresponding to the Pliensbachian to Toarcian. This formation is notable for coal

resources in Liaoning. Fossil woods from this horizon include the following taxa: *Protosciadopityoxylon liaoxiense* Zhang et Zheng, *P. liaoningense* Zhang, Zheng et Ding, *P. jehouense* (Ogura) Zhang et Zheng, *Sciadopityoxylon heizyoense* (Shimakura) Zheng et Zheng, *Xenoxylon latiporosum* (Cramer) Gothan, *Protophyllocladoxylon*

chaoyangense Zhang et Zheng and *P. franconicum* Vogellehner (Zhang et al., 2000a). Growth rings are well developed in these woods with wider early wood and narrow late wood, normally 1-2 tracheids wide and maximum 5-6 tracheids. These anatomical features may imply that the climate in western Liaoning was warm and humid during the Early Jurassic with seasonal variations: long spring and summer seasons and a shorter winter season. The megaplant assemblages in the Beipiao Formation (Zhang and Zheng, 1987) show that ferns are the dominant group in the assemblages, with diverse *Cladophlebis* foliages of larger fronds. The ferns were growing under the canopy of an arborescent forest dominated by conifers and ginkgoaleans, which are tolerant of a warm and humid climate. The fossil woods in the Beipiao Formation were dominated by conifers, which are the coal-forming plants during the Early Jurassic.

Middle Jurassic: Middle Jurassic woods in this timespan are represented in the Tiaojishan Formation in western Liaoning and the Yima Formation in Henan Province. The latter is an early Middle Jurassic coal deposit, corresponding to Aalenian to Bajocian. Some fossil woods were reported from this formation, including the bennettitalean *Perisemioxylon* and conifer *Protocupressinoxylon*. These woods demonstrate distinct growth rings, implying that the palaeoclimatic conditions were warm and humid with seasonal variations.

The Middle Jurassic Tiaojishan Formation in Beipiao City, western Liaoning (corresponding to the Bathonian to Callovian) contains a variety of plant fossils including foliages and conifer woods (Wang et al., 2006). Abundant wood genera are recognized in this formation, including *Araucarioxylon batuense* Duan, *Haplomyeloxylon tiaojishanense* Zhang and Wang, *Protopiceoxylon chaoyangense* Duan, *Xenoxylon latiporosum* (Cramer) Gothan, *X. hopeiense* Chang, *Protosciadopityoxylon liaoningense* Zhang, Zheng and Ding. In addition, some fossil cycad-like stems belonging to *Lioxylon liaoningense* Zhang et al., have been found in this formation. The floristic signature of the Tiaojishan Formation indicates that subtropical to temperate warm and humid climates prevailed during the late Middle Jurassic in the Beipiao area. Growth ring pattern analysis of the fossil conifer wood demonstrates a consistent and distinct seasonal climate during this interval in western Liaoning (Wang et al., 2006). Additionally, fossil conifer woods have also been recorded from the Middle Jurassic in the Zhuolu, Hebei Province, close to western Liaoning, including *Cupressinoxylon fujeni* Mathews et Ho, *Protopiceoxylon extinctum* Gothan, and *Xenoxylon hopeiense* Chang. The distinct growth rings of these woods infer the same climatic conditions as those of western Liaoning during the Middle Jurassic.

Late Jurassic: There are various of fossil wood horizons in the Upper Jurassic of northern China. Among them, the Tuchengzi Formation (corresponding to Oxfordian to Kimmeridgian) is remarkable and representative of the palaeoclimate conditions. This is an extensively developed deposit composed of red and variegated calcareous and tuffaceous mudstones, sandstones and conglomerates. The lower part of this formation is lacustrine sediments formed in arid environments and fossils are sparse. The middle part of this formation is composed of red conglomerate with sandstone intercalations, represented by arroyo or wadi alluvial sediment containing no fossils; and the upper part is sand dunes composed of eolian sandstones. Interspersed locally there are desert oases lake deposits with a sparse xerophytic vegetation, such as the cheirolepidiaceae plants of *Brachyphyllum* and *Pagiophyllum* (Deng

and Shang, 2002), as well as the conifers *Schizolepis*, *Pityolepis* and the czecknowskialean *Leptostrobus*. Fossil woods reported from this formation include *Protophyllocladoxylon franconicum*, *Xenoxylon ellipticum* and *X. latiporosum*. It is noteworthy that the foliages of the above conifers bear distinct xerophytic structures with small scale-like leaves and thick cuticles. The fossil woods contain obvious growth rings and false rings (Zheng et al., 2001; Zheng, 2004). The *Classopollis* pollen in this formation can reach over 86% (Pu and Wu, 1982). In general, the evidence from fossil plants, palynomorphs and fossil wood assemblages supports an arid and subtropical to warm temperate palaeoclimate in the Late Jurassic of western Liaoning that was characterized by distinct seasonality. Meanwhile, a potential terminal Jurassic monsoonal climate also affected this region, resulting in desert eolian sandstone deposits.

In northern Hebei, the Tuchengzi Formation is slightly different from that in western Liaoning in sedimentary features, characterized by fluvial deposits with regional lake fishes and bivalves. A petrified forest marked by *Xenoxylon latiporosum* (Cramer) Gothan and *Scotoxylon yansingense* Zhang et Zheng has been reported (Duan, 1986; Zhang et al., 2000b). The cross section of these woods show distinct growth rings. Palynological evidence indicates that *Classopollis* pollen reached up to 15-91% in this formation in Xuanhua, Hebei (Zhang, 1989). Such evidence demonstrates that during the Late Jurassic period, the general climatic conditions in northern Hebei were similar to those in western Liaoning, but the aridity was less strong than there, probably indicating a seasonal arid or semi-arid and semi-humid climate. However, there are no desert deposits in northern Hebei.

Jurassic wood from Southern Floristic Province

The Jurassic floras from southern China belong geographically to the Euro-Sinian Region, representing a subtropical vegetation (Zhou, 1995). However, the fossil wood specimens in this region are rare. Up to now, they have been reported only from two horizons of limited extent in Sichuan and Anhui provinces (Fig.3). *Araucarioxylon zigongensis* was documented in the Middle Jurassic Xintiangou and Xiashaximiao Formations in Zigong, Sichuan Province, and shows distinct growth rings (Duan and Peng, 1998). These two formations are composed mainly of purple-red mudstones, sandy mudstones with intercalations of siltstones and basal medium-grained sandstones with cross bedding. The fossil assemblages including ostracodes, bivalves, vertebrates and plants, and other sedimentary facies indicate that the fossil woods were growing in subtropical regions with a warm and cool climate as well as distinct seasonal aridity (Zhou, 1995).

Additionally, *Cupressinoxylon hanshanense* has been recognized from the Upper Jurassic in Anhui Province (Zhang and Cao, 1986). The taxon is characterized by a very narrow late wood (only 2-3 tracheids broad) with irregular growth rings. The wood specimens were found from the Hanshan Formation, which is composed of a series of dark purple-red, grayish-yellow sandstones and conglomerates with a thickness of 450 m. Fossil plant foliages were reported from the lower part of this formation, comprising fern fronds (such as *Klukia*), bennettitaleans (*Ptilophyllum*), as well as many conifers (represented by *Cherolepidiaceae*), and some twigs may belong to *Cupressinoxylon* (Cao, 1985). The above deposits and plant fossil assemblages imply arid and dry climate.

Conclusions

As an important proxy for palaeoenvironmental reconstruction, fossil wood increasingly improves our understanding of vegetation history and palaeoclimatic conditions. Fossil wood from the non-marine Jurassic deposits of China provides clues for investigation of terrestrial biodiversity and climatic variations. Diverse Jurassic fossil wood taxa are taxonomically referred to coniferales, cycadales and bennettitales. The horizons of the Jurassic wood range through Lower, Middle and Upper Jurassic intervals, and are especially abundant in Aalenian to Bajocian, Bathonian to Callovian and Oxfordian to Tithonian. Phytogeographically, the Jurassic woods from China occur mainly in the Northern Floristic Province. An analysis of growth ring features indicates distinct and seasonal climate variations in the Northern Floristic Province during the Early, Middle and Late Jurassic. This is of particular significance for exploring the Jurassic terrestrial vegetation history and climate change, and is therefore crucial for the regional and global correlations between the marine and non-marine Jurassic.

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