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Climatic change during the Palaeocene to Eocene based on fossil plants from Fushun, China

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ABSTRACT

By applying the Coexistence Approach (CA) to palynological data from the Laohutai, Lizigou, Guchengzi, Jijuntun and Xilutian Formations in Fushun, northeastern China, a quantitative reconstruction of the Palaeocene to Eocene climate is made. During that time, Mean Annual Temperature changed from 11.3 to 21 °C, Mean Annual Precipitation from 654 to 1540 mm, Mean Temperature of the Warmest Month from 19.4 to 28.2 °C, Mean Temperature of the Coldest Month from 3.6 to 13.9 °C, Mean Annual Range of Temperature from 12.8 to 23.5 °C, Mean Maximum Monthly Precipitation from 175 to 354 mm, and Mean Minimum Monthly Precipitation from 8 to 27 mm. All the parameters in the five formations indicate a subtropical climate. This situation is different from the current climate at the same site, a mid-temperate and continental monsoon climate, with a Mean Annual Temperature of 6.6 °C and a Mean Annual Precipitation of 804 mm. In addition, the climatic parameters obtained from megafossil data (only found in the Jijuntun Formation) were analyzed and approximate those from the palynological data. The parameters from the palynological data support the view that the Palaeogene climate of Northeast Asia and North America was similar, but unlike that of Europe.

1. Introduction

Although the investigation of past climate has made significant advances in the world recently, the quantitative reconstruction of palaeoclimate using multidisciplinary methods is still in progress. Even though the latter needs to be improved, the results of quantitative reconstructions of palaeoclimate have improved our understanding of global change. The ocean water temperatures in the last 65 million years have been studied in a quantitative fashion (Zachos et al., 2001), and climate change in Central Europe since 45 million years ago has been reconstructed quantitatively (Mosbrugger et al., 2005). The climate in the Palaeogene of North America has been established quantitatively (e.g. Davies-Vollum, 1997; Wing et al., 1999; Wilf, 2000). Similar works on the quantitative reconstruction of the Cainozoic climate in China are in a developmental phase (Liang et al., 2003; Kou et al., 2006; Yao et al., 2009; Li et al., 2009; Hao, et al., 2009). The present paper is devoted to a quantitative reconstruction of Palaeocene and Eocene climates in northern China based on palynological data from the West Opencast Coalmine at Fushun, Liaoning Province (Fig. 1).

The West Opencast Coalmine consists of five formations, i.e. Laohutai, Lizigou, Guchengzi, Jijuntun and Xilutian Formations from bottom to top (Fig. 2). Abundant fossils of plants and insects have been found in this coalmine. Wood of *Piceoxylon fushunese*, *Chamaecyparioxylon chinense*, *Juniperoxylon chinense* etc., was reported from the Lizigou Formation (Du, 1987). Over 70 species of leaves and fruits were found in the Jijuntun Formation, including *Metasequoia*, *Keteleeria*, *Ginkgo*, *Cercidiphyllum*, *Sequoia*, and *Glyptostrobus* (Palibin, 1906; Florin, 1922; Endo, 1926, 1928, 1934, 1936, 1942, 1951; WGCPC, 1978; Liu et al., 1991; Liu et al., 1996; Geng et al., 1999; Liu and Li, 2000; Manchester, et al., 2005; Wang et al., 2010). Some 20–34 sporomorph taxa, were identified in the five formations, e.g. *Abietineaepollenites*, *Laricoidites*, *Podocarpidites*, *Taxodiaceaepollenites*, *Alnipollenites*, *Caryapollenites*, *Cupuliferoipollenites*, *Juglanspollenites*, *Liquidambarpollenites*, *Momipites*, *Palmaepollenites*, *Pterocaryapollenites*, *Quercoidites*, *Rutaceoipollenites*, *Tiliaepollenites*, and *Ulmipollenites* (Song and Tsao, 1976; Sun et al., 1980). Insects, such as *Eopalpomyitis unca*, *Chironomus minimus*, *Eosciophila microtrichodis*, and *Macrocera melanopoda* were

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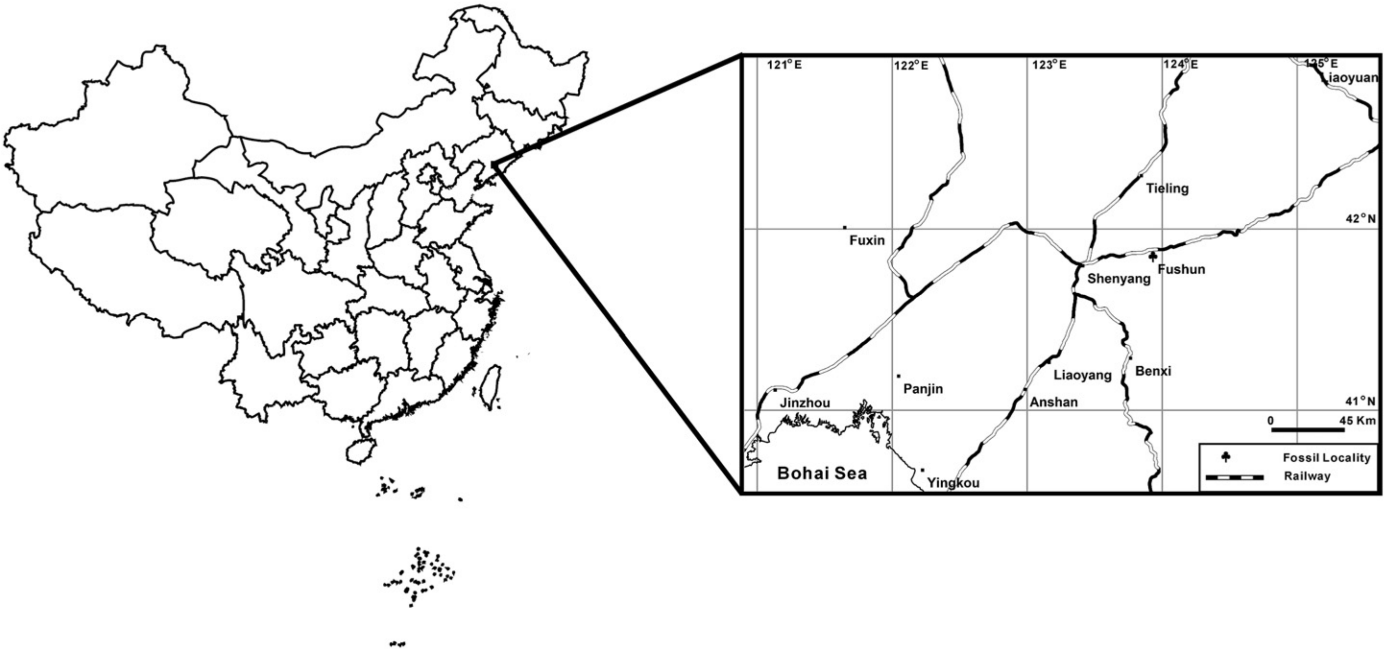

Fig. 1. Map of China showing the position of the Fushun locality.

discovered in the upper three formations, Guchengzi, Jijutun and Xilutian belonging to the Eocene (Ping, 1931; Hong et al., 1974, 1980, 2000; Hong, 1983). All these fossils represent a moist and warm climate during the Early Cainozoic (WGCPC, 1978; Sun et al., 1980).

Based on the palynological data obtained from the coalmine (Sun et al., 1980) and macrofossils from the Jijuntun Formation (mainly WGCPC, 1978), we obtained the palaeoclimatic parameters using the Coexistence Approach (CA) (Mosbrugger and Utescher, 1997). The results demonstrate a subtropical climate in Fushun during the Palaeocene and Eocene. This is more similar to the situation in North America than that in Europe.

2. Materials and methods

The West Opencast Coalmine (41°50′N, 123°54′E) at Fushun (Fig. 1) is the largest opencast coalmine in Asia, with the sediments of five formations exposed. The lower two Formations of Laohutai and Lizigou were ascribed to the Palaeocene, while the upper three Formations of Guchengzi, Jijuntun and Xilutian belong to the Eocene, based on the data of pollen, macrofossils and insects (Hong et al., 1980) (Fig. 2). The Laohutai Formation belongs to the earliest Palaeocene, 65 million years old, by K–Ar methods (Wang and Wang, 1982; Wang and Wang, 1985) and by palaeomagnetic determination (Wang et al., 1982).

The principle of CA (Mosbrugger and Utescher, 1997) is based on the concept of “nearest living relative (NLR) philosophy”. It assumes that the climatic tolerance of an ancient taxon was similar to that of a (systematically) NLR. Based on this assumption, each fossil taxon in an assemblage is attributed to a modern taxon and the modern environmental tolerance for that taxon is collated from its distribution. This of course assumes that the modern taxon occupies a spatial range that fully reflects its environmental tolerance.

The spectra of tolerances for all the NLRs are then examined and the maximum overlap of tolerance ranges used to define the most probable ancient environmental parameters for that assemblage. Range outliers indicate possible anomalous evolutionary changes in a taxon or taxa in relation to the majority of taxa, or a mismatch of the fossil to an appropriate NLR. Exclusion of these outliers, minimize the effect of misidentification and “anomalous” environmental signals due to evolution (Mosbrugger and Utescher, 1997; Mosbrugger, 1999; Xu et al., 2000; Uhl et al., 2003; Liang et al., 2003; Roth-Nebelsick et al., 2004; Mosbrugger et al., 2005).

In the present paper, the palynological data (Sun et al., 1980) (Table 1) of Fushun were employed, while the identification of the NLRs of the sporomorphs is largely based on Song et al. (1999). The fossil leaves and fruits from the Jijuntun Formation were incorporated into this work and the NLRs (total 54) (Table 2) of the macrofossils taken from WGCPC (1978), Liu et al. (1991), Liu et al. (1996), Geng et al. (1999), Manchester et al. (2005) and Wang et al. (2010). The climatic tolerances of the NLRs were collated from the climate recorded within the area of their modern distribution based on Wu and Ding (1999). The modern climatic data recorded by the meteorological stations of China were obtained from publications of the Information Department of Beijing Meteorological Centre (IDBMC) (1983a, b, 1984a, b, c, d). Some NLRs have a distribution which extends beyond the limits of China. For example, the climatic tolerances of *Pinus*, *Picea*, and *Larix* might be expected to be wider than those based on Chinese species. We have attempted to augment the climatic tolerances by integrating climatic data from other parts of the plant's range (e.g. http://www.geologie.uni-bonn.de/Palaeoflora/Palaeoflora_home.htm). Kou et al. (2006)'s procedure was adopted to determine the seven palaeoclimatic variables: Mean Annual Temperature (MAT), Mean Annual Range of Temperature (MART), Warm Month Mean Temperature (WMMT), Cold Month Mean Temperature (CMMT), Mean Annual Precipitation (MAP), Mean Maximum monthly Precipitation (MMaP) and Mean Minimum monthly Precipitation (MMiP).

For example, the full ranges of the coexisted climatic intervals (except MART) for all taxa in the Laohutai Formation are illustrated in Fig. 3. The coexisting interval (see Table 3) of the MAT was between 11.5 and 20.9 °C with the boundaries of the range determined by Cycadaceae and *Cedrus*. The interval of the CMMT lay between 3.6 and 12.6 °C, as determined by *Engelhardia* and *Cedrus*. The interval of the WMMT must have been between 22.5 and 28.2 °C, based on Cycadaceae, *Picea* and *Rhus*. The interval of the MART fell between 12.8 and 23.5 °C, as determined by *Picea* and *Liquidambar*. The interval of the MAP lay between 794 and 1484 mm, as indicated by *Myrica* and *Picea*. The interval of the MMiP must have been between 8 and 25 mm determined also by Palmae and *Picea*. The interval of the MMaP was between 175 and 353 mm, as indicated by *Cedrus* and *Carpinus*.

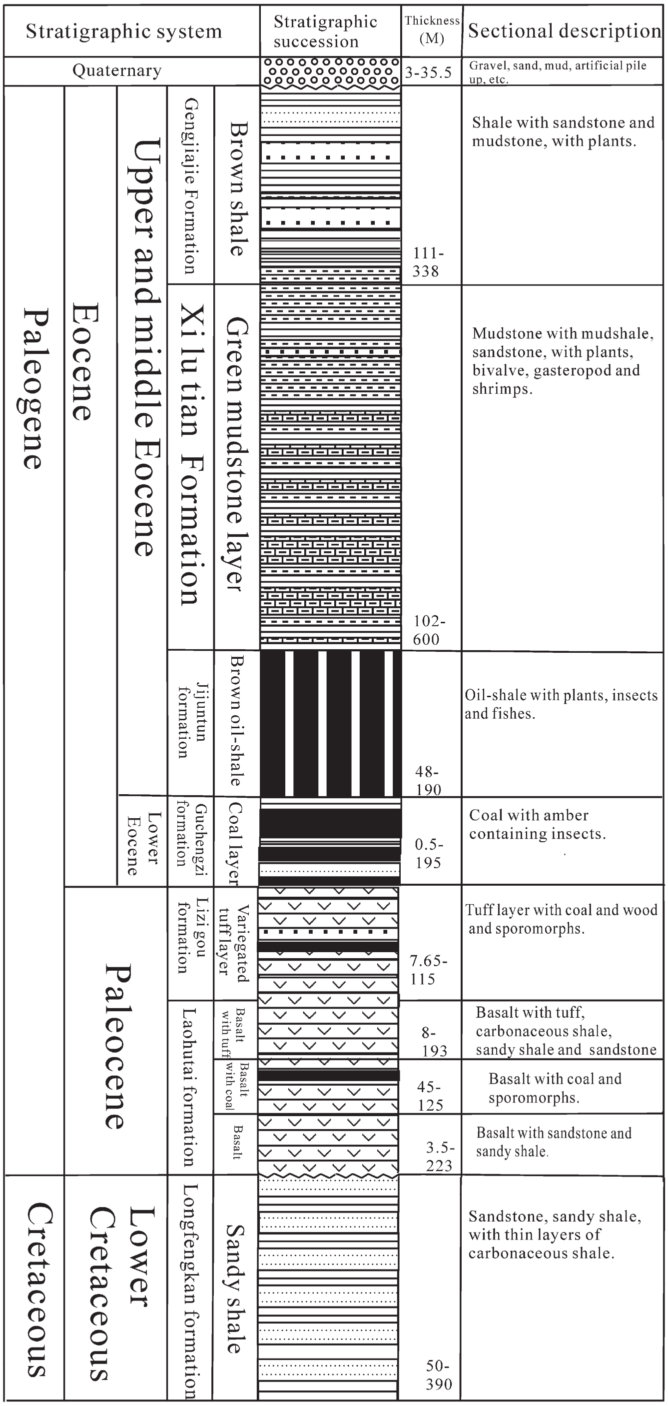

Fig. 2. Sedimentary succession in the Fushun Opencast Mine (revised from Hong et al., 1980).

Finally, the seven parametric data of palaeoclimatic intervals of the five pollen assemblages (one Formation contains one pollen assemblage) and one megafossil flora in the Jijuntun Formation were established using their extreme taxa (see Tables 3 and 4).

3. Results and discussion

3.1. Evolution of temperature

The temperatures changed from Palaeocene to Eocene in Fushun. The MAT during the Laohutai Formation was 11.5–20.9 °C, and 11.3–20.9 °C during the Lizigou Formation. After that, the MAT rose to 14.8–21 °C (Guchengzi and Jijuntun Formations), before falling to 11.5–20.9 °C during the Xilutian Formation. During the Palaeogene, the MAT varied between 11.3 °C and 21 °C (Fig. 4, Table 3). Almost all formation (4 formations except Guchengzi Formation)'s upper boundary taxon is *Cedrus*.

The CMMT during the deposition of the five formations oscillated between 3.6 and 12.6 °C (Laohutai Formation), and (Lizigou Formation), 9.1–13.9 °C (Guchengzi Formation), and 9.1–12.6 °C (Jijuntun Formation), and 3.6–12.6 °C (Xilutian Formation). It was noted that the same climatic range in the Laohutai, Lizigou and Xilutian Formations was determined by the same taxa, upper ones were *Engelhardia* and lower ones were *Cedrus* (Fig. 4, Table 3). In addition, *Cedrus* was also the upper boundary taxon of the Jijuntun Formation. All these were nearly the same to that in MAT. The WMMT also varied with a WMMT of 22.5–28.2 °C in the Laohutai, 23.9–27.5 °C in the Lizigou, 19.4–24.7 °C in the Guchengzi and Jijuntun, and 22.5–26.6 °C in the Xilutian Formation (Fig. 4, Table 3).

The MART, is more uniform, being 12.8–23.5 °C in the Laohutai, and the Lizigou, 14.2–23.5 °C in Guchengzi, and 13.2–23.5 °C in the Jijuntun and Xilutian Formations. In the Laohutai and Lizigou Formations the lower boundary taxon is *Picea*, in Jijuntun Formation the lower boundary taxon is *Larix*, in the other two formations the lower one is *Platycarya*, while the upper boundary taxon in the five formations is always *Liquidambar* (Fig. 4, Table 3). As the MART values for *Elytranthe*, which is present in the Guchengzi and Jijuntun Formations, lie outside the coexistence interval, this genus is considered to be an outlier. The MART underwent only minor change or remained uniform throughout the Palaeocene to Eocene of the Fushun area.

All these temperature intervals changed within a limited range, in another words, there was no abrupt temperature change during the early Palaeogene in Fushun, and they demonstrate that a subtropical climate had become established in the Fushun area during the early Palaeogene.

3.2. Evolution of precipitation

The values of the MAP from the five formations range between 654 and 1540 mm and unlike the MAT are fairly uniform (Fig. 4, Table 3). Similarly, the values of the MMaP (179–354 mm) and MMiP (8–27 mm) only vary slightly (Fig. 4, Table 3). The boundary taxa for MAP, MMiP and MMaP in the five formations are a little different, but the upper boundary taxon of MAP and MMIiP in the five formations is the same genus, *Picea*, except in Guchengzi Formation. thus indicating that the parameters underwent only minor change (Fig. 4, Table 3).

All the parameters of temperature and precipitation established in this work indicate that the climate was moist, mild and demonstrate a typical subtropical climate for the Fushun area, Northeast China from the Palaeocene to Eocene.

Today Fushun belongs to the mid-temperate zone and possesses a continental monsoon climate with MAT (6.6°C) and MAP (804 mm) (IDBMC, 1983a; Deng et al., 1998); the average altitude of this area is about 100–400 m. It is thus completely different from the Palaeogene climate of Fushun.

3.3. Comparison with the climatic parameters reconstructed from the macrofossils of the Jijuntun Formation

Based on the fossil leaves and fruits from the Jijuntun Formation, the following climatic parameters were obtained: MAT 15.4–16.3 °C, CMMT 2–7.9 °C, WMT 24.–24.9 °C, MART 22.1–23.5 °C, MAP 872–1654 mm, MMiP 23–27 mm and MMaP 184–212 mm, while the climatic parameters obtained from the palynological data from the same formation are MAT 14.8–20.9 °C, CMMT 9.1–12.6 °C, WMMT 19.4–24.7 °C, MART 13.2–23.5 °C, MAP 794–1484 mm, MMiP 8–25 mm and MMaP 175–309 mm. A comparison of the two data sets shows that the parameters

Table 1
List of palynomorphs from Palaeocene to Eocene in Fushun and their nearest living relatives (NLR).

Pollen taxa	Laohutai fm	Lizigou fm	Guchengzi fm	Jijuntun fm	Xilutian fm	NLR
Abietineaepollenites	+		+	+	+	*Pinus*
Cedripites	+	+		+	+	*Cedrus*
Cedrus					+	*Cedrus*
Cycadopites	+				+	Cycadaceae
Keteleeria				+	+	*Keteleeria*
Laricoidites			+			*Larix*
Parcisporites		+		+		Podocarpaceae
Picea				+	+	*Picea*
Piceapollenites	+	+				*Picea*
Pinus			+	+	+	*Pinus*
Pinuspollenites	+	+	+	+		*Pinus*
Podocarpidites	+	+	+	+	+	*Podocarpus*
Taxodiaceaepollenites	+	+	+	+	+	Taxodiaceae
Alnipollenites	+	+	+	+	+	*Alnus*
Betulaceoipollenites	+	+				*Betulaceae*
Betulaceoipollenites	+	+				*Myricaceae*
Carpinipites	+			+		*Carpinus*
Caryapollenites	+	+	+	+	+	*Carya*
Cupuliferoipollenites		+	+	+	+	Castaneae(Castanea)
		+	+	+	+	Castanopsis
Cyrillaceaepollenties				+	+	Castaneae(Castanea)
				+	+	Castanopsis
Cyrillaceaepollenties				+	+	*Cyrillaceae*
Echitricolpites					+	Labiatae
Elaeagnus					+	*Elaeagnus*
Elytranthe			+	+		*Elytranthe*
Engelhardtioipollenites	+	+		+	+	*Engelhardia*
Fraxinuspollenites				+	+	*Oleaceae*
Ilexpollenites		+				*Ilex*
Juglanspollenites	+	+	+	+	+	*Juglans*
Liquidambarpollenites	+	+	+	+	+	*Liquidambar*
Lonicerapollis					+	*Lonicera*
Ludwigia		+	+			*Ludwigia*
Momipites	+	+	+	+	+	Juglandaceae
Moraceae	+					Moraceae
Myricipites	+	+		+		*Myrica*
Nyssapollenites					+	Nyssaceae
Palmaepollenites	+	+	+	+	+	Palmae
Paraalnipollenites	+	+	+			Betulaceae
Pistacia					+	*Pistacia*
Platycarya		+		+	+	*Platycarya*
Pterocaryapollenites		+	+	+	+	*Pterocarya*
Quercoidites	+	+	+	+	+	*Quercus*
Rhoipites	+			+	+	*Rhus*
Rutaceoipollenites		+	+	+	+	*Rutaceae*
Salixipollenites	+	+			+	*Salix*
Tiliaepollenites			+	+	+	Tiliaceae
Triatriopollenites	+					Myricaceae
Ulmipollenites	+	+	+	+	+	*Ulmus*

Note: fm = formation; NLR = near living relatives.

of MAT, WMT and MART obtained from the palynological taxa exhibit a broader range of temperature than those extracted from the fossil leaves and fruits, whereas the CMT acquired from the palynological data is higher and warmer than that acquired from the fossil leaves and fruits. The MMaP obtained by palynological means has broader limits than those of the megafossils, while the other two parameters, MAP and MMiP merely overlapped. The main reason is that the boundary taxa are different in the two groups (Tables 3 and 4). The phenomenon that two sets of parameters did not completely coincide has been noted in the Shanwang Miocene flora (Liang et al., 2003).

3.4. Climatic similarity between Northeast China and North America during the Early Palaeogene

In the early Palaeogene, the deduced land connection between Northern America and Eastern Asia and the North Atlantic land connection allowed for floristic exchange between the two continents, while the Turgai Seaway hindered plants from spreading between Europe and Asia in the Eocene. In the Oligocene Europe and Asia became united (Wen, 1999; Manchester, 1999; Tiffney, 2000; Collinson and Hooker, 2003) (Fig. 5, revised from Scotese, 1997). However, the fossil plant taxa and vegetation differed between Asia and Europe at that time (Wen, 1999; Manchester, 1999; Collinson and Hooker, 2003), so the climatic regime would appear to have been distinct on the two continents.

Few fossil floras in Northeast China of Early Palaeogene age have been studied with a view to reconstructing the palaeoclimate. They are the Early Palaeocene Wuyun flora (49°14′30″N, 129°28′00″E) (All the longitude and latitude data of the floras in this work have been converted into palaeolongitude and palaeolatitude with POINT TRACKER, and appear in the palaeogeographical map, Fig. 5) with its MAT of 14.8–16.6 °C, and MAP of 816–1389 mm (Hao et al., 2009). The data were obtained using the same methodology as in the present paper. In the case of the Early Eocene Yilan flora (46°10′N, 129°15′E) (Fig. 5) with its MAT of 13.2 °C (He and Tao, 1994), and the Middle Eocene Huadian flora (42°59′54″N, 126°51′58″E) (Fig. 5) with its MAT of 10 °C, the data were based on foliar physiognomy (Manchester et al., 2005), while the Eocene Hunchun flora (42º51′N, 130º21′E) (Fig. 5)

Table 2
List of megafossils in the Jijuntun Formation of Fushun.

Fossil taxa	Near living relatives
Acacia aquilonia	*Acacia concinna*
Acer arcticum	*Acer*
Acer subpictum	*Acer*
Ailanthus fushunensis	*Ailanthus altissima*
Alnus ellipsophyllaa	*Alnus nepalensis*
Alnus luxuriosa	*Alnus japonica*
Alnus prenepalensis	*Alnus nepalensis*
Ampelopsis acerifolia	*Ampelopsis brevipedunculata*
Betula speciosa	*Betula ermanii*
Betula fushunensis	*Betula luminifera*
Carpinus latifolia	*Carpinus pubescens*
Celtis peracuminata	*Celtis tetrandra*
Cercidiphyllum arcticum	*Cercidiphyllum japonicum*
Cinnamomum naitoanum	*Cinnamomum*
Comptonia anderssenii	*Comptonia*
Corylus laxinervis	*Corylus*
Craigia	*Craigia*
Cycas anomostoma	*Cycas*
Eucommia cf. *montana*	*Eucommia ulmoides*
Exochorda antique	*Exochorda racemosa* and *Exochorda serratifolia*
Fagus chenesis	*Fagus*
Firmiana sp.	*Firmiana platanifolia*
Fothergilla rarinervia	*Fothergilla*
Fraxinus juglandina	*Fraxinus chinensis*
Glyptostrobus europaeus	*Glyptostrobus pensilis*
Hamamelites inaequalis	*Hamamelites*
Hydrangea longifolia	*Hydrangea chinensis*
Keteleeria sp.	*Keteleeria davidiana*
Lindera antique	*Lindera glauca*
Meliosma rigidofolia	*Meliosma rigida*
Mimosites variabilis	*Mimosa pudica*
Paliurus colombii	*Paliurus*
Phellodendron grandifolium	*Phellodendron amurense*
Pinus sp	*Pinus*
Populus glandulifera	*Populus davidiana*
Populus sinensis	*Populus simonii*
Quercus rhombifolia	*Quercus*
Rhamnus duensis	*Rhamnus*
Rosa hilliae	*Rosa*
Schisandra fushunensis	*Schisandra chinensis*
Schisandra glandulosa	*Schisandra propinqua*
Sequoia chinensis	*Sequoia*
Taxodium tinajorum	*Taxodium*
Torreya cf.jackii	*Torreya jackii*
Toxicodendron fushunensis	*Toxicodendron delavayi*
Trochodendron sp.	*Trochodendron aralioides*
Ulmus fushunensis	*Ulmus*
Viburnum crenatum	*Viburnum farreri*
Zelkova ungeri	*Zelkova serrata*
Ziziphus sp.	*Ziziphus*

with its MAT of 14.3–14.9 °C and MAP of 798–1344 mm (Kou, 2005), used a methodology similar to that applied in the present paper. All the above MATs lay between 10 and 16.6 °C in the early Cainozoic of Northeast China, while the MAPs ranged from 798 to 1344 mm.

In the present paper, the sum of the parameters from all five Formations in Fushun is MAT 11.3–21 °C and MAP 654–1540 mm. These results are similar to those of the above floras. The changing range of the MATs and MAPs reflect a subtropical climate in Northeast China during Early Cainozoic times. In Northeast Wyoming, the early Palaeocene climate obtained using the Climate Leaf Analysis Multivariate Program (CLAMP), was MAT 12 °C and MAP 2300 mm (Davies-Vollum, 1997). In Southwest Wyoming (about 41–42°N) (Fig. 5) the Late Palaeocene–early Eocene climate was assessed using leaf physiognomy and taxonomic affinities of the plant macrofossils. The MATs and MAPs changed from late Palaeocene to Eocene, in Late Palaeocene from 12 °C to 19 °C, and a MAP of 1300–1500 mm. The MAT in Early Eocene reached 21 °C, with a MAP of 1400 mm, while in the middle Eocene the MAT was 20 °C, but the MAP had dropped to 800 mm. The range of the MAT was about 12–21 °C and MAP 800–1500 mm (Wing et al., 1999; Wilf, 2000). In the Middle Eocene of Oregon (Fig. 5), the proportion of entire-margined leaves infers a MAT of 14°–17 °C (Manchester, 2000). In other words, all the MAT and MAP values in North America are similar to those of Northeast China.

In Europe, the MAT obtained from the Fontllonga section (Tremp Formation, South Central Pyrenees, Spain) (Lleida 41°37′N 00°38′E) (Fig. 5) with Ba/Ca palaeo-thermometer approximated 28.0 ± 6.7 °C in the Early Palaeocene, while the MAT based on the NLRs of fossil fish was 27–30 °C (Domingo et al., 2007).

In the Weisselster and Lausitz Basins (Germany) (Fig. 5), the climatic changes from Middle Eocene to Pleistocene were inferred from the fossil floras and the Coexistence Approach (CA). The MAT was 23–25 °C in the Middle Eocene, and then fell to 16–21 °C, followed by a warming trend and another decrease to 16–20 °C at the end of the Eocene. Meanwhile, the MAP was about 1000–1600 mm, increased to 1400–1600 mm, before falling to 1100–1300 mm at the end of Eocene (Mosbrugger et al., 2005). Based on the leaf physiognomy from Messel, Germany (Fig. 5), the MAT was 25–30 °C, while the CMMT was not less than 10 °C (Manchester et al., 2005). Whether fossil fish or fossil plants are employed, the values of the MAT and MAP in the Early Cainozoic were higher than those of East Asia and North America.

Accordingly, the present results indicate that the climatic parameters in East Asia and North America in the Early Cainozoic were very similar, but different from those of Europe (Manchester et al., 2005). The climate in the world during the Early Cainozoic was warm, with many regions characterized by a subtropical climate.

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References

Collinson, M.E., Hooker, J.J., 2003. Palaeogene vegetation of Eurasia: framework for mammalian faunas. Deinsea 10, 41–83.

Davies-Vollum, K.S., 1997. Early Palaeocene palaeoclimatic inferences from fossil floras of the western interior, USA. Palaeogeography, Palaeoclimatology, Palaeoecology 136, 145–154.

Deng, X.R., Liu, W.D., Cai, J.F., 1998. Subtropical Zone of China. Hubei Education Publishing House, Wuhan. (in Chinese).

Domingo, L., López-Martínez, N., Soler-Gijón, R., Grimes, S.T., 2007. A multi-proxy geochemical investigation of the early Paleocene (Danian) continental palaeoclimate at the Fontllonga-3 site (South Central Pyrenees, Spain). Palaeogeography, Palaeoclimatology, Palaeoecology 256, 71–85.

Du, N.Z., 1987. Preliminary study on Paleocene fossil woods from Fushun of Liaoning Province. Botanical Research 3, 63–81 (pls. 9 (in Chinese, with English abstract)).

Endo, S., 1926. Preliminary report of the studies on the Paleogene plant fossils from the Fushun coal mines. Journal of Geography Society of Tokyo 38 (453), 627–633 (in Japanese).

Endo, S., 1928. A new Paleogene species of *Sequoia*. Japanese Journal of Geology and Geography 6, 27–29.

Endo, S., 1934. The geological age of the Fushun Group, south Manchuria. Proceedings of Imperial Academy of Tokyo, vol. 10(8), pp. 486–489 (pl. 1).

Endo, S., 1936. New fossil species of *Sequoia* from the Far-East. Proceedings of Imperial Academy of Tokyo 12 (6), 172–175.

Endo, S., 1942. On the fossil flora from the Shulan Coal-field, Kirin Province and the Fushun Coal-field, Fengtien Province. Bulletin of the Central National Museum of Manchoukuo, vol. 3, pp. 33–47 (pls. 16–17. (In Japanese, with English summary)).

Endo, S., 1951. On the fossil Acer from Japan, Korea and south Manchuria. II. Short papers, Institute of Geology and Palaeontology. Sendai 3, 52–58.

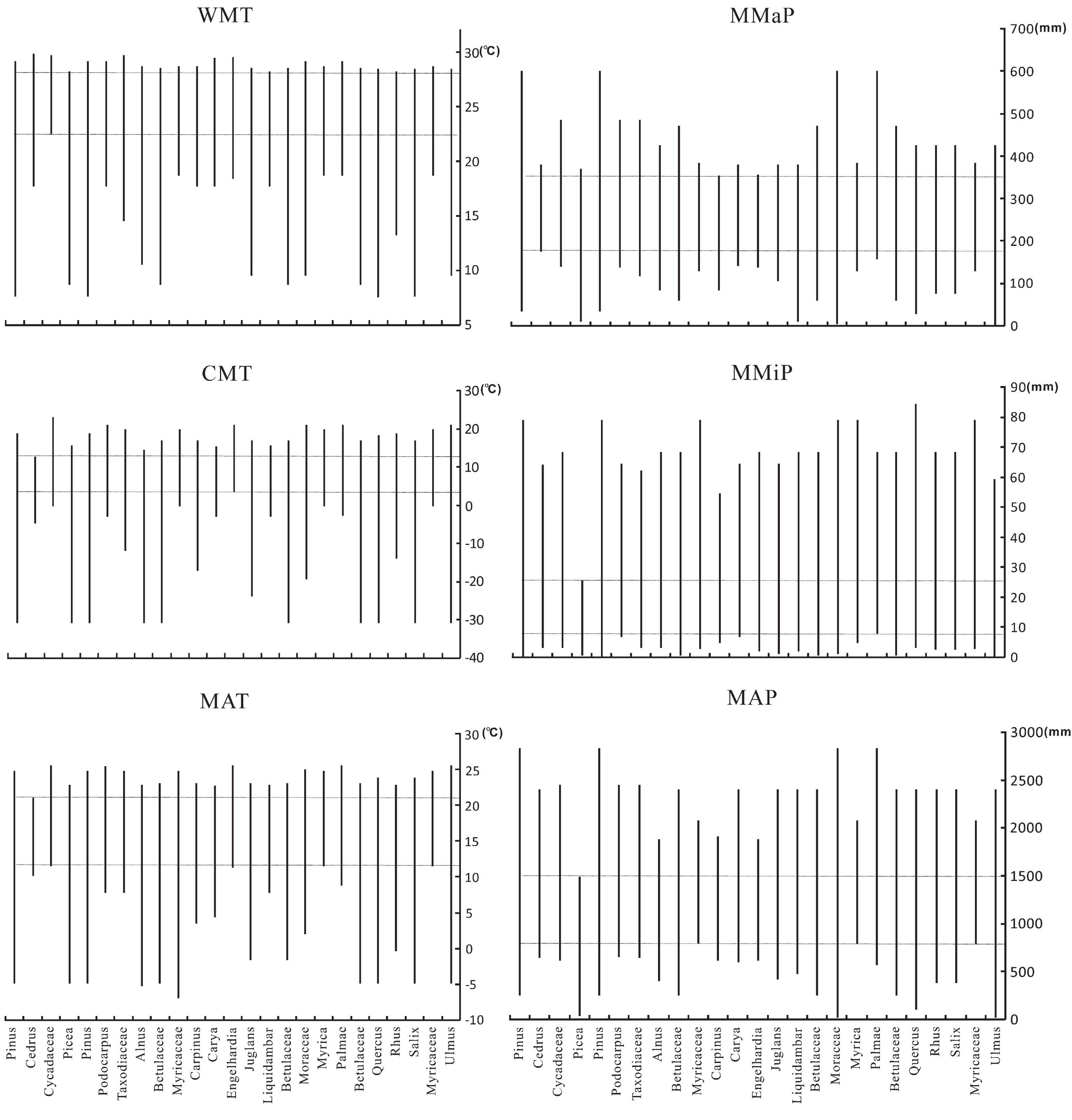

Fig. 3. Coexistence intervals from pollen assemblage of Laohutai Formation in Fushun flora.

Florin, R., 1922. Zur altertiaren Flora der südlichen Manchurei. Palaeontologia Sinica, Series A 1 (1), 1–45 (pls. 1–3).

Geng, B.Y., Manchester, S.R., Lu, A.M., 1999. The first discovery of *Eucommia* fruit fossil in China. Chinese Science Bulletin 44 (16), 1506–1508.

Hao, H., Ferguson, D.K., Wang, Y.F., Li, C.S., 2009. Early Paleocene vegetation and climate in Jiayin, NE China. Climatic Change (published onling:11 November 2009).

He, C.X., Tao, J.R., 1994. Paleoclimatic analysis of Paleogene flora in Yilan County, Heilongjiang. Acta Botanica Sinica 36 (12), 952–956.

Hong, Y.C., 1983. Discovery of new fossil Pseudoscorpionids in amber. Bulletin of the Tianjin Institute of Geology and Mineral Resources. Chinese Academy of Geological Sciences 8, 23–29 (in Chinese, with English abstract).

Hong, Y.C., Yang, T.C., Wang, S.T., Wang, S.E., Li, Y.K., Sun, M.R., Sun, H.C., Tu, N.C., 1974. Stratigraphy and palaeontology of Fushun coal-field, Liaoning Province. Acta Geologica Sinica 48 (2), 113–150 (pls. 8 (in Chinese with English abstract)).

Hong, Y.C., Yang, Z.Q., Wang, S.T., Sun, X.J., Du, N.Q., Sun, M.R., Li, Y.G., 1980. A Research on the Strata and Palaeontology of the Fushun Coal Field in Liaoning Province. Science Press, Beijing. (in Chinese).

Hong, Y.C., Guo, X.R., Ren, D., 2000. A new genus Eopalpomyitis gen. nov. from Eocene Fushun amber and discussion of its taxonomic position. Acta Parasitologica et Medica Entomologica Sinica 7 (4), 225–233 (Check the exact title of this journal).

http://www.geologie.uni-bonn.de/Palaeoflora/Palaeoflora_home.htm

IDBMC (Information Department of Beijing Meteorological Center), 1983a. Land Climate Data of China (1951–1980) (part II). China Meteorological Press, Beijing. (in Chinese).

IDBMC (Information Department of Beijing Meteorological Center), 1983b. Land Climate Data of China (1951–1980) (part VI). China Meteorological Press, Beijing (in Chinese).

IDBMC (Information Department of Beijing Meteorological Center), 1984a. Land Climate Data of China (1951–1980) (part I). China Meteorological Press, Beijing (in Chinese).

Table 3
Coexistence intervals of Fushun palynological data.

Climate parameter	Laohutai Formation		Lizigou Formation		Guchengzi Formation		Jijuntun Formation		Xilutian Formation	
	Climate value	Bordering taxa	Climate value	Bordering taxa	Climate value	Bordering taxa	Climate value	Bordering taxa	Climate value	Bordering taxa
MAT (°C)	11.5–20.9	Cycadaceae-*Cedrus*	11.3–20.9	*Engelhardia-Cedrus*	14.8–21	*Elytranthe*	14.8–20.9	*Elytranthe-Cedrus*	11.5–20.9	Cycadaceae, *Keteleeria-Cedrus*
CMMT (°C)	3.6–12.6	*Engelhardia-Cedrus*	3.6–12.6	*Engelhardia-Cedrus*	9.1–13.9	*Elytranthe -Larix*	9.1–12.6	*Elytranthe-Cedrus*	3.6–12.6	*Engelhardia-Cedrus*
WMMT (°C)	22.5–28.2	Cycadaceae-*Picea,Rhus, Liquidambar*	23.9–27.5	*Myrica-Picea, Liquidambar*	19.4–24.7	*Elytranthe*	19.4–24.7	*Elytranthe*	22.5–26.6	Cycadaceae-Cyrillaceae
MART(°C)	12.8–23.5	*Picea-Liquidambar*	12.8–23.5	*Picea-Liquidambar*	14.2–23.5	*Larix-Liquidambar*	13.2–23.5	*Platycarya-Liquidambar, Keteleeria*	13.2–23.5	*Platycarya-Liquidambar, Keteleeria*
MAP(mm)	793.9–1484.3	*Myrica-Picea*	793.9–1484.9	*Myrica-Picea*	654–1540.2	*Elytranthe, Podocarpus-Elytranthe*	793.9–1484.3	*Myrica-Picea*	784.7–1484.3	*Keteleeria-Picea*
MMiP (mm)	7.9–25.4	Palmae-*Picea*	7.9–25.4	Palmae-*Picea*	7.9–27	Palmae-*Larix*	7.9–25.4	*Keteleeria,* Palmae-*Picea*	10.2–25.4	Nyssaceae-*Picea*
MMaP (mm)	175–353	Cedrus-*Carpinus*	175–354	*Pterocarya, Cedrus-Engelhardia*	175–309	*Pterocarya-Elytranthe*	175–309	*Cedrus, Pterocarya-Elytranthe*	179.4–354	Nyssaceae-*Engelhardia*

IDBMC (Information Department of Beijing Meteorological Center), 1984b. Land Climate Data of China (1951–1980) (part III). China Meteorological Press, Beijing (in Chinese).

IDBMC (Information Department of Beijing Meteorological Center), 1984c. Land Climate Data of China (1951–1980) (part IV). China Meteorological Press, Beijing (in Chinese).

IDBMC (Information Department of Beijing Meteorological Center), 1984d. Land Climate Data of China (1951–1980) (part V). China Meteorological Press, Beijing (in Chinese).

Kou, X.Y., 2005. Studies on Quantitative reconstruction of Cenozoic climate in China by palynological data. Ph.D. Thesis. Institute of Botany, Chinese Academy of Science. Beijing, China.

Kou, X.Y., Ferguson, D.K., Xu, J.X., Wang, Y.F., Li, C.S., 2006. The reconstruction of paleovegetation and paleoclimate in the Late Pliocene of West Yunnan, China. Climatic Change 77, 431–448.

Li, J.F., Ferguson, D.K., Yang, J., Feng, G.P., Wang, Y.F., Li, C.S., 2009. Early Miocene vegetation and climate in Weichang District, North China. Palaeogeography, Palaeoclimatology, Palaeoecology 280, 47–63.

Liang, M.M., Bruch, A., Collinson, M., Mosbrugger, V., Li, C.S., Sun, Q.G., Hilton, J., 2003. Testing the climatic estimates from different palaeobotanical methods: an example from the Middle Miocene Shanwang flora of China. Palaeogeography, Palaeoclimatology, Palaeoecology 198, 279–301.

Liu, Y.J., Li, C.S., 2000. On *Metasquoia* in Eocene age from Liaoning Province of northeast China. Acta Botanica Sinica 42 (8), 873–878 (in Chinese, with English abstract).

Liu, Y.S., Guo, S.X., Ferguson, D.K., 1996. Catalogue of Cenozoic megafossil plants in China. Palaeontographica Abt. B 238, 141–179.

Liu, Y.S., Zhou, Z.Y., Li, H.M., 1991. The first discovery of fossil *Cycas* in China. Chinese Science Bulletin 36 (22), 1758–1759 (In Chinese).

Manchester, S.R., 1999. Biogeographical relationships of North American tertiary floras. Annals of the Missouri Botanical Garden 86 (2), 472–522.

Manchester, S.R., 2000. Late Eocene fossil plants of the John Day Formation, Wheeler County, Oregon. Oregon Geology 62 (3), 51–63.

Manchester, S.R., Chen, Z.D., Geng, B.Y., Tao, J.R., 2005. Middle Eocene flora of Handian, Jilin Province, Northeastern China. Acta Palaeobotanica 45 (1), 3–26.

Mosbrugger, V., 1999. The nearest living relative method. In: Jones, T., Rowe, N. (Eds.), Fossil Plants and Spores: Modern Techniques. Geological Society, London, pp. 261–265.

Mosbrugger, V., Utescher, T., 1997. The coexistence approach—a method for quantitative reconstructions of tertiary terrestrial palaeoclimate data using plant fossils. Palaeogeography, Palaeoclimatology, Palaeoecology 134, 61–86.

Mosbrugger, V., Utescher, T., Dilcher, D.L., 2005. Cenozoic continental climatic evolution. PNAS 102, 14964–14969.

Ping, Ch., 1931. On a blatoid insect in the Fushun amber. Bulletin of Geological Society of China 11 (2), 205–207.

Palibin, J.W., 1906. Fossile Pflanzen aus den Kohlenlagern von Fuschun in der südlichen Mandshurei. Verhandlungen der Kaiserlichen Russischen Mineralogischen Gesellschaft zu St. Petersburg, 2 Series 44, 419–434.

Roth-Nebelsick, A., Utescher, T., Mosbrugger, V., Diester-Haass, L., Walther, H., 2004. Changes in atmospheric CO_2 concentrations and climate from the Late Eocene to Early Miocene: palaeobotanical reconstruction based on fossil floras from Saxony, Germany. Palaeogeography, Palaeoclimatology, Palaeoecology 205, 43–67.

Scotese, C.R., 1997. Paleogeographic Atlas, paleomap Progress Report No. 90-0497. Department of Geology, University of Texas, Arlington, Texas.

Song, Z.C., Tsao, L., 1976. The Paleocene spores and pollen grains from the Fushun Coal Field, Northeast China. Acta Palaeontologica Sinica 15 (2), 147–164 (In Chinese with English summary).

Song, Z.C., Zheng, Y.H., Li, M.Y., Zhang, Y.Y., Wang, W.M., Wang, D.N., Zhao, C.B., Zhou, S.F., Zhu, Z.H., Zhao, Y.N., 1999. Fossil spores and pollen of China Vol.1. The Late Cretaceous and Tertiary Spores and Pollen. Science Press, Beijing, pp. 1–910 (pls. 1–207 In Chinese with English summary).

Sun, X.J., Du, N.Q., Sun, M.R., 1980. Research on Early Tertiary Fushun Group palynology of the Fushun Coal Field in Liaoning Province. In: Hong, Y.C., Yang, Z.Q., Wang, S.T., Sun, X.J., Du, N.Q., Sun, M.R., Li, Y.G. (Eds.), A Research on the Strata and Palaeontology of the Fushun Coal Field in Liaoning Province. Science Press, Beijing, pp. 55–98 (pls. 9 In Chinese).

Tiffney, B.H., 2000. Geographic and climatic influences on the Cretaceous and Tertiary history of Euramerican floristic similarity. Acta Universitatis Carolinae-Geologica 44 (1), 5–16.

Uhl, D., Mosbrugger, V., Bruch, A., Utescher, T., 2003. Reconstructing palaeotemperatures using leaf floras-case studies for a comparison of leaf margin analysis and the coexistence approach. Review of Palaeobotany and Palynology 126, 49–64.

Wang, J.Y., Wang, D.F., 1982. Age determination by K–Ar method for the bottom of the Palaeocene Laohutai Formation at Fushun district. Bulletin of the Geological Society of Liaoning Province 1, pp. 110–115 (in Chinese, with English abstract).

Wang, J.Y., Wang, D.F., 1985. Age determination of basalt of Palaeocene Laohutai Formation in Fushun district by delation method of K–Ar elements. Bulletin of the Geological Society of Liaoning Province 1, pp. 86–90 (in Chinese, with English abstract).

Wang, D.F., Gao, R.F., Wang, J.Y., Fan, Y.Q., 1982. Paleomagnetic determination for lower limits of Early Cretaceous and Palaeocene systems in Liaoning. Bulletin of the Geological Society of Liaoning Province 1, pp. 116–121 (in Chinese, with English abstract).

Wang, Q., Manchester, S.R., Li, C.S., Geng, B.Y., 2010. Fruits and leaves of *Ulmus* from the Paleogene of Fushun, Northeastern China. International Journal of Plant Science 171 (2), 221–226.

Wen, J., 1999. Evolution of eastern Asian and eastern north American disjunct distributions in flowering plants. Annual Review of Ecology and Systematics 30, 421–455.

WGCPC, 1978. Notes on coal-forming rocks and flora from Fushun, Liaoning Province. In: WGCPC (Ed.), Cenozoic Plants of China. Science Press, Beijing, pp. 163–170 (in Chinese).

Wilf, P., 2000. Late Paleocene–early Eocene climate changes in southwestern Wyoming: paleobotanical analysis. Geological Society of America Bulletin 112 (2), 292–307.

Wing, S.L., Bao, H.M., Koch, P.L., 1999. An early Eocene cool period? Evidence for continental cooling during the warmest part of the Cenozoic. In: Huber, B.T., Macleod, K., Wing, S.L. (Eds.), Warm Climates in Earth History. Cambridge University Press, Cambridge, pp. 197–237.

Table 4
Coexistence intervals of Fushun megafossil flora.

Climate parameter	Climate value	Bordering taxa
MAT	15.4–16.3 (°C)	*Acacia concinna–Exochorda racemosa* and *Exochorda serratifolia*
CMMT	2–7.9 (°C)	*Carpinus pubescens–Populus simonii*
WMMT	24–24.9 (°C)	*Keteleeria davidiana–Craigia*
MART	22.1–23.5 (°C)	*Cercidiphyllum japonicum–Keteleeria davidiana*
MAP	871.8–1654.1 mm	*Alnus japonica–Phellodendron amurense*
MMiP	22.7–27 mm	*Meliosma rigida–Alnus nepalensis*
MMaP	183.6–211.8 mm	*Eucommia ulmoides–Viburnum farreri*

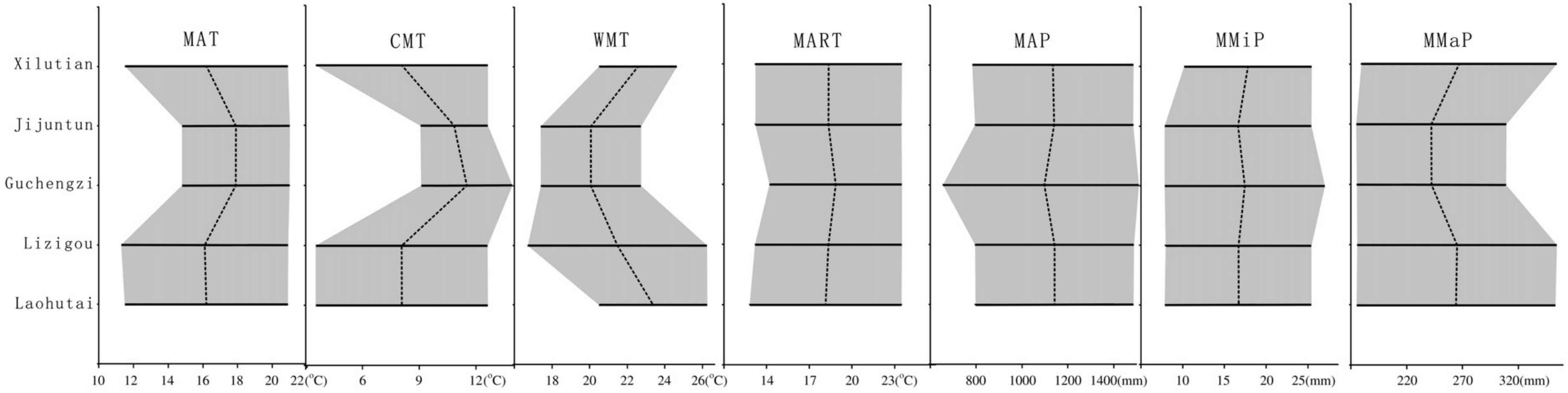

Fig. 4. Palaeocene–Eocene climatic history of Fushun, estimated from palynological assemblages using the Coexistence Approach.

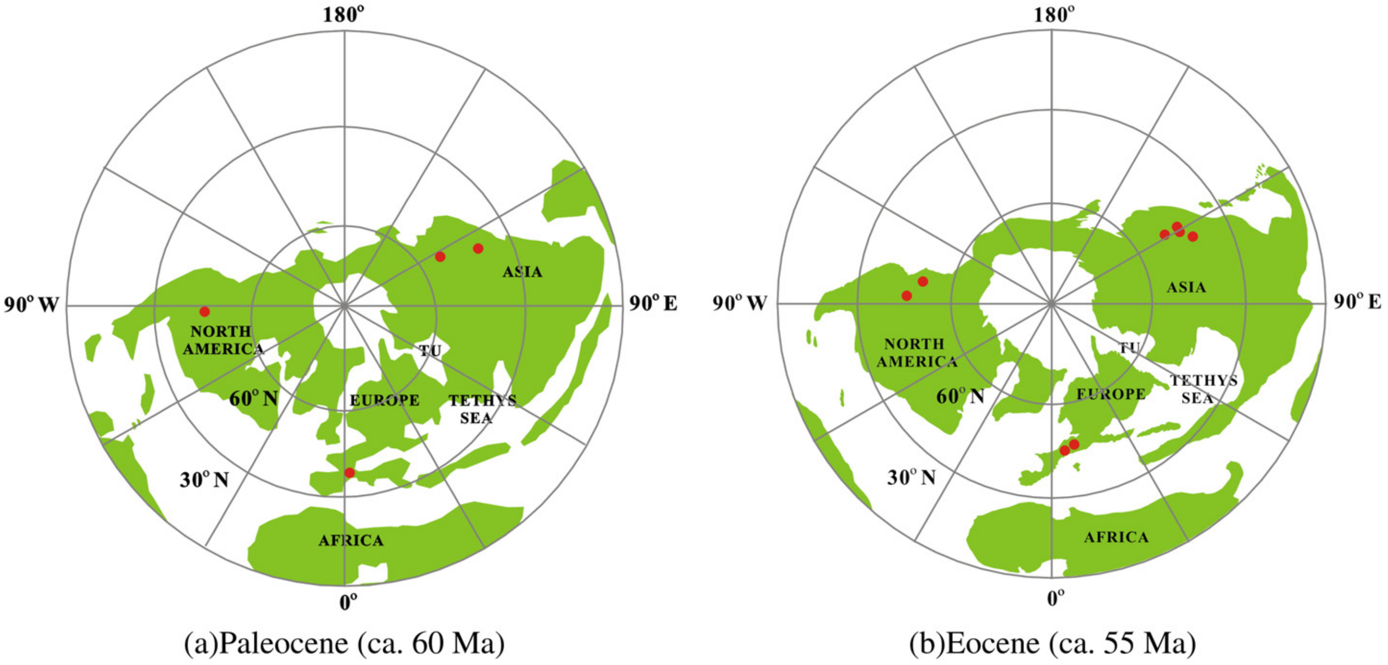

Fig. 5. Palaeogeographical map of the world showing the position of Fushun and Wuyun (China), South Central Pyrenees (Spain), Southwest Wyoming (USA) in Palaeocene, and Yilan, Hunchun, Fushun and Huadian (China), Southwest Wyoming and Oregon (USA), Weisselster and Lausitz Basins, Messel (Germany) in Eocene.

Wu, Z.Y., Ding, T.Y., 1999. Seed Plants of China. Yunnan Science and Technology Press, Kunming. (Electronic publication in Chinese).

Xu, J.X., Wang, Y.F., Li, C.S., 2000. A method for quantitative reconstruction of Tertiary palaeoclimate and environment—coexistence approach. In: Li, C.S. (Ed.), Advances in Plant Science, vol. 3. China Higher Education Press, Beijing and Springer-Verlag, Heidelberg, pp. 195–203 (in Chinese).

Yao, Y.F., Bera, S., Ferguson, D.K., Mosbrugger, V., Paudayal, K.N., Jin, J.H., Li, C.S., 2009. Reconstruction of paleovegetation and paleoclimate in the Early and Middle Eocene, Hainan Island, China. Climatic Change 92, 169–189.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 292, 686–693.