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PALEOGENE EVOLUTION OF PRECIPITATION IN NORTHEASTERN CHINA SUPPORTING THE MIDDLE EOCENE INTENSIFICATION OF THE EAST ASIAN MONSOON

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ABSTRACT

The timing of the development of the East Asian monsoon in the geologic past is critically important for paleoclimatological studies, yet few quantitative data are available. Based on palynomorphs from six formations, supplemented by leaf fossils from one of these formations in Fushun, northeastern China, we present a quantitative estimate of the evolution of precipitation in this area during the middle Paleocene–late Eocene. The results demonstrate that seasonal precipitation prevailed during the interval, suggesting that the monsoonal system had already developed by this time. Comparing Paleogene climatic results from different latitudes in eastern China, we conclude that the East Asian monsoon must have been significantly enhanced after the late middle Eocene (~41–40 Ma), due to increased precipitation differentiation between wet and dry months as shown in the present study. The influence of both the uplift of the Da Hinggan Mountains in northeastern Asia on regional topography and the India-Asia collision globally may have contributed to early monsoon intensification by their influence on air mass movement and associated precipitation patterns in the monsoonal realm.

INTRODUCTION

The modern climate in eastern and southern Asia is dominated by the Asian monsoonal system, which comprises the South Asian monsoon with dry winters and wet summers in the area of the northern and northeastern Indian Ocean, and the East Asian monsoon, which impacts the climates of China, the Korean Peninsula, and Japan, with relatively dry conditions in winter and heavy rain in late spring to early summer (Clift and Plumb, 2008; Molnar et al., 2010). The East Asian monsoon system has a complex spatio-temporal structure, consisting of a warm and wet summer monsoon that widely impacts areas from the subtropics to mid-latitudes, and a cold and dry winter monsoon that emanates from the Siberian High and penetrates deeply into the equatorial Maritime Continent region (Chang, 2004; Molnar et al., 2010). The history of this monsoon in the geological past is a hot topic and highly debated in paleoclimate studies. Previous studies have focused on its evolution in the Neogene (e.g., An et al., 2001; Wang et al., 2005; Miao et al., 2011), but little is known about early development of the monsoon in the Paleogene. Wang et al. (1997) subdivided the evolution of the East Asian monsoon into four stages: pre-monsoon stage (Paleocene–early Eocene), transitional stage (late Eocene–Oligocene), Stage I (Miocene–Pliocene), and Stage II (late Pliocene to present). Because of the zonal distribution shift in paleoclimate patterns induced by paleobotanical and lithologic evidence throughout China, however, the details needed to quantify the Paleogene monsoon in the first two stages are still lacking. Based on fossil and sedimentological evidence, Sun and Wang (2005) inferred that the monsoon system initiated around the Oligocene–Miocene boundary (~23 Ma), because this appeared to be the time when paleoclimate distribution patterns in China started to reorganize. The Paleogene pattern was characterized by latitudinal zonation with an arid zone throughout the middle of China, whereas the Neogene pattern was characterized by an arid zone restricted only to northwestern China. This distributional transformation, however, may provide evidence only for a stage when the East Asian monsoon essentially intensified to a near-modern level, rather than the time when it initiated.

In general, a monsoon refers to the seasonal alternation of wind direction caused by atmospheric circulation shifts, and the associated temporal differentiation of precipitation resulting from asymmetric heating of land and sea (Trenberth et al., 2000). In paleoclimatology, however, wind direction can be documented by only a few specific sedimentological conditions, exemplified by eolian sediments and volcanic ash deposits, most commonly in the Quaternary (e.g., Amundson et al., 1996; Parrish, 1998; Figueiral et al., 2002). Alternatively, seasonal differentiation of precipitation serves as the main indicator of monsoon development history (Herold et al., 2011). In recent years, advances in paleoclimatic reconstruction methodologies using fossil plants and palynomorphs have made it possible to quantitatively reconstruct seasonal precipitation (e.g., Utescher et al., 2009; Bruch et al., 2011; Liu et al., 2011).

Middle Paleocene–upper Eocene sediments with abundant macro- or palynofloras are well developed in the Fushun coal mine in northeastern China (e.g., Hong et al., 1980; Wang, 1985; Liu et al., 1996), which represents one of the best regions in East Asia for paleoclimatic investigations of this interval (Fig. 1). Moreover, recent advances in absolute age control, i.e., paleomagnetism and isotopic dating, allow us to pinpoint paleoclimate conditions within particular stratigraphic levels of the coal mine (Fig. 2). Previous climatic studies of both macro- and microfloras from Fushun have significantly improved paleoclimatic interpretations (e.g., Shi et al., 2008; Su et al., 2009; Wang et al., 2010), but seasonal precipitation and evolution of the monsoon were not addressed. We here employ the Coexistence Approach (CA) to quantitatively reconstruct precipitation in this area, including both annual and seasonal precipitation, in order to provide insight into the pattern of early development of the East Asian monsoon in the Paleogene.

MATERIALS AND METHODS

The Coexistence Approach is organ independent and works for both macroplants and palynomorphs whenever their modern botanical affinities can be determined (Mosbrugger and Utescher, 1997). This method uses climate tolerances of all nearest living relatives (NLRs) known for a given fossil flora by assuming that the tolerances of a particular fossil taxon are not significantly different from its modern counterpart (Mosbrugger and Utescher, 1997; Bruch and Zhilin, 2007; Utescher et al., 2007). For fossil pollen data, the CA approach only requires the presence or absence of pollen taxa, regardless of their

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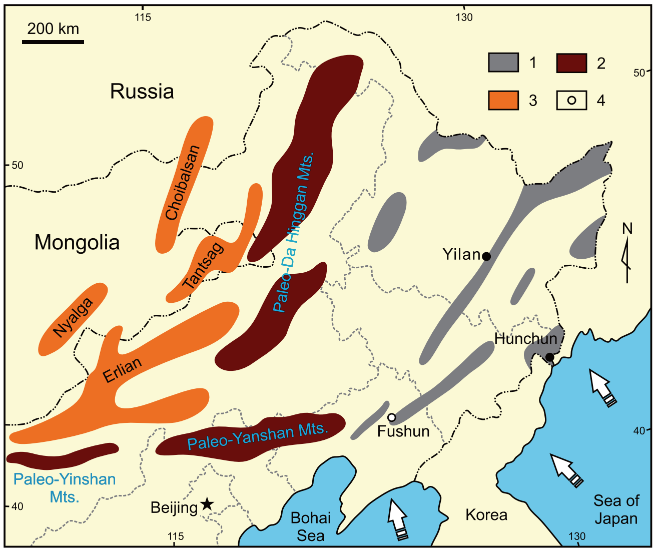

FIGURE 1—Schematic map showing paleogeographic setting in the Paleogene and plant fossil sites of northeastern China (modified from Wang, 1985). 1 = coal-bearing basins; 2 = paleomountains; 3 = basin with red beds or evaporites; 4 = site of palynomorphs and leaf fossils used in this study. Arrows denote direction of the East Asian summer monsoon.

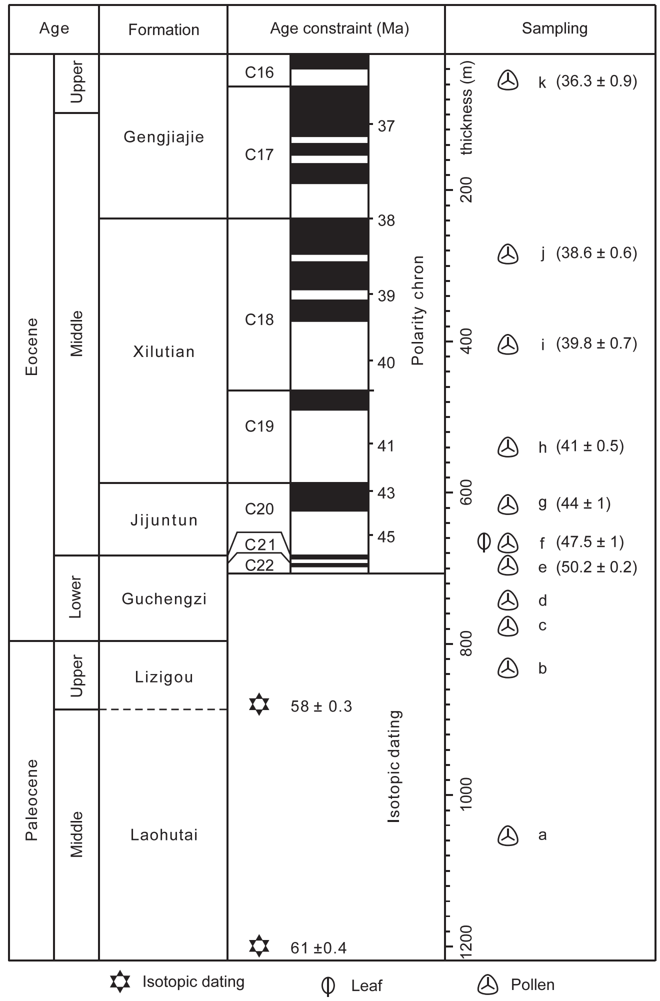

FIGURE 2—Absolute age constraints of the Fushun coal mine section and ages of palynofloras (a–k) and leaf assemblage (within palynoflora f) used in this study (Table 2, Appendix). See Figure 3 for estimated error ranges of ages. Isotopic dating results from F. Shi (2010, personal communication).

abundance (Mosbrugger and Utescher, 1997). Difficulties may arise when the CA is applied to Paleogene floras, because some Paleogene taxa are extinct and their direct NLRs cannot be identified. This hypothesis has been tested by counting 25 taxa randomly extracted from a Paleogene data pool containing 100 taxa (Mosbrugger and Utescher, 1997; Mosbrugger et al., 2005). The results suggest that the coexistence percentages for Paleogene floras (89%–100%) are almost identical to those for Neogene floras. Simulation experiments on some modern genera, including *Eucryphia*, *Ceratopetalum*, *Doryphora*, and *Atherosperma*, indicate that environmental tolerances have a strong physiological basis, and likely reflect those of their fossil counterparts (Read and Hill, 1989). In addition, morphological and anatomical evidence also shows high similarities between Paleocene taxa and their NLRs in the structure of both leaf and reproductive organs (Manchester et al., 2002), supporting their similarity in environmental tolerances. In light of these considerations, it is reasonable to assume that the physiological and morphological responses of Paleogene taxa to environmental impacts closely resemble their NLRs and hence CA can be safely used for those taxa that still have living relatives.

The original dataset in the literature on the Fushun coal mine (Hong et al., 1980) does not permit us to conduct a high-resolution climate analysis due to the large interval sampled. Therefore, for the present study, which has a focus on general trends in climate evolution, we combined the continuous pollen assemblages from the adjacent layers of Hong et al. (1980) into individual palynofloras, separated by those layers yielding no pollen. A total of eleven pollen floras (Fig. 2a–k) from eleven different stratigraphic levels of a continuous section, supplemented by one leaf fossil assemblage from the same layer as palynoflora f (Fig. 2; Appendix), at the Fushun coal mine in Liaoning Province, northeastern China (Fig. 1) was compiled from the literature (Appendix; Hong et al., 1980; Qu, 1993; Liu et al., 1996). Lithologically, each formation within the section is characterized by distinct strata, including yellow-gray sandstone intercalated by coal seams (Laohutai Formation), overlain by gray-green tuff intercalated with coal seams (Lizigou Formation), followed by a thick coal layer with a roof and bottom of dark shale (Guchengzi Formation), oil shale and black shale (Jijuntun Formation), gray-green mudstone and shale (Xilutian Formation), and brown shale and variegated siltstone (Gengjiajie Formation) (Hong et al., 1980).

The ages of palynofloras e–k are interpolated by using the paleomagnetic results of Zhao et al. (1994), who sampled the same section where pollen and leaf fossils were collected by Hong et al., (1980; section No. E8600). The geomagnetic polarity time scale of Cande and Kent (1992) was followed in Zhao et al. (1994). The age error ranges of our interpolation are estimated according to the strata thickness of each flora (Fig. 2, right-hand column).

The NLRs of fossil taxa were determined mainly to the generic level and sometimes to the family level (Appendix), due to the fact that we often cannot link a fossil species to a modern one as discussed by Liu et al. (2011). For the NLR determinations of Paleogene pollen taxa in China, we followed Song et al. (1999; see also Song et al., 2004; Wang, 2006), who comprehensively reviewed the Upper Cretaceous–Neogene palynological records and pollen sequence correlations in the Cenozoic palynofloristic regions throughout China. For detailed CA procedures, refer to Mosbrugger and Utescher (1997).

By querying the Palaeoflora Database (Utescher and Mosbrugger, 1997–2010, http://www.palaeoflora.de/), three precipitation parameters were calculated (in millimeters): mean annual precipitation (MAP), mean precipitation of the driest month (LMP), and mean precipitation of the wettest month (HMP). Three other parameters, i.e., mean annual range of precipitation (MARP, difference between wettest and driest

TABLE 1—List of the number of fossil palynomorph taxa, nearest living relatives (NLRs), and climate-limiting NLRs that define the upper and lower limits of the coexistence intervals in this study.

	Taxa (*N*)		MAP		HMP		LMP	
Floral assemblage	Fossil	NLR	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Gengjiajie Formation (middle–upper Eocene)								
k	54	36	*Planera*	*Planera*	Cycadaceae	*Rhus*	*Lygodium*	*Celtis*
Xilutian Formation (middle Eocene)								
j	24	20	Cyatheaceae	*Planera*	Cyatheaceae	*Planera*	Cyatheaceae	*Ephedra*
i	21	17	*Planera*	*Planera*	Cyrillaceae	*Comptonia*	*Comptonia*	*Ephedra*
h	31	20	Cyatheaceae	*Lonicera*	Cyatheaceae	*Comptonia*	*Comptonia*	*Cedrus*
Jijuntun Formation (middle Eocene)								
g	24	17	*Comptonia*	*Comptonia*	*Liquidambar*	*Comptonia*	*Comptonia*	*Cedrus*
f	65	52	*Lygodium*	Gleicheniaceae	*Corylopsis*	*Comptonia*	*Comptonia*	*Celtis*
Guchengzi Formation (lower Eocene)								
e	16	14	*Planera*	*Planera*	*Liquidambar*	*Planera*	*Planera*	*Pterocarya*
d	34	25	Cyatheaceae	*Comptonia*	Cyatheaceae	*Larix*	*Sciadopitys*	*Ephedra*
c	25	17	*Abies*	*Larix*	*Sciadopitys*	*Larix*	*Larix*	*Ephedra*
Lizigou Formation (upper Paleocene)								
b	32	26	*Planera*	*Ostrya*	Cycadaceae	*Hamamelis*	*Hamamelis*	*Platycarya*
Laohutai Formation (middle Paleocene)								
a	46	33	*Planera*	*Ostrya*	Cycadaceae	*Rhus*	*Rhus*	*Cedrus*

months in mm), the ratio of LMP to MAP (%), and the ratio of HMP to MAP (%), were further calculated by differences in mean values between the WMMT (warmest month mean temperature) and the CMMT (coldest month mean temperature), and HMP and LMP, respectively. A list of the number of fossil taxa, NLRs, and climate-limiting NLRs used in the CA analysis is in Table 1.

RESULTS: MIDDLE EOCENE MONSOONAL INTENSIFICATION

The estimated precipitation parameters of each stratigraphic level are given in Table 2 and illustrated in Figure 3 according to absolute age dating. Meteorologically, seasonal variations in precipitation are prominent throughout the observed Paleogene period in Fushun, with evidently low precipitation in the dry months (LMP) but remarkable highs in wet months (HMP) (Table 2; Fig. 3). Moreover, hydrological seasonality was enhanced in the late middle Eocene ($\sim$ 40 Ma), as represented by the distinct divergence between wet (HMP) and dry (LMP) month precipitation and by the change in the ratios of HMP and LMP to MAP, while the MAP remained relatively constant through this time period (Fig. 3). The mean annual range of precipitation (MARP) was also dramatically increased during this interval (Table 2). These data indicate that the seasonal differentiation of precipitation considerably intensified at this time, which appears to correlate with a long-term temperature decline after the mid-Eocene climatic optimum (Zachos et al., 2008, fig. 2). Notably, seasonality in precipitation during the middle–late Eocene was also observed in areas of China other than Fushun, including the middle–late Eocene Yilan and Hunchun floras (Fig. 1; northeastern China), the middle Eocene Changle flora (central China) and the Changchang flora (Hainan Island, southern China) (Su et al., 2009; Yao et al., 2009). The prevalence of the seasonally changing pattern in precipitation throughout the whole of eastern China strongly suggests that the East Asian monsoon significantly intensified in the middle Eocene.

TABLE 2—Quantitative reconstruction of climatic parameters of all eleven floras of the middle Paleocene to late Eocene of Fushun.

Floral assemblage	MAP (mm)	HMP (mm)	LMP (mm)	MARP (mm)	Ratio of HMP (%)	Ratio of LMP (%)
Gengjiajie Formation (middle–upper Eocene)						
k	897–1355	187–195	19–24	170	14.1–21.3	1.6–2.3
Xilutian Formation (middle Eocene)						
j	1035–1355	134–196	12–45	137	12.2–15.9	2.1–2.8
i	897–1355	109–153	24–45	97	9. 7–14.6	2.6–3.9
h	1035–1362	134–153	24–41	111	10.5–13.9	2.4–3.1
Jijuntun Formation (middle Eocene)						
g	735–1362	109–153	24–41	99	9.6–17.8	2.4–4.4
f	1122–1281	148–153	19–24	129	12.4–13.4	1.8–1.9
Guchengzi Formation (lower Eocene)						
e	897–1355	109–196	50–64	96	11.3–17.0	4.2–6.4
d	1035–1362	134–143	25–45	104	10.2–13.4	2.6–3.4
c	373–1206	130–143	25–45	102	11.3–36.6	2.9–9.4
Lizigou Formation (upper Paleocene)						
b	897–1355	109–153	24–37	101	9.7–14.6	2.3–3.4
Laohutai Formation (middle Paleocene)						
a	897–1355	109–153	24–41	99	9.7–14.6	2.4–3.6

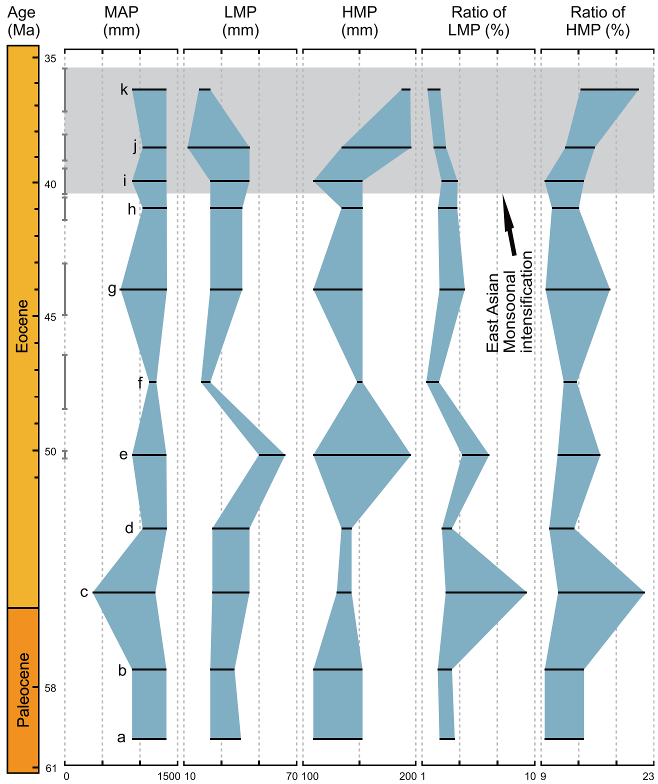

FIGURE 3—Calculated precipitation variations from lower Paleogene sites in Fushun coal mine section. Absolute age of horizons as in Figure 2. Letters a–k and horizontal lines correspond to individual floras (Fig. 2, Table 2) from which each precipitation parameter was calculated using the coexistence approach. Vertical bars to the left of the flora codes are estimated age error ranges of the paleomagnetic dating. Blue shading shows the general trend of precipitation evolution.

Topographically, the most noteworthy event in northeastern Asia is apparently the uplift of the paleo-Da Hinggan Mountains, which reached their near-modern elevation (>1200 m) at least by the early Paleocene (Fig. 1; Shao et al., 2005). The elevated mountains separated two basins with distinct sedimentary characteristics, that is, oil- and coal-bearing deposits to the east, and red beds and evaporites to the west (Fig. 1). The eastern side must have generally received high precipitation throughout the middle Paleocene to Eocene with MAPs not less than 790 mm (for most floras, mean value >1000 mm; Table 2). On the contrary, the widespread red beds and evaporites developed on the western side strongly indicate interior aridity, although no quantitative estimate could be made due to the lack of plant fossils and palynomorphs there. The clear-cut distribution of precipitation simply implies that the uplift of the Da Hinggan Mountains played an important role in the early intensification of the East Asian monsoon. In other words, the eastern side of the Da Hinggan Mountains was influenced by wet airflow from the Pacific Ocean, while located in the rain shadow, the western side was mainly dominated by dry continental winds (Fig. 1).

In a global context, the land-ocean reconfiguration during the early Paleogene, especially the oblique collision of the Indian Plate with Asia (Tapponnier et al., 2001), may also have contributed to the early development of a monsoon climate by reframing the ocean currents and asymmetric land-sea heating (Molnar et al., 2010). These paleogeographical factors could have had strong impacts on the formation of continental climate in central Asia and hence continent-ocean thermal interactions (Tapponnier et al., 2001; Dupont-Nivet et al., 2008). On the other hand, similar to its modern role as a barrier to air circulation, the early uplift of the proto-Tibetan Plateau to almost modern elevations (≥40 Ma; Tapponnier et al., 2001; Wang et al., 2008) must have affected the path of the subtropical jet stream, which marks the boundary between cold, dry air from the north and warm, wet air from the south. This uplift was important because the air current and precipitation patterns of the East Asian monsoon differ from other monsoonal systems in atmospheric circulation and are associated with frontal systems and a jet stream (Molnar et al., 2010). As indicated in Molnar et al. (2010), the elevated proto-plateau may also have interacted on the locus of the jet stream and associated moisture convergence, moving this air current from its winter position south of Tibet to pass directly over the plateau and then northward to reach northeastern Asia.

CONCLUSIONS

Seasonality of precipitation in the middle Paleocene–late Eocene in Fushun, northeastern China, is demonstrated based on calculations from fossil palynofloras and a single leaf assemblage, providing support for the presence of an early monsoonal climate. The seasonal distribution of precipitation was considerably enhanced after the late middle Eocene (~41–40 Ma). Along with a similar thermal and hydrological configuration from low to middle-high latitudes of eastern China in the middle–late Eocene, it is clear that the East Asian monsoon intensified in the late middle Eocene.

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REFERENCES

Amundson, R., Chadwick, O., Kendall, C., Wang, Y., and DeNiro, M., 1996, Isotopic evidence for shifts in atmospheric circulation patterns during the late Quaternary in mid-North America: Geology, v. 24, p. 23–26, doi: 10.1130/0091-7613(1996)024<0023:iefsia>2.3.co;2.

An, Z., Kutzbach, J.E., Prell, W.L., and Porter, S.C., 2001, Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan plateau since Late Miocene times: Nature, v. 411, p. 62–66, doi: 10.1038/35075035.

Bruch, A.A., and Zhilin, S.G., 2007, Early Miocene climate of Central Eurasia: Evidence from Aquitanian floras of Kazakhstan: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 248, p. 32–48, doi: 10.1016/j.palaeo.2006.11.014.

Bruch, A.A., Utescher, T., and Mosbrugger, V., 2011, Precipitation patterns in the Miocene of Central Europe and the development of continentality: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 304, p. 202–211, doi: 10.1016/j.palaeo.2010.10.002.

Cande, S.C., and Kent, D.V., 1992, A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic: Journal of Geophysical Research, v. 97, p. 13917–13951, doi: 10.1029/92jb01202.

Chang, C.P., 2004, East Asian Monsoon, World Scientific Series on Meteorology of East Asia: World Scientific, Singapore, 565 p.

Clift, P. D., and Plumb, R.A., 2008, The Asian Monsoon: Causes, History and Effects: Cambridge University Press, Cambridge, UK, 270 p.

Dupont-Nivet, G., Hoorn, C., and Konert, M., 2008, Tibetan uplift prior to the Eocene–Oligocene climate transition: Evidence from pollen analysis of the Xining Basin: Geology, v. 36, p. 987–990, doi: 10.1130/g25063a.1.

Figueiral, I., Mosbrugger, V., Rowe, N., Utescher, T., Jones, T., and Von Der Hocht, F., 2002, Role of charcoal analysis for interpreting vegetation change and paleoclimate in the Miocene Rhine Embayment (Germany): PALAIOS, v. 17, p. 347–365, doi: 10.1669/0883-1351(2002)017<0347:rocafi>2.0.co;2.

Herold, N., Huber, M., Greenwood, D.R., Muller, R.D., and Seton, M., 2011, Early to middle Miocene monsoon climate in Australia: Geology, v. 39, p. 3–6, doi: 10.1130/g31208.1.

Hong, Y.C., Yang, Z.Q., Wang, S.T., Sun, X.J., Du, N.Q., Sun, M.R., and Li, Y.G., 1980, A Research on the Strata and Palaeontology of the Fushun Coal Field in Liaoning Province: Science Press, Beijing, 98 p. (in Chinese).

Liu, Y.S., Guo, S.X., and Ferguson, D.K., 1996, A catalogue of Cenozoic megafossil plants in China: Palaeontographica Abteilung B: Paläophytologie, v. 238, p. 141–179.

Liu, Y.S., Utescher, T., Zhou, Z., and Sun, B., 2011, The evolution of Miocene climates in North China: Preliminary results of quantitative reconstructions from plant fossil records: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 304, p. 308–317, doi: 10.1016/j.palaeo.2010.07.004.

Manchester, S.R., Akhmetiev, M.A., and Kodroul, T., 2002, Leaves and fruits of *Celtis aspera* (Newberry) comb. nov. (Celtidaceae) from the Paleocene of North America and Eastern Asia: International Journal of Plant Sciences, v. 163, p. 725–736.

Miao, Y., Fang, X., Herrmann, M., Wu, F., Zhang, Y., and Liu, D., 2011, Miocene pollen record of KC-1 core in the Qaidam Basin, northeastern Tibetan Plateau and implications for evolution of the East Asian monsoon: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 299, p. 30–38, doi: 10.1016/j.palaeo.2010.10.026.

Molnar, P., Boos, W.R., and Battisti, D.S., 2010, Orographic controls on climate and paleoclimate of Asia: Thermal and mechanical roles for the Tibetan Plateau: Annual Review of Earth and Planetary Sciences, v. 38, p. 77–102, doi: 10.1146/annurev-earth-040809-152456.

Mosbrugger, V., and Utescher, T., 1997, The coexistence approach: A method for quantitative reconstructions of Tertiary terrestrial palaeoclimate data using plant fossils: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 134, p. 61–86, doi: 10.1016/S0031-0182(96)00154-X.

Mosbrugger, V., Utescher, T., and Dilcher, D.L., 2005, Cenozoic continental climatic evolution of Central Europe: Proceedings of the National Academy of Sciences, USA, v. 102, p. 14964–14969, doi: 10.1073/pnas.0505267102.

Parrish, J.T., 1998, Interpreting Pre-Quaternary Climate from the Geologic Record: Columbia University Press, New York, 338 p.

Qu, S., 1993, Characteristic and its geological significance of the palynological assemblage of the Lower Tertiary Genjiajie Group in Fushun Basin: Journal of Changchun University of Earth Sciences, v. 23, p. 411–415 (in Chinese with English abstract).

Read, J., and Hill, R.S., 1989, The response of some Australian temperate rain forest tree species to freezing temperatures and its biogeographical significance: Journal of Biogeography, v. 17, p. 21–27.

Shao, J.A., Zhang, L.Q., Xiao, Q.H., and Li, X.B., 2005, Rising of Da Hinggan Mts in Mesozoic: A possible mechanism of intracontinental orogeny: Acta Petrologica Sinica, v. 21, p. 789–794 (in Chinese with English abstract).

Shi, Y.Z., Liu, Z.J., Liu, R., Du, J.F., Zhang, J., and Liu, P., 2008, Quantitative reconstruction of the Eocene palaeoclimate in the Fushun Basin, Liaoning Province: Journal of Jilin University (Earth Science Edition), v. 38, p. 50–55 (in Chinese with English abstract).

Song, Z., Zheng, Y., Li, M., Zhang, Y., Wang, W., Wang, D., Zhao, C., Zhou, S., Zhu, Z., and Zhao, Y., 1999, Fossil Spores and Pollen of China. Vol. 1. Late Cretaceous and Tertiary Spores and Pollen: Science Press, Beijing, 910 p. (in Chinese).

Song, Z.C., Wang, W.M., and Huang, F., 2004, Fossil pollen records of extant angiosperms in China: Botanical Review, v. 70, p. 425–458, doi: 10.1663/0006-8101(2004)070[0425:FPROEA]2.0.CO;2.

Su, T., Xing, Y.W., Yang, Q.S., and Zhou, Z.K., 2009, Reconstructions of mean annual temperature in Chinese Eocene paleofloras based on leaf margin analysis: Acta Palaeontologica Sinica, v. 48, p. 65–72 (in Chinese with English abstract).

Sun, X., and Wang, P., 2005, How old is the Asian monsoon system?: Palaeobotanical records from China: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 222, p. 181–222, doi: 10.1016/j.palaeo.2005.03.005.

Tapponnier, P., Zhiqin, X., Roger, F., Meyer, B., Arnaud, N., Wittlinger, G., and Jingsui, Y., 2001, Oblique stepwise rise and growth of the Tibet Plateau: Science, v. 294, p. 1671–1677, doi: 10.1126/science.105978.

Trenberth, K.E., Stepaniak, D.P., and Caron, J.M., 2000, The global monsoon as seen through the divergent atmospheric circulation: Journal of Climate, v. 13, p. 3969–3993, doi: 10.1175/1520-0442(2000)013<3969:tgmast>2.0.co;2.

Utescher, T., and Mosbrugger, V., 1997–2010, PALAEOFLORA. Data base for palaeoclimate reconstructions using the Coexistence Approach, http://www.palaeoflora.de/. Checked October 2010.

Utescher, T., Djordjevic-Milutinovic, D., Bruch, A., and Mosbrugger, V., 2007, Palaeoclimate and vegetation change in Serbia during the last 30 Ma: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 253, p. 141–152, doi: 10.1016/j.palaeo.2007.03.037.

Utescher, T., Mosbrugger, V., Ivanov, D., and Dilcher, D.L., 2009, Present-day climatic equivalents of European Cenozoic climates: Earth and Planetary Science Letters, v. 284, p. 544–552, doi: 10.1016/j.epsl.2009.05.021.

Wang, C., Zhao, X., Liu, Z., Lippert, P.C., Graham, S.A., Coe, R.S., Yi, H., Zhu, L., Liu, S., and Li, Y., 2008, Constraints on the early uplift history of the Tibetan Plateau: Proceedings of the National Academy of Sciences, USA, v. 105, p. 4987–4992, doi: 10.1073/pnas.0703595105.

Wang, H., 1985, Atlas of the Paleogeography of China: Cartographic Publishing House, Beijing, 143 p. (in Chinese with English abstract).

Wang, P., Bradshaw, M., Ganzei, S.S., Tsukawaki, S., Hanssan, K.B., Hantoro, W.S., Poobrasert, S., Burne, R., Zhao, Q., and Kagami, H., 1997, West Pacific marginal seas during the Last Glacial Maximum: Amplification of environmental signals and its impact on monsoon climate, *in* Wang, P., and Berggren, W.A., eds., Proceedings of the 30th International Geological Congress, vol. 13: VSP, Utrecht, p. 65–85.

Wang, P., Clemens, S., Beaufort, L., Braconnot, P., Ganssen, G., Jian, Z., Kershaw, P., and Sarnthein, M., 2005, Evolution and variability of the Asian monsoon system: State of the art and outstanding issues: Quaternary Science Reviews, v. 24, p. 595–629, doi: 10.1016/j.quascirev.2004.10.002.

Wang, Q., Ferguson, D.K., Feng, G.P., Ablaev, A.G., Wang, Y.F., Yang, J., Li, Y.L., and Li, C.S., 2010, Climatic change during the Palaeocene to Eocene based on fossil plants from Fushun, China: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 295, p. 323–331, doi: 10.1016/j.palaeo.2010.06.010.

Wang, W.M., 2006, Correlation of pollen sequences in the Neogene palynofloristic regions of China: Palaeoworld, v. 15, p. 77–99, doi: 10.1016/j.palwor.2006.03.002.

Yao, Y.F., Bera, S., Ferguson, D., Mosbrugger, V., Paudayal, K., Jin, J.H., and Li, C.S., 2009, Reconstruction of paleovegetation and paleoclimate in the early and middle Eocene, Hainan Island, China: Climatic Change, v. 92, p. 169–189, doi: 10.1007/s10584-008-9457-2.

Zachos, J.C., Dickens, G.R., and Zeebe, R.E., 2008, An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics: Nature, v. 451, p. 279–283, doi: 10.1038/nature06588.

Zhao, C., Ye, D., Wei, D., Chen, B., and Liu, D., 1994, Tertiary in Petroliferous Regions of China: Petroleum Industry Press, Beijing, 156 p. (in Chinese).

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APPENDIX—List of Paleogene pollen and leaf floras from Fushun, northeastern China, and corresponding nearest living relatives (NLRs). Determination of the NLRs is mainly according to Song et al. (1999). NLR1, NLR2 = fossil taxa with two NLRs; ex. = taxa excluded from the coexistence approach analysis, and these include taxa for which the NLR cannot be determined, aquatic, and relict taxa.

Fossil	NLR1	NLR2	Note
Flora a. Laohutai Formation, middle Paleocene (Hong et al., 1980)			
Laevigatosporites	Polypodiaceae		
Stereisporites	Bryophyta		
Foveosporites	*Lycopodium*?		
Deltoidospora			ex.
Punctatisporites			ex.
Podocarpidites	*Podocarpus*		
Cedripites	*Cedrus*		
Piceaepollenites	*Picea*		
Abietineaepollenites	Pinaceae		
Pinuspollenites	*Pinus*		
Taxodiaceaepollenites	taxodioid Cupressaceae		
Ephedripites	*Ephedra*		
Cycadopites	Cycadaceae	Magnoliaceae	

APPENDIX—Continued.

Fossil	NLR1	NLR2	Note
Ostryoipollenites	*Ostrya*		
Fushunpollis			ex.
Casuarinidites	Casuarinaceae		
Salixipollenites	*Salix*		
Comptonia	*Comptonia*		
Myricipites	*Myrica*		
Caryapollenites	*Carya*		
Engelhardtioidites	*Engelhardia*		
Juglanspollenites	*Juglans*		
Alnipollenites	*Alnus*		
Betulaepollenites	Betulaceae?		
Betulaceoipollenites	Betulaceae		
Momipites	Juglandaceae		
Carpinipites	*Carpinus*		
Cornaceoipollenites	Cornaceae		
Paraalnipollenites	Betulaceae		
Quercoidites	*Quercus*		
Ulmoideipites	*Planera*		
Ulmipollenites	*Ulmus*		
Buxapollis	*Buxus*		
Arecipites	Arecaceae		
Magnolipollis	*Magnolia*	*Michelia*	
Liquidambarpollenites	*Liquidambar*		
Rhoipites	*Rhus*		
Moraceae	Moraceae		
Proteacidites	Proteaceae		
Palmaepollenites	Arecaceae		
Plicapollis			ex.
Tricolporopollenites			ex.
Polyatriopollenites			ex.
Triatriopollenites	Myricaceae		
Retitricolpites			ex.
Dicolpopollis	Arecaceae		
Flora b. Lizigou Formation, upper Paleocene (Hong et al., 1980)			
Granulatisporites	Pteridaceae		
Schizaeoisporites	Schizaeaceae		
Converrucosisporites			ex.
Laevigatosporites	Polypodiaceae		
Podocarpidites	*Podocarpus*		
Cedripites	*Cedrus*		
Piceaepollenites	*Picea*		
Taxodiaceaepollenites	taxodioid Cupressaceae		
Parcisporites	Podocarpaceae		
Comptonia	*Comptonia*		
Myricipites	*Myrica*		
Caryapollenites	*Carya*		
Juglanspollenites	*Juglans*		
Pterocaryapollenites	*Pterocarya*		
Platycarya	*Platycarya*		
Engelhardtioidites	*Engelhardia*		
Alnipollenites	*Alnus*		
Betulaepollenites	Betulaceae?		
Paraalnipollenites	Betulaceae		
Momipites	Juglandaceae		
Quercoidites	*Quercus*		
Liquidambarpollenites	*Liquidambar*		
Ostryoipollenites	*Ostrya*		
Elytranthe	*Elytranthe*		
Hamamelis	*Hamamelis*		
Rutaceoipollenites	Rutaceae		
Pistillipollenites			ex.
Gothanipollis	Loranthaceae		
Tricolpopollenites			ex.
Ulmoideipites	*Planera*		
Triatriopollenites	Myricaceae		
Cycadopites	Cycadaceae	Magnoliaceae	
Flora c. Lower part of Guchengzi Formation, lower Eocene (Hong et al., 1980)			
Laevigatosporites	Polypodiaceae		
Schizaeoisporites	Schizaeaceae		
Pinus	*Pinus*		

APPENDIX—Continued.

Fossil	NLR1	NLR2	Note
Abiespollenites	Pinaceae		
Sciadopityspollenites	*Sciadopitys*		
Podocarpidites	*Podocarpus*		
Laricoidites	*Larix*		
Taxodiaceaepollenites	taxodioid Cupressaceae		
Ephedripites	*Ephedra*		
Parcisporites	Podocarpaceae		
Caryapollenites	*Carya*		
Juglanspollenites	*Juglans*		
Alnipollenites	*Alnus*		
Betulaepollenites	Betulaceae?		
Momipites	Juglandaceae		
Quercoidites	*Quercus*		
Salix	*Salix*		
Tricolporopollenites			ex.
Tiliaepollenites	*Tilia*		
Ulmipollenites	*Ulmus*		
Ludwigia	*Ludwigia*		
Pistillipollenites			ex.
Aquilapollenites			ex.
Trialapollenites			ex.
Elythranthe	*Elytranthe*		
Flora d. Middle part of Guchengzi Formation, lower Eocene (Hong et al., 1980)			
Cyathidites	Cyatheaceae		
Osmundacidites	*Osmunda*?		
Schizaeoisporites	Schizaeaceae		
Schizosporis			ex.
Laevigatosporites	Polypodiaceae		
Podocarpidites	*Podocarpus*		
Pinuspollenites	*Pinus*		
Abietineaepollenites	Pinaceae		
Taxodiaceaepollenites	taxodioid Cupressaceae		
Ephedripites	*Ephedra*		
Psophosphaera	Araucariaceae		
Laricoidites	*Larix*		
Sciadopityspollenites	*Sciadopitys*		
Comptonia	*Comptonia*		
Caryapollenites	*Carya*		
Juglanspollenites	*Juglans*		
Pterocaryapollenites	*Pterocarya*		
Alnipollenites	*Alnus*		
Betulaepollenites	Betulaceae?		
Momipites	Juglandaceae		
Paraalnipollenites	Betulaceae		
Quercoidites	*Quercus*		
Cupuliferoipollenites	*Castanea*		
Ulmipollenites	*Ulmus*		
Elytranthe	*Elytranthe*		
Liquidambarpollenites	*Liquidambar*		
Rutaceoipollenites	Rutaceae		
Tiliaepollenites	*Tilia*		
Tricolporopollenites			ex.
Ludwigia	*Ludwigia*		
Palmaepollenites	Arecaceae		
Pistillipollenites			ex.
Aquilapollenites			ex.
Trialapollenites			ex.
Flora e. Upper part of Guchengzi Formation, lower Eocene (Hong et al., 1980)			
Schizaeoisporites	Schizaeaceae		
Pinuspollenites	*Pinus*		
Psophosphaera	Araucariaceae		
Taxodiaceaepollenites	taxodioid Cupressaceae		
Caryapollenites	*Carya*		
Juglanspollenites	*Juglans*		
Pterocaryapollenites	*Pterocarya*		
Alnipollenites	*Alnus*		
Betulaepollenites	Betulaceae?		
Momipites	Juglandaceae		
Ulmoideipites	*Planera*		
Quercoidites	*Quercus*		

APPENDIX—Continued.

Fossil	NLR1	NLR2	Note
Cupuliferoipollenites	*Castanea*		
Liquidambarpollenites	*Liquidambar*		
Pistillipollenites			ex.
Tricolporopollenites			ex.
Flora f. Lower part of Jijuntun Formation, middle Eocene (Hong et al., 1980; Liu et al., 1996)			
Microfossil			
Osmundacidites	*Osmunda*?		
Polypodiaceoisporites	Pteridaceae		
Concavisporites	Gleicheniaceae?		
Leiotriletes			ex.
Podocarpidites	*Podocarpus*		
Abiespollenites	Pinaceae		
Keteleeria	*Keteleeria*		
Ephedra	*Ephedra*		
Alnipollenites	*Alnus*		
Betulaepollenites	Betulaceae?		
Corylus	*Corylus*		
Corylopsis	*Corylopsis*		
Arecaceae	Arecaceae		
Juglanspollenites	*Juglans*		
Engelhardtioipollenites	*Engelhardia*		
Platycarya	*Platycarya*		
Cupuliferoipollenites	*Castanea*		
Liquidambar	*Liquidambar*		
Nyssa	*Nyssa*		
Lonicerapollis	*Lonicera*		
Rutaceoipollenites	Rutaceae		
Tricolpollenites			ex.
Triporopollenites	*Corylus*	*Ostrya*	
Tricolporopollenites			ex.
Leaf fossils			
Lygodium	*Lygodium*		
Ginkgo	*Ginkgo*		ex.
Glyptostrobus	*Glyptostrobus*		
Metasequoia	*Metasequoia*		ex.
Sequoia	*Sequoia*		ex.
Taxodium	*Taxodium*		
Torreya	*Torreya*		
Keteleeria	*Keteleeria*		
Salvinia	*Salvinia*		ex.
Pinus	*Pinus*		
Fagus	*Fagus*		
Quercus	*Quercus*		
Acer	*Acer*		
Alnus	*Alnus*		
Sabalites	*Sabal*		
Nelumbo	*Nelumbo*		ex.
Mimosites	*Mimosa*		
Betula	*Betula*		
Comptonia	*Comptonia*		
Viburnum	*Viburnum*		
Ailanthus	*Ailanthus*		
Banksia	*Banksia*		
Paliurus	*Paliurus*		
Firmiana	*Firmiana*		
Ampelopsis	*Ampelopsis*		
Zizyphus	*Zizyphus*		
Meliosma	*Meliosma*		
Cercidiphyllum	*Cercidiphyllum*		
Celtis	*Celtis*		
Hydrangea	*Hydrangea*		
Rosa	*Rosa*		
Rhus	*Rhus*		
Phellodendron	*Phellodendron*		
Hamamelites	*Hamamelis*		
Dryophyllum			ex.
Lindera	*Lindera*		
Sparganium	*Sparganium*		
Populus	*Populus*		
Corylus	*Corylus*		
Betula	*Betula*		

APPENDIX—Continued.

Fossil	NLR1	NLR2	Note
Carpinus	*Carpinus*		
Exochorda	*Exochorda*		
Dryophyllum	*Dryophyllum*		
Acacia	*Acacia*		
Cycas	*Cycas*		
Flora g. Upper part of Jijuntun Formation, middle Eocene (Hong et al., 1980)			
Laevigatosporites	Polypodiaceae		
Cedripites	*Cedrus*		
Juglanspollenites	*Juglans*		
Rhoipites	*Rhus*		
Deltoidospora			ex.
Abietineaepollenites	Pinaceae		
Piceaepollenites	*Picea*		
Podocarpidites	*Podocarpus*		
Pinuspollenites	*Pinus*		
Ephedripites	*Ephedra*		
Callialasporites			ex.
Myricipites	*Myrica*		
Comptonia	*Comptonia*		
Betulaepollenites	Betulaceae?		
Alnipollenites	*Alnus*		
Momipites	Juglandaceae		
Caryapollenites	*Carya*		
Pterocaryapollenites	*Pterocarya*		
Cupuliferoipollenites	*Castanea*		
Quercoidites	*Quercus*		
Ulmipollenites	*Ulmus*		
Liquidambarpollenites	*Liquidambar*		
Tiliaepollenites	*Tilia*		
Tricolporopollenites			ex.
Flora h. Lower part of Xilutian Formation, middle Eocene (Hong et al., 1980)			
Deltoidospora			ex.
Stereisporites			ex.
Cyathidites	Cyatheaceae		
Cedripites	*Cedrus*		
Abietineaepollenites	Pinaceae		
Taxodiaceaepollenites	taxodioid Cupressaceae		
Ephedripites	*Ephedra*		
Ginkgo-Cycadopites	*Ginkgo*	*Cycas*	ex. *Ginkgo*
Alnipollenites	*Alnus*		
Lonicerapollis	*Lonicera*		
Quercoidites	*Quercus*		
Cupuliferoipollenites	*Castanea*		
Ulmipollenites	*Ulmus*		
Tricolpopollenites			ex.
Tricolporopollenites			ex.
Juglanspollenites	*Juglans*		
Pterocaryapollenites	*Pterocarya*		
Liquidambarpollenites	*Liquidambar*		
Rutaceoipollenites	Rutaceae		
Comptonia	*Comptonia*		
Tiliaepollenites	*Tilia*		
Rhoipites	*Rhus*		
Palmaepollenites	Arecaceae		
Salix	*Salix*		
Carpinus	*Carpinus*		
Momipites	Juglandaceae		
Pentapollenites			ex.
Caryapollenites	*Carya*		
Betulaepollenites	Betulaceae?		
Cyrillaceaepollenites	Cyrillaceae		
Orbiculapollis			ex.
Flora i. Middle part of Xilutian Formation, middle Eocene (Hong et al., 1980)			
Abietineaepollenites	Pinaceae		
Pinus	*Pinus*		
Taxodiaceaepollenites	taxodioid Cupressaceae		
Ephedripites	*Ephedra*		
Ginkgo-Cycadopites	*Ginkgo*	*Cycas*	ex. *Ginkgo*
Juglanspollenites	*Juglans*		
Pterocaryapollenites	*Pterocarya*		

APPENDIX—Continued.

Fossil	NLR1	NLR2	Note
Cupuliferoipollenites	*Castanea*		
Quercoidites	*Quercus*		
Ulmoideipites	*Planera*		
Ulmipollenites	*Ulmus*		
Liquidambarpollenites	*Liquidambar*		
Tricolpollenites			ex.
Podocarpidites	*Podocarpus*		
Comptonia	*Comptonia*		
Engelhardtioipollenites	*Engelhardia*		
Rutaceoipollenites	Rutaceae		
Symplocoipollenites	Symplocaceae		
Palmaepollenites	Arecaceae		
Cyrillaceaepollenites	Cyrillaceae		
Tricolporopollenites			ex.
Flora j. Upper part of Xilutian Formation, middle Eocene (Hong et al., 1980)			
Laevigatosporites	Polypodiaceae		
Cedripites	*Cedrus*		
Juglanspollenites	*Juglans*		
Rhoipites	*Rhus*		
Deltoidospora			ex.
Abietineaepollenites	Pinaceae		
Picea	*Picea*		
Podocarpidites	*Podocarpus*		
Pinuspollenites	*Pinus*		
Ephedripites	*Ephedra*		
Callialasporites			ex.
Myricipites	*Myrica*		
Comptonia	*Comptonia*		
Betulaepollenites	Betulaceae?		
Alnipollenites	*Alnus*		
Momipites	Juglandaceae		
Caryapollenites	*Carya*		
Pterocaryapollenites	*Pterocarya*		
Cupuliferoipollenites	*Castanea*		
Quercoidites	*Quercus*		
Ulmipollenites	*Ulmus*		
Liquidambarpollenites	*Liquidambar*		
Tiliaepollenites	*Tilia*		
Tricolporopollenites			ex.
Flora k. Gengjiajie Formation (middle–upper Eocene) (fossils were from the upper part of the formation, upper Eocene; Qu, 1993)			
Pediastrum			ex.
Sphagnumsporites	Sphagnaceae		
Inapertisporites			ex.
Dicellaesporites			ex.
Osmundacidites	*Osmunda*?		
Schizaeoisporites	Schizaeaceae		
Alsophilidites			ex.
Verrutetraspora	*Pteris*		
Polypodiaceaesporites	Polypodiaceae		
Rouseisporites			ex.
Lygodiumsporites	Lygodiaceae		
Gleicheniidites	Gleicheniaceae		
Delloidospora			ex.
Biretisporites	Hymenophyllaceae		
Undulatisporites	Gleicheniaceae?		
Podocarpidites	*Podocarpus*		
Cycadopites	Cycadaceae	Magnoliaceae	
Cedripites	*Cedrus*		
Pinuspollenites	*Pinus*		
Taxodiaceaepollenites	taxodioid Cupressaceae		
Ephedripites	*Ephedra*		
Salixipollenites	*Salix*		
Caryapollenites	*Carya*		
Faguspollenites	*Fagus*		
Juglanspollenites	*Juglans*		
Alnipollenites	*Alnus*		
Paraalnipollenites	Betulaceae		
Betulaepollenites	Betulaceae?		
Momipites	Juglandaceae		
Sporopollis			ex.

APPENDIX—Continued.

Fossil	NLR1	NLR2	Note
Cyrillaceaepollenites	Cyrillaceae		
Quercoidites	*Quercus*		
Ulmoideipites	*Planera*		
Ulmipollenites	*Ulmus*		
Celtispollenites	*Celtis*	*Aphananthe*	
Liquidambarpollenites	*Liquidambar*		
Meliaceoidites	Meliaceae	*Cipadessa*	
Rhoipites	*Rhus*		
Proteacidites	Proteaceae		
Peltandripites	*Peltandra*	*Smilax*	
Lonicerapollis	*Lonicera*		
Tiliaepollenites	*Tilia*		
Cornaceoipollenites	Cornaceae		
Rutaceoipollis	Rutaceae		
Triatriopollenites	Myricaceae		
Lemna	*Lemna*		ex.
Striatricolpites			ex.
Sapindaceidites	Sapindaceae		
Magnolipollis	*Magnolia*	*Michelia*	
Retitricolpites			ex.
Tricolpopollenites			ex.
Labitricolpites	Lamiaceae		
Intratriporopollenites			ex.