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How old is the Asian monsoon system?—Palaeobotanical records from China

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Abstract

The recent discovery of monsoon records in early Miocene raised a question of the time when the East Asian monsoon system initiated. A distinguishing feature of the modern monsoon system is its geographic distribution which disturbs the zonal pattern indigenous to the planetary climate system, and the appearance of the monsoonal climate pattern in the geological records should signify the onset of the monsoon system. Here we present the results of a compilation of palaeobotanical and lithological data from 125 sites over China, that has revealed two completely different patterns of climate zones: the Palaeogene pattern with a broad belt of aridity stretched across China from west to east, and the Neogene pattern with the arid zone restricted to northwest of China which has persisted until today. The reorganization of the climate system around the Oligocene/Miocene boundary provides evidence for the establishment of the modern East Asian monsoon. Since then, the Neogene has witnessed significant variations of the monsoon system, including enhancement of aridity and monsoon intensity at about 15–13 My, around 8 My and 3 My. The new data do not support the onset of the Asian monsoon system around 8 My. Rather, the new data led to a hypothesis that the transition to the monsoon climate system in East Asia occurred in the latest Oligocene.

Keywords: East Asian monsoon; Palaeogene; Neogene; Pollen; Palaeovegetation; Aridity

1. Introduction

Over the past 20 years, the Asian monsoon has become an increasing attraction for the scientific community, and numerous palaeo-records have invaluably contributed to our understanding of the monsoon system. One of the outstanding issues in the monsoon studies is the age of the present Asian monsoon system. To determine the initiation of the current monsoon system is crucial not only for knowledge of the monsoon history but also for recognition of the mechanism of its variations.

The studies of long-term evolution of the Asian monsoon started with ODP Leg 117 in the Arabian

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Sea in 1987 (Prell et al., 1991). Post-cruise analyses have dated the onset of monsoon-related upwelling to about 8.5 My (Kroon et al., 1991), and a combination of marine with terrestrial data indicated a major intensification of the Indian monsoon around 8 My (Prell et al., 1992; Prell and Kutzbach, 1992). On the other hand, the East Asian monsoon was intensively studied in the loess–paleosol sequences in China, and the beginning of deposition about 2.6 My was taken as the onset of monsoons, due to the alternating predominance of the winter and summer East Asian monsoons (Li, 1991; Ding et al., 1992; Liu and Ding, 1993). Later, the Red Clay underlying the loess sequence was found to be also of wind-blown origin, and the history of aeolian deposits of the Loess Plateau was extended to 7–8 My (Sun et al., 1997, 1998; Ding et al., 1998, 2001; An et al., 2001). Since the uplift of the Himalayan Mountains and the Tibetan Plateau can lead to enhanced aridity in the Asian interior and to the Asian monsoon system (Kutzbach et al., 1993), the nearly coincident beginning of upwelling in the Indian Ocean and dust accumulation in central China about 8 My was as attributed to the "onset of the Indian and east Asian monsoons", which in turn implies a significant increase in altitude of the Plateau (An et al., 2001).

However, this concept of Asian monsoon initiation was challenged by new findings. The recent discovery of a Miocene loess sequence at Qinan, western Loess Plateau in central China, has extended the Chinese dust history back to early Miocene (Guo et al., 2002). A total of 231 interbedded, loess–palaeosol layers represent a nearly continuous history of aeolian dust accumulation from 22 to 6.2 My, indicating that large source areas of aeolian dust and energetic winter monsoon winds existed since early Miocene, at least 14 My earlier than previously thought. The role of summer monsoon is implied from the palaeosol layers which show significantly more intensive weathering than those in the pleistocene loess–palaeosol sequence (Guo, personal communication). The progressive extension of the loess–palaeosol records in age, from 2.4 My to ~8 My and then 22 my, raised a serious question: "How old is the Asian monsoon system?" Shall we expect even older loess in future discoveries?

Noticeably, all the above discussion on the monsoon evolution is based on time-series with climate changes shown in stratigraphic sequences which are dependant on completeness of the sequence and on its geography. To avoid the limitations, an alternative approach is to consider the spatial patterns of climate zonation. A distinguishing feature of the monsoon system is its geographic distribution which disturbs the zonal pattern indigenous to the planetary climate system. This approach was adopted to address the global climate evolution during both the Mesozoic and Cenozoic (Parrish et al., 1982), but that work was based solely on lithological proxies of climate, namely coal and evaporites, also with a very coarse resolution. As these authors noted, "the most reliable" should be the "palaeophytogeographical patterns" which, unfortunately, exists only for younger ages. However, the petroleum exploration of non-marine deposits in China over decades contributed to an accumulation of enormous palynological data which are potential sources of palaeoclimate evidence for monsoon studies.

Over 20 years ago, Chinese scientists already noticed the early evidence of monsoon evolution when summarizing the data from oil exploration and stratigraphic studies. Thus, a compilation of pollen data revealed the presence of a broad belt of aridity stretched across China from west to east in the late Cretaceous and Paleocene (Sun, 1979). The change from arid to humid climatic conditions in East China occurred around the Oligocene/Miocene boundary, with the arid zone restricted to northwest China in the Neogene, and this baseline change in climate zonation of China was interpreted as transition from a planetary to monsoonal system in atmospheric circulation (Zhou, 1984; Wang, 1984). Chinese scientists believe that it was the East Asian summer monsoon that brought moisture from the ocean to East China, and the reorganization of the climate system around the Oligo/Miocene boundary provides evidence for enhancement if not establishment of the East Asian summer monsoon (see Fig. 3 in Wang, 1990a; Fig. 1 in Liu, 1997).

Over the last few years, we compiled all available pollen and other palaeobotanical data from a total of 125 sites throughout China (Fig. 1) from the Paleocene to the Pliocene, to examine the transition of phytogeographical and climatic zonation at the latest Oligocene in the present paper. The results will help us to clear up various misunderstandings about

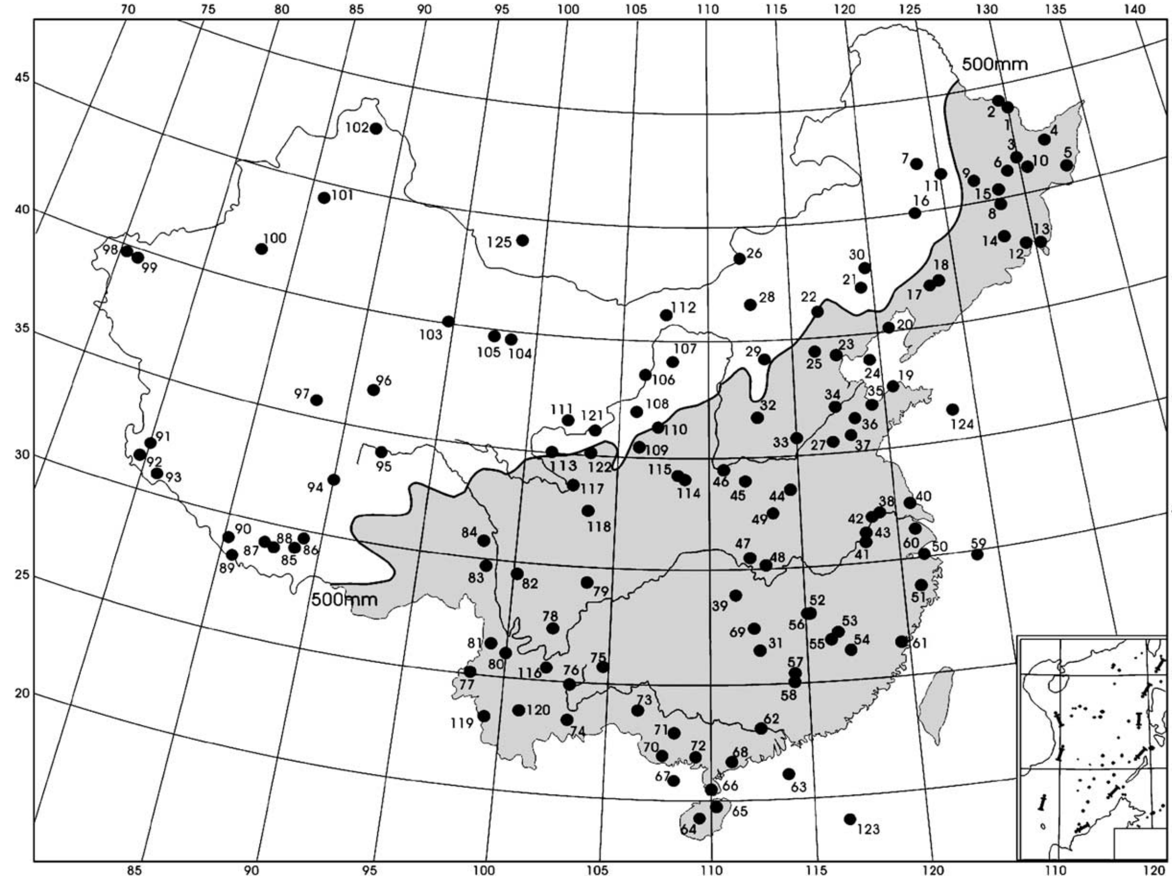

Fig. 1. Location of plant fossil sites. The 500 mm isoline of annual precipitation marks the boundary between humid–semihumid (grey-shaded) and arid–semiarid (white) areas at the present time.

the evolution of the Asian monsoon system and aridity in Asia.

2. Physical geography of China

Located in the East Asia, China is bordered by the Earth's highest mountains and largest plateau, the Tibet, in its southwest and the largest ocean—The Pacific Ocean in the east. Elevations are high in the west and low in the east. The average altitude of the Tibetan Plateau is ca. 4500 m and it is no more than 500 m a.s.l. for the plains and hills of east China. Due to strong land–ocean thermal contrast and the dynamics and thermal effects of the Tibet Plateau, China's climate is controlled mainly by the East Asian monsoon system. The surface monsoon flow patterns in summer and winter over China are distinctly different. In winter, the region is controlled by the Siberian High, and dry–cold continental air masses flow southwestwards from inner Asia to the ocean. As a consequence, China experiences a cold and dry climate, much more severe than other regions of the similar latitude. Summer is just the reverse: warm and humid air masses from Highs over the Pacific and Indian Oceans bring abundant rainfall to the Chinese continent, except in the northwest and on the Tibetan Plateau. Consequently, southeast China then is more humid than comparable regions of the same latitude (Wu, 1980; Editor Board of Natural Geography of China, 1979; Fu et al., 2002). In China the average rainfall decreases from southeast to northwest. Average annual precipitation in the southeast coastal region, e.g., Fujian, Guangdong, and southern slope of the Himalaya exceeds 2000 mm, whereas in northwest China, e.g., Xinjiang, Ningxia, Qinghai and northern Tibet it is less than 100 mm, and even less than 50 mm in the Tarim and Chaidam Basins (Editor Board of Natural Geography of China, 1979). The 500 mm isohyet inclines from northwest to southeast and serves as a climatic boundary dividing China into two parts: The southeast part belongs to the humid and semi-humid region, while the northwest part to the arid and semi-arid one (Fig. 1).

The patterns of air temperature in east and west of China are different. Controlled by solar radiation, the annual average temperature rises from north to south in the east, whereas the affect of the raised relief exceeds any latitudinal effect in the west. For example, in East China it averages only -5 °C in the extreme north and 25 °C in Hainan Island in the south. In the West China the annual mean temperature over most of the Tibetan Plateau is above 0 °C, but in the Tarim Basin to its north is above 12 °C. According to air temperature China can be divided into cool-temperate, temperate, subtropical and tropical zones (Editor Board of Natural Geography of China, 1979).

The East Asian monsoon system creates specific vegetation zones in China (Fig. 2). The forests are mainly distributed in the east and southeast, being replaced to the northwest by steppe and desert due to the weak summer monsoon influence, and the Tibetan Plateau supports montane and cold vegetation (Wu, 1980; Editor Board of Natural Geography of China, 1983).

2.1. Forest of south and east China

Five forest zones can be divided from north to south (Fig. 2):

I *Cold-temperate conifer forest* Consists mainly of boreal conifers such as *Abies sibirica*, *Picea*

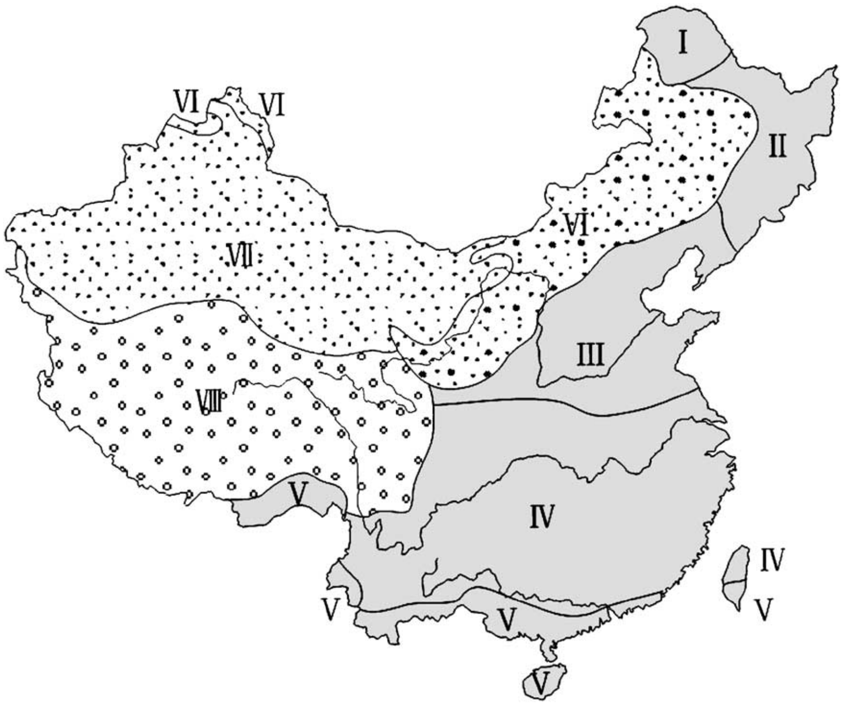

Fig. 2. Modern vegetation zones in China. Grey area denotes Forest vegetation zones, the rest in dotted patterns. I. Cold-temperate conifer forest; II. Temperate mixed conifer-broadleaved forest; III. Warm-temperate broadleaved deciduous forest; IV. Subtropical evergreen broadleaved forest; V. Tropical rainforest and seasonal rainforest; VI. Steppe; VII. Desert; VIII. Tibet–Qinghai cold and highland vegetation.

obovata, *Larix sibirica*, etc., together with *Pinus* and *Sabina*. Annual average temperature measures 2.2 to 5.5 °C. Annual precipitation is 350 to 550 mm.

II *Temperate mixed conifer and broadleaved forest*. *Pinus koraiensi*s, temperate in nature, is the main component in the conifers together with some cold-temperate species of *Picea* and *Abies*. Broadleaved deciduous trees include chiefly *Quercus mongolica*, *Betula costata*, *Tilia amurensis*, *Ulmus propiqua*, etc. Annual average temperature is 2 to 8 °C. Annual precipitation is 500 to 1000 mm.

III *Warm-temperate broadleaved deciduous forest*. Some genera from the Fagaceae such as *Quercus* and *Castanea* are the main components of the forest. Betulaceae (*Betula*, *Carpinus*, *Alnus*), Juglandaceae (*Juglans, Pterocarya*), Tiliaceae (*Tilia*), Salicaceae (*Poplus, Salix*) and Ulmaceae (*Ulmus, Celtis*) are very well represented. Pine forest (*Pinus densifolia, P. armandii*) is also widely distributed. Annural mean temperature is 9 to 14 °C. Annual precipitation is 500 to 900 mm.

IV *Subtropical evergreen-broadleaved forest*. Under control of the summer monsoon, it is hot and humid in spring and summer, but somewhat drier in winter. Evergreen Fagaceae such as *Castanopsis, Cyclobalanopsis, Lithocarpus* and evergreen *Quercus* are the main components. Lauraceae (*Machilus, Phoebe*), Theaceae (*Camellia, Eurya*) and tropical and subtropical ferns also very well represented. Annual precipitation is above 1000 mm, reaching 3000 mm at a maximum.

V *Tropical rainforest and seasonal rainforest*. The most southern vegetation zone in east China is marked by high humidity and temperature, but with clear rainy and dry seasons. Annual mean temperature is 20 to 26 ° C. Annual precipitation is above 1500 mm, reaching 5000 mm in some areas. The wet season occurs from April to October; with the other months comparatively dry. Evergreen broadleaved forest is dominated by species of families such as Moraceae, Meliaceae. Sapindaceae. Tiliaceae, Euphorbiaceae, Sapotaceae, Palmae and Dipterocarpaceae. There are also tropical pine forests of *Pinus latterii* and *P. khasya* in low-land, hilly and low montane areas.

2.2. Steppe and desert

VI *Temperate steppe*. Steppe in China is the eastern extent of the Europe–Asian Steppe and is composed chiefly of perennial grasses such as *Stipa, Festuga, Cleistogenes, Artemisia* and *Sanguisorba* form shrub and semi-shrub land.

VII *Desert*. This covers the most arid regions of northwest China. There are some inner-continental grand basins such as the Junggar, Tarim, Qaidam Basins interrupted by high mountains such as Tian Shan, Qilian Shan and Kunlun Shan. Moisture rarely penetrates these high mountains and the region is under control of the continental high pressure air masses and experiences a very dry climate. Rainfall is less than 100 mm in 80% of this region and even less than 30 mm in the centres of the basins. Vegetation is very open and large areas of bare land occur. Most species such as those from *Salsola, Anabasis, Suaeda* within the Chenopodiaceae are the constructive components of the desert. In addition, species from Zygophyllaceae (*Nitraria*), Asteraceae, Poaceae, Rosaceae, Leguminosae and Polygalaceae are important elements. *Ephedra* (*E. przewalskii*) will be frequently mentioned below as it is a main component of a special shrub desert community.

2.3. Tibetan high elevation and cold vegetation

VIII *Tibetan high elevation and cold vegetation*. Most areas of the Plateau are above 4500 m and the climate is cold and dry with most parts covered by ice and snow for 6 months or more each year. The vegetation is quite open and comprises desert, grassland and grassy meadow.

3. Materials and methods

3.1. Climatic proxies

This study on the evolution of East Asian monsoon is mainly based on published Pelaeogene and Neogene paleobotanical data of China including fossil pollen and spores, and macro-plant fossils of leaves, seeds, etc. (Fig. 1). In all probability, not all of the related data have been included in this paper, but we believe that we have not missed any important information. At the same time we also paid attention to those sediment characteristics which clearly reflect environment during deposition. Because monsoon influence on vegetation is mainly expressed as rainfall, so in discussion of ecology of fossil plants our emphasis is chiefly placed on the humidity controls as climate proxies from fossil data.

3.1.1. Arid climate proxy of pollen

In this paper we choose those pollen types which were widely distributed in Cenozoic sediments deposited under arid climate such as evaporites (gypsum, halite, mirabilite, glauberite) and red deposits. The first choice is the pollen of *Ephedra*. This is a gymnosperm genus that probably originated in the Triassic, and today is mainly distributed in arid and semi-arid regions of northwestern China (Yang, 2002). Its fossil representative (*Ephedripites*) with easily recognizable morphology is found widely in Cenozoic evaporites. For example, percentages of *Ephedripites* in the Paleocene thick halite deposit vary from 10 to 50% of pollen assemblages in Jiangxi (site 52, He and Sun, 1977a,b). Tong et al. (2001) counted 313 pollen samples from middle and late Eocene evaporites and discovered *Ephedripites* with averages of 30% in halite, 20% in glauberite and 15% in purple mudstone. All those sediments mentioned above were deposited under arid conditions. Therefore, we hypothesize that pollen assemblages with over 15% of *Ephedripites* denote arid or semi-arid environments.

Besides *Ephedripites*, there are other pollen types with a specific morphology close to modern Proteaceae in pollen structure. The fossil genera are *Proteacidites* and *Beaupreaidites*, etc., which were often found together with *Ephedripites* in evaporites, especially in northwest China and Inner Mongolia. An exceptional example is Eocene gypsum of Otog Banner (site 107, Fig. 1) where Proteaceae pollen reaches 25% to 38% in pollen assemblages (Song and Zhang, 1990).

Pollen of *Nitraria* (Zygophyllaceae) and Chenopodiaceae occur mainly in Neogene and Quaternary evaporites, and also serve as arid climatic proxies. Although they both have fossil names, e.g., *Nitraripollis* for *Nitraria* and *Chenopodipollis* for Chenopodiaceae, we will use the modern plant names here, because these taxa are also found in relatively young sediments. At the present time both pollen mother plants are shrubs or herbs distributed mainly in desert or semi-desert areas.

In the Neogene pollen assemblages containing high proportions of herbs or shrubs such as *Artemisia*, other Asteraceae, Chenopodiaceae, Poaceae, Polygonaceae (*Calligonum*), Liliaceae, Zygophyllaceae, etc., usually indicate open vegetation and dry climate.

It has long been accepted that *Shizaeoisporites* and *Classopollis* belong to extinct plants and they are widely represented in evaporites of late Cretaceous and early Palaeogene age in the Northern Hemisphere, and hence are used as arid climatic proxies in this paper (e.g., Wang et al., 1990a,b).

3.1.2. Arid climate proxy of fossil leaves

Morphology of plant leaves (size, texture, margin of leaf) can reflect habitat environment. For example, large leaves with entire margins and soft texture are indicative of warm, humid habitats. On the contrary, small leaves with coriaceous texture and toothed margins denote harsher conditions (Tao et al., 2000). It is generally accepted by paleobotanists in China that the extinct fossil leaf form named *Palibinia* found widely in red clay often with gypsum and other evaporites of Paleocene and Eocene age in southeast China is a proxy of arid and semi-arid climates. The leaves of *Palibinia* are no more than 0.5 cm in width, very coriaceous in texture and tooth margined; all of these characters denote an arid habitat of the plant (Tao, 1965, 1983; Li and Chen, 2002).

At the same time we collected climate indicative sedimentation data for each epoch from Paleocene to Pliocene; for example, evaporites (e.g., gypsum, halite, glauberite, etc.) are arid climatic proxies, and oil shale and coal represent humid ones (e.g., Song et al., 1983; Li and Gu, 1994; Liu et al., 1998).

3.2. Stratigraphy

Except for the palaeo-Tethys areas in the west, Cenozoic sediments of China are mainly terrestrial in nature, separately deposited in hundreds of basins across the region (Fig. 3). Therefore, dating and correlation of strata present a formidable challenge. Oil companies in China have used geophysical and palaeomagnetic methods to date strata of some oil-bearing basins such as in the Qaidam, Jianghan, Juixi Basins, as well as Jiyang and Liaohe Depressions in the Bohai Gulf Basin (see Fig. 3), and then, based on these approaches have correlated sediments of many oil basins in China in the middle part of 1990s (Ye et al., 1993). In this paper, we broadly accept these age correlations but in most cases our chronology is based on paleontological evidence (see Table 1).

Tertiary pollen data in China, like elsewhere, usually have poorly resolved time constraint and in most cases is based solely on plant fossil correlations. Therefore, data presented here should also be considered to be of low time resolution, and our further discussion will be focused on differences between epochs.

4. Evolution of Cenozoic vegetation: representative pollen profiles in China

In order to demonstrate the history of climatic change in China, three more or less complete and

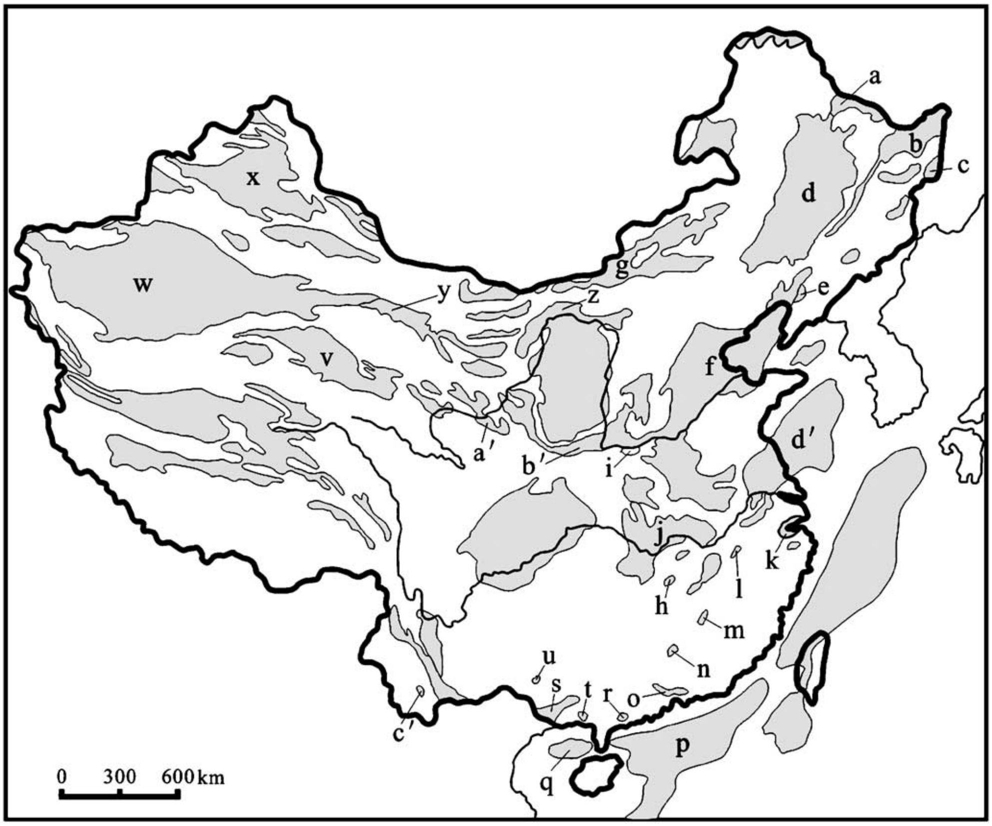

Fig. 3. Cenozoic sedimentary basins in China (Wang, 1985; Ye et al., 1993). Letters denote the basins mentioned in this paper: a. Jiayin Basin (site 1 in Fig. 1 and Table 1); b. Sanjiang Basin (site 4); c. Hulin Basin (site 5); d. Songliao Basin (site 11); e. Fushun Basin (site 18); f. Bohai Gulf Basin (sites 20, 23–25, 33–34); g. Erlian Basin (site 26); h. Hengyang Basin (site 31); i. Zhoukou Basin (site 44); j. Jianghan Basin (site 48); k. Changhe Basin (site 50); l. Qingjiang Basin (site 52); m. Chijiang Basin (site 57); n. Nanxiong Basin (site 58); o. Sanshui Basin (site 62); p. Zhujiangkou Basin (site 63); q. Beibu Bay Basin (site 67); r. Maomin Basin (site 68); s. Nanning Basin (site 71); t. Hepu Basin (site 72); u. Baise Basin (site 73); v. Qaidam Basin (site 96); w. Tarim Basin (sites 98–100); x. Jungaar Basin (site 101); y. Jiuquan Basin (site 104); z. Hetao Basin (site 112); a′. Xining–Minhe Basin (site 111); b′. Weihe Basin (site 115); c′. Jinggu Basin (site 120); d′. South Yellow Sea Basin (site 124).

Table 1
Locations of palaeobotanical sites (Fig. 1)

No.	Site	Location	Age	Type of fossil	Reference	Age control
1	Jiayin Basin	49°N, 130°E	Palaeo	leaf	Xiong, 1986	A C
2	Furao	49°20′N, 129°36′E	Palaeo	pollen	Liu, 1983	C
3	Tangyuan	46°44′N, 129°55′E	Palaeo	leaf	Zhang et al., 1990a	C
4	Sanjiang Basin	47°N, 132°E	Oligo–Plio.	pollen, leaf	Zhao et al., 1994	C
5	Hulin Basin	43°06′–46°20′N, 130°0′–133°48′E	Oligo	leaf	Zhao et al., 1982, 1994	A C
6	Yilian	46°10′N, 129°15′E	Eo–Oligo	leaf, pollen	Zhao et al., 1982, 1994; He and Tao, 1997; Tao et al., 2000	A C
7	Fulaerji	47°12′N, 123°36′E	Plio	pollen	Liu et al., 1990	A C
8	Ningan Basin	44°–44°40′N, 128°50′–130°E	Oligo–Mio.	leaf	Zhao et al., 1982, 1994	A C
9	Southern Yilian-Yiton Graben,	46°N,127°E	Eo–Mio	pollen	Zhao et al., 1994	A C
10	Huanan	46°10′N, 130°30′E	Mio	leaf, pollen	Liu et al., 1995; Liu, 1998	C
11	Songliao Basin	46°N, 125°E	Oligo–Plio	leaf, pollen	Xia and Wang, 1987; Zhao et al., 1994	C
12	Longjing	42°45′N, 129°30′E	Oligo	leaf	Guo and Zhang, 2002	C
13	Hunchun	42°51′N, 130°21′E	Eo–Mio	leaf, pollen	Guo and Li, 1979; Liu, 1987	C
14	Dunhua	43°21′N, 128°11′E	Mio	leaf.	Li and Yang, 1984a	C
15	Yanshou	45°28′N, 128°21′E	Eo	leaf	Zhao et al., 1994	C
16	Qianan	44°47′N, 123°44′E	Plio	pollen	Jia et al., 1989; Xia and Wang, 1987	C
17	Shenbei coalfield	41°48′N, 123°23′E	Eo	leaf	Zhao et al., 1994	A C
18	Fushun Basin	42°N, 123°E	Palaeo–Eo	leaf, pollen, wood	Song and Tsao, 1976; Institute of Botany and Nanjing Institute, 1978; Sun et al., 1980a; Du, 1987	C
19	Huangxian	37°40′N, 120°30′E	Palaeo	pollen	Li et al., 1992	C
20	Liaohe River Depression		Palaeo	pollen	Yao et al., 1994	A C
21	Chifeng	42°30′N, 118°15′E	Mio	leaf, pollen, wood	Tao et al., 1994, 2000	A C
22	Wuluogong		Mio	pollen	Gan, 1982	A C
23	Huanghua Depression		Palaeo–Eo, Mio–Plio	pollen	Institute of Petroleum and Nanjing Institute, 1978; Li and Liang, 1981	A C
24	Bohai Wan Gulf Basin		Eo–Plio	pollen	Guan et al., 1982; Yao et al., 1994; Design and Research Institute, 1989	C
25	Jizhong Depression		Paleo–Plio.	pollen	Cai et al., 1998; Tao et al., 2001	C
26	Erlian Basin	43°39′N, 111°58′E	Mio	pollen	Wang, 1990b	B C
27	Taian	35°30′N, 117°E	Eo	leaf	Li and Chen, 2002	C
28	Shangdu-Huade	41°35′N, 112°32′E	Oligo–Mio	pollen	Wang and Zhang, 1990	C
29	Fanzhi	39°17′N, 113°22′E	Eo–Oligo	pollen	Zhang, 1983	C
30	Ju'ud League		Mio	leaf	Zhang, 1986	C
31	Hengyang Basin	26°30′N, 112°18′E	Palaeo–Eo	leaf	Li, 1965; Li and Chen, 2002	C
32	Yushe Basin	37°6′N, 113°E	Plio	leaf, pollen	Cao and Cui, 1989; Shi et al., 1993; Shi et al., 1994; Liu et al., 2002	A B C
33	Dongpu region	35°45′N, 115°E	Eo–Oligo	leaf, pollen	Research Institute and Nanjing Institute, 1989; Tao, 1983	C
34	Jiyang Depression	36°58′N, 117°12′E	Palaeo–Eo	leaf, pollen	Yao et al., 1994	A C
35	Changwei Depression	36°46′–36°52′N, 119°13′–119°25′E	Palaeo–Eo	pollen	Yao et al., 1994	B C

Table 1 (*continued*)

No.	Site	Location	Age	Type of fossil	Reference	Age control
36	Shanwang	36°30′N, 118°21′E	Mio	pollen, leaf	Institute of Botany and Nanjing Institute, 1978; Li, 1978; Liu, 1986; Liu and Leopold, 1992, 1994	A B C
37	Mengyin	35°42′N, 117°57′E	Eo	pollen	Lei, 1986	B C
38	Yizheng	32°10′N, 119°07′E	Palaeo	leaf	Li and Chen., 2002	C
39	Taoyuan	28°54′N, 111°28′E	Eo	leaf	Li and Zheng 1995; Li and Chen, 2002	C
40	Jiangsu area		Palaeo–Eo, Mio	pollen	Song et al., 1981; Zhang and Qian, 1992	B C
41	Nanling-Xuancheng Basin	30°55′–31°57′N, 118°19′–118°44′E	Palaeo–Eo	pollen	Zhang et al., 1993	A C
42	Nanjing	32°02′N, 119°0′E	Mio–Plio	leaf	Li et al., 1984, 1987	C
43	Wuhu	31°20′N, 118°23′E	Eo	pollen	Li, 1986	C
44	Zhoukou Basin	33°38′N, 114°38′E	Paleo–Mio	pollen	Mao et al., 1995; Zhang et al., 1993	C
45	Tantou Basin	34°N, 112°E	Palaeo–Eo	pollen	Wang et al., 1984	C
46	Lingbao Basin	34°31′N, 110°51′E	Palaeo–Eo	pollen, leaf	Sun et al., 1985; Tao et al., 2000	B C
47	Dangyang	30°30′N, 112°18′ °E	Palaeo	leaf	Li and Chen, 2002	C
48	Jianghan Basin		Palaeo–Mio		Paleontological Group, 1976; Li et al., 1978; Zhang et al., 1993; Tong et al., 2001	A C
49	Wucheng	32°30′N, 113°30′E	Eo	leaf, pollen	Liu and Kong, 1978; Li and Chen, 2002	B C
50	Changhe Basin	30°15′N, 121°15′E	Palaeo–Eo	pollen	Wang et al., 1994	C
51	Xianju-Ninghai	28°09′–29°14′N, 120°43′–121°30′E	Mio	leaf, pollen	Zheng, 1982; Li, 1984a	C
52	Qingjiang Basin	28°N, 115°17′E	Palaeo–Eo	leaf, pollen	He and Sun, 1977a,b; Sun,1979; Li and Chen, 2002	B C
53	Nanfeng	27°13′N, 116°31′E	Mio	pollen	Sun and He, 1987	C
54	Mingxi	26°22′N, 117°11′E	Mio	pollen	Zheng, 1987	C
55	Guangchang	26°50′N, 116°19′E	Mio	pollen	Sun and He, 1987	C
56	Lingjiang	28°03′N, 115°13′E	Eo	leaf, pollen	He and Sun, 1977a,b; Li and Chen, 2002	B C
57	Chijiang Basin	25°23′N, 114°22′E	Palaeo–Eo	pollen	Sun and He, 1980	B C
58	Nanxiong Basin	25° N, 114°20′E	Palaeo–Eo	pollen	Zhang, 1981; Wu and Yu, 1981; Li, 1989	B C
59	Continental Shelf of East China Sea		Palaeo–Plio	pollen	Song et al., 1985; Sun et al., 1989; Zhang et al., 1990b	C
60	Yuyao	30°N, 119°E	Plio	leaf	Guo, 1983	C
61	Zhangpu	24°20′N, 117°45′E	Mio	leaf, pollen	Zheng, 1984, 1987	C
62	Sanshui Basin	23°05′N, 112°32′E	Palaeo–Eo	leaf, pollen	Guo, 1979; Song et al., 1986	B C
63	Zhujiangkou (Pearl River Mouth) Basin		Oligo–Plio	pollen	Sun et al., 1981; Lei, 1985	C
64	Changchang Basin		Palaeo–Eo	leaf	Guo, 1965, 1979	C
65	Fushan Depression		Palaeo–Plio	pollen	Sun et al., 1980c, 1981, 1982	C
66	Leizhou Peninsula		Palaeo–Plio.	pollen	Sun et al., 1980c, 1981, 1982	C
67	Beibu Bay, the South China Sea		Palaeo–Plio	pollen	Sun et al., 1981, 1982; Li, 1987	C
68	Maoming Basin	21°40′N, 110°50′E	Oligo	leaf	Guo, 1979	B C
69	Xiangxiang	27°26′N, 112°12′E	Eo	leaf	Li and Chen, 2002	C
70	Shangsi Basin	22°04′–22°10′N, 107°00′–107°15′E	Eo–Oligo	leaf	Guo, 1979	

(continued on next page)

Table 1 (*continued*)

No.	Site	Location	Age	Type of fossil	Reference	Age control
71	Nanning Basin	22°43′–23°00′N, 108°05′–108°63′	Eo–Oligo	leaf	Ning et al., 1994	B C
72	Hepu Basin	21°35′–21°58′N, 108°41′–109°36′E	Palaeo	leaf, pollen	Yang, 1993	C
73	Baise Basin	23°28′–23°55′N, 106°34′–107°21′E	Eo–Mio	leaf	Guo, 1979	B C
74	Kaiyuan	23°42′N, 103°14′E	Mio	leaf, pollen	Institute of Botany and Nanjing Institute, 1978; Li and Wu, 1978; Tao et al., 2000	B C
75	Pianxian	25°51′N, 104°38′E	Eo	leaf	Zhang, 1983	C
76	Yiliang	24°54′N, 103°07′E	Mio	wood	Tao, 1984	C
77	Tengchueng	25°N, 98°31′E	Mio	leaf	Tao and Du, 1982	C
78	Dechang	27°24′N, 102°9′E	Plio	leaf	Guo, 1978	C
79	Zhaotong	29°19′N, 103°42′E	Mio–Plio	pollen	Song, 1988	B C
80	Eryuan	26°6′N, 99°56′E	Plio	leaf, pollen	Tao and Kong, 1973; Institute of Botany and Nanjing Institute, 1978	C
81	Lanping	26°41′N, 99°E	Plio	leaf	Tao, 1986	C
82	Litang	29°35′N, 100°11′E	Eo	leaf, pollen	Chen et al., 1983, 1986; Guo, 1986	C
83	Markam	29°38′N, 98°41′E	Mio	leaf, pollen	Tao and Du, 1987	C
84	Gongo	30°48′N, 98°17′E	Eo	leaf, pollen	Song and Li, 1982; Li and Zheng, 1995	C
85	Rikeze	29°17′N, 88°49′E	Eo	leaf	Geng and Tao, 1982	C
86	Namling	29°43′N, 89°E	Mio–Plio	leaf, pollen	Li and Guo, 1976; Song and Liu, 1982b	C
87	Ngamring (Angren)	29°18′N, 87°13′E	Eo	leaf	Tao, 1981	C
88	Lbaze (Lazi)	29°N, 87°37′E	Eo	leaf	Tao, 1988a,b	C
89	Xixabangma Feng Mt (Shisha Pangma)	28°20′N, 85°45′E	Plio	leaf, pollen	Hsü et al., 1973	C
90	Gyirong	28°56′N, 85°17′E	Plio	pollen	Zheng, 1983	BC
91	Gar	32°30′N, 80°E	Eo, Mio	leaf	Geng and Tao, 1982	C
92	Zanda Basin	32°20′N, 79°30′E	Plio	pollen	Li and Liang, 1983; Li and Zhou, 2002	BC
93	Burang	30°20′N, 81°05′E	Plio	pollen	Cao, 1982	BC
94	Lunpola Basin	32°30′N, 90°E	Oligo–Mio	pollen	Wang et al., 1975; Song and Liu, 1982a	C
95	Area between Kunlun and Tanggula Moutain)	35° 30′–32°30′N, 92°–94°E	Mio–Plio	pollen	Kong et al., 1981	C
96	Qaidam Baisn		Eo–Plio	pollen	Zhu et al., 1985; Yang et al., 1994	A C
97	Zhenquancuo	36°N, 87°E	Plio	pollen	Huang and Liang, 1983	C
98	Wuqia, west Tarim Basin	39°42′N, 75°11′E	Palaeo–Mio	pollen	Wang et al., 1990a,b; Yang et al., 1994	A C
99	Kashi, west Tarim Basin	39°31′N, 75°56′E	Palaeo–Eo	pollen	Wang et al., 1990a,b; Zhang and Zhan, 1991; Zhang and Qian, 1992; Yang et al., 1994	A C
100	Kuqa (Kuche)	41°41′N, 82°58′E	Palaeo–Mio	pollen	Zhao et al., 1982; Wang et al., 1990a,b; Zhang and Zhan, 1991; Yang et al., 1994; Jin et al., 2002	A C
101	Jungaar Basin		Eo–Mio		Sun and Wang, 1990; Yang et al., 1994	A B C
102	Altay (Altai)	47°48′N, 87°E	Palaeo	leaf	Guo et al., 1984	C
103	Dunhuang	40°N, 94°43′E	Oligo–Plio	pollen	Ma, 1991	C

Table 1 (*continued*)

No.	Site	Location	Age	Type of fossil	Reference	Age control
104	Jiuquan Basin (Chiuchuan)	39°43′, 98 N °30′E	Eo–Mio	pollen	Song, 1958; Yang et al., 1994	A C
105	Jiuxi Basin	39°47′N, 97°32′E	Mio–Pleisto	pollen	Ma et al., 2004	A C
106	Yinchuan Graben	38°28′N, 106°16′E	Oligo–Mio	pollen	Yang et al., 1994	B C
107	Otog Benner	39°7′N, 107°58′E	Palaeo–Eo	pollen	Song and Zhang, 1990	B C
108	Tongxin	36°58′N, 105°56′E	Oligo	pollen	Sun, 1982	C
109	Zhangyi	35°30′N, 106°E	Eo	leaf	Li, 1979	C
110	Huanxian	36°23′N, 107°11′E	Eo	pollen	Li, 1979; Li and Chen, 2002	C
111	Xining-Minhe Basin	36°34′–36°18′N, 101°44′–102°48′E	Palaeo–Mio	pollen	Sun et al., 1980a,b,c, 1984; Wang et al., 1990a,b	B C
112	Hetao Basin	39°20′–41°20′N. 105°–112°E	Palaeo	pollen	Yang et al., 1994	C
113	Zekong (Zeku)	35°3′N, 101°30′E	Mio	leaf	Guo, 1980	C
114	Weinan	34°09′N, 108°33′E	Eo	leaf	Tao, 1965	C
115	Weihe Basin		Eo–Plio	pollen	Sun et al., 1980a	B C
116	Yuanmou Basin	25°30′N, 102°E	Plio	pollen	Liu and Li, 2002	B C
117	Zoige (Ruoergai)	33°37′N, 102°56′E	Mio	leaf, pollen	Liu, 1996; Liu and Li, 2002	C
118	Songpan	32°38′N, 103°37′E	Mio	leaf pollen	Liu and Li, 2002	C
119	Cangyuan	23°9′N, 99°14′E	Oligo	leaf	Guo and Chen, 1989	C
120	Jinggu	23°28′N, 100°41′E	Oligo	leaf	Guo and Chen, 1989	C
121	Lanzhou, Gansu	36°2′N, 103°45′E	Oligo	leaf	Geng et al., 2001	B C
122	Linxia	35°10′–35°51′, 102°30′–104°E	Oligo–Mio	pollen	Li et al., 1997; Ma et al., 1998	A C
123	ODP1148	18°50′N, 116°34′E	Oligo	pollen	Wu et al., 2003	C
124	Haema-1, Kachi-1, northern South yellow Sea Basin	35°54′N, 123°57′E; 35°18′N, 123°57′ E	Palaeo–Eo,Mio	pollen	Yi et al., 2003	AC
125	Za-altai Gobi, southern Mongolia		Palaeo	leaf	Makul'ekov, 1988	BC

Geographical coordinates of some sites not shown in the table can be found in Fig. 1 or Fig. 3. Age control: A—palaeomagnetism, thermoluminescence or radioactive datings; B—biostratigraphy based on vertebrate fossils; C—biostratigraphy based on paleobotanical fossils.

representative Tertiary pollen profiles will be briefly introduced: Western Tarim Basin, NW China; Xining–Minhe Basin, northeastern Tibetan Plateau; and Jianghan Basin, East China.

4.1. Western Tarim Basin, Xinjiang (Fig. 4) (Wang et al., 1990a,b; Zhang and Zhan, 1991; Yang et al., 1994)

Tarim Basin is the largest and driest desert basin, and one of the large-scale, oil-bearing regions of China (Fig. 3w). The centre of the basin, the Taklimakan Desert, is surrounded by the high mountain ranges: Tian Shan in its north; Kunlun Shan and Altun Shan in the south. In the west of the Basin where the Tian Shan and Kunlun Shan join the relief reaches ca. 7500 m a.s.l. The basin floor is located in rain shadow and has an average annual rainfall less than 100 mm, although in montane areas the average annual rainfall can reach 300 to 400 mm. The city of Kashi, for example, has an average annual temperature of 11.7 °C and the annual rainfall is 61.4 mm. Consequently, vegetation there is low and open and is comprised of shrubs, mainly from Chenopodiaceae and Zygophyllaceae, and grasses (Editor Board of Natural Geography of China and Chinese Academy of Sciences, 1979).

The Tarim formed as a wide and open basin from a narrow fault during the Cretaceous. Sea water of the Paratethys penetrated eastwards in the Paleogene and littoral sediments occur in the Basin's southwest. The lower sections are white gypsum intercalated with dolomite, sandstone and limestone while the upper facies are clay and organic limestone. Terrestrial red sandstone and clay intercalated with gypsum occurs in the east part of the Basin. Since the Miocene the surrounding mountains were progressively uplifted.

Consequently, in relative terms, the whole basin began to subside and red clastics intercalated with gypsum and halite were deposited. During the Pliocene the basin area was reduced and became more enclosed, resulting in a progressive increase in desertification (Tian et al., 1989).

The pollen profile from site Wuqia and Kashi (sites 98 and 99, Fig. 1), western Tarim Basin, shows climatic change since the late Cretaceous (Fig. 4) (Wang et al., 1990a,b; Zhang and Zhan, 1991).

The *Late Cretaceous* is characterized by a large number of spores of *Schizaeoisporite* and pollen of *Classopollis* found in mudstones and siltstones with gypsum, indicating an arid climate.

The *Paleocene* sediment is composed of red and grey limestones, shelly limestones and red mudstones intercalated with gypsum and dolomite. The gypsum and dolomite can reach several hundreds meters in thickness. The pollen assemblages are marked by high proportions of arid plants. There is no pollen data of the earliest Paleocene. The early and middle Paleocene period is dominated by *Classopollis* (23–48%) while the later period is dominated by *Ephedripites* (19–48%). Proteaceae pollen types occur through the whole profile in considerable proportions. Chenopodiaceae pollen appeared in the late Paleocene, but only in trace amounts. In addition a number of pollen types are related to modern tropical and subtropical evergreen arboreal plants, such as *Quercoidites, Cupuliferoipollenites* (Fagaceae), *Ilexpollenite* (Aquifoliaceae) *Sapotaceoidaepollenites* (Sapotaceae), *Sapindaceidites* (Sapindaceae), and *Rutaceoipollenites* (Rutaceae), etc., and others are probably related to modern deciduous trees from *Ulmoideipites, Ulmipollenites* (Ulmaceae), *Betulaceoipollenites* (Betulaceae) and *Juglanspollenites* (Juglandaceae). At the same time, there are a large number of pollen types which have no modern analogues. The large amounts of aridity-indicative pollen types and diversity of pollen types related to tropical and subtropical plants suggest that the climate was dry, but rather warm during the Paleocene.

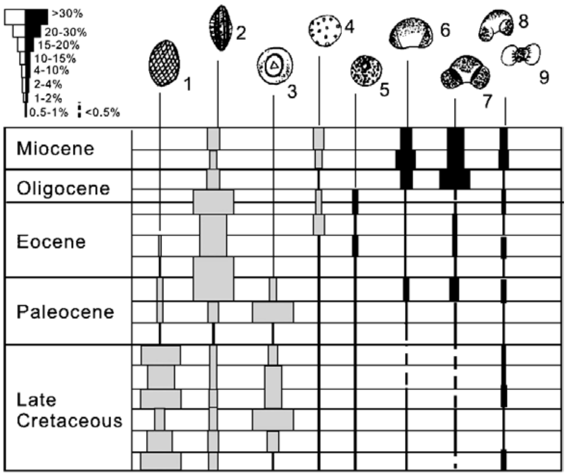

Fig. 4. Pollen diagram of selected types at Wuqia, west Tarim Basin (site 98) (Adapted from Wang et al., 1990b). Grey bars indicate arid plants: 1. *Schizaeoisporites*; 2. *Ephedripites*; 3. *Classopollis*; 4. Chenopodiaceae; black bars indicate plants inhabiting humid areas: 5. *Sparganium*; 6. *Piceapollenites*; 7. *Pinuspollenites*; 8. *Cedripites*; 9. *Podocarpidites* (modified from Wang et al., 1990b).

The *Eocene* record is comprised of shallow marine brown-red and green-yellow mudstones, white gypsum and shelly limestones, with fossil oysters and foraminifera. *Ephedripites* still dominates the pollen assemblages, averaging 26%. *Nitraria* pollen began to appear. *Classopollis* completely disappeared. Except for this the Eocene pollen assemblages have no clear difference with those of Paleocene age. From this we infer dry and warm climate during the two epochs.

The *Oligocene* is represented by brown and greyish yellow mudstones and sandy mudstones intercalated with many layers of white crystallized gypsum. Fossil foraminifera and bivalves have been found. Pollen assemblages are quite low in diversity. In the early period *Ephedripites* was still the dominant (up to 40%), but during the late Oligocene it decreased to averages of only about 11%,. At the same time a large number of various conifer saccade pollen appear, such as *Pinus* type (22%), *Picea* type (10%) and small percentage values for *Abies, Cedrus* and *Podocarpus*. These conifers usually grow in montane regions with humid and cool climate. The pollen profile is located on the southern slope of Tian Shan Mountain at ca. 1000 m a.s.l. and the surroundings are high mountains over 3000 m at the present time. The pollen data indicate a more humid and cooler climate than the early Oligocene, and this is probably related to uplift of the western part of Tarim Basin during the late Oligocene.

Miocene sediments are light brown and greyish green sandstones and mudstones intercalated with gypsum. Pollen assemblages in the Miocene are much more diversified than those of the Oligocene. Conifer pollen values increased to ca. 60%. These include *Pinus, Picea, Abies, Cedrus* and *Podocarpus*, and small amounts of *Tsuga* and *Keteleeria. Ephedripites* are present at amounts of 7% to 16%, and is thus similar to the late Oligocene. A major characteristic of the Miocene record is the abundance of herbaceous pollen types, mainly Asteraceae, Liliaceae, Labiatae, Chenopodiaceae and the aquatics *Sparganium, Nelumbo*, etc. It is most likely that continuing uplift of mountains around the Tarim Basin was the prime factor resulting in expansion of the conifers (Tian et al., 1989). Conditions were probably less humid in the lowland regions.

The *Pliocene* pollen record is absent in this area.

4.2. Xining–Minhe Basin, Qinghai (Sun et al., 1984; Wang et al., 1990a,b; Ma et al., 1998)

The Basin is on the northeastern edge of the Tibetan Plateau (Fig. 3a′) and is surrounded by mountains of about 4000 m high. The floor of the Basin is 2000 to 3000 m a.s.l. Its continental setting gives it a cold and dry climate today. The city of Xining located at 2261.2 m a.s.l., has an average annual temperature of 5.6 °C and annual precipitation of 371.2 mm. The study site (site 111, Fig. 1) has grassland vegetation composed mainly of *Stipa bugeana* and *S. breviflora* (Figs. 5 and 6).

This Basin began as a small fault in the early Cretaceous, on top of Palaeozoic metamorphic rocks covered with Cretaceous and Tertiary terrigenous sediments. Tectonics due to collision of the Indian and Asian plates led to local uplift and the basin itself shrank during the late Pliocene and Quaternary.

In the *late Cretaceous* white and red gypsum layers were laid down alternating with reddish-brown mudstones. Pollen assemblages are dominated by arid types such as *Shizaeoisporites* (3.8–23.6%) and *Ephedripites* (1–35%), all reflecting an arid climate.

The *Paleocene* record is comprised of reddish-brown or dark-grey mudstones with muddy gypsum or aggregates of gypsum. The pollen assemblages are dominated by *Ephedeipites* (up to 60% and usually averaging more than one-third of the assemblages). Proteaceae pollen values reach up to 18%. Percentages of *Schizaeoisporites* decrease significantly (averaging 4.9%) in the lower sections and are even less in the upper parts. *Nitraria* pollen occurs in trace amounts. In

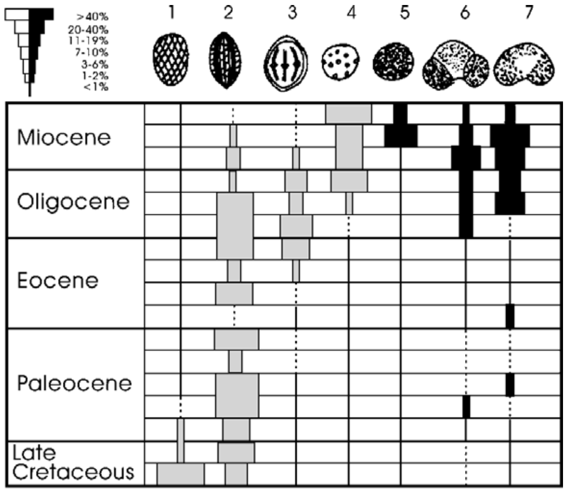

Fig. 5. Pollen diagram of selected types at Xining–Minhe Basin (site 111) (adapted from Wang et al., 1990b). Grey bars indicate arid plants: 1. *Schizaeoisporites*; 2. *Ephedripites*; 3. *Nitraria*; 4. Chenopodiaceae; black bars indicate plants inhabiting humid areas: 5. *Potomogeton*; 6. *Pinuspollenites*; 7. *Piceaepollenites* (modified from Wang et al., 1990b).

addition, a number of tropical and sub-tropical plants including *Quercus, Castanopsis, Engelhardtia, Liquidambar, Nyssa*, Sapindaceae and Rutaceae occur, plus some others with poorly defined modern analogues, such as *Nanlinpollis* and *Jianhanpollis*, etc. The climate interpreted from the pollen data is generally dry but the average temperature is relatively high.

The *Eocene* sediment is mottled or brown-red mudstones and pale grey muddy gypsum. In the early Eocene *Ephedripites* decreased and occurred sporadically but increased sharply in middle and late Eocene (reaching 37.3%). Proteaceae pollen almost disappeared, while *Nitraria* increased reaching 10 to 14% in the middle and late Eocene. Apart from these differences another notable change is the high percentage (3% to 35%) of a pollen type with three pores close to that of modern *Celtis* (Ulmaceae), probably representing the development of a temperate climate in the Eocene. Thus Eocene climates seem to be variable but with early stages relatively humid and later stages somewhat drier.

Early–middle Oligocene sediment is composed of lumpy and muddy gypsum, red mudstone and locally mirabilite and halite with vertebrate fossils. Pollen of arid plants dominated the pollen assemblages: average percentages for *Ephedripides* are 29%, *Nitraria* 27.5%, and there are small amounts of Chenopodia-

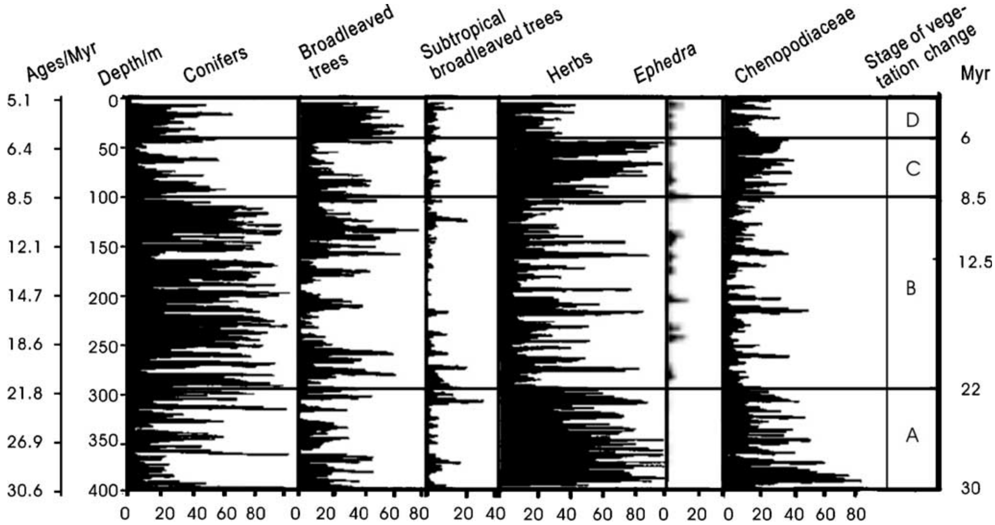

Fig. 6. Late Cenozoic percentage pollen diagram (30–5 My) at Linxia (Site 122) (modified from Ma et al., 1998).

ceae. *Celtis* pollen decreases from the Eocene and pollen of conifers began to appear and increases upwards through the profile. The climate appeared dry and relatively cool, probably as a result of the uplift of the Tibetan Plateau (Tapponnier et al., 2001).

Late Oligocene sediments are light yellow or brown mudstones and siltstones with muddy gypsum in the upper levels. The pollen assemblages differ significantly from those of the early Oligocene with decreased *Ephedripites* and *Nitraria* and increased Chenopodiaceae (33.7%). In addition, conifer pollen values are higher, include *Picea* (mean of 13.6%), *Tsuga* (about 7%), plus low proportions for *Pinus, Abies* and *Cedrus*. All of these conifers are distributed today in montane habitats, for example *Picea crassifolia* grows at 2400 to 3400 m a.s.l. in Qilian Shan, north of the pollen site, where annual rainfall is 400 to 500 mm. Such high pollen percentages of *Picea* indicate that there was spruce forest near the pollen profile and consequently the climate was cooler and more humid in the montane areas, but dry and desert or grassland vegetation developed in lower areas. Opinions differ on the precise age of this section, it was determined as early Miocene based on fossil rabbits and mice such as *Tachyoryctoides, Tataromys, Sinolagomys*, etc., but Wang et al. (1990a,b) assign it to late Oligocene based on correlation of the pollen data with those from Xinjiang.

The *early Miocene* in this site is equivalent to the Aquitanian and Burdigalian in Europe, based on fossil vertebrate fauna in the light brown mudstones with muddy siltstones and in the uppermost gypsum-rich fine sandstone. The pollen assemblages are quite different from older strata; pollen of arid plants is present in low proportions: *Ephedripites* (1–6%), *Nitraria* (2.5%), Chenopodiaceae (4.5%). At the same time pollen of temperate deciduous trees becomes more diverse and though *Ulmus* (*Ulmipollenite*) is present in significant numbers, all other types occur in low proportions, e.g., *Quercus, Carpinus, Juglans, Carya, Celtis* and *Zelkova*, etc. The montane conifers are present in significant percentages, e.g., *Picea* (4–24%), *Pinus* (up to 18%) and *Abies* as well as *Tsuga* in low percentages. The climate deduced from pollen data was much more humid and cooler than previously.

Middle Miocene sediments are light brown massive mudstones intercalated with muddy siltstones and gypsic fine sandstone. The pollen assemblage is similar to those of the early Miocene. Pollen values of the arid plants are still low; *Ephedripites* is found only in trace amounts; while Chenopodiaceae values are around 16%. At the same time montane conifers have increased, especially *Picea* (ranging from 9% to 47%) and aquatic plant percentages are higher, e.g., *Potamogeton* (1–33%). The pollen data denote a cooler, but humid climate at that time. The chronology was determined by fossil vertebrates such as *Protalactaga turgurensis, Megacricetodon sinensis*.

Late Miocene sediments are yellow, grey and brown mudstones, and sandstones with gravels containing fossil vertebrates. Pollen data are remarkably different from the early Miocene. The mean proportion of Chenopodiaceae reached 56.5%, while pollen of temperate trees and montane conifers significantly decreased in proportions. The climate had become very dry and probably open and desert vegetation spread across the basin.

There is no Pliocene pollen record in this area.

4.3. Jianghan Basin, Hubei (Zhang et al., 1993)

The Basin is situated in southeast China (site 48, Figs. 1 and 3j) in the middle of the sub-tropical warm and humid climate zone today. Wuhan city, for example, has an average annual temperature of 16.3 °C; and the mean annual rainfall is 1260 mm. The main native vegetation is subtropical evergreen broad-leaved forest (Wu, 1980). At the present time the Jianghan Basin is an extensive flat plain, but before the Neogene it was a large fault depression with the richest evaporites and the best oil-producing environment in southern China. During the Paleogene oil, gas, halite, and gypsum were developed in the basin. From the late Cretaceous to early Eocene the halite accumulated up to more than 2000 m in thickness. The whole basin was uplifted at the end of the Paleogene and the basin area became a flood plain during the Neogene and Quaternary (Chen et al., 1989). A large body of pollen data has been compiled by the oil companies, but we have found that the pollen records are not appropriately represented. Therefore, no pollen diagrm for the Jainghan Basin is shown here. Instead, we will bravely introduce the pollen data obtained from petroleum boreholes drilled in the western part of the basin (Zhang et al., 1993).

Early Paleocene is composed of grey or brown-red mudstones with gypsum, mirabilite and halite sediments containing pollen and gastropods. The bottom of the section is paleomagnetically dated to 65 My. *Ephedripites* (26%) and Ulmaceae (*Ulmoideipites* and *Ulmipollenites*) (27.7%) form a large part of the pollen assemblages. Proteaceae occurs in low proportions and some Araliaceae, Rutaceae, Sapindaceae and Palmae suggest modern tropical and subtropical vegetation. The climate at that time might have been dry and warm.

Late Paleocene and early Eocene strata contain the main petroleum and halite deposits in the Jianghan Basin. The lithology consists basically of purple or dark-grey mudstones and muddy gypsum. The top of this series of deposits was dated by potassium–argon as 52 My. In the pollen assemblages *Ephedripites* decrease to ca. 15%, while *Taxodiaceaepollenites* (Taxodiaceae) appears sporadically, but occasionally does reach 34% reflecting a humid or swampy habitat. Ulmaceae still occurs in high proportion (12–15%). The pollen records show a semi-arid or sub-humid environment, and most likely an alternation of humid and arid climates during that time.

The *late and middle Eocene* strata are composed of rhythmic layers of muddy gypsum, glauberite, oil shales and halite. *Ephedripites* again dominates the pollen assemblages, usually to about 20%, but reaching 54% at its maximum. Ulmaceae also occurs in high proportions (reaching 59%). Taxodiaceae values are ca. 15%, occasioanlly reaching 31%. The climate indicated by the pollen and lithological data suggest quite dry conditions but occasional alternation of drier and more humid episodes.

The *Early Oligocene* has dark grey mudstones, sandstones, muddy gypsum and oil shales. *Ephedripites* values are lower (averaging ca. 13%). Ulmaceae pollen dominates this stage averaging above 30% and the pollen of arid plants contains small amounts of *Nitraria*. Taxodiaceae fluctuates around 10%. The climate deduced from pollen records was still dry, probably with alternation of drier and more humid stages.

The lithology of *Late Oligocene* is greyish green mudstones interbedded with siltstones and containing oil shales, marls, and muddy gypsum. Pollen grains have been found solely in its lower part and preservation is rather poor. *Ephedripites* values are about 10%, while Taxodiaceae values are higher and reach up to 31%. The climate was probably more humid than earlier, but it is not clear whether it was due to a real amelioration of the climate or only a humid stage in a long arid period because of the very low resolution of pollen record.

The *Miocene* sediments are mudstones, sandstones interbedded with gravels and locally freshwater limestones. A great change in the nature of the pollen assemblages took place. *Ephedripites* almost disappeared and Taxodiaceae also decreased considerably. Fern spores as warm and humid climatic indicators occurred in high proportions (averaging 27%). Pine pollen is also present in large amounts and became dominant. Pollen of both temperate (*Ulmus, Juglans, Celtis Betula, Corylus, Carpinus*, etc.) and subtropical broadleaved (*Magnolia, Ilex.* Palmae, Sapindaceae, Myrtaceae, etc.) trees occurred in rather high diversity. The pollen and sedimentation records suggest that the arid climate of Paleogene time was completely replaced by humid one in the Miocene (Paleontological Group of Jianghai Oil Bureau, 1976).

The *Pliocene* is absent in the basin. Quaternary clay and sand deposits directly cover the Miocene sediments.

The pollen profiles from three basins described above illustrate the dataset we compiled from 125 sites over China. Many sites do not provide pollen sequences as long as those shown here, but there are a number of paleobotanical sites with occurrences of fossil leaves which yield more reliable stratigraphic and/or paleoenvironmental evidence (Table 1). Although the available records are highly unequal in quality, the dataset has enabled us to reconstruct the history of aridity and monsoon climate in China.

5. Evolution of Cenozoic arid zone in China

The Palaeogene environment settings in China here inherited from those of the Cretaceous (Wang, 2005). Here we focus on the Cenozoic Era because we believe that the modern East Asian Monsoon System was formed within that time interval, and its initiation should be expressed as the development of humid conditions in east and southeast China. In this paper we explore the distribution and migration of the arid zone based on paleobotanical records and sediment facies.

5.1. Paleogene

Tectonic deformation in late Mesozoic ("Yanshan movement") and then Cenozoic growth of the Himalayan–Tibetan orogen resulted in spreading rift basins in the east and compressional depression basins in the west of China. During the decades of oil and gas exploration, a total of 246 basins with Cenozoic sediments have been identified, mostly filled with non-marine sediments of Palaeogene age, and marine sediments of the same age are restricted to west Tarim Basin, southern Tibet, and Taiwan (Wang, 1985; Ye et al., 1993).

5.1.1. Paleocene (Figs. 7A and 8A)

It had long been considered that Paleocene deposits were absent in China because of tectonic movements between the Cretaceous and the Eocene. Paleocene sediments have only been recognized since fossil mammals were discovered in 1959 in Xinjiang. Since then a further 32 basins with Paleocene deposits have been discovered. They occur in limited areas, usually less than 1000 m in thickness and predominantly of non-marine origin (Ye et al., 1993).

Paleocene paleobotanical records were first reported in the 1970s when pollen from coal strata in Fushun, northeastern China (Song and Tsao, 1976) (site 18, Fig. 1) and in thick halite in Qingjiang, southeastern China (He and Sun, 1977a,b) (site 52, Fig. 1) were found. These represent totally different environments. The pollen data of the first site suggested a warm and humid environment, while *Ephedripites* in the halite deposit at Qingjiang indicates a warm but very dry environment. Dry environments in a very humid region influenced by summer monsoon rainfall today was a surprise and led the first author to gather more data of Paleocene age from southeast China. Synthesizing the data available in the late 1970s, Sun (1979) suggested a broad arid vegetation zone covered all of China except the northeast from the late Cretaceous to the Paleocene.

At present, two vegetational and climatic zones are recognized (Fig. 7A), though their boundary is unclear due to insufficient data coverage.

5.1.1.1. Temperate-subtropical humid vegetation zone of northern China. In this zone Paleocene sediments are scattered in several small basins. Coal and oil shale deposits are quite widely distributed but no evaporites have been so far discovered (Fig. 8A). Both fossil pollen and leaves of all sites pointed to a warm and humid environment, with only one exception at site 25 (Table 1; Fig. 1). Examination of the following three sites (sites 18, 1

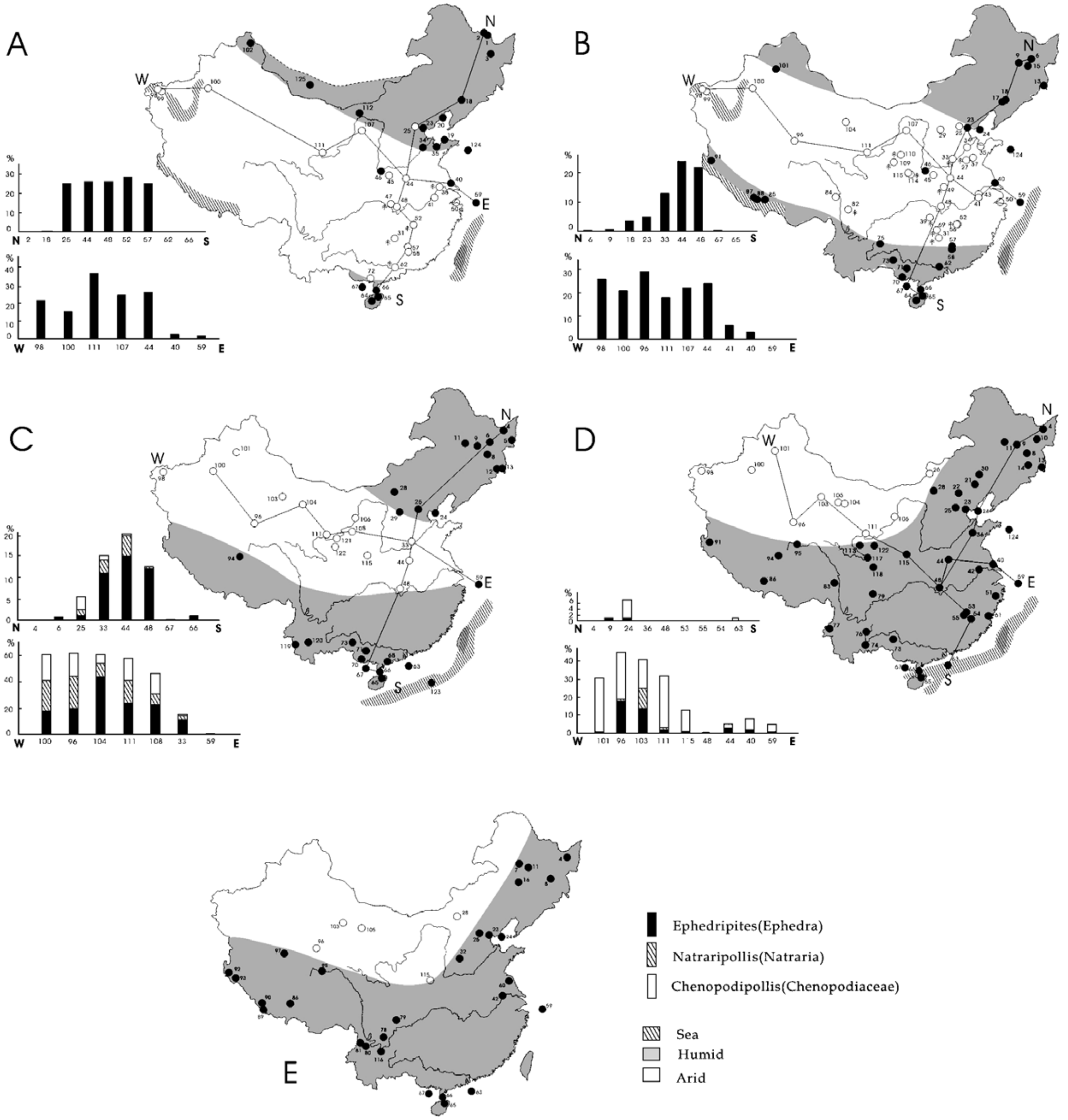

Fig. 7. Evolution of climate zones in China throughout Cenozoic based on palynological and paleobotanical data. (A) Paleocene, (B) Eocene, (C) Oligocene, (D) Miocene, (E) Pliocene. Black circles denote sites with humid–subhumid climates; open circles denote sites with arid and semiarid climate. Each epoch, but Pliocene (E), is provided with two transects showing *Ephedripites* % (black bar), a proxy of arid–semiarid climate. For the Oligocene (C) and Miocene (D), *Natraria* % (hatched bar) and Chenopodiaceae % (white bar) are displayed in addition to *Ephedripites* % (black bar).

and 19, Fig. 1) from the middle, northern and southern parts of this zone clearly identify its vegetation and climate.

Fushun coal field (site 18): the Paleocene is composed of a series of basalts and tuffs intercalated with coal, carbonaceous shales and siltstones. Pollen is

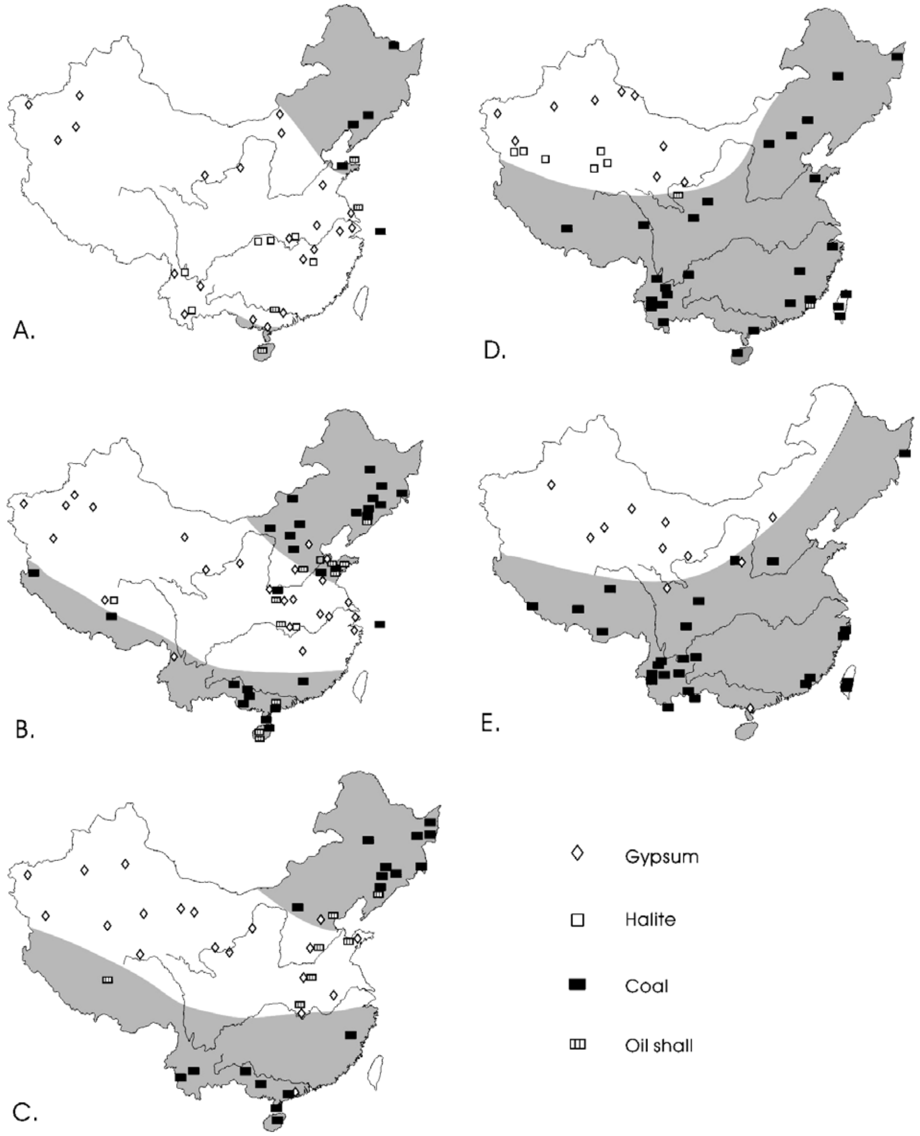

Fig. 8. Distribution of lithological proxies of climate from Paleocene to Pliocene, displaying a noticeable correspondence with paleobotanically based zonation in Fig. 6. (A) Paleocene, (B) Eocene, (C) Oligocene, (D) Miocene, (E) Pliocene. White symbols (gypsum, salt) are indicative of arid climate; black (coal) and hatched (oil shale) of humid climate (based on Li and Gu, 1994 and Liu, 1997, as well as lithology of pollen profiles).

abundant in the carbonaceous shales and arboreal pollen dominates the assemblages (up to 80%) with *Paraalnipollenites, Betulaepollenites, Betulaceoipollenites, Momipits* (which might be assigned to modern Betulaceae) and others growing in moist and temperate habitats. There are also some pollen types associated with tropical and subtropical environments such as *Caryapollenites*, *Engelhardtioidites* and *Liquidambarpollenites;* and some Taxodiaceae, *Cedrus* and, *Podocarpus* taxa with modern subtropical montane gymnosperm trees (Song and Tsao, 1976; Sun et al., 1980b). In a tuff of late Paleocene age fossil wood was found and identified as *Taxodioxylon, Sequoioxylon, Cedroxylon, Piceoxylon* and others related to modern moisture loving environments and now distributed in subtropical montane areas above 1000 m a.s.l. (Du, 1987). Both palaeobotanical and lithological records indicate a temperate to warm and humid environment at that time.

Jiayin Basin, Heilongjiang (site 1) is located in the extreme north of this zone. The Paleocene sedimentis composed of siltstones, carbonaceous shales and coal. In the siltstones and shales fossil leaves are found and consist mainly of broadleaved deciduous trees such as *Betula, Cercidiphyllum, Protophyllum Ampelopsis* and some hygrophyte needle-leaved trees like *Sequoia* and *Metasequoia*. The leaves of broadleaved trees are medium-sized and sawtoothed indicating humid conditions. In the palynological assemblages, high percentages of fern spores found in the same sediments also indicate a temperate-warm and humid condition at that time (Xiong, 1986). Similar fossil plant leaves also occur in Tanyuan (site 3) and Furao (site 2). In Furao, geographically close to site 1, pollen-rich Paleocene strata show compositions similar to those of the Fushun coalfield. *Paraalnipollenites*, *Betulaepollenites, Betulaceoipollenites Momipits* and pollen from Taxodiaceae are the dominant components, again indicating a humid environment (Liu, 1983).

In *Huang County*, Shandong (site 19) from the southern part of the zone, the late Cretaceous and early Paleocene records are composed mainly of red mudstones with some pollen of arid plants such as *Ephedripites*, *Ulmoideipites* and Proteaceae. The late Paleocene sediments contain oil shales and thin layers of coal. Pollen assemblages are marked by high percentages of *Pinus* and Taxodiaceae and a high diversity of temperate humid environment broadleaved trees, e.g., *Paraalnipollenites, Betulaepollenites, Betulaceoipollenites Momipits*. A series of pollen sites (Fig. 1) occur around the Huang County such as Liaohe River Depression (site 20), Huanghua Depression (site 23), Jiyang Depression (site 34) and Changwei Depression (site 35) and they have very similar pollen marked by the presence of *Paraalnipollenites, Betulaepollenites,* and *Betulaceoipollenite* (Yao et al., 1994).

The humid vegetation zone most likely extended westwards through southern Mongolia to the northern-most part of northwest China (Fig. 7A). Fossil *Taxodium* (currently occurs in wet places in North America), *Glyptostrobus* (in swampy areas of southern China), *Trochodendrocarpus, Viburnum, Ulmus* have been reported from Paleocene alluvial and lacustrine deposits at Za-altay Goby, southern Mongolia (site 125, Fig. 1) (Makul'ekov, 1988). Further westward, in Altay, in northern northwest China (site 102), abundant fossil leaves similar to those of Jiayin Basin and Za-altay Goby have been identified, including *Ditaxocladus planiphyllus* (an extinct plant from the Cupressaceae), *Sequoia langsdorfii, Taxodium tinajorum, Glyptostrobus europaeus*, *Cercidiphyllum diversifolium, Betula subpubescens, Corylus bellatula, Juglans, Pterocarya*, etc., making all together 38 species. Most of the fossil leaves have marginal teeth, coriaceaos texture and palmate venation, and some of them are very large; for example *Platanus* sp. is more than 30 cm in both length and width (Guo et al., 1984). The fossil plants of the both sites indicate a warm-temperate and humid environment, most like those of the northeastern China in the Paleocene.

5.1.1.2. Subtropical arid vegetation zone of south China. This zone occupied a major part of China with its northern boundary at ca. 37° to 38°N in the eastern part, and at ca. 45°N in the western part (see Fig. 7A). The southern boundary reached almost to the extreme south of China. The arid vegetation zone seemed to stretch westwards beyond China. In this zone evaporites such as gypsum, halite, mirabilite, potash and alkali salts are widely distributed (Fig. 8A).

Pollen assemblages in this zone are marked by a high proportion of *Ephedripites*. Fig. 7A shows that the highest proportions are found in mid and northwestern China, such as at west Trim Basin (sites 97, 98; averaging >21%), Kuqa (site 100; 15%), Xining–Minhe Basin (site 111; 36%) (Wang et al., 1990a,b), Zhoukou region (site 44; 26%) (Mao et al., 1995), and Jianghan Basin (site 48; 26%) (Zhang et al., 1993). All sites with high proportions of *Ephedripites* are associated with evaporite deposits; for example, in the late Paleocene, a halite intercalated with thin layers of mudstone of ca. 400 m in thickness occurs in Qingjiang Basin (site 52), and mean percentages of *Ephedripites* account for up to 28% and occasionally 50% at the most (He and Sun, 1977a,b). Pollen of Proteaceae, another indicator of aridity, chiefly occurred in the northwestern China, but its percentages were very variable, being, for example, 25% to

37.6% at Otog Benner in Inner Mongolia (site 107), 0% to 27% for Xining–Minhe Basin, and, in most pollen sites no more than 5%. Besides, some arid indicator spores and pollen of relictual Cretaceous plants, e.g., *Shezaeoisporites and Classopollis* are found in Paleocene sediments in a number of sites from northwest China, e.g., Tarim Basin, Kuqa, and Xining–Minhe Basin. The pollen types of *Ulmoideipites, Ulmipollenites* and *Quercoidites* occur in rather high proportions. *Rutaceoipollenites, Rhoipites* and *Sapindaceidites* were distributed very widely, but in rather low frequencies. Some now extinct pollen with three pores called *Normapollis* were also represented. Conifer pollen and fern spores were in low proportions. The pollen records all indicate dry, but probably subtropical warm conditions in the Paleocene.

The arid pollen types decreased in percentages towards the east and southeast. For example, *Ephedripites* has very low frequencies or is absent in the eastern and southern coastal areas. Thus, in Jiangsu area (site 40) and near the coastal area of the East China Sea, *Ephedripites* amounts to only 2.5% of pollen in Paleocene mudstones and marls, indicating a semi-humid environment (Song et al., 1981; Wang et al., 1994). A little further south in Changhe Depression (site 50) no *Ephedripites* was found and large quantities of conifer pollen occur inferring a more humid climate. Further east on the continental shelf area of East China Sea (site 59), the non-marine Paleocene terrigenous sediments with pollen types such as *Paraalnipollenites, Betulaepollenites, Betulaceoipollenites* and *Momipites,* suggest humid conditions (Song et al., 1985; Sun et al., 1989). *Ephedripites* frequencies also decrease southwards; for example in Sanshui Basin, Guangdong (site 62), *Ephedripites* amounts to only 2.5%, but the occurrence of fossil *Palibinia* leaves, at least, indicate a semiarid environment. Along the far southern coast *Ephedripites* occur only as single grains or has disappeared.

There are few macrofossil plant localities in this zone and almost all are concentrated in its southeastern part. These include: Hengyang (site 31), Yizheng (site 38), Dangyang (site 47), Qingjiang (site 52) and Sanshui (site 62). To take Hengyang as an example, the Paleocene deposits consist of mottled conglomerates, brown-red and purple red shales and sandstones with gypsum, and a variety of fossils occur including fish, plant leaves, ostracods, as well as pollen. All the fossil leaves have been assigned to one genus *Palibinia* with four species. *Ehedripites* accounts for a large part of the pollen assemblages (Li, 1965; Li and Zheng, 1995; Li and Chen, 2002). All other known fossil sites show similarities to the one mentioned above in the dominance of *Palibinia*, and very low diversity of fossils found in sediments with red beds and evaporites. The fossil leaves also indicate a dry environment in the southeast part of China at the time.

In summary, we can conclude that in the Paleocene a wide spread arid belt occurred in mid and low latitude China, and it is only in the coastal areas of the modern East and South China Seas that the aridity was reduced. This climate pattern exhibited by vegetation distribution can be demonstrated with transects across the country. Thus, the N–S transect of *Ehedripites* % in pollen assemblages shows high values in its middle part belonging to the broad arid belt, while in the W–E transect within the arid belt *Ehedripites* % maintains its high values and declines only closing to the coastal areas in the east (Fig. 7A).

5.1.2. Eocene (Figs. 7B and 8B)

The Eocene was a period of maximum subsidence of the terrestrial basins and, hence, of large lakes in China. In the eastern part of China, a series of fault basins developed during the Eocene as a result of tectonic movement of the Pacific and Eurasian Plates. Some of them were very extensive and accumulated very thick piles of sediments. For example, Eocene deposits were more than 2000 m thick in the Bohai Gulf Basin (Fig. 3f), ca. 3000 m thick in the Zhoukou Basin (Site 44, Fig. 1), and ca. 4000 m in the Jianghan Basin (Fig. 3j). In the west of China the Tethys gradually retreated westwards; at the end of Eocene it had almost disappeared and only a gulf remained in the west of the Tarim Basin; marine sediments were, therefore, of limited distribution (Ye et al., 1993).

Evaporites were still very widely distributed, even though the distribution of dark rocks such as coal and oil shales expanded, especially in the northeast of China. Instead of evaporites, coal and oil shales appeared in some locations along the southern margin of the Tibetan Plateau and along the coastal areas of South China. Even in the arid zone thin layers of oil shales occurred in thick evaporite deposits (Fig. 8B).

For this time period palaeobotanical evidence is plentiful. The pattern was different to the Paleocene. In the Eocene the arid vegetation in the extreme south of China was replaced by more humid one, so that three latitudinal vegetation zones can be identified as follows (Fig. 7B).

5.1.2.1. Subtropical humid vegetation zone of northern China. The area of this zone remained about the same for the Paleocene.

At beginning of the Eocene three large fault zones began to form in northeastern China. This resulted in a series of lacustrine and swampy deposits with coal and oil shales. A number of large coal fields such as those at Fushun (site 18) and Shenbei (site 17) were formed. Fossil leaves and pollen have been discovered in many places, but the most famous ones come from the Fushun Coalfield where fossil leaves, insects and fishes were recovered. More than 70 taxa of fossil leaves were identified among which *Metasequoia, Sequoia, Glyptostrobus* and *Taxodium* are most abundant, followed by broadleaved deciduous plants belonging to *Cercidiphyllum arcticum, Comptonia anderssonii, Alnus luxuriosa* and *Betula fushunensis*, plus the evergreen broadleaved genera *Cinnamomum* and *Dryophyllum*. Remarkable is the occurrence of tropical and subtropical plants *Cycas anomostoma* and *Sabalite*s, together with four species of ferns that also inhabit tropical and subtropical conditions today. The palaeobotanical data thus indicate a subtropical mixed evergreen and deciduous forest and a warm, humid climate at that time (Institute of Botany and Nanjing Institute, 1978; Li and Zheng, 1995).

There are a number of macrofossil plant locations such as Yilan (site 6), Hunchun (site 13), Yanshou (site 15) and Shenbei Coalfields (site 17) rather similar to Fushun Coalfield in fossil taxa, although differing from the latter in being less diverse in palaeo-flora. *Taxodium, Glyptostrobus, Sequoia* and *Metasequoia* occur at every location, and broadleaved deciduous taxa such as *Betula, Alnus, Quercus, Comptonia, Circidiphyllum,* and evergreen broadleaved plants of *Cinnamomum, Sabalites* and *Magnolia* can be found at most of the locations.

Pollen taxa from those locations closely resemble the assemblages represented by the fossil leaves (Sun et al., 1980b). Together the fossils denote a mixed broadleaved deciduous and evergreen forest flourishing at that time under humid subtropical conditions.

There are very few palaeobotanical records from the west of this zone. The only one so far studied occurs in the southern part of Jungaar Basin (site 101) where a various colored mudstone with Eocene vertebrate fossils (*Bothriodon* sp., *Trionychividea* sp., etc.) (Li, 1984b) were found. Pollen assemblages are rather different from those of other sites in northwestern China, with low frequencies of *Ephedripites* reaching up to 10% in the early stage of the late Eocene and occurring sporadically during the rest of the epoch. The pollen assemblages are marked by high proportions of *Cupuliferoipollenites*, a pollen type probably produced by an evergreen tree belonging to *Castanopsis* (Fagaceae). In addition a large quantity of aquatic plant pollen (*Potomogeton* and *Sparganium*) and fresh water algae *(Pediastrum)* were found. The pollen records imply humid conditions across most of the Eocene (Sun and Wang, 1990).

5.1.2.2. Subtropical to tropical arid to semiarid vegetation zone of middle China. This zone developed from the subtropical arid vegetation of south China in the Paleocene, but its southern boundary advanced northwards to ca. 25°N in the east, and to north of the Yarlung Zangbo River on the Tibetan Plateau in the west. The east and west parts of the zone had different character in sedimentation, paleobotany and environment, so we will introduce them separately.

As mentioned, a number of large lakes developed in the Eocene, while some marine sediments are present in the west Tarim Basin, yielding oysters and foraminifera. All of the other basins were terrestrial and contained mainly red clastic rocks with widespread gypsum, halite, mirabilite, gypsum, and dolomite. Fossil pollen is abundant in the west Tarim (sites 98, 99), Qaidam (site 96) and Xining–Minhe Basins (site 111). The pollen assemblages are marked by high frequencies of arid plants, mainly *Ephedripites* and *Nitraria*, with for example, the first taxon accounting for 29% on average and the latter one more than 30% in the Qaidam Basin, and similar values occur in the Kuqa (site 100) and Wuqia(site 98), west Tarim Basin. A new arid climate indicator pollen type-Chenopodiaceae (*Chenopodipollis*) appeared in a few basins in the later stages of the late Eocene, with values of 16% in the Qaidam Basin and trace amounts in other basins. In addition, *Ulmipollenites, Ulmoideipites* and *Quercoidites* were very common. A number of pollen types probably related to tropical and subtropical plants such as *Liquidambarpollenites, Ilexpollenites Sapidaceoidites* and *Myrtaceidites* were distributed rather widely, but in low frequencies. Conifer pollen assigned to *Pinus* and *Picea* also occur and Taxodiaceae was present in trace amounts. The pollen data suggest desert vegetation mainly from *Ephedra* and *Nitraria* was distributed across the basins and trees occurred on the mountains (Wang et al., 1990a,b; Zhu et al., 1985). The climate was probably warm and dry. δ^{34}S analysis of gypsum from the west Tarim Basin produced an average value of 20.5‰, indicating a hot and dry environment during the marine regression and associated evaporite deposition (Yang et al., 1994).

Extensive faulting occurred in the east portion of the arid zone during the Eocene. This resulted in a series of shallow to deep water basins and some of them were significant in size and with thick sediment accumulations as in the Bohai Gulf (site 24, Figs. 1 and 3f) and Jianghan Basins (site 48, Figs. 1 and 3j). Verious colored deposits containing gypsum, halite and mirabilite were very widely distributed and at the same time, oil shale and oil-cut mudstone occurred as well. Locally, as mentioned above, the Eocene record was composed of rhythmic layers of gypsum and halite with oil shales, as observed in the Jianghan Basin. Though *Ephedripites* still dominated the pollen assemblages, Taxodiaceae pollen was more common in comparison with the western part of this zone. In Zhoukou Basin (site 44), for example, in the early Eocene *Ephedripites* recorded 17.6%, and Taxodiaceae 10.7%; in the middle and late Eocene *Epheripides* was 25% and 4.7%, and Taxodiaceae 35% and 18%, respectively (Mao et al., 1995). Moreover, *Ephedripites* declined and Taxodiaceae increased eastwards and southwards, as shown on the continental shelf of the East China Sea (site 59) where Taxodiaceae accounted for 23% to 34% (Song et al., 1985; Sun et al., 1989). Tong et al. (2001) counted 313 pollen samples from glauberite, halite, grey mudstones intercalated with oil shales around the late Eocene in the Jianghan Basin (site 48) (dated by paleomagnetic method as 42 to 32 My). *Ephedripites* and Taxodiaceae were the dominant components in the pollen assemblages. Those authors took the percentage differences of *Ephedripite* and Taxodiaceae as a humidity proxy. The positive values indicate a comparatively arid climate and the negative ones the reverse. As seen from Fig. 9, most values were positive, but negative values were recorded for comparatively short time intervals. These results suggest that this time interval climate was dry, but with short, relatively humid stages. Both of palynological and lithological data give clear evidence that the climate of the east part of the zone during the Eocene was dry, but over the dry "background" an alternation of comparatively dry and humid phases was overprinted, in stark contrast to the west part of this zone where the climate for almost the whole Eocene was dry.

A total of 12 macro-plant fossil locations of the Eocene age were reported from southeast and central

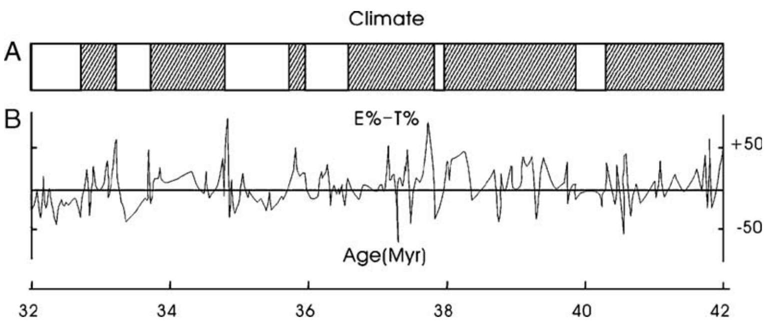

Fig. 9. Fluctuation of humidity superimposed on the background of arid climate around the end of Eocene in Jianghan Basin (site 48) (adapted from Tong et al., 2001). A. Alternation of arid–semiarid (shaded) and humid–subhumid (open) stages inferred from B. The percentage differences between E% (*Ephedripite*s, an arid indicator) and T% (Taxodiaceae pollen, a humid indicator), with the positive values indicating more arid and negative more humid climate.

China. All of them possess *Palibinia* and exhibit low diversity of fossil types (see Fig. 7B, marked by leave symbol). These include Lingjiang (site 56), two sites in Xiangxiang (site 69), Hengyang (site 31), Taoyuan (site 39) and Litang (site 82), Dawenkou near Taian (site 27), Puyang (site 33), Wucheng (site 49), Weinan (site 114), Huanxian (site 110), and Zhangyi (site 109). The sediments with *Palibinia* consisted of red clastic rocks with gypsum, trona, and halite. In Wucheng for example, *Palibinia* was buried in greyish green shales and oil shales intercalated with several layers of trona and halite, where trona alone may reach several hundred meters in thickness. The fossil leaves were discovered in shales together with the evergreen taxa *Torreya* and *Grevillea*, indicating a dry climate with high mean air temperature (Liu and Kong, 1978). Eocene fossil floras containing *Palibinia* have also been found in south Turkmenistan (35.30° N, 61.50° E) and the Isle of Wight, southern England (50°24′N, 120°W) (cited from Li and Chen, 2002) suggesting that the arid vegetation zone of central China extended westwards through Kazakhstan, Turkmenistan and to the coastal areas of the Tethys (Li, 1965, 1979; Li and Chen, 2002).

5.1.2.3. Tropical humid vegetation zone of southern China. In the Eocene coal and oil shales were widely distributed and no evaporite has been found in this zone. A number of macrofossil plants occurred. In coal-bearing deposits from the Changchang Basin (site 64) 10 types of fossil leaves were identified including ferns (*Osmunda*), aquatic plants (*Nelumbo nipponica, Salvinia*) and some leaves assigned to evergreen trees as *Cinnamomum lanceolata, Citrus* and *Sabalites*. The leaves were large in size and most of them were entire-margined suggesting a humid tropical environment (Guo, 1965, 1979). Other fossil plant locations close to the Changchang Basin with similar fossil include Baise (site 73), Shangsi (site 70), Nanning (site 71) and Panxian Basins (site 75).

In the southern Tibetan Plateau area, along the coast of the Tethys a few of fossil plant sites, such as Lbaze (site 88), Rikeze (site 85) and Gar (site 91) are known. At Lbaze 32 species of fossil leaves from 25 genera were found.They include *Magnolia, Annona, Ficus, Sapindus, Evodia* and *Sabalites*. Most of these are now components of tropical rainforest. More than 80% of the fossil leaves are entire-margined and above 70% were evergreen and most of them were medium-sized indicating a humid environment with relatively high temperature (Tao, 1988a,b). *Ficus* and *Eucalyptus*[1] were the main elements at Rikeze and Gar also suggesting humid and relatively hot conditions (Geng and Tao, 1982). A more complete Eocene pollen record was discovered from the continental shelf of the South China Sea (sites 66–67). In the early Eocene pollen diversity was very low and the palm (*Monocolpopollenites*) dominated the assemblages probably indicating tropical swampy habitants and a hot, humid climate. Absence of mangroves and marine alga suggests it was largely a fresh water environment. Subsequently temperate taxa (*Salix, Betula, Alnus*) mixed with tropical and subtropical plants replaced palm and dominated the pollen assemblages. At the same time a large number of fresh water algae (e.g., *Pediastrum*) and a water fern (*Ceratopteris*) occur. All of these indicate a warm, humid and mainly terrestrial environment at the middle Eocene. Appearances of brackish water alga and pollen of Trilobapollis, related to an extinct mangrove indicate that the continental environment was replaced by marine shelf conditions in the late Eocene. Climate had remained warm and humid (Sun et al., 1981, 1982).

Thus, the Eocene arid belt is similar to that of the Paleocene, and, also, the aridity reduced only in the coastal areas of the modern East and South China Seas. The N–S and W–E transects of *Ehedripites* in pollen assemblages display a similar trend to that in the Paleocene, but the values of *Ehedripites* percentages are in general lower than those in the Paleocene (Fig. 7B).

5.1.3. Oligocene (Figs. 7C and 8C)

During the Oligocene northwestern China was progressively elevated with the uplift of the Tibetan Plateau (Tapponnier et al., 2001). The Tethys thus completely retreated from the west Tarim Basin. At the same time uplift and erosion in the eastern China led to an absence of Oligocene sediments across extensive areas. Consequently, the distribution and thickness of

[1] The fossil occurrences of *Eucalyptus* in the Eocene deposits has been repeatedly reported from China (e.g., Chen et al., 1983; Guo, 1986). Since the genus is native to the Southern Hemisphere in the modern world, the identification is to be double checked.

Oligocene was much reduced in comparison with the Eocene, especially in southeastern China, and apart from the continental shelf of the East and South China Seas, only very limited amounts of Oligocene sediments, plant macrofossils and pollen have been found.

The available palaeobotanical and lithological data indicate that the Oligocene has the same basic signature of vegetation and climate of the Eocene, at least in the early Oligocene. But due to the limited distribution of Oligocene sediments and paleobotanical data, the boundaries of the three zones described here are not well defined.

5.1.3.1. Northeast temperate and humid vegetation zone. Before the Oligocene the humid vegetation zone probably extended though Mongolia to the northern part of northwestern China, but in Oligocene the humid zone was reduced and all of northwestern China became arid. A number of macro- and microfossil plant fossils were discovered in northeastern China with the Sanhe fossil flora in Longjing (site 12) being one of the representatives. In grey argillaceous siltstones with coal 24 macrofossil taxa were found including two water plants *Salvinia* and *Typha*, broadleaved deciduous trees of *Quercus, Fagus* and *Castanea* amongst others, and *Glyptostrobus, Sequoia, Metasequoia* from the Taxodiaceae. These data suggest a mixed conifer and broadleaved deciduous forest and a warm, humid climate. Guo and Zhang (2002) indicated that the temperature and rainfall were higher at that time compared to today. In Hulin (site 5), Sanjiang (site 4) and Yilang Basins (site 6), most of the fossil leaves found in coal bearing deposits were from temperate deciduous trees such as *Acer*, also indicating a humid environment.

Pollen data of this time are sparse and reconstructions remain uncertain. In coal-bearing sediments from Songliao Basin (site 11), Taxodiaceae (42–51%) dominated the pollen assemblages and fern spores were also rather high in frequencies. Nevertheless, most of pollen types belong to temperate deciduous tree taxa such as *Juglanspollenites, Betulaceoipollenites*, and *Ulmuspollenites* (Zhao et al., 1994). In the southern part of this zone fossil pollen sites, for example Fanzhi (site 29), contain large numbers of Taxodiaceae and subtropical tree taxa in the early Oligocene shales and lignites, indicating a warm and humid climate at that time. But the chronology depends on comparison with other pollen data (Zhang, 1998).

In summary, the fossil leaf and pollen data indicate warm-temperate and humid conditions in northeastern China in the Oligocene.

5.1.3.2. Subtropical arid and semiarid vegetation zone of central China. Due to the limited number of fossil sites it is difficult to determine the boundaries of this zone, but the available pollen and lithological data indicates that the southern boundary shifted northwards and the northern part of northwestern China became arid. Overall the arid zone somehow became narrower in the eastern part and wider in the western part of China.

Oligocene sediments from the continental shelf of the East China Sea provide much of the story since Oligocene sediments were absent in the southeast of China and have been found only in the large basins located west of ca. 115°E, such as Dongpu (site 33), Zhoukou (site 44), Weihe Basins (site 115) in central China, and Xining–Minhe (site 111), Qaidam (site 96), Tarim (sites 98–100) and Southern Jungaar Basins (site 101) in its western part.

In northwestern China the Oligocene is marked mainly by red clastic rocks often intercalated with gypsum and halite. Pollen assemblages were still dominated by pollen types of arid plants, but in comparison with the Eocene Chenopodiaceae significantly increased and in some locations even exceeded *Ephedripites* in pollen frequencies. For example, in Qaidam Basin (site 96) Oligocene pollen assemblages contain *Ephedripites* (13.8% to 26.7%), *Nitraria* (12.8% to 40%), and Chenopodiaceae (9.4% to 30%). Additionally, conifer pollen such as *Picea*, *Cedrus, Pinus,* and *Abies,* and pollen of temperate plants increased and at the same time pollen proportions of tropical and subtropical plants declined. These records indicate that desert shrubs were probably distributed around the lake basin, open deciduous forest was scattered on the montane slopes and conifers grew at higher elevations. It was dry and warm, but the air temperature was likely lower than that of the Eocene (Zhu et al., 1985). The pollen records are similar at Qaidam (site 96), Kuqa (site 100), Xining–Minhe (site 111), Jiuquan (site 104) and Southern Jungaar Basins (site 101). There are exceptional sites such as west Tarim Basin (sites 98, 99) where pollen of arid plants (*Ephedripites* up to 40%) was dominant in the early Oligocene, but in the late Oligocene a considerable amount of conifer pollen appeared (*Pinus* 22%, *Picea* 10% and low proportions of *Cedrus, Abies, Podocarpus*) and, at the same time, pollen of arid plants declined from 52% to 18%. This change of pollen composition might be related to uplift of mountains around the western Tarim Basin (west Kunlun and west Tian Shan Mountains) which provided the necessary cooler and more humid environment for montane forests.

Only a few Oligocene pollen sites are known in the east part of this zone, moreover, some of these yielded incomplete pollen data, for example in Zhoukou (site 44) and Jianghan (site 48) Basins. A more or less complete Oligocene pollen record was reported from the Dongpu Basin (site 33), where the Early Oligocene consists of purple-red and greyish green mudstones with gypsum and halite, and the pollen assemblages including *Ephedripites* (up to 16.3%), *Nitraria* (4.6%), and a few of Chenopodiaceae indicate a fairly arid climate. In the late Oligocene pollen assemblages from various colored mudstones with small amounts of oil shale, *Ephedripites* declined to 5.1%, Chenopodiaceae to 2.4%, *Nitraria* to 0.5%, and meanwhile pollen types indicating a more humid climate, e.g., fern spores (12.3%) and conifers (23% with *Pinus, Picea* and *Cedrus*) increased significantly (Research Institute of Exploration and Nanjing Institute, 1989). However, the studied pollen samples were taken from boreholes and the chronology was based on correlation with other pollen records, so caution about the interpretation of the data is warranted.

In contrast to this, brown mudstones intercalated with greyish green sandstones and conglomerates from the Weihe Basin (site 115), located in central China revealed two Oligocene pollen assemblages. In the lower assemblage Chenopodiaceae (14%), a small amount of *Ephedripites* and large number of pollen from aquatic plants, such as *Jussiaea* (a tropical water or swampy herb) and *Potamogeton* occur. The pollen assemblage of the overlying section contains high pollen proportions of arid plant taxa (Chenopodiaceae 23%, *Ephedripites* 17%) and low proportions of hygrophilous plants implying a more humid climate in the early Oligocene and arid one afterwards (Sun et al., 1980a).

In general, during the Oligocene the vegetation was xerophytic and the climate arid in the northwest, but the altitudinal zonation of the vegetation appeared in the western part probably due to uplift of the mountain ranges. For the eastern part of this zone, so far, it is still not clear if there was a real climatic change–from arid to humid conditions through the early to late Oligocene–or whether this change only represented some humid stages during the Oligocene. An important feature of vegetation change in the Oligocene was gradual replacement of *Ephedripites* by C4 plants such as Chenopodiaceae and *Nitraria.*

5.1.3.3. Tropical and subtropical humid vegetation zone of southern China. A series of small Oligocene coal-bearing basins have yielded Oligocene fossils. These include Shangsi (site 70), Baise (site 73), Nanning (site 71), Jinggu (site 120) and Cangyuan Basins (site 119). For example, at Jinggu the Oligocene was composed of dark grey mudstones, oil shales sandstones and coal, rich in fossil leaves mainly of evergreen broadleaved trees and with a small number of deciduous tree taxa. These included *Quercus, Lithocarpus* and *Dryophyllum* (extinct) from the Fagaceae, and *Phoebe, Nothaphoebe* and *Machilus* from the Lauraceae, as evergreen broadleaved components, and *Carya, Rose* and *Sorbus* as broadleaved deciduous trees. The vegetation deduced from the fossil flora represents a southern subtropical evergreen broadleaved forest and a warm and humid climate (Institute of Botany and Nanjing Institute, 1978; Guo and Chen, 1989).

In the northern part of the South China Sea (sites 63, 65–67) the Oligocene mudstones and sandstones contain abundant pollen and spores. The assemblages are dominated by fern spores in which *Ceratopteris* (water fern, fossil name is *Magnastriatites hawardi*) is a chief element and some species of *Lygodium, Cyathea* are represented. All these fern taxa grow in tropical and subtropical areas at the present day. Pollen taxa present are mainly tropical and subtropical evergreen broadleaved trees of *Alchornea, Sonneratia* and *Rhizophora,* but there were pollen types belonging to conifer and broadleaved deciduous tree taxa as well. These include *Ulmus, Alnus, Tilia, Cedrus, Dacrydium, Tsuga, Picea, Pinus* and others. In the late Oligocene only one genus, *Pinus,* acheived up to 40% of the pollen assemblages. The significant rise of conifer pollen frequencies indicates that there were mountains covered by conifer forest in southern China and evergreen broadleaved forest mixed with deciduous trees in the lowlands; mangroves grew along the coast at that time. The climate was probably warm and humid (Sun et al., 1980c, 1981).

Only one pollen site in the west part of this zone has records; this is Lunpola Basin, Bankog (Tibet) (site 94). Pollen assemblages in the various colored mudstones, sandstones and black shales are dominated by conifers (*Picea, Cedrus, Pinus Abies* and *Tsuga*) which account for up to 80% of the total pollen and spores. The pollen site is situated at ca. 4000 m a.s.l. at the present, while the fossil pollen record suggests an altitude of ca. 3000 m a.s.l. with a somewhat cool and humid climate during the Oligocene (Song and Liu, 1982a).

Thus, the southern part of China, especially the coastal areas, was covered with tropical or subtropical evergreen broadleaved forest and the climate was humid and hot. The middle of the Tibetan Plateau was already raised enough to enable alpine conifer forest to grow there.

In summary, the Oligocene climate pattern inherits that of the Paleocene and Eocene, but the arid belt stretching across China becomes narrower. Because in the Oligocene the indicator of arid climate *Ephedripites* was gradually replaced by C4 plants such as Chenopodiaceae and *Nitraria*, we may use the sum of *Ephedripites*, *Nitraria* and Chenopodiaceae percentages to estimate the degree of aridity. As seen from Fig. 7C, the N–S and W–E transects of the arid plants percentages revealed the same pattern as in the Paleocene and Eocene.

5.2. Neogene

In a tectonic and palaeogeographic context, the Neogene of China differs considerably from the Palaeogene. In the Neogene the pronounced uplift of the Himalayas was accompanied by a general subsidence of east China. By end of the Oligocene, the history of Cretaceous–Palaeogene rift basin in eastern China was completed and since then large areas in eastern China have been covered by extensive alluvial plains replacing the individual lacustrine basins of Palaeogene age. Therefore, non-marine deposits, usually fluvial and lacustrine in origin, occur in flat bottomed depressions and are composed of mudstones and sandstones partly rich in fossil leaves and palynomorphs (Wang, 1990a).

In northwestern China Neogene deposits are largely distributed in some of the large basins inherited from the Palaeogene, e.g., the Qaidam (site 96), Tarim (sites 98–99), Jungaar (site 101) and Jiuquan (site 104) Basins. In result of differential tectonic movement of the northwest, the Neogene deposits were very thick with, for example, up to 2000 m in the Qaidam Basin; coarse clastic rocks with evaporites were very widely developed (Yang et al., 1994).

In southwestern China and the southern Tibetan Plateau the Neogene is found as limnic deposits with lignite. It was a very important lignite-forming period in southwestern China and the lignite deposits can reach up to about a thousand meters and these contain abundant plant fossils.

The palaeobotanical and lithological evidence shows major changes in climate and vegetation between the Palaeogene and Neogene. The broad arid vegetational and climatic belt from the Paleogene collapsed and the arid zone was restricted to northwest China while the climate in eastern China became very humid under the influence of the East Asian monsoon circulation system (Wang, 1990a). Therefore, in the Neogene there were only two major vegetation zones in China: the arid zone in the northwest and the humid zone in the east and southwest (Figs. 7 and 8).

5.2.1. Miocene (Figs. 7D and 8D)

Although there were two major vegetation zones in the Miocene, the Tibetan Plateau has to be discussed separately from the rest of the humid zone because of the substantial difference in vegetation. Hence the Miocene vegetation will be introduced in the following order: the arid zone in northwest, the humid forest zone influenced by Asian monsoon system, and finally the temperate deciduous forest zone of the Tibetan Plateau.

5.2.1.1. Arid vegetation zone of northwest China. The latitudinal arid vegetation zone during the Paleogene (Figs. 7A–C and 8A–C) retracted to the northwestern part of China (Figs. 7D and 8D). The southern boundary of the Miocene arid zone retreated northwards to about 35° N and its eastern boundary seemed to expand. But this is based only on one pollen site near Erlian Basin (site 26) from the Tonggur Formation with a middle and late Miocene age dated by vertebrate fossils, and it contained a large number of herbaceous pollen taxa such as Chenopodiaceae (17.5–26.8%) and *Artemisia* (18.4–23.9%), inferring a steppe or forest steppe vegetation (Wang, 1990b).

At this time the Tethys Sea water had retreated completely from the western part of this zone. Terrestrial red clastic rocks intercalated with gypsum, halite and other evaporites were widely distributed.

In the Miocene of Linxia pollen profile (site 122; Fig. 6) herbaceous pollen declined significantly by comparison with the Oligocene, and pollen of needle-leaved and broadleaved trees increased markedly between 21.8 and 8.5 My, indicating that forest vegetation replaced forest–steppe, and a warm and humid climate developed. Following this herbaceous pollen increased and tree pollen decreased remarkably between 8.5 and 6.0 My suggesting a developing steppe vegetation and a reduced temperature and humidity. Since 6.0 My the herbaceous pollen values fell and the tree pollen increased again ending this cool and humid (during most of this epoch) Miocene episode (Ma et al., 1998). We introduce this profile in order to compare with other sites in the arid zone. A very similar situation of a sudden deterioration of climate around the late Miocene was found in the Jiuxi Basin (site 105), where the herbaceous pollen accounted up to 90% between 8.6 and 8.4 My (Fig. 10), reaching its maximum for the whole of the Neogene and indicating a stage of falling temperature and humidity, though it lasted for much shorter interval than at the Linxia Profile (Ma et al., 2004). Remarkable is the record of an arid–semiarid climate in the Jiuxi Basin at least since 13.8 Ma with an interval of increased humidity between 11.2 and 8.6 Ma (Fig. 10). This is broadly correlated with the Qinnan section of loess deposits where two intervals are distinguished by higher dust accumulation: 15–13 Ma and 8–7 Ma (Guo et al., 2002).

Similar amelioration of climate in the early–middle and deterioration in late Miocene time has been observed in a series of pollen profiles from northwest China, though there the resolution of pollen records and chronology is low. For example, in the Xining–Minhe Basin (site 111), cited earlier in Section 4.2, the pollen assemblages of early and middle Miocene showed marked minima in pollen proportions of arid plants (Fig. 5). In the Qaidam Basin (site 96) pollen of arid plants (*Ephedripites, Natraria* and Chenopodiaceae) accounted for more than 60% in the Oligocene, declined to 46% by the early Miocene and 31% in the middle Miocene, while

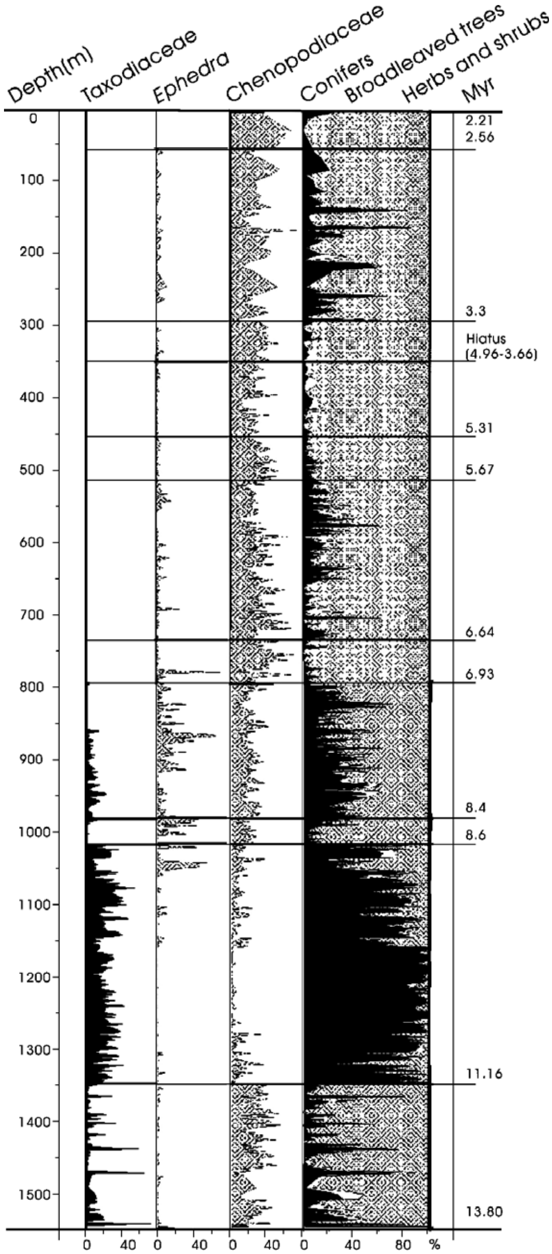

Fig. 10. Late Cenozoic pollen diagram (2.21–13.80 my) at Jiuxi Basin (Site 105) (after Ma et al., 2004).

at the same time pollen values of conifers rose to 31% and 76% respectively, with *Picea* contributing about half of the total pollen. This denotes a shift to a cooler and more humid climate in the early and middle Miocene. In the late Miocene pollen of arid plants increased (up to 57%) and pollen of conifers and broadleaved trees decreased indicating a return to a cool and dry climate (Zhu et al., 1985). Nevertheless, the amplitude of this climate change was expressed much more weakly than that in the Linxia profile. In the Dunhuang Basin (site 103) the early Miocene was a period of maximum pollen frequencies of conifers for the entire Cenozoic (Ma, 1991).

In summary, Miocene vegetation and climate was quite varied in northwest China, possibly indicating instability during the early stages of the evolution of the East Asian monsoon system.

5.2.1.2. Humid forest vegetation zone influenced by the Asian monsoon system. This was a time of very broad forest vegetation cover across all of eastern and southwestern China. There was variation from place to place and we will briefly introduce this below from north to south.

In northeast China there are a number of plant fossil sites and Dunhua (14) might be regarded as representative. Here a rich deposit of plant leaves was found in white diatomite and this flora was composed of broadleaved deciduous trees dominated by *Castanea ungeri, Quercus miovariabilis, Q. miocrispula* and *Fagus stuxibergii* belonging to the Fagaceae, but *Taxodium dubium* and *Glyptostrobus* also had a significant role. Most of their modern equivalents are hygrophilous and thermophilous tree species growing on mountains south of the Changjiang (Yangtze) River in the present. The altitude of the fossil site probably was 750 to 1500 m a.s.l.; the climate might have been warm and humid and the average annual temperature between 10 and 16 °C (Li and Yang, 1984).

In Shanwang (site 36) of northern China, one of the most famous Miocene fossil sites in the country, a rich fossil fauna and flora includes mammals, fish, snakes, insects, birds and plants preserved in diatomite sandwiched between basalt and tufaceous conglomerate (Yang and Yang, 1994). More than 100 species of fossil plants, mainly angiosperm leaves, stems, flowers, catkins, fruits and seeds were found. Most of the fossils plants are from broadleaved deciduous trees such as *Acer, Carpinus, Zelkowa, Juglans, Hamamelis* and *Carya*. A smaller number of evergreen broadleaved trees also occur, such as *Laurus, Ficus* and *Sapindus*. This flora is transitional between temperate and subtropical forms (Institute of Botany, and Nanjing Institute, 1978; Li, 1978). Pollen data suggested that the Shanwang flora was roughly comparable to modern vegetation in the summer wet mountain area of the middle and lower Changjiang River Valley, which requires a moist summer climate (Liu, 1986; Liu and Leopold, 1992, 1994).

There are a number of fossil pollen and plant locations northwest of Shanwang. In Chifeng (site 21) fossil woods of *Pseudotsugaxylon pingzhangensis, Piceaxylon* and *Pinusxylon* indicate a warm and humid climate (Tao et al., 1994). Ju'ud League (site 30) has yielded fossil leaves all of which belong to temperate deciduous tree taxa such as *Betula miolu-minifera, Carpinus* sp., *Cercidiphyllum cf. crenatum* and *Taxodium* sp., also indicative of a warm and humid climate (Zhang, 1986). In dark grey and calcareous mudstones of Shangdu-Huade (site 28) a rich pollen flora mainly from broadleaved deciduous trees (*Ulmus, Zelkowa, Juglans, Corylus*, etc.) occurs with a small number of subtropical trees (*Castanopsis*, Meliaceae, Rutaceae) (Wang and Zhang, 1990). In a coal deposit sandwiched between basalts at Wuluogong (site 22), pollen assemblages are marked by a high proportion of conifers (*Picea, Tsuga, Pinus*) (Gan, 1982). All of above plant fossils indicate a forest vegetation and with a warm and humid climate for that time.

Further south in the low and middle reaches of the Changjiang River a series of fossil sites occur. Around Nanjing (site 42) fossil leaves are preserved in alluvial muddy siltstones and silty mudstones, and consist mainly of *Podogonum ochningense*—a hygrophilous and thermophilous plant (ca. 44.5% to 87.2% of the fossil flora). Besides, some other hygrophilous and thermophilous plants, e.g., *Cocculus rotundifolius, Entada mioformosana, Morus* sp., *Zelkowa* sp. and *Lequminosites* sp. are also found. These represent a warm and humid climate. The chronology is based on fossil vertebrates and comparable to the European Orleanian and Vallesian stages (Li et al., 1984, 1987). In Jianghan Basin (site 48) pollen of arid plants declined from more than 10% in the Oligocene to trace amounts in the Miocene, and this coincides with the appearance of fern spores in high frequency (Paleontological Group, 1976). The picture was similar in Zhoukou Basin (site 44) where about 20% of pollen from arid plants in early Oligecene (late Oligocene absent) were reduced to 2% (Chenopodiaceae) and the dominants were broadleaved trees, mainly *Liquidambar, Ulmus* and *Quercus* indicating that the climate had changed from arid or semiarid in the Oligocene to comparatively humid conditions in the Miocene (Mao et al., 1995).

In the Weihe Basin (site 115), located in central China, high proportions of pollen of the water plant-*Trapa* (33%) and a declining proportion of arid plants (Chenopodiaceae 11%, *Ephedripites* 3%) in the Miocene also infer a shift to much more humid climate in the Miocene. The pollen bearing bed was dated by fossil vertebrates *Oioceros lishanensis, Listriodon lishannensis,* and *Alleptox minor* as Miocene and probably middle Miocene in age (Sun et al., 1980a; Li, 1984b).

In southeastern China near the East China Sea there are some Miocene fossil sites. In mudstones, sandstones and conglomerates intercalated with oil shales and lignite at Zhangpu (61) fossil leaves and pollen show the presence of tropical montane trees (*Podocarpus, Dacrydium* and *Phyllocladus*), lowland rainforest (*Anodendron* from the Apocynaceae, *Arenga, Calamus* from the Palmae, *Ficus* from the Moraceae) and mangrove (*Barringtonia*). These show that the climate was warm and with a very high humidity (Zheng, 1987, 1988; Zheng and Wang, 1994). The continental shelf of the South China Sea since the Miocene sees large numbers of mangrove pollen, mainly *Rhizophora* and *Sonneratia*, marine dinoflagelates and pollen of tropical and subtropical plants (e.g., *Castanopsis, Ilex*, Palmae and Sapotaceae); denoting the advance of the marine environment and that the climate was hot and humid (Sun et al., 1981).

At that time, the warm and humid air masses could reach to southwest China and the southeast part of the Tibetan Plateau without obstruction. Lignites and fossil plants are widely distributed in the southwest. In the coal beds of Kaiyuan (site 74) and Tengcueng (site 77), for example, rich fossil plant assemblages are composed mainly of evergreen broadleaved tree species from the families Fagaceae, Lauraceae and Lequminosae. Today such taxa occur in subtropical and even tropical areas with high air temperature and abundant rainfall (Institute of Botany and Nanjing Institute, 1978; Guo and Chen, 1989; Tao and Du, 1982; Li and Zheng, 1995).

5.2.1.3. Temperate deciduous forest zone of the Tibetan Plateau. We know two fossil plant locations in the southern Tibetan Plateau: Namling and Gar. Namling (site 86) is located at about 4000 m a.s.l. on the northern slope of the Himalayas, and it yields a very rich collection of Miocene fossil plants and pollen. The lower part of the section contains coal bearing deposits with fossil leaves of temperate deciduous trees such as *Betula parautilis, Poplus latior, Carpinus, Ulmus* and *Rubis*, and larger leaves suggest warm-temperate and humid conditions. In the upper part of the section there are some alpine oak leaves from *Quercus semicarpifolia, Q. pannosa* and evergreen shrubs such as *Rhododendron* and *Thermopsis.* These smaller leaved species with tooth margins indicate that the climate had changed from temperate and humid to cool and humid, most likely associated with uplift of the Himalayas (Li and Guo, 1976; Guo and Chen, 1989). Gar (site 91) is situated at about 5000 m a.s.l. in southeast Tibet and contains fossil leaves of temperate deciduous plants (e.g., several species of *Populus, Salix* and *Albizzia*). The leaves are small in size and tooth-margined, and this infers a temperate and moist climate and that the fossil site might be situated at ca. 2500 ma.s.l. at that time (Geng and Tao, 1982).

In the northern Tibetan Plateau between Kunlun Shan and Tanggula Shan Mountains (site 95) fossil pollen records are recovered from a series of boreholes. Pollen assemblages are marked by very high proportions of fern spores (mainly *Drynaria* and *Lepisorum*) reaching up to 65% of total pollen and spore counts. Besides, pollen of subtropical tree taxa (*Quercus, Carya* and *Melia*) and montane plants (*Tsuga* and *Rhododendron*) occur in low proportions. Kong et al. (1981) suggested a subtropical mixed broadleaved and deciduous forest flourished and a warm, humid climate prevailed in the region for this period of the Miocene. The pollen sites then might have been located at no more than 2000 m a.s.l. At Zekog (site 113) in northeastern Tibetan Plateau, fossil leaves and fruits are found in brown-red and green siltstones with fibrous gypsum. The fossil flora consists mainly of broadleaved deciduous trees, e.g., *Podogonium, Salix, Acer* and one of the gymnosperm-*Taxus*, along with some aquatic or swamp herbs (e.g., *Typha* and *Phragmites*). Guo (1980) considered that "their modern equivalents are known to spread over the lower and middle reaches of the Yellow River and the flora may indicate a temperate to warm and arid climate". But we believe that the fossil flora might best match mesic habitat. Anyhow, this fossil site was most likely situated close to the boundary between the arid and humid vegetation zones. Ages of these records are based on correlation of pollen data. If the dating is correct, it indicates that during the Miocene forest still survived in northern and north-eastern Tibetan Plateau.

In summary, a great change of vegetation and climate occurred from the start of the Miocene. The zonal arid vegetation of mid latitude China collapsed, and east and southeast China, and even the Tibetan Plateau, developed humid forest vegetation areas, though with different vegetation characteristics. The arid vegetation retreated to northwest China. This again is best represented by the transects of arid plant percentages (sum of *Ephedripites* %, *Nitraria* % and Chenopodiaceae %). As shown by Fig. 7D, only individual sites contain arid plant pollen in east China (see the N–S transect), all the high values are restricted to the northwest part of the country (the W–E transect).

5.2.2. Pliocene (Figs. 7E and 8E)

The distribution patterns of vegetation and climate in the Pliocene were similar to those of Miocene, with the arid zone in the northwest part of China, expanded somewhat in the Pliocene.

5.2.2.1. Arid vegetation zone of northwest China. The arid vegetation advanced east- and southeast-wards to the Shangdu-Huade (site 28) and Weihe Basins (site 115) which were earlier covered mainly by forest (compare Fig. 7D,E). Herbaceous pollen reached dominance in the Pliocene. For example, *Ephedripites* accounted for 60% in the Weihe Basin and near 80% in the Shangdu-Huade Basin (Wang and Zhang, 1990; Sun et al., 1980a). The replacement of the Miocene forest with steppe or forest–steppe in the Pliocene infers a transition from more or less humid climate to an arid one.

There are no macro-plant fossil occurrences and only a few pollen sites in this zone. All of the pollen data are dominated by herbs, mainly Chenopodiaceae, *Artemisia* and at a lesser extent *Nitraria* and *Ehedripites*. At the Jiuxi Basin (site 105) in the early Pliocene (5.7–3.3 My) herbaceous pollen mainly of *Artemisia* and Chenopodiaceae account for up to more than 80% (even 100% in some samples), indicating arid steppe or desert–steppe vegetation. In the late Pliocene (3.3–2.2 My) pollen assemblages are still dominated by herbs, but in comparison with the early Pliocene, some *Picea* became common in some short humid phases (Ma et al., 2004). Pollen assemblages in the Qaidam (site 96) (Zhu et al., 1985) and Dunhuan Basins (site 103) (Song, 1958; Ma, 1991) are also marked by very high herbaceous pollen values but with low time resolution, nevertheless indicating an open vegetation and an arid climate.

5.2.2.2. Humid forest vegetation zone influenced by the Asian monsoon system. Several pollen records have been published for northeast China: Fulareji (site 7), Songliao Basin (site 11), Qianan (site 16) and others. At Fulareji, for example, tree pollen values are high in the early Pliocene (until 3 My) and consist of broadleaved deciduous tree species such as *Betula, Castanea, Ulmus. Alnus,* and *Juglans*, plus some subtropical components (e.g., *Carya, Liquidambar* and *Podocarpus*) denoting that humid broadleaved forest vegetation was developed at that time. Late Pliocene (3.0–2.0 My) herb pollen accounts for up to more than 80% of the assemblages. The record indicates broadleaved forest vegetation and a more warm and humid climate than those from before 3.0 My. Today the site is located in temperate steppe vegetation and the climate is rather dry. The timing of the change from forest to steppe occurred at ca. 2.0 My. The profile was dated by themoluminescence and paleomagnetic methods (Liu et al., 1990). The other pollen sites show very similar records. At Qianan (site 16), for example, pollen assemblages were dominated by temperate deciduous tree taxa before 2.4 My and later by pollen of herbaceous taxa. The age at the site was determined by paleomagnetism (Jia et al., 1989). In Songliao Basin (site 11) Pliocene deposits contain fossil leaves and pollen of temperate deciduous trees, e.g., *Poplus, Betula, Alnus, Acer* and *Corylus* (Xia and Wang, 1987; Zhao et al., 1994). This indicates that the middle part of northeast China was humid and forested during the Pliocene and that the steppe vegetation and dry climate of today seem to have existed since the early Quaternary.

In Yushe Basin of north China (site 32) a very rich plant and animal fossil assemblage is present in mudstones, sandy mudstones and marls. The chronology was fixed by ^{10}Be and paleomagnetic methods as 5.1 to 1.8 My (Shi et al., 1994). Pollen data showed that before 2.3 My this area was covered mainly by forest vegetation which was interrupted for several short periods with steppe or steppe–parkland. The forest vegetation consisted mainly of subtropical broadleaved taxa (*Carya, Liquidambar* and *Hamamelis*) and conifers (mainly *Picea*) inferring a relatively warm and humid climate. The subtropical taxa diminished in frequencies up the profile and had disappeared from the area by ca. 2.3 My. Since then the herbaceous pollen mainly of *Artemisia* and Chenopodiaceae dominate the assemblages (Cao and Cui, 1989; Shi et al., 1993). Huanghua Depression in the Bohai Gulf Basin (site 23) may represent the east part of the northern China Plain. Pliocene age pollen is found in black shalestones and is mainly from temperate broadleaved deciduous tree taxa such as *Quercus, Ulmus, Alnus* and *Corylus*. Subtropical components like *Carya, Liquidambar, Engelhardtia* and *Corylopsis* occur also in rather high frequencies. The climate was probably humid and relatively warm (Li and Liang, 1981; Guan et al., 1982; Design and Research Institute, 1989).

Very few areas of southern China have Pliocene fossil plant sites, and most of them are situated near the coast of the East and South China Seas. Pliocene fossil plants from Yuyao (site 51), representative of montane areas of eastern China, have a mixed of broadleaved trees (*Machilus, Myrica, Liquidambar* and *Ormosia*), subtropical montane conifers (*Cedrus Tsuga*) and boreal conifers (*Abies* and *Picea*). The fossil leaves are of moderate size, thin or in some cases coriaceous in texture, with tooth or entire margins indicating subtropical montane forest vegetation and a comparatively warm and humid climate (Guo, 1983). In coastal areas and the continental shelf of the South China Sea, a series of pollen sites such as at the Zhujiangkou (Pearl River Mouth) Basin (site 63), Fushan Depression (site 65), Leizhou Peninsula (site 66) and the continental shelf of the South China Sea (site 67) are known. Plentiful pollen and spores are found in Pliocene mudstones with foraminifers (*Globoquadrina altispira*, *G. venezuelana*) and calcareous nannofossils (*Discoaster brouweri, Sphenolithus abies*). Pollen types of tropical and subtropical lowland evergreen broadleaved trees are dominant in which *Castanopsis,* a main component of tropical lowland rainforest, seasonal rainforest and subtropical lowland evergreen broadleaved forest, accounts for up to 25 to 40% of total pollen. Fern spores and pollen of evergreen broadleaved trees or shrubs are also important, such as *Myrica, Saururus, Piper* and *Anodendron.* The vegetation is interpreted as reflecting a warm and humid Pliocene climate in the southern coastal area of China (Sun et al., 1980c; Lei, 1985).

In southwest China, Pliocene lignite-bearing lacustrine and swampy sediments in several small basins yield plentiful plant fossils. At Eryuan (site 80), located in the middle of the region, fossil leaves in lignite bearing sediments consist mainly of alpine oaks such as *Quercus semicarpifolia, Q. spathulata* and are accompanied by some deciduous trees such as *Acer paxii, Celties bungeana* and *Populus*. Cones of *Pinus yunnanensis,* seeds of *Abies* and fruits of *Trapa* are also found. The vegetation recognized through the fossil plants is that of a mixed conifer and broadleaved forest in a subtropical mountain setting at ca. 2500 m a.s.l., i.e., close to the present altitude (Tao and Kong, 1973). Two plant fossil bearing sites, Lanping (site 81) and Dechang (site 78), are found to be very similar to Eryuan. These also contain fossil leaves from alpine oaks with entire margins (modern alpine oaks in the region have toothed margins), suggesting a warmer and moister climate compared to today. This is indicative of intensification of the summer monsoon and, hence, may be a response to uplift of the Himalayas (Guo, 1978; Tao, 1986).

5.2.2.3. Subalpine forest zone of the Tibetan Plateau. Pliocene pollen records are reported from the southern slopes of the Himalayas and the northern part of the Tibetan Plateau, but macro-fossil plants are known only from Xixiabangma (Mount Shisha Pangma, site 89), which is one of the highest peaks of the central Himalayas (8013 m a.s.l.). At an altitude of 5700 to 5900 m a.s.l. on the northern slope, fossil leaves of evergreen alpine oaks are preserved in greyish yellow sandstones. Species present are *Quercus semicarpifolia, Q.* cf. *pannosa* and *Q.* cf. *senescens*. Pollen analysis reveals a large amount of *Cedrus* and *Quercus*. The chronology was determined by correlation with fossil plants from Kashmir, Ebene of Bulgaria and Cantal, southern France. The fossils were interpreted to indicate a warm climate and an altitude about 2500 m a.s.l. at the time (Hsü et al., 1973), although the way of palaeo-altitude estimation was debated (Molnar and England, 1990).

Pollen sites in Zanda Basin (site 92) are located at 3700 to 4405 m a.s.l. in the western part of the northern slope of Himalayas. It contains vertebrates and pollen in lake deposits, which have been dated as middle and late Pliocene on the basis of the fossil vertebrate *Palaeotragus microden.* Pollen assemblages consist mainly of montane conifers such as *Cedrus, Picea* and *Abies*, and significant amounts of fern spores suggesting a subalpine conifer forest then flourished at about 2500 to 3000 m a.s.l., about 700 to 1900 m lower than today (Li, 1983; Li and Liang, 1983; Li and Zhou, 2002). Very close to the above mentioned site with respect to pollen assemblages is the Gyirong Basin (site 90), situated at 4000 to 4300 m a.s.l. on the northern slopes of the Himalayas; it yields middle and late Pliocene vertebrates and pollen of subalpine conifers indicating that the area has been uplifted by ca. 2000 m since then (Zheng, 1983). The fossil floras indicate that the Himalaya area was ca.2000 m lower in the middle and late Pliocene, and that moisture from the Indian monsoon could once reach there and brought plenty of rainfall.

Two fossil sites are known for the northern Tibetan Plateau, i.e., Zhenquancuo (site 97) and an area between Kunlun and Tanggula Mountains (site 95). Lake Zhenquancuo is located between 4800 m and 4930 m a.s.l. and pollen assemblages found in lake sediments are marked by dominance of *Picea* and *Pinus*, together with *Cedrus, Podocarpus*, and trace amounts of deciduous trees (*Quercus* and *Corylopsis*). The vegetation registered in the pollen record is interpreted as a subalpine conifer forest. This demands warmer and more annual rainfall (no less than 600 mm) than at the present time (100 to 400 mm). Huang and Liang (1983) surmised that the altitude was much lower in Pliocene than it is today. The chronology is based on correlations with other pollen data.

Overall, then, forest vegetation still occurred on the Tibetan Plateau during the Pliocene indicating that the altitude at that time was low enough to permit passage of Indian monsoon moisture.

In summary, the distribution pattern of vegetation and climate in the Pliocene maintained that of the Miocene, with some expansion in arid area (Fig. 7E). Due to the limited fossil sites, no transects can be made for the percentages of arid plants in pollen assemblages.

6. Discussion: evolution of the East Asian monsoon system

To summarize, the compiled set of palaeobotanical and lithological data has revealed a radical change in climate pattern of China since the Paleocene (Figs. 7 and 8). The predominance of xerophilous plants like *Ephedripites* and occurrence of huge piles of halite and gypsum in southeast China, particular in the middle and lower reach of Changjiang during the Paleocene, presents a striking contrast to the humid climate today. As seen from our discussion above, the Paleocene witnessed the most extreme typical aridity in the broad W–E belt across China, which experienced some fluctuations during the Eocene as shown by the appearance of intercalated layers denoting relatively humid conditions. More significant fluctuations occurred in the Oligocene, especially its late stage, but the limited distribution of deposits of that epoch hampered a detailed reconstruction. The Miocene displayed a substantially different climate patterns, with the arid zone restricted to the northwest which then expanded east- and southeast-ward during the Pliocene and has been maintained through the Quaternary.

Despite of all the detail differences between epochs in the Cenozoic, two contrasting patterns of climate zone distribution can be recognized: the Paleogene pattern with a arid belt stretching across the country (Fig. 11C), and the Neogene one with the arid zone in the northwest (Fig. 11B). The latter is very close to what we have today: the arid–semiarid zone of China is restricted to its northwest (Fig. 11A). The modern climate pattern in China is a result of the Asian

Fig. 11. Distribution of arid zone in China: A. Modern, the 200 mm and 500 mm isohyets delineate the arid–semiarid zone (Editor Board of Natural Geography of China, 1979); B. Miocene as an example of the Neogene climate pattern; C. Eocene exemplifying the Palaeogene. Arid area is shown in white, and humid in grey.

monsoon circulation which brings moisture to the eastern and southwestern parts of China, leaving the northwest as arid due to the absence of the summer monsoon influence.

As shown by a preliminary estimation, the vapor source for summer precipitation in eastern China is provided mainly by the East Asian monsoon (68%), and the rest 32% by the Indian monsoon (Chen, 1992). The similarity in climate pattern of China between the Neogene and the present suggests the existence of the monsoon system since the Miocene. Our dataset provides further evidence for reorganization of the climate system in China around the Oligo/Miocene boundary and supports the notion about the early Miocene establishment of the East Asian monsoon system (Zhou, 1984; Wang, 1990a; Liu, 1997; Liu et al., 1998).

However, the compiled evidence for the early initiation of the East Asian monsoon is at odds with the statement about the "onset of the Indian and east Asian monsoons" about 8 My supposedly related to a significant increase in altitude of the Tibetan Plateau (An et al., 2001). Fig. 12 displays the Neogene records of marine and terrestrial proxies of monsoon and aridity: the percentage of planktonic foraminifer *Neogloboquadrina* in the South China Sea indicative of monsoon-related high productivity (Fig. 12B, Wang, 2001; Wang et al., 2003); δ^{13}C of black carbon as a C4 plant proxy again from the South China Sea (Fig. 12A, Jia et al., 2003); occurrence of eolian deposits in the Loess Plateau, China, with the proportion of wind-blown minerals with grain size >19 mm in loess and red clay (winter monsoon proxy) and variations of magnetic susceptibility (summer monsoon proxy) (Fig. 12D and C, An et al., 2001; Guo et al., 2002); and dust flux from the central Pacific related to aridity in Asia (Fig. 12E; Rea et al., 1998). The relatively heavy δ^{13}C values of black carbon imply the occurrence of C4 plants on the land associated with monsoon climate. Since the earliest peak of δ^{13}C appeared about 20 My (Fig. 12A), the record was interpreted as early Miocene initiation of the monsoon system (Jia et al., 2003). This is well in line with the discovery of the Miocene loess (22–6 My) in China (Guo et al., 2002). Like its Pleistocene equivalent, the Miocene loess testifies to enhanced aridity in the dust source areas and energetic winter monsoon winds required for dust transport. Development of palaeosols in the Miocene loess sequence indicates increased moisture supply by summer monsoon winds. Thus, the East Asian monsoon has existed through the Neogene, since 20–22 My at the latest.

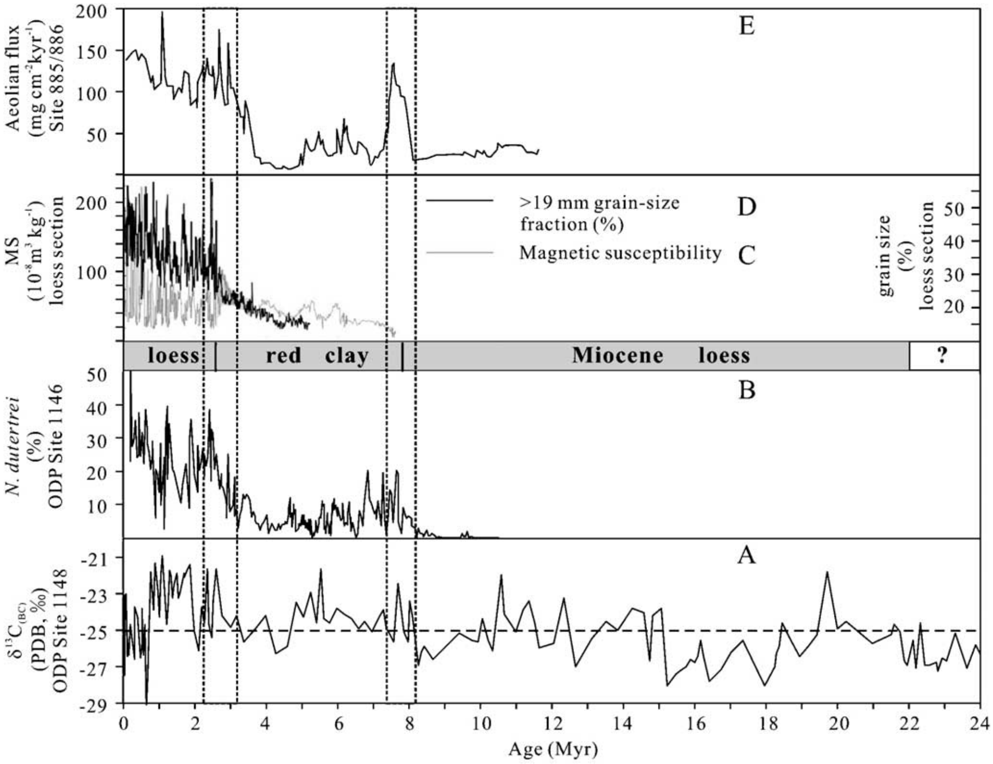

Fig. 12. Neogene records of East Asian monsoon and aridity evolution. (A) Isotopic composition of black carbon, ODP Site 1148, South China Sea (Jia et al., 2003); (B) *Neogloboquadrina dutertrei* %, ODP Site 1146, South China Sea (Wang, 2001; Wang et al., 2003); (C) Magnetic susceptibility and (D) >19 μm grain size fraction % from the Zhaojiachuan section on the Loess Plateau (An et al., 2001), and the time range of loess, red clay and Miocene loess in northern China (Guo et al., 2002); (E) Dust flux (mg/cm^2/ky), ODP Sites 885/886, central Pacific (Rea et al., 1998). Dotted lines show the time intervals of enhancement of the East Asian monsoons around 8 My and 3 My.

Fig. 12 also shows further evolution of the East Asian monsoon. Noticeable is the peak around 8 My in dust flux from Asia (Fig. 12E), in *Neogloboquadrina* % (Fig. 12B), and in black carbon isotope (Fig. 12A) from the South China Sea, suggesting an enhancement of the Asian monsoon system. This event broadly coincides with the beginning of the red clay deposition in the Loess Plateau and the increased *Globigerina bulloides* percentages in the Arabian Sea, previously taken as evidence for the onset of the Asian monsoon system (e.g., An et al., 2001). It becomes clear now that this was a major event within the long history of monsoon evolution. In the Miocene loess sequence, two intervals are distinguished by higher dust accumulation: 15–13 My and 8–7 My (Guo et al., 2002). These were periods of enhanced aridity in the source areas, as evidenced by pollen data from Jiuxi Basin, northeast of Tibet (Ma et al., 2004) and sediment records in the Pacific (Rea et al., 1998). The next major event in evolution was the monsoon enhancement around 3 My associated with the beginning of accumulation of the Plio-Pleistocene loess, when all monsoon proxies raised to a higher level (Fig. 12).

Therefore, the Asian monsoon system has a longer history than previously thought, but the monsoon system also displays great variability. The readers are referred to review papers (e.g., Wang, 2005; Wang et al., 2005) for further discussions on the driving factors of the monsoon evolution, and here we only demonstrate that the reorganization of the climate pattern in China around the Paleogene/Neogene boundary signified the onset of the Asian monsoon system. An open question is the precise time and the nature of the transition in climate system, whether it was a gradual, stepwise or abrupt. As the majority of our data are terrestrial records with oil-exploratory drill holes as an important source, the insufficient time constraint of these non-marine deposits preclude the possibility of studying the Oligocene/Miocene transition in detail. Fortunately, ODP site 1148, northern South China Sea (site 123, Fig. 1) has recovered the entire sequence over the past 32 my and revealed that the most significant tectonic deformation occurred around 25 My (Wang et al., 2003). This was recorded as a slumping section with the strongest excursions in all logging curves and with four stratigraphic unconformities that together erased a record of about 3 my in the late Oligocene (Li et al., 2005). Geochemical analyses found a drastic shift of source areas of sediment at the same time (Li et al., 2003). This new finding coincides with our records showing instability in climate during the late Oligocene (Section 5.1.3).

All these have led us to a hypothesis that the East Asian monsoon system started to develop in the latest Oligocene as a response to tectonic deformation of Asia. Although the data available now are still limited, the hypothesis is testable with additional data from further investigations.

7. Conclusions

1. A compilation of palaeobotanical and lithological data from oil exploration and stratigraphic studies in China has revealed a completely different pattern of climate zones in the Paleogene when a broad belt of aridity stretched across China from west to east. This is inherited from the Late Cretaceous and well displayed in particularly during the Paleocene.
2. From the Early Miocene up to now, the arid zone has been restricted to northwest China, and the Paleogene/Neogene contrast suggests a transition from a planetary to monsoonal system in atmospheric circulation. In other words, it must be the East Asian summer monsoon that brought moisture from the ocean to east China, and the reorganization of the climate system around the Oligocene/Miocene boundary provides evidence for the establishment of the East Asian monsoon.
3. The early Miocene occurrence of the East Asian monsoon is supported by a number of new discoveries: the Miocene loess–paleosol sequence at Qinan, western Loess Plateau in China, from 22 My to 6 My (Guo et al., 2002); the early Miocene occurrence of C4 plants in the South China Sea region as early as 20 Ma (Jia et al., 2003); and the middle Miocene mammalian faunas about 16 to 14 Ma from northern Thailand suggestive of a monsoon-like wet climate (Ducrocq et al., 1994).
4. In the Neogene, the monsoon system displays great variability both in space and time, and there is evidence for enhanced aridity and monsoon intensity at 15–13 My, around 8 My and 3 My. The new data do not support the notion about onset of the Asian monsoon system around 8 My.
5. Insufficient time constraint of non-marine Cenozoic deposits in China does not permit a detailed study on the Oligocene/Miocene transition. Additional work is needed to find out the precise time (late Oligocene or end of Oligocene) and the nature (gradual or abrupt) of this important transition. According to the data available now, the transition is hypothetically assigned to the latest Oligocene.

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