The vegetation and climate change during Neocene and Early Quaternary in Jiuxi Basin, China

MA Yuzhen[1], FANG Xiaomin[1,2], LI Jijun[1], WU Fuli[1] & ZHANG Jun[1]

1. Key Laboratory of Western China's Environmental Systems and College of Resources and Environment, Lanzhou University, Lanzhou 730000, China;
2. State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075, China

Correspondence should be addressed to Ma Yuzhen (email:yzhma@lzu.edu.cn)

Received April 4, 2003

Abstract Sporopollen record in the Laojunmiao Section at Yumen in the Hexi Corridor foreland depression at the northern margin of the Tibetan Plateau revealed that during the period of 13.0—11.15 Ma the ecological environment of the Jiuxi Basin is characterized by steppe vegetation and a semi-moist climate. During 11.16—8.60 Ma prevailed forests of cypress and a still warmer, moister climate; steppe vegetation and dry climate began probably at about 8.6 Ma. Although aridification had been relaxed time and again during 8.40—6.93 Ma (forest-steppe, warm-semi-moist), 6.64—5.67 Ma (open-forest and steppe, warmer-semi-moist) and 5.42—4.96 Ma (steppe, semi-arid), the climate in the region became drier and drier in response to the frequent occurrence of aridity during 6.93—6.64 Ma (steppe, semi-arid), 5.67—5.42 Ma (desert-steppe, arid), 3.66—3.30 Ma (desert-steppe, arid) and 2.56—2.21 Ma (desert, arid). Perhaps the important findings of our study are the notable expansion of drought-enduring plants during 3.66—3.30 Ma and about 2.56 Ma and the replacement of vegetation by vast arid desert.

Keywords: Tibetan Plateau, Hexi Corridor, sporopollen record, ecological environment, vegetation evolution, aridification.

DOI: 10.1360/03yd0110

Desertification and aridification in the inland of Asia are the important scientific issues pertaining to the existing environment of mankind and the sustainable development of society in western China. The onset and evolution sequence, development and process of history and the mechanism of this transition are thought to be one of the most attractive hot objects of research on climatic changes in the Northern Hemisphere during the Cenozoic, which may have involved glaciation in the Northern Hemisphere and the uplift of the Tibetan Plateau. Studies of large-scale eolian dust accumulation in the Xifeng and Lingtai loess sections on the Loess Plateau showed that desertification must have occurred in the inland of Asia during Late Miocene (8 Ma) and must have been associated with the uplift of the Tibetan Plateau during this period of time[1—5]. Development of aridification in Asia and South America reflected the enhancement of dust accumulation rates in South and North Pacific during 8—7.7 Ma. Particularly at 3.6 Ma there occurred a drastic increase in dust accumulation rate, which is also explained to be closely related to the uplift of the

Tibetan Plateau[6]. The prevalence of steppe and C_4 steppe vegetation during the Early-Middle Miocene in Pakistan, South and North America and Africa[7,8] suggests that ecological changes marked by the predominance of real steppe vegetation took place during 8—4 Ma[7,8]. Whether the expansion of C_4 steppe vegetation is due to the decrease of CO_2 concentrations in the atmosphere or to the variation of precipitation and climatic temperature caused by tectonic movement is still a question in open. The above question could not be accurately solved before further evidence is developed[9]. Recent studies have further demonstrated that the source areas of aeolian dust and energetic winter monsoon to transport dust materials must have existed in the inland of Asia during the Early Miocene (22 Ma), which indicates the initial phase of desertification[5]. The information about vegetation and environment developed from the surroundings of the Tibetan Plateau and inland-basin strata is a piece of direct evidence for the desertification and aritification in the inland of Asia. We have obtained vegetation and climatic change records in the past 30 Ma in the Linxia Basin of northern Tibetan Plateau[10], but they cannot fully indicate the process of aritification in the inland of Asia, partly because the Linxia Basin is not located in the center of the inland. Cenozoic sediments of great thickness were widely deposited in the Jiuxi Basin of the Hexi Corridor located in the inland of Asia, which is very important for the study of environmental and climatic changes both in northern Tibetan Plateau and in the inland of Asia. Detailed sporopollen studies of the Laojunmiao Section, which has been accurately dated, at Yumen have been conducted and the results provide strong scientific evidence for the above described climatic/ environmental changes.

1 Section and chronology-stratigraphy

The Laojunmiao Section, located at Yumen (97°32′E, 39°47′N) in southern Jiuxi Basin, consists of the Shulehe Fm., including the Getanggou and Niugetao members, Yumen, Jiuquan and Gobi gravel formations (Fig. 1). The whole section is 1960 m thick. The focus of our discussion is placed on the sporopollen record from the Shulehe Fm. and the lower portion of Yumen gravels (1539 m thick).

The Getanggou Member (>608 m) consists of siltstones and mudstones intercalated with muddy sandstones or pebbly sandstones; the Lower Niugetao Member (608—847 m) is composed mainly of interbeddings of sheet-like sandstones, siltstones and mudstones; the Middle Niugetao Member (847—1020 m) is made up of sandy conglomerates, pebbly sandstones, gravely sandstones and muddy sandstones; the Upper Niugetao Member (1020—1206 m) is comprised of thick gravels and sandstones. Yumen gravels (1206—713 m) consist largely of thick layers of pebbles to cobble conglomerates and sandy conglomerates intercalated with lenticular or banded sandstones and muddy sandstones.

Paleomagnetic samples of mudstone and siltstone were taken at 2 m intervals. Each oriented block sample was cut into 3 sets of parallel cubic specimens, some of which were measured at the Paleomagnetism Laboratory of the Institute of Geology and Geophysics, CAS, on a 2G Enterprises cryogenic magnetometer, and the others were measured at Geological Department, University of Michigan, on a 2G Enterprises cryogenic magnetometer under zero magnetic field condition.

Results of paleomagnetic study showed that a total of 21 normal polarity zones and 21 reversed polarity zones are clearly recognized in the Laojunmiao Section, most of which can be well correlated with the standard polarity time-scale[11] (Fig. 2). As viewed from the above paleomagnetic results, it can be seen that there is a good linear correlation between depth and age, as shown in Fig. 2, except for a few points of unconformity, paleomagnetic age can be well correlated with fossil age of the strata and ESR age[12]. That is to say, the age is reliable. Therefore, the boundary ages of the Getanggou and Niugetao members and the Yumen, Jiuquan and Gobi gravel formations in the section are >13—8.3 Ma, 8.3—< 4.9 Ma, 3.66—0.9 Ma, 0.8—0.14 Ma, and 0.14—0 Ma, respectively. Geochronological age of the sporopollen assemblage is about 13—2.21 Ma[13].

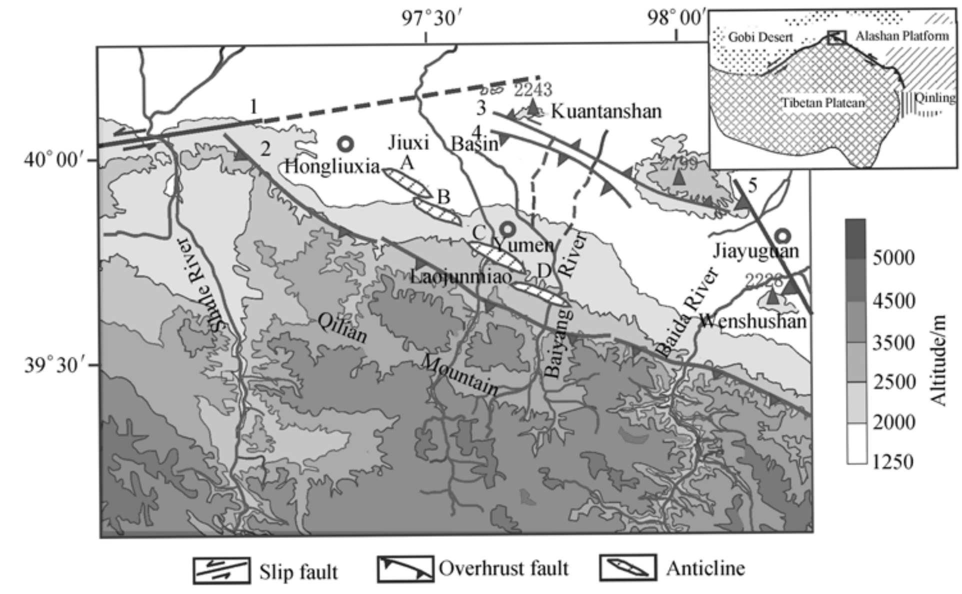

Fig. 1. The tectonic setting of the studied area and location map of the section. 1, the Alythn Fault; 2, the North Qilian fault; 3, the Jiayuguan-Wenshushan Fault; 4, the Kuantanshan Fault; 5, the xinminbao Fault; A, the Qingcaowan Anticline; B, the Yaerxia Anticline; C, the Laojunmiao Anticline; D, the Shiyougou Anticline

2 Sporopollen record

Six hundred and fifteen samples (615) for sporopollen analysis were taken at 1—2 m intervals from the lower portion of the Yumen gravel and the Shulehe Fm. of the Laojunmiao Section. The procedure of fossil sporopollen analysis is described as follows: 100—150 g of sediment sample was treated with 36% HCl and 73% concentrated hydrofluoric acid (HF), respecttively. Furthermore, the sporopollen was concentrated and the remaining material after acid reaction was sieved through a 10 μm mesh in an ultrasonic bath. The prepared specimens were mounted with glycerol and examined (×400). More than 100 sporopollen grains were acquired from most of the samples (97%). Approximately 200 sporopollen grains were collected from 85% of the samples and over 1000 grains were obtained from some of the samples. Eighty-eight taxa were identified. 28 families and 34 genera of fossil pollens and spore were identified. Based on the proportions of coniferous, temperate and warm-temperate deciduous trees, and herbaceous plants, in combination with sporopollen concentrations and A/C ratios, nine sporopollen assemblage zones were distinguished and are numbered from 1 (bottom) to 9 (top) as shown in Figs. 3 and 4.

Zone 1 (0—204 m, 13.0—11.15 Ma): *Artemisiaepollenites*-*Chenopodipollis*. This zone is characterized by low sporopollen concentrations and A/C ratios (1—2). Herbaceous plants (7.38%—99.08%), including mainly *Artemisiaepollenites* (6.55%—77.65%) and *Chenopodipollis* (2.42%—50.09%) along with *Echitricolporites*, *Tubulifloridites*, *Graminidites, Nitrariadites* and *Ephedripites*, are dominant. Coming next are coniferous trees (0.21%—85.54%), consisting of *Inaperturopollenites* (0.21%—50.34%) and *Taxodiaceaepollenites* (2.45%—72.06%) with minor *Piceaepollenites* and *Pinuspollenites*. The amounts of temperate and warm-temperate (0%—21.12%) deciduous sporopollen grains, composed of *Salixipollenites, Ulmipollenites*, *Quercoidites* and *Momipites*, are relatively low.

Zone 2 (204—539 m, 11.15—8.60 Ma): *Inaperturopollenites*-*Taxodiaceaepollenites*. The highest sporopollen concentrations are produced in this zone. This zone is characterized by a pronounced peak of conifers (23.95%—99.51%), consisting mainly of *Inaperturopollenites* (8.57%—89.22%) and *Taxodiaceaepollenites* (2.36%—53.78%). The growth of herbaceous plants (10.62%—85.14%), including mainly *Artemisiaepol-*

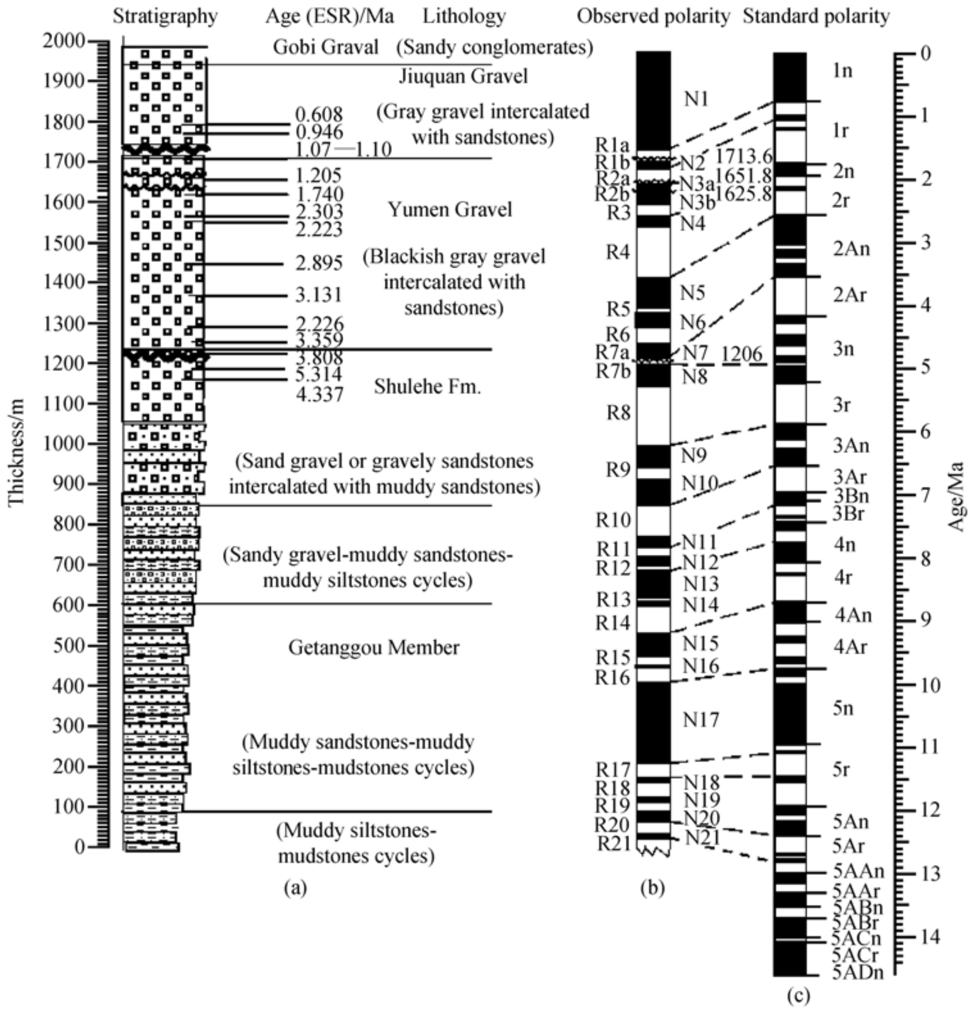

Fig. 2. Stratigraphy, Paleomagnetic and Chronology of Laojunmiao section. Characterization of stratigraphy and paleomagnetic in (a) and (b) from [13]; (c) from [11]; ESR ages from [12].

lenites (1.05%—38.29%) and *Chenopodipollis* (0.45%—35.33%), is greatly suppressed. There are only minor amounts of temperate and warm-temperate deciduous trees comprised of *Betulaceoipollenites, Salixipollenites, Quercoidites* and *Ulmipollenites*.

Zone 3 (539—573 m, 8.60—8.40 Ma): *Artemisiaepollenites-Chenopodipollis-Ephedripites*. Sporopollen concentrations and A/C ratios (1—2) are relatively high. Drastic increases in herbaceous plants (39.75%—98.45%) occurred primarily at the expense of coniferous (0.51%—32.90%) and temperate and warm-temperate deciduous trees (0%—12.25%). The zone is marked by high percentages of *Artemisiaepollenites* (19.32%—55.76%), *Chenopodipollis* (8.69%—28.26%), *Ephedripites* (1.53%—44.44%) and *Echitricolporites* (2.85%—26.08%) and minor amounts of *Piceaepollenites*, *Pinuspollenites*, *Inaperturopollenites*, *Salixipollenites* and *Momipites.*

Zone 4 (573—772 m, 8.40—6.93 Ma): *Inaperturopollenites-Artemisiaepollenites-Chenopodipollis-Ephedripites.* Sporopollen concentrations and A/C ratios (1) are relatively low. Coniferous trees (5.91%—62.07%) consist mainly of *Inaperturopollenites* (6.32%—55.38%) and *Taxodiaceaepollenites* (0%—20.9%) and their proportion is higher than in zone 3, but lower than in zone 2. Herbaceous plants (30.51%—

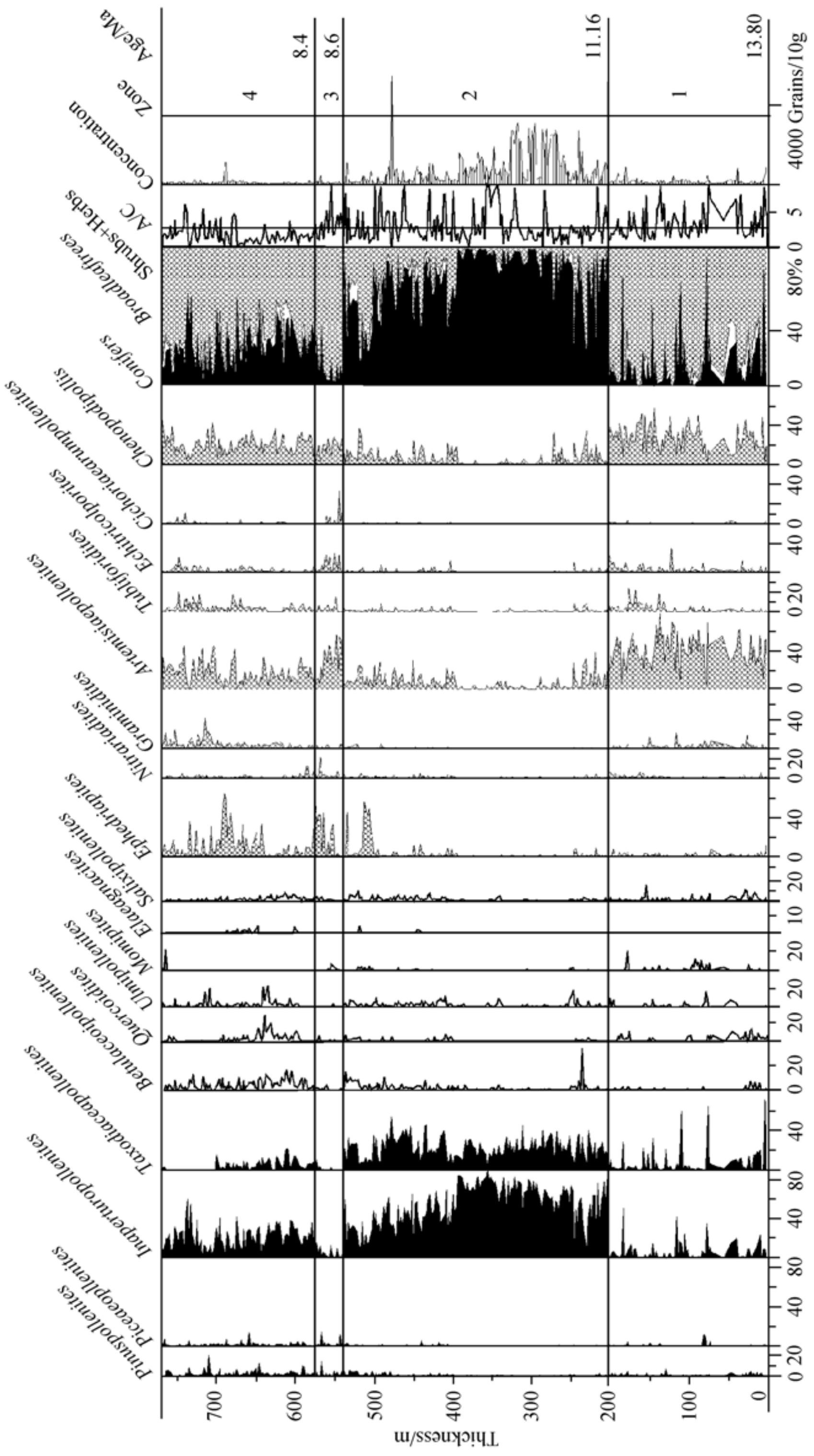

Fig. 3. Sporopollen percentage diagram of the Laojunmiao section.

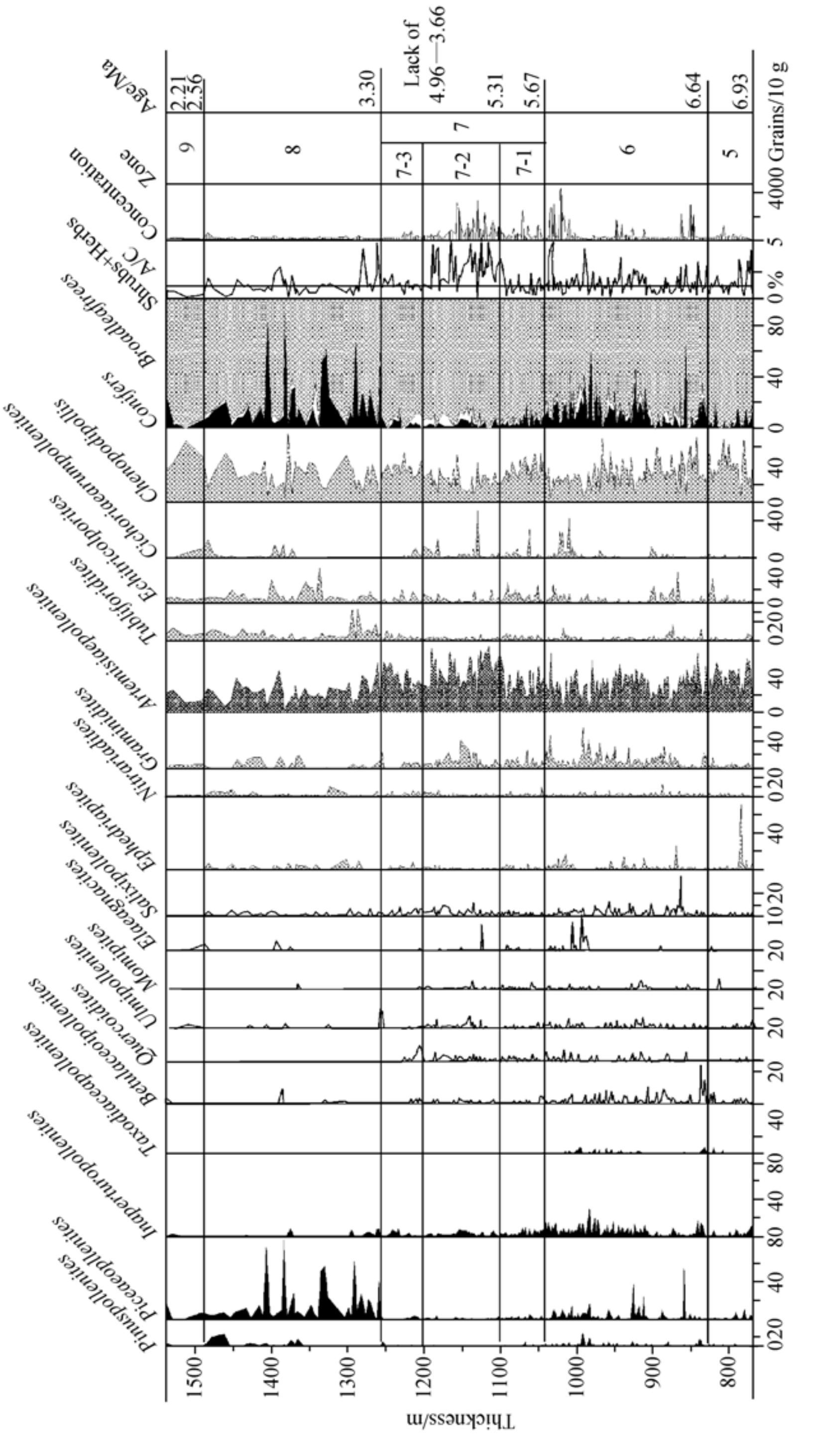

Fig. 4. Sporopollen percentage diagram of the Laojunmiao section.

94.44%) including mainly *Artemisiaepollenites* (3.53%—44.30%), *Ephedripites* (0.79%—54.95%) and *Chenopodipollis* (4.01%—37.89%) tend to decline. Temperate and warm-temperate deciduous trees 1.34%—28.13%), comprising of *Betulaceoipollenites*, *Quercoidites*, *Salixipollenites*, *Ulmipollenites*, *Momipites* and *Elaeagnacites,* are higher in percentage.

Zone 5 (772—834 m, 6.93—6.64 Ma): *Artemisiaepollenites-Chenopodipollis-Ephedripites.* Sporopollen concentrations are higher and A/C ratios are lower. Coniferous (0.30%—15.79%), temperate and warm-temperate deciduous (0.31%—7.56%) trees are sharply declined against a drastic increase in the proportion of herbaceous (80.00%—99.60%) plants, which consist mainly of *Artemisiaepollenites* (18.63%—55.22%), *Chenopodipollis* (14.89%—65.31%) and *Ephedripites* (1.17%—10.16%). Coniferous, temperate and warm-temperate deciduous taxa (e.g. *Inaperturopollenites*, *Piceaepollenites*, *Pinuspollenites*, *Taxodiaceaepollenites*, *Betulaceoipollenites*, *Salixipollenites* and *Ulmipollenites*) are prevailing.

Zone 6 (834—1044 m, 6.64—5.67 Ma): *Artemisiaepollenites-Graminidites-Piceaepollenites.* Sporopollen concentrations and A/C ratios are relatively high. The percentage of coniferous (0.35%—58.78%) trees is higher than in zone 5 but lower than in zone 4. What is notable is a drastic increase in the percentage of *Piceaepollenites* (0%—24.06%, even up to 54.20%) along with *Inaperturopollenites* (0.61%—20.85%), *Taxodiaceaepollenites* (0%—5.75%) and *Pinuspollenites*. Herbaceous (35.87%—99.16%) plants, comprised mainly of *Artemisiaepollenites* (15.43%—47.13%), *Chenopodipollis* (13.53%—56.23%) and *Graminidites,* are dominant in spite of a decline. Temperate and warm-temperate deciduous trees (e.g. *Betulaceoipollenites, Quercoidites, Salixipollenites, Ulmipollenites, Momipites* and *Elaeagnacites*) also are commonly seen (0.62%—18.70%).

Zone 7 (1044—1257 m, 5.67—3.30 Ma): *Artemisiaepollenites-Chenopodipollis.* This zone is characterized generally by an increase in the percentage of herbaceous plants and a decrease in the percentage of coniferous, temperate and warm-temperate deciduous trees and it can be divided into three subzones.

Subzone 7—1 (1044—1100 m, 5.67—5.31 Ma): *Artemisiaepollenites-Chenopodipollis.* Sporopollen concentrations and A/C ratios (≤1) are relatively low. The percentage of herbaceous (79.24%—98.79%) plants is higher than in zone 6, which consist mainly of *Artemisiaepollenites* (14.56%—50.19%) and *Chenopodipollis* (21.19%—53.14%). The percentages of coniferous (0.48%—19.17%), temperate and warm-temperate deciduous (0.38%—8.33%) trees tend to decrease, with minor *Inaperturopollenites, Piceaepollenites, Betulaceoipollenites*, *Salixipollenites* and *Ulmipollenites* only.

Subzone 7—2 (1100—1206 m, 5.31—4.96 Ma): *Artemisiaepolenites-Chenopodipollis-Graminidites-Salixipollenites.* Sporopollen concentrations and A/C ratios (0.5—4.8) are relatively high. Remarkable increases are noticed in temperate and warm—temperate deciduous taxa (0.53%—13.56%) including *Salixipollenites* (0.42%—7.01%), *Ulmipollenites* (0.36%—6.02%) and *Quercoidites* (0.36%—4.03%). Coniferous trees remain unchanged. Herbaceous (82.04%—98.68%) plants are dominated in spite of a slight decrease in proportion, which are composed mainly of *Artemisiaepollenites* (20.39%—74.21%), *Chenopodipollis* (7.94%—51.46%) and *Graminidites* (3.43%—41.09%).

Subzone 7—3 (1206—1257 m, 3.66—3.30 Ma): *Chenopodipollis-Artemisiaepollenites.* This subzone is marked by lower sporopollen concentrations and A/C ratios (≤1) and the predominance of herbaceous (83.47%—100%) plants. The sporopollen taxa are mainly *Chenopodipollis* (25.14%—53.65%) and *Artemisiaepollenites* (16.03%—55.69%) in addition to *Echitricolporites*, *Tubulifloridites*, *Graminidites*, *Nitrariadites* and *Cichoriaearumpollenites, Salixipollenites* and *Ephedripites.*

Zone 8 (1258—1485 m, 3.30—2.56 Ma): *Pice-*

aepollenites-Artemisiaepollenites-Echitricolporites. Sporopollen concentrations and A/C ratios (≤1) are relatively low. The outstanding feature is the striking increase of *Piceaepollenites*, which became the dominant species for the first time. Alternative occurrence of five cycles of vegetation was noticed with respect to coniferous trees (49.11%—88.03%), which are dominated by *Piceaepollenites* (41.07%—85.90%) and herbaceous plants (48.31%—98.02%), including *Artemisiaepollenites* (22.58%—46.03%) and *Chenopodipollis* (21.71%—53.33).

Zone 9 (1485—1539 m, 2.56—2.2 Ma): *Chenopodipollis-Artemisiaepollenites*. Sporopollen concentrations and A/C ratios (≤0.5) are low. Herbaceous plants (83.47%—100%) consisting mainly of *Chenopodipollis* (35.71%—66.61%) and *Artemisiaepollenites* (13.11%—24.71%) reached their highest level in this zone and arboraceous pollen is absent.

3 Discussion of ecological significance about important pollen taxa

Vegetation distributing and ecological behavior is dominated by climatic conditions, however adaptability between plant and environment has changed at different stage of plant evolvement in geological epoch. Therefore, we first try to discuss the relationship between modern surface pollen and major plant and modern ecological environment, historical geobotany about important pollen taxa, which mainly consist of *Piceaepollenites*, *Inaperturopollenites*, *Taxodiaceaepollenites*, *Artemisiaepollenites* and *Chenopodipollis* in this section.

3.1 *Piceaepollenites*

Piceaepollenites seems to be related to *Picea*. Today, *Picea* usually prevails in the settings marked by relatively cool, moist climate and clearly demarcated four seasons. *Picea* along with *Pinus*, *Acer*, *Lonicera*, *Rosa*, and *Salix*, grow mainly in the north[14], but *Picea* along with *Abies*, *Tsuga* and *Acer*, *Betula*, *Fagus*, *Quercus* can be found in the south[15]. Modern sporopollen data from surface soil show that a very high percentage of *Picea* sporopollen (20%—80%) suggests the existence of spruce forest or approximation to a spruce forest; a relatively low percentage of *Picea* pollen (10%—30%) seems to be associated with water transportation (alluvial deposits)[16]; a low percentage of *Picea* pollen (1%—5%) appears to be related to long-distance air transportation; a very low percentage of *Picea* pollen (2%—3%) is found in desert and steppe-desert areas[15,17—20].

It is believed that the earliest *Picea* pollen fossils appeared in the Oligocene strata of Middle Europe, even throughout Europe, North America and Japan after Oligocene. *Picea* pollen fossils are generally present in the Oligocene strata of China, *Picea* with Fagaceae, Betulaceae, *Ulmus*, *Juglans* are common in the Miocene and Pliocene strata[15,21－23], but in northeastern Tibet and the Qaidam Basin *Picea* with sub-tropic, and warm temperate components (e.g. *Quercus*, *Melia*, Rutaceae, *Castanea*) can be found in Late Eocene strata[21]. So, in restoration of paleo-vegetation and climate based on sporopollen assemblages, other main elements contemporaneous with *Picea* should be taken into full consideration.

3.2 *Inaperturopollenites* and *Taxodiaceaepollenites*

The inaperturate pollen of taxa is divided two types (*Inaperturopollenites* and *Taxodiaceaepollenites*). *Inaperturopollenites* and *Taxodiaceaepollenites* are circular or more or less isodiametric in shape. Pollen grains contain no Taxodiaceae's papilla but *Taxodiaceaepollenites* are usually double-splited. The exine is relatively thin and can be divided or not. The ornamentation is faint, coarse or granular[21,24]. *Inaperturopollenites* and *Taxodiaceaepollenites* seem to be related to Cupressaceae and Taxodiaceae or other species[25,26]. The characteristics of most genera of Cupressaceae[27—29] are similar to those of *Inaperturopollenites* and *Taxodiaceaepollenites* (Fig. 5).

Today *Cupressus*, associated with sub-tropic and warm-temperate components, generally appears in the areas at the altitude of 300—1000 m above sea level, south of the Changjiang (Yangtze) River. *Platycladus*, associated mainly with *Ulmus*, *Salix*, *Quercus*, *Celtis*, Rosaceae, and Gramineae, grow at mountains side and

Fig. 5. The shape of important pollen types in the studied section. 1, 2, *Platycladus* (surface pollen in Huangdiling, Shaanxi); 3, *Inaperturopollenites*; 4, *Taxodiaceaepollenites*; 5, *Chenopodipollis*; 6, *Betulaceoipollenites*; 7, *Ulmipollenites;* 8, *Artemisiaepollenites*; 9, *Quercoidites.*

piedmont belts at the altitude of 600—1500 m above sea level in North China (e.g. in northern Qinling). Drought-, cold-resistant *Sabina* and *Juniperus* with alpine shrubs and meadows are distributed in southwestern China at the altitude of 2800—4300 m above sea level.

From Late Cretaceous to Pliocene *Inaperturopollenites* and *Taxodiaceaepollenites* were dominated in some parts of North Hemisphere, though the associated components are different. In Neocene *Inaperturopollenites* and *Taxodiaceaepollenites* were associated with Pinaceae, Fagaceae, Ulmaceae, Betulaceae and herbaceous plants[24,25]. As viewed from their history of biogeographical evolution, *Inaperturopollenites* and *Taxodiaceaepollenites* may have grown at lower altitudes above sea level under warm-moist climate conditions in the early period and gradually adapted themselves to temperate and moister environment.

3.3 *Artemisiaepollenites* and *Chenopodipollis*

Artemisia probably originated from northern Asia. Today *Artemisia* is commonly seen in desert, semi-desert, steppe, and forest-steppe, with a semi-arid climate in the temperate areas of Asia, though growing very well in steppe regions[17]. Chenopodiaceae came into being along the eastern shore of Mediterranean under semi-arid climate condition. Today Chenopodiaceae have become a typical species in the areas at the altitude of 300—2000 m at sea level in desert, steppe and saline-sodic areas where an arid and semi-arid climate prevails[30].

Previous sporopollen studies showed that *Artemisia* and Chenopodiaceae are generally super-representative of sporopollen in surface soils. Minor amounts of *Artemisia* and Chenopodiaceae pollen present in sporopollen assemblages may be indicative of their extraneous origin, while their higher percentages (over 30%) suggest the *in-situ* existence of *Artemisia* and Chenopodiaceae. In addition, when Chenopodiaceae and *Artemisia* are dominated in sporopollen assemblages, the ratio of *Artemisia* over Chenopodiaceae (i.e., A/C ratio) can be used as an index of aridity. Chenopodiaceae is more common in desert vegetation (arid can be used climate), whereas *Artemisia* is characteristic of steppe (semi-arid) and tends to increase generally with precipit-ation[15,17,31—35].

4 Vegetation and climate change

During the period of 13.0—11.15 Ma the sporopollen assemblages characterized by the predominance of herbaceous plants, higher A/C ratios (1—2), and lower temperate and warm-temperate pollen elements suggest steppe vegetation and a semi-moist climate. From 11.16 to 8.60 Ma, the predominance *of Inaperturopollenites* and *Taxodiaceaepollenites* probably indicates a typical forest of Cupressaceae growing at the altitude of 1000—1500 m above sea level under a warmer and relatively moist environment, just like the modern climate prevailing along the northern slopes of the Qinling Ranges.

Since 8.60 Ma the sporopollen assemblages of herbaceous plants, have become dominant, with a dramatic decline in coniferous, temperate and warm-temperate deciduous components, indicating the climate at 8.40 Ma was much drier than during the period of 13.80—11.15 Ma. This situation lasted till 8.40 Ma. Since 8.60 Ma, temperate and warm-emperate deciduous components have gradually and drought-enduring plants have grown luxuriantly. During 8.40—6.93 Ma the percentage of coniferous trees including *Inaperturopollenites* and *Taxodiaceaepollenites* increased but is lower than in zone 2; the percentage of herbaceous plants decreased but is higher than in zone 2, and the percentages of temperate and warm-temperate deciduous trees are high, probably showing a forest-steppe vegetation of Cupressaceae, *Artemisia*, *Ephedra* and Chenopodiaseae, implying the climate was warmer and moister than before.

During 6.93—6.64 Ma the percentage of herbaceous plants increased drastically again and whereas that of coniferous, temperate and warm-temperate deciduous components decreased sharply, showing the vegetation and climate are the same as those prevailing during the period of 8.60—8.40 Ma. Between 6.64 and 5.67 Ma the percentage of herbaceous plants decreased, and that of *Graminidites* and coniferous trees increased while herbaceous plants were dominant, which seems to indicate an open forest-steppe vegetation and a warm and semi-moist climate. In addition, the percentage of *Piceaepollenites* drastically increased in some stages and *Piceaepollenites* became one of the important species while *Piceaepollenites* would be a long-distance transported component.

At 5.67 Ma one conspicuous feature is that A/C ratios began to become lower than 1 and *Taxodiaceaepollenites* disappeared. The predominance of herbs and trace amounts of arbors during 5.67—5.42 Ma suggest that desert-steppe vegetation and arid climate would prevail more extensively in the region, implying the intensification of aridification. The higher A/C ratios (0.5—4.8) and the increase of *Graminidites*, and temperate, warm-temperate deciduous trees from 5.42 Ma to 4.96 Ma may indicate that the steppe vegetation prevailed and semi-arid climate turned relatively moist.

Lower-than-1 A/C ratios, trace amounts of arbors and disappearance of *Quercoidites* during the period of 3.66—3.30 Ma provide evidence for the existence of a desert-steppe vegetation under the dry climate condition. During the period of 3.30—2.56 Ma *Piceaepollenites* became dominant with rare temperate arbors, herbs and shrubs, reflecting that the climate was cool and moist at that time. During this period of time the higher percentages of *Artemisiaepollenites* and *Chenopodipollis* and lower A/C ratios (≤1) imply the prevalence of desert-steppe vegetation and arid climate. During this period spruce forest prevailing under cool and moist climate condition and desert-steppe under arid climate condition appeared alternatively, implying strong climatic fluctuations. The dominance of *Chenopodipollis,* lower A/C ratios (≤0.5), rare plant species, and almost disappearance of arbors during the period of 2.56—2.21 Ma demonstrated the expansion of desert vegetation, the development of arid climate and intensification of aridification.

5 Correlation and discussion

The registration of steppe vegetation during the period of 13.0—11.15 Ma in the Jiuquan area can be well compared with the cooling event in northern and southern hemisphere during the Middle Miocene. For example, the data from Ocean Drilling Program Sites 865, 871, 872 indicate that the drastic drop of P_{CO_2} during 16—13 Ma indicates the climate turned cold, which may have been associated with the enhancement of glaciation on Antarctica[36]; ice rafted sediments appeared for the first time at 12 Ma on Norway-Greenland[37]; the $\delta^{18}O$ data from the Atlantic display that a large-scale cooling event took place at about 15—13 Ma[37]; the large sources areas of aeolian dust from the source regions and materials brought about by energetic winter monsoon during 15—13 Ma were deposited in the inland areas of Asia [5].

The expansion of steppe and aridification events during the Late Miocene (8 Ma) also took place in Pakistan, South America, North America and Africa. The increase of evaporation capacity, the intensification of aridification and enlargement of grassland are evidenced by $\delta^{18}O$ records from Pakistan, Nepal, East Africa, North America and East Mediterranean [9]. The development of aridification in Asia and South America was reflected by the increase of dust accumulation rates in the South and North Pacific during the period of 8—7.7 Ma[6]. Higher aridity in Asia was recorded in relatively abundant aeolian deposits (7—5 Ma) in the Xifeng and Lingtai sections on the Loess Plateau [2, 3]. All this can be compared with “the last-stage cooling event of Miocene”, as revealed by the expansion of ice sheets in Antarctica and the occurrence of Greenland ice sheets at about 7 Ma[36], which may illustrate the climatic fluctuations in this period of time are of global and regional scale. M. Pagani (1999) pointed out that global-scale tectonic movement might have been responsible for global climatic change[9]. The development of global glaciation and the reduction of evaporation capacity of the ocean should be taken into consideration at the same time. The expansion of steppe and the occurrence of aridification event during the Late Miocene (8.60, 6.93 and 5.67 Ma) in the Jiuquan area are a manifestation of climatic fluctuations, probably in response to global arid and cold events.

The development of aridification recorded by sporopollen and the uplift of the Tibetan Plateau also have a coupling relation, though there are different opinions about the uplifting rates in each of the periods during Cenozoic, but its dramatic uplift at 3.4—3.3 Ma and 2.5—2.6 Ma must have occurred[38—40]. The alternative occurrence of spruce forest prevailing under cool and moist climate condition and desert-steppe prevailing under the arid climate condition in the Jiuquan area during the period of 3.30—2.56 Ma provides strong evidence for extensive climatic fluctuations. Intensification of aridification and rapid development of desert vegetation during 2.56—2.21 Ma also reflect the rapid uplift of the Tibetan Plateau. The dramatic increase of dust accumulation rates in the Xifeng and Lingtai sections of the Loess Plateau and North Pacific during 3.6—2.6 Ma revealed that there had occurred two obvious aridification events, of which the extent is higher than that during the period of 7—5.6 Ma and these two events are attributable to much more rapid uplift of the Tibetan Plateau and strengthening of Asian winter monsoon system[2,3,6]. The vegetation evolution and aridification probably correspond to the uplift of the Tibetan Plateau.

6 Conclusions

(1) During the period of 13.0—1.15 Ma the ecological environment of the Jiuxi Basin is characterized by a steppe vegetation and a semi-moist climate. Cypress forest and warm-moist climate prevailing during 11.16—8.60 Ma showed that the ecological environment turned better than before.

(2) The dry climate trend started probably at about 8.6Ma, as indicated by the replacement of forest by steppe vegetation. Although aridification seems to have been relaxed time to time during 8.40—6.93 (forest-steppe, warm-semi-moist climate), 6.64—5.67 (open-forest and steppe, warm-semi-moist climate) and 5.42—4.96 Ma (steppe, semi-arid climate), the frequent occurrence of aridification events during 6.93—6.64 (steppe, semi-arid climate), 5.67—5.42 (desert-steppe, arid climate), 3.66 — 3.30 (desert-steppe, arid climate) and 2.56—2.21 Ma (desert-arid climate) made the climate in this area become drier and drier. Especially during the periods of 3.66—3.30 Ma and 2.56 Ma aridification was further intensified, resulting in the change of vegetation into an arid-desert type. At the same time, under the aridification trend the inland areas of Asia underwent frequent arid/moist climatic fluctuations.

(3) During 13.0—2.21 Ma there were five important turning points: at 8.6 Ma the arid climate began to

develop; at 5.67 Ma desert-steppe began to develop; at 3.30 Ma warm deciduous trees disappeared; during 3.30—2.56 Ma spruce forest prevailing under cool and moist climate condition and desert-steppe prevailing under arid climate condition occurred alternatively, indicating that the climate is unstable; at 2.56 Ma desert developed and aridification was intensified.

(4) Climate changes during the periods of 13.0—11.15, 8.60—8.40, 6.93—6.64 and 5.67—5.42 Ma seem to be related to many factors and the climate transition at 3.30 Ma and 2.56 Ma has a coupling relation with the uplift of the Tibetan Plateau.

Acknowledgements This work was supported by the Key Basic Research and Development Plan (Grant No. G1998040809), the National Natural Science Foundation of China (Grant No. 40171094) and the Hundred Talents Program of the Chinese Academy of Sciences (Renjiaozi [2000] 05). The authors wish to thank Yang Shengli, Yan Maodu, Zhao Zhijun, Cao Jixiu, Fu Kaidao and Shi Zhengtao for their help with field work and laboratory assistance.

References

1. Song, Y. G., Fang, X. M., Li, J. J. et al., The late Cenozoic uplift of Liupan Shan, China, Science in China, Ser. D, 2001, 44(Supp.): 176—184.[Abstract] [PDF]
2. Guo, Z. T., Peng, S. Z., Hao, Q. Z. et al., Late Tertiary development of aridification in northwestern China: Link with the Arctic ice-sheet formation and Tibetan uplifts, Quaternary Sciences (in Chinese), 1999, 6: 556—566.
3. Sun, Y. B., An, Z. S., History and variability of Asian interior aridity recorded by eolian flux in the Chinese Loess Plateau during the past 7 Ma, Science in China, Ser. D, 2002, 45(5): 420—429. [Abstract] [PDF]
4. An, Z. S., Kutzbach, J. E., Prell, S. C., Evolution of Asian monsoons and phrased uplift of the Himalaya-Tibetan Plateau since Late Miocene times, Nature, 2002, 411: 62—66.
5. Guo, Z. T., Ruddiman, W. F., Hao, Q. Z. et al., Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China, Nature, 2002, 416: 159—163.[DOI]
6. Rea, D. K., Snoeckx, H., Joseph, L. H., Late Cenozoic eolian deposition in the North Pacific: Asian drying, Tibetan uplift, and cooling of the Northern Hemisphere, Paleoceanography, 1998, 13(3): 215—224. [DOI]
7. Quade, J., Cerling, T. E., Bowman, J. R., Development of the Asian monsoon revealed by marked ecologic shift in the latest Miocene of northern Pakistan, Nature, 1989, 342: 163—166. [DOI]
8. Quade, J., Cater, J. M. L., Ojha, T. P. et al., Late Miocene environmental change in Nepal and the northern Indian subcontinent: Stable isotopic evidence from paleosols, Geol. Soc. Am. Bull., 1995, 107: 1381—1397. [DOI]
9. Pagani, M., Freeman, K. H., Arthur, M. A., Late Miocene atmospheric CO_2 concentrations and the expansion of C_4 grasses, Science, 1999, 285: 876—879. [DOI]
10. Ma, Y. Z., Li, J. J., Fang, X. M., A record of polynoflora and climatic evolution of Red Bed between 30.6 to 5.0 MaBP, Linxia Basin, Chinese Science Bulletin (in Chinese), 1998, 43(3): 301—304.
11. Cande, S. C., Kent, D. V., Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic, Journal of Geophysical Research, 1995, 100(B4): 6093—6095. [DOI]
12. Shi, Z. T., Ye, Y. G., Zhao, Z. J. et al., ESR dating of late Cenozoic molassic deposits in the Jiuxi Basin, Science in China, Ser. D, 2001, 44(Supp.): 203—209. [Abstract] [PDF]
13. Fang, X. M., Zhao, Z. J., Li, J. J. et al., Magnetostratigraphy of the late Cenozoic Laojunmiao anticline in the northern Qilian Mts. and its implication on the northern Tibet uplift, Science in China, Ser. D (in Chinese), 2004, 34(2): 97—106.
14. Wu, Z. Y., Vegetation of China (in Chinese), Beijing: Science Press, 1995.
15. Li, W. Y., Quaternary Vegetation and Environment of China (in Chinese), Beijing: Science Press, 1998, 1—50.
16. Xu, Q. H., Wu, C., Meng, L. Y. et al., Pollen assemblage feature of different geomorphologic units and different sedimentary facies, North China Plain, Chinese Science Bulletin (in Chinese), 1994, 39(19): 1792—1795.
17. Li, W. Y., Yan, S., Research of Quaternary Polynology, Chaiwopu Basin (ed. Shi, Y. F.), Quaternary Climatic Change and Hydrologic Geological Events of Chaiwopu Basin, Xinjiang (in Chinese), Beijing: Oceanic Press, 1990, 46—72.
18. Li, W. Y., The relation between pollen and plant of *Abies*, and succession of forest vegetation, Bashan region of Shennongjia, Acta Geographica Sinica (in Chinese), 1991, 46(2): 186—193.
19. Yan, S., Xu, Y. Q., Spore-pollen association in surface-soil in Altay, Xinjiang, Arid Land Research (in Chinese), 1989, 1: 26—33.
20. Yan, S., The discussion on the pollen of pine family in surface soil in Xinjiang, Arid Land Geography (in Chinese), 1993, 16(3): 1—9.
21. Research Institute of Exploration and Development, Qinghai Petroleum Administration and Nanjing Institute of Geology and Palaeolitology, Chinese Academy of Sciences, A Research on Tertiary Palynology from the Qaidam Basin, Qinghai Province (in Chinese), Beijing: Petroleum Industry Publishing House, 1985.
22. Liu, G. G., Lepold, E. B., Palaeoecology of a Miocene flora from the Shanwang formation, Shandong Province, Northern East China, Palynology, 1992, 16: 187—212.
23. Shi, N., Cao, J. X., Lars, K. S., Late Cenozoic vegetational history and the Pliocene-Pleistocene boundary in the Yushe basin, S.E. Shanxi, China, Grana, 1993, 32: 260—271.
24. Song, Z. C., Cao, L., Zhou, H. Y. et al., Early Tertiary Spores and Pollen Grains From the Coastal Region of Bohai (in Chinese),

Beijing: Science press, 1978.
25. Song, Z. C., Zhen, Y. H., Liu, J. L. et al., Sporepollen Association of Cretaceous and Tertiary, Jiangsu Province (in Chinese), Beijing: Geological Publishing House, 1981.
26. Song, Z. C., Zhen, Y. H., Li, M. Y. et al., Fossil Spores and Pollen of China (1): Late of Cretaceous-Tertiary Spores and Pollen (in Chinese), Beijing: Science Press, 1999.
27. Wang, F. S, Chien, N. F., Zhang, Y. L. et al., Pollen Flora of China (in Chinese), Beijing: Science Press, 1995.
28. Erdtman, G., An Introduction to Pollen Analysis, Waltham: The Chronica Botanica Company, 1954, 129—145.
29. Moore, P. D., Webb, J. A., Pollen Analysis, Oxford: Blackwell Scientific Publications, 1991, 10—38.
30. Zhu, G. L., Origin, differentiation, and geographic distribution of the Chenopodiaceae, Acta Phytotaxonomica Sinica (in Chinese), 1995, 34(5): 486—504.
31. Weng, C.Y, Sun, X. J., Chen, Y. S., Numerical characteristics of pollen assemblages of surface samples from the west Kunlun Mountains, Acta Botanica Sinica (in Chinese), 1993, 35(1): 69—79.
32. Yan, S., Quaternary sporepollen assemblage feature and succession of vegetation, Xinjiang, Arid Land Geography (in Chinese), 1991, 2: 1—8.
33. Huang, C. X., A study on pollen in surface soil from the western Xizang, Arid Land Geography (in Chinese), 1993, 16(4): 75—83.
34. Wang, F. Y., Song, C. Q., Sun X. J., Study on surface pollen in middle Inner Mongolia, China, Acta Botanica Sinica (in Chinese), 1996, 38(11): 902—909.
35. El Moslinmny, A., The ecological significance of common non-arboreal pollen example from dry land of the Middle East, Rev. Palaeobot. Palyn., 1990, 64: 343—350. [DOI]
36. Pearson, P. N., Palmer, M. R., Atmospheric carbon dioxide concentrations over the past 60 million years, Nature, 2000, 406: 695—699. [DOI]
37. Jin, X. C., Zhou, Z. Y., Wang, P. X., Ocean Drilling Program and Earth Sciences in China (in Chinese), Shanghai: Tongji University Press, 1995.
38. Shi, Y. F., Li, J. J., Li, B. Y. et al., Uplift and environmental evolution of Tibet Plateau (eds. Sun, H. L., Zheng, D.), The Formation, Evolution and Development of Qinghai-Xizang Plateau (in Chinese), Guangzhou: Guangdong Provincial Technologic Press, 1998, 73—138.
39. Li, J. J., Wen, S. X., Zhang, Q. S. et al., A discussion on the period, amplitude and type of the uplift of the Qinghai-Xizang Plateau, Sci. in China, Ser. B (in Chinese), 1979, (6): 608—616.
40. Zhong, D. L., Ding, L., Rising process of the Qinghai-Xizang (Tibet) Plateau and its mechanism, Science in China, Ser. D, 1996, 39(4): 369—376.