Vol. 42 No. 3 SCIENCE IN CHINA (Series D) June 1999

Eolian evidence from the Chinese Loess Plateau: the onset of the Late Cenozoic Great Glaciation in the Northern Hemisphere and Qinghai-Xizang Plateau uplift forcing*

AN Zhisheng (安芷生)[1], WANG Sumin (王苏民)[2], WU Xihao (吴锡浩)[3], CHEN Mingyang (陈明扬)[1], SUN Donghuai (孙东怀)[1], LIU Xiuming (刘秀铭)[4], WANG Fubao (王富葆)[5], LI Li (李　力)[1], SUN Youbin (孙有斌)[1], ZHOU Weijian (周卫健)[1], ZHOU Jie (周　杰)[1], LIU Xiaodong (刘晓东)[6], LU Huayu (鹿化煜)[1], ZHANG Yunxiang (张云翔)[7], DONG Guangrong (董光荣)[8] and QIANG Xiaoke (强小科)[1]

(1. The State Key Laboratory of Loess and Quaternary Geology, Chinese Academy of Sciences, Xi'an 710054, China; 2. Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China; 3. Institute of Geomechanics, Chinese Academy of Geological Sciences, Beijing 100081, China; 4, Macquarie University, Sydney, Australia; 5. Geography Department, Nanjing University, Nanjing 210008, China; 6. Lanzhou Institute of Plateau Atmospheric Physics, Chinese Academy of Sciences, Lanzhou 730000, China; 7. Geology Department, Northwest University, Xi'an 710069, China; 8. Lanzhou Institute of Desert, Chinese Academy of Sciences, Lanzhou 730000, China)

Received September 16, 1998

Abstract On the basis of a newly-constructed record of magnetic susceptibility (SUS) and the depositional rate change of eolian loess-red clay sequences in the last 7.2 Ma BP from the Loess Plateau, together with a comparison of a record of $\delta^{18}O$ values from the equatorial East Pacific Ocean and eolian Quartz flux variations from the North Pacific Ocean, the evolutionary process of the Late Cenozoic Great Glaciation in the Northern Hemisphere can be divided into three stages: the arrival stage around 7.2—3.4 Ma BP, the initial stage at about 3.4—2.6 Ma BP, and the Great Ice Age since 2.6 Ma BP. The evolution of the East Asian monsoon is characterized by paired winter and summer monsoons, and it is basically composed of the initial stage of weak winter and summer monsoons, the transitional stage of simultaneous increase in intensity of winter and summer monsoons, and the prevailing stage of strong winter and weak summer monsoons, or weak winter and strong summer monsoons. The Late Cenozoic global tectonic uplift, particularly the Qinghai-Xizang Plateau uplift and the associated CO_2 concentration variation, controls the cooling processes of the onset of Great Glaciation and the long-term changes of East Asian monsoom climate in the Northern Hemisphere to a large extent. The accelerating uplift of the Qinghai-Xizang Plateau between 3.4 and 2.6 Ma BP provided an important driving force to global climiatic change.

Keywords: Late Cenozoic, eolian deposits of Loess Plateau, Great Glaciation in the Northern Hemisphere, East Asian monsoon evolution, Qinghai-Xizang Plateau uplift.

The process of gradual cooling of the Cenozoic global climate and the successive development of

* Project supported by the foundation of Chinese Academy of Sciences (Grant No. KZ951-A1-402), the State Science and Technology Committee (Grant No. 95-pre-40) and the Chinese Nature Science Foundation (Grant No. 49672140).

ice sheets in both polar areas poses the question as to what caused the commencement of the Great Glaciation. This period is marked by an alternating glacial and interglacial climate, as well as a mountain glaciation occurring in the Northern Hemisphere. This question is still unsolved so far, even though it has been studied for a long time. Recently, with the proposed hypothesis of tectonic uplift-driven climatic change[1,2], a sharp isotopic variation of benthic foraminifera from the equatorial Pacific has been used to indicate the initial age of the Great Glaciation. The various physical and chemical porcesses caused mainly by the uplift of the Qinghai-Xizang Plateau, and its climatic response have been used to interpret the arrival of the Great Glaciation. These studies have proved extreme controversy among international scientists. Since the eolian depositional sequence from the Loess Plateau provides a true record of the formation and evolution of East Asian monsoon conditions[3], it is not only a reflection of the Great Glacial climate change in the Northern Hemisphere[4], but also a response to the Qinghai-Xizang Plateau uplift[5]. Here, we present new data of eolian loess-redclay sequences from the Loess Plateau for further discussion of these questions such as the onset of the Late Cenozoic Great Glaciation in the Northern Hemispere, and Qinghai-Xizang Plateau uplift forcing.

1 Eolian record from the Loess Plateau

Eolian deposition of sediments is an extremely sensitive response to the changes of configuration and intensification of atmospheric circulation, and can be indirectly regarded as important geological evidence of climate change driven by tectonic uplift forcing. There are two types of eolian deposits from the Loess Plateau: one consists of loess-paleosol sequences, including Holocene loess, Malan loess, Lishi loess and Wucheng loess, the other consists of the so-called red loess-paleosol sequences, which are commonly recognized as *Hipparion* red clay in North China, identified as eolian red clay in some areas[6—8]. Loess or red clay distribution areas within the Loess Plateau of the middle reaches of the Yellow River close to the eastern boundary of the Qinghai-Xizang Plateau with an altitude of 3000 m are located above the second terrace of the East Asian geomorphologic landscape. Its northwest, north and northeast boundaries are formed by deserts (fig. 1). Lingtai County, and Xifeng County, on the Dongzhi Yuan (Tableland), Gansu Province, are located virtually at the center of the Loess Plateau. The former is to the south, and the latter is to the north. The characteristic loess and red clay profiles from these two areas provide an example of eolian deposition over the last 7.2 Ma (figure 2).

The Lingtai profile outcrops at Renjiapo, ca. 13 km to the south of the county (35°04′N, 107°39′E). From the top of the Yuan (the tableland) downward, the bottom boundary depths of Malan, loess, Lishi loess, Wucheng loess and red clay are 6.2, 88.0, 168.3, and 288.6 m respectively. They are parallel sequences, unconformably overlying the Cretaceous red-clay formation. Magnetic stratigraphic studies show that the boundary depths of the polarity chrons are 54.4 m for B/M, 165.9 m for M/Ga, 199.7 m for Ga/Gi, 262.6 m for Gi/Chron3An, and 275.9 m for Chron3An/3Ar. In this paper, we use the polarity timescale of Shackleton et al.[9] to determine (or place) the boundary ages of polarity chrons and subchrons.

The Xifeng section is composed of both loess and red clay profiles. A profile containing loess-paleosol sequences is located at Hejiayao (35°20′N, 107°E), 2 km away from eastern Xifeng City and a red-clay sequence profile is located at Bajiazui (35°53′N, 107°27′E), 16 km away from the west of the city. Through repeated samplings around the boundary between the Wucheng loess and the red

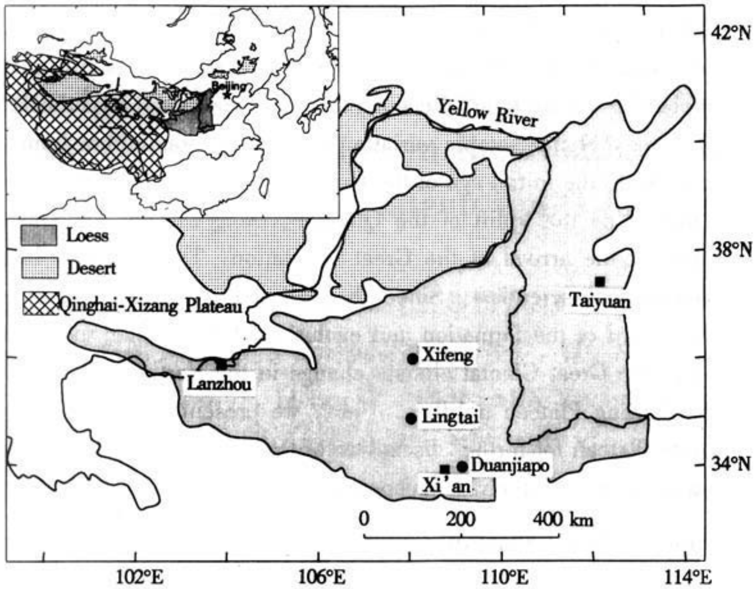

Fig. 1. Geographic location map showing the Loess Plateau and adjacent desert area and Lingtai and Xifeng profiles from Gansu Province.

clay of both profiles, and on the basis of established SUS data, it is possible to combine both sequences to form a complete loess-red clay sequence for the Dongzhi Yuan (tableland). The polarity boundary for the Hejiayao profile is derived from data collected from the nearby Hujiayaoxian profile[10]. Both profiles provide a magnetic stratigraphy for the Xifeng section. Data from the combined section indicate that the Malan loess is 10.4 m thick, the Lishi loess about 95.6 m thick, with the Wucheng loess and red-clay sequences being 57.9 and 58.1 m thick, respecitvely. Underlying these sequences is an alluvial sand unit having a thickness of 10 m (the bottom of the profile has not been exposed yet). The chron boundaries are at 67.7 m (B/M), 163.9 m (M/Ga), 187.6 m (Ga/Gi), and 212.8 m (Gi/Chron3An). The boundary ages for all chrons and subchrons are the same as those from the Lingtai profile.

A horizon rich in mammalian fossils was discovered in the Lingtai profile within the red-clay sequences about 16 m below the Wucheng loess, or 184 m below the surface. Preliminary excavation and fossil identification shows that the faunal assemblage contains Rodentia, *Nyctereutes sinensis*, *Pentalophodon* sp, *Hipparion houfenense*, Rhinocerotidae, Giraffidae, *Gazella blachi* and *Antilosphila licenti*. The undetermined faunal assemblage is quite similar to the Houfeng fauna: its megnetostratigraphic horizon is exactly in the Gauss chron belt, and it agrees with that of standard locality in Jingle of Shanxi Province[11]. The faunal assemblage indicates that there was an ecological environment of thin forest cover and steppe.

The loess and red-clay sequences within the Lingtai and Xifeng profiles were sampled at 2.5 and 5 cm intervals respectively, and Ca nodules of different sizes were sampled from the bottom of the paleosol units for paleoenvironmental studies. The magnetic susceptibility (SUS) of each sample was measured in the laboratory using a Bartington MS2 meter. SUS measurements were also carried out in

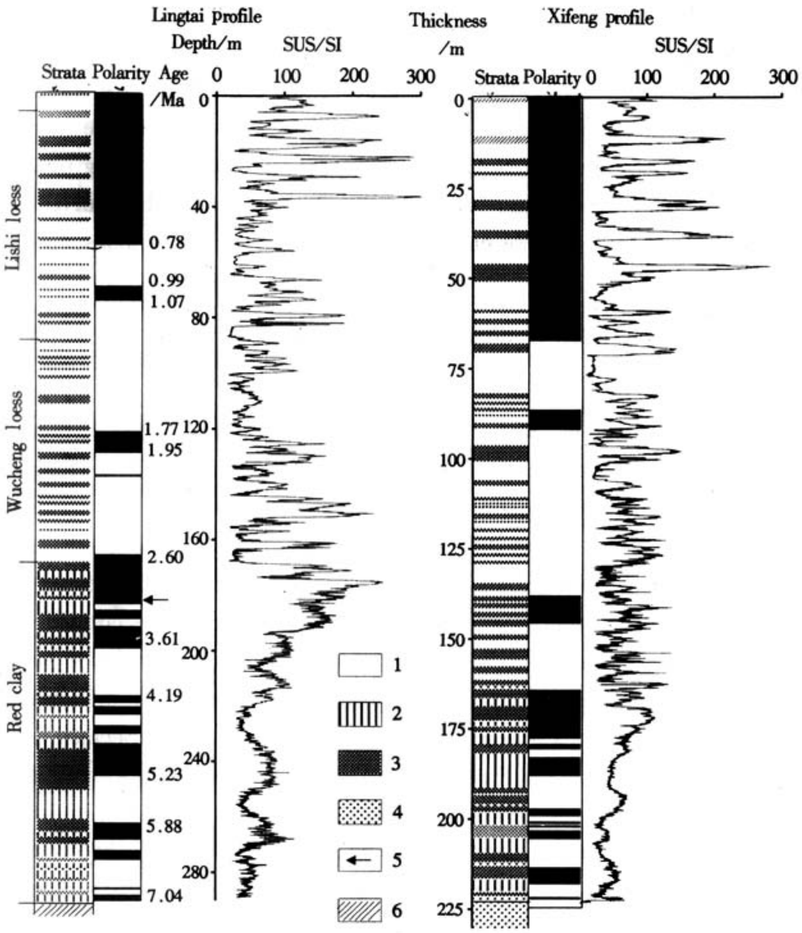

Fig. 2. Late Cenozoic sequence of eolian dust deposits, magnetostratigraphy and SUS curves from Lingtai and Xifeng profiles of the Loess Plateau. (The data of magnetostratigraphy and SUS of Lingtain profile are derived from ref. [8], red clay stratigraphy, magnetostratigraphy and SUS of the Xifeng profile are derived from ref. [6], and its magnetic susceptibility curve has been calibrated. The Quaternary magnetic stratigraphic boundary of the Xifeng profiel is referred to Kukla and An[10]; the polarity chronology table in the figure is used[9].) 1, Loess; 2, red loess; 3, paleosol; 4, fluvial sand; 5, horizon bearing mammal fossil; 6, bedrock.

the field on the marked layers of loess and paleosol. There was no obvious inconsistency between pedogenic intensity and magnetic susceptibility values from loess-paleosol sequences, as SUS values for the S5 paleosol were highest as would have been expected. A similar phenomenon occurs, within the red loess-paleosol sequences, where SUS values significantly increase in the Gauss chron zone, with the maximum peak appearing within its upper portion. We resampled 18 representative logs of loess, red loess and paleosol units from the Lingtai profile, and these samples were sent to the Institute of Geophysics, Chinese Academy of Sciences, and Macquarie University in Australia for environmental magnetism studies. IRM and thermal magnetic analysis shows that there is no essential difference in magnetic minerals and magnetization characteristics between red loess-paleosol and loess-paleosol sequences. The magnetic minerals are mainly magnetite, maghemite and hematite. Therefore, SUS values from red loess-paleosol sequences within the Lingtai and Xifeng profiles can be viewed as an indicator of summer monsoon change in a similar manner to those from loess-paleosol sequence[3].

Because of differences in resolution and deposition rate of the different units within the Lingtai and Xifeng profieles, the SUS curves show general agreement, but there are significant discrepancies in some details. For example, Lingtai contains red-clay complexes around the Ga/Gi boundary, with corresponding oscillations; Xifeng is a single red-clay unit with corresponding peaks missing. Therefore, when we discuss the paleoclimatic problem, magnetic susceptibility curves should be supplementary with each other. In this way we can objectively display summer monsoon characteristics on a different time scale.

2 Evidence of onset of the Late Cenozoic Great Glaciation

From the Late Eocene to the Early Oligocene, ice sheet developed on the Antarctic continent[12,13]. Until the Late Miocene, when the Antarctic ice sheet expanded further, glaciers from the North Polar continental area initially appeared. Later, at about 11 Ma BP, icebergs from Scandinavia and the Greenland ice cap deposited debris on the VΦring Plateau in the Norwegian Sea[14]. From 7 Ma BP, glacial-oceanic sediments from the Greenland ice cap were distributed in the Irminger Basin at the northwestern end of the North Atlantic Ocean[15]. Since 2.8 Ma BP, continuous ice-rafted detritus has occurred in the Norwegian Sea[14]. As well, ice islands have contained moraine deposits with an age of 3.1 Ma BP. From 3 to 3.1 Ma BP, mountain glaciers developed on the Nevada Range in the United States, which is located in mid-latitudes[16,17]. There were moraine beds in the Gauss chron located in sequences on the Chinese Qinghai-Xizang Plateau[18]. Becuase it is difficult to observe and identify early mountain glacial relics, this Late Miocene and Pliocene glacial evidence is not enough to fully indicate climatic conditions from the Northern Hemisphere at that time. Therefore, in addition to the eolian deposit records from the Loess Plateau, $\delta^{18}O$ isotopic records from the equatorial ocean provide further evidence to prove the onset of the Great Glaciation in the Northern Hemisphere. A $\delta^{18}O$ curve of core V28-178 (43°37′N, 179°36′W) published in 1977 from the equatorial Pacific Ocean has shown that before the Mammoth subchron in the Gauss chron at about 3.4 Ma BP according to new polarity time scale[19,20], the Northern Hemisphere began to experience a climate characteristic of glacial-interglacial conditions and then an glacial intensification commenced around 2.6 Ma BP. A more detailed oxygen isotope record from the ODP site 846 taken from the East Pacific Ocean near the equator (3°5.80′S, 90°49.01′W) has provided evidence of global climatic change over the last 6.1 Ma. This record shows frequent fluctuations and long-term changes in the generally stable amplitude during the period from 6.1 to 3.4 Ma BP. An ice volume increase and temperature decrease trend began around 3.4 Ma BP, but a maximum gradient occurred during the period from 3.4 to 2.6 Ma BP. Since the SUS curves from loess/red clay profiles in the Loess Plateau reflect summer monsoon changes in low-latitude and equatorial oceans, they can be compared with the $\delta^{18}O$ curve from the equatorial Pacific Ocean (fig. 3). The SUS curve chronology in fig. 4 is based on polarity boundary ages, using the SUS matching method[10]. The chronology of the Lingtai profile covers 7.2 Ma, and SUS or $\delta^{18}O$ curve fluctuations in the period from about 7.2 to 3.4 Ma BP indicate high-frequency oscillations in a 10000-year scale and small amplitude changes on a million-year scale. These reflect East Asian summer monsoon conditions which started to intensify from 3.4 Ma BP and reached their maximum around 3 to 2.8 Ma BP. This could be regarded as the Pliocene Optimum in East Asia on the basis of degree of precipitation. From 2.8 to 2.6 Ma the climate came close to the characteristics

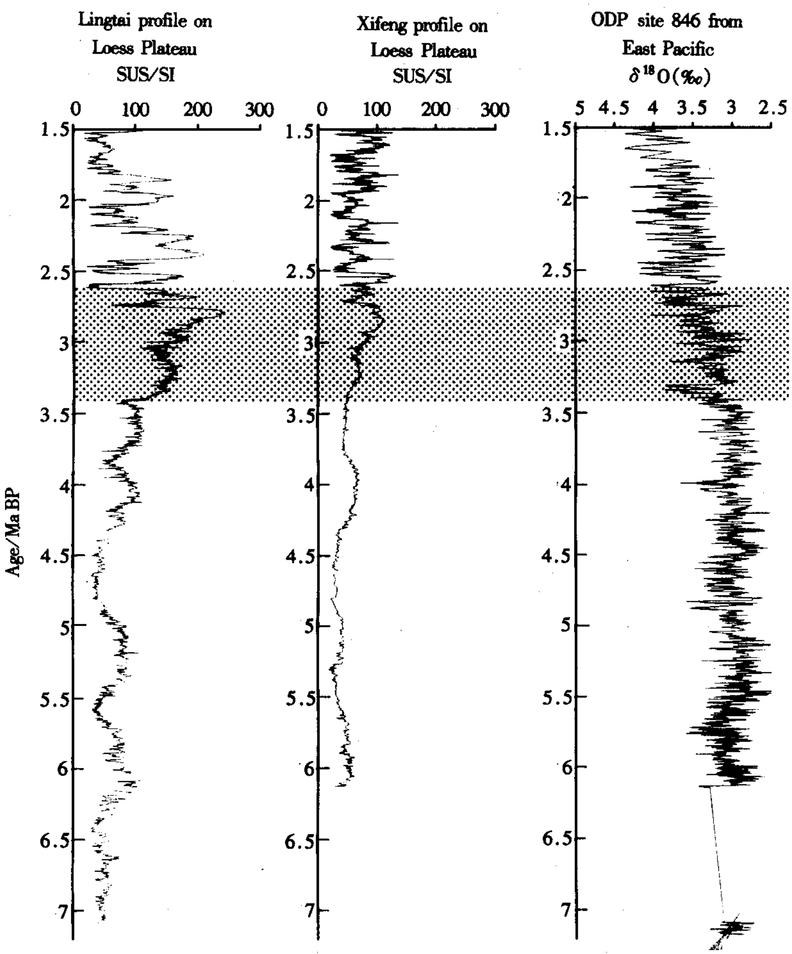

Fig. 3. Comparison of SUS curve from Lingtai and Xifeng with the oxygen isotopic curve from the East Pacific Ocean near the equator[9]. Shaded area in the figure shows the intensification period of the summer monsoon reflected by SUS from 3.4 to 2.6 Ma BP. This is in agreement with the period of obvious incease of global ice volume reflected by the oxygen isotope record.

of Great Ice Age fluctuations. At around 2.6 Ma BP, the $\delta^{18}O$ curve indicates large amplitude glacial-interglacial fluctuations globally, while temperature decreased with oscillation. At the same time, eolian deposits from the Loess Plateau changed from red loess-paleosol sequences to typical loess-paleosol sequences. The basic concept is that loess deposition corresponds to a glacial period, and paleosol layer corresponds to an interglacial period. Detailed records of monsoon climate change on different time scales are characterized by the complementary nature of East Asian winter and summer monsoons with a higher variability during the Great Glaciation.

According to the polarity boundry ages and corresponding stratigraphic thickness from the Lingtai and Xifeng profiles, we can calculate an average eolian sedimentation rate for different periods (fig. 4). Fig. 4 also shows that the two curves started to increase in value significantly at about 3.4 Ma BP. This phenomenon agrees with the evidence of an abrupt increase of eolian quartz flux from the northern Pacific Ocean at around 3.2 Ma BP[12] (this time sequence is a 1981 sequence), indicating that there may exist some linkage between them. The Lingtai profile additionally shows a further in-

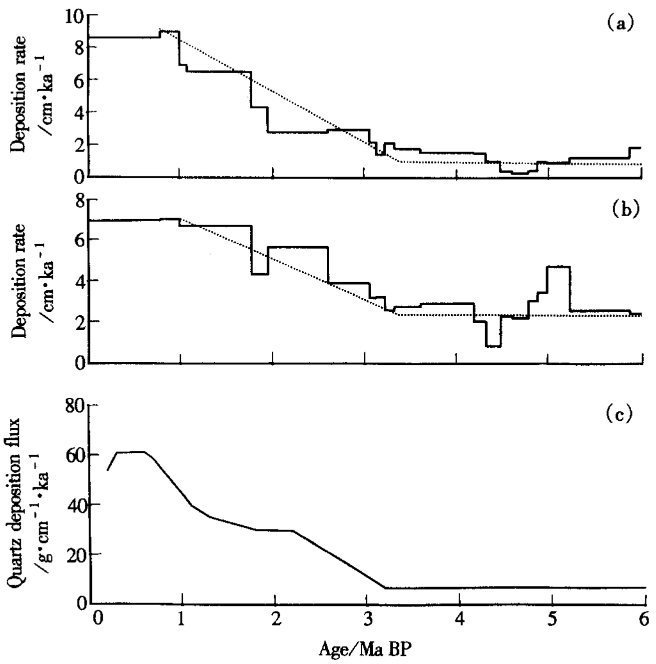

Fig. 4. The correlation of eolian deposition rate from the Loess Plateau and eolian quartz deposition flux change from the northern Pacific Ocean[21] in the last 6 Ma. The dotted line in the figure represents the trend of deposition rate change. (a) Xifeng priofile; (b) Lingtai profile, (c) Core LL44-GPC3 in the northern Pacific Ocean.

crease around 2.6 Ma BP. The eolian sedimentation rate of the Loess Plateau depends on the aridification of source areas to a large extent, and hence is related to the Mongolian high-pressure system, which is also associated with the Northern Hemisphere polar and higher-latitude ice sheets. This deposition rate could thus be regarded as a proxy of winter monsoons to a certain extent. A comparison of fig. 4 with fig. 3 shows that the intensification of the winter monsoon reflected by the average eolian sedimentation rate from the Loess Plateau occurred simultaneously with the intensification of summer monsoons. On the basis of the above information, we may conclude that winter monsoon signal-bearing eolian deposits from the Loess Plateau indirectly recorded the arrival of the Late Cenozoic Great Glaciation and the whole process of glacial-interglacial climatic change in the Northern Hemisphere (the period from 7.2 to 3.4 Ma BP represents the arrival stage, that from 3.4 to 2.6 Ma BP, the initiation stage, and that at about 2.6 Ma BP, the Great Ice Age).

3 Qinghai-Xizang Plateau uplift

Loess-red clay sequences from the Chinese Loess Plateau containing pedogenic carbonate illuvial horizons indicate that the East Asian summer and winter monsoon climates commenced at about 7.2 Ma BP, when the Qinghai-Xizang Plateau, which played a significant part in monsoon climate evolution, reached a significant height. From 3.4 Ma BP, the East Asian winter and summer monsoons basically intensified simultaneously. At the same time global ice volume started to increase significantly. The simultaneous intensification of winter and summer monsoon conditions may only be interpreted as indicating acceleration of Qinghai-Xizang Plateau uplift during the period between 3.4 and 2.6 Ma BP. Research into the late Cenozoic Qinghai-Xizang Plateau uplift[22,23] shows that the present geomorphologic framework of the Plateau was established initially be tectonic movement between 8 and 7 Ma BP and fault basins of different sizes and orientations were formed successively. During the early Late Miocene or Middle Miocene, the coal series or lacustrine strata occurring in the middle and southeastern Tibet[24] were pushed up to the tops of the Gandes, Nyanqentanglha and Hengduan Mountains by this tectonic movement. On the basis of estimates of fossils of mid subtropical mountain type deciduous and broad-leaved trees, and spore pollen flora, the deposition surface at that time reached an altitude of 1800 to 2000 m.

From 7.2 Ma BP in the eastwest strike of Zhada Basin[25] and the northsouth strike of Jilong Basin[26] together with other tectonic basins distributed between the Himalayas and Kunlun Mountains, 500 to 1000 m thick gravel layers, especially lacustrine and fluvio-lacustrine strata, with ages of the Late Miocene-Pliocene-Early Pleistocene were deposited. These were depostits associated with the mountáin denudation and the plateau surface development. The aggradation of these basins smoothed out the landscape relief. During this period, particularly in the Gauss chron (3.58 to 2.58 Ma BP), Molasse type sediments deposited in the outskirts of the plateau. The conglomerate with a thickness of 300 m formed during the period of about 3.7—3.1 Ma BP in the Pliocene lacustrine strata of the Karewa Basin, Kashmir[27]. In the Tianshan Mountain area[28], especially along the north foot of the West Kunlun Mountains[22,29] more than 3000 m of Xiyu conglomerate were deposited. More than 200 m of moraine deposits and (or) Pliocene gravel layer[30,31], underlying a lacustrine layer named Qiangtang Formation, outcrop in a basin near the mouth of the East Kunlun Mountains. A 60-m thick gravel layer named Jishi Formation was intercalated in the Cenozoic strate in the Linxia Basin located at the north foot of the West Qinling Mountains[32,33]. A gravel layer was also formed underlying a lacustrine deposit within the Xigeda Formation[34] in the ara of Hengduan Mountains. Later, at the beginning of the Matuyama chron, a gravel layer within the Gongba Formation formed in a lacustrine strata of the Jiabula Formation[35] from the north foot of the mid Himalaya Mountain transformed into a gravel layer named Gongba Formation[35]. Xiyu conglomerate from the north foot of the West Kunlun Mountains and Tianshan Mountains also showed an accelerated deposition rate. Lacustrine deposits of Shulehe Formation at the northeast foot of the Qilian Mountains transformed into a gravel layer named Yumen Formation[36]. The above temporal and spatial distribution of moraine type sediments accompanying mountain uplift indicates that strong tectonic movement took place around the outskirts of the Qinghai-Xizang Plateau during the Gauss chron and the Early Matuyama chron. This comprehensive analysis indicates that the period 3.4—2.6 Ma BP is one of intensive uplift of the Qinghai-Xizang Plateau. Within the plateau, continuous denudations and aggradations still existed within specific relief and at a specific height. The process of development of the Plateau surface with a characteristic tectonic geomorphology marked by the development and extinction of paleolakes completely terminated at about 1.5—1.3 Ma BP.

The changes in height of the aggradational basin surface during the development period of the Plateau surface in the Pliocene-Early Pleistocene still remain questionable so far. Examination of less detailed pollen data from the Zhada Group[25] and the Jilong Group[37] indicates that the warm period of the Gauss chron or interglacial is characterized mainly by *Pinus*, *Cedrus*, *Picea*, *Abies Larix*, and broad-leaved decidous trees, while the cold period or glacial is mainly represented by shrub and herb. More detailed pollen data from the Zongga Formation of the Jilong Group, studied by the Institute of Geology and Mechanics, show that between 3.6 and 2.0 Ma BP, a *Cedrus-Picea* or *Abies-Cedrus* pollen zone occurred alternatively with a sparse spore pollen zone. In the present vertical vegetation zone[38] of the south slope of the mid Himalaya Mountains the base zone of vegetation is the tropical rain forest with an upper limit of 1000—1200 m, and the upper limit of the evergreen broad-leaved forest is at 2500 m. In the Jilongzangbu Valley, a mixed zone of needle broad-leaved forest occurs at an altitude of 2500—3100 m, and at 3100—4000 m there is a zone of dark needle-leaved forest. Besides, the present *Gedrus* forest relic is distributed at an altitude of 1900—2900 m on the south slope of the Himalaya, a height similar to that of the mixed needle broad-leaved forest zone. Based on the above information, it is reasonable to imagine that the seasonal temperature for growth of the Late Pliocene plants is similar to that of the present. In Zhada and Jilong Group only spore pollen flora of a transitional zone from mixed needle, broad-leaved forest to dark coniferous forest was discovered. They should grow on the slope at an altitude of around 3000 m, which indicates that the aggradational basin surface had reached at least 2500 m. This altitude can be regarded as an average height of aggradational basins suface in the southern part of the Qinghai-Xizang Plateau. However, the corresponding average height of the mountains could be 500—1000 m higher, that is, 3000—3500 m above sea level. This agrees with the altitude of the mid Himalaya estimated on the basis of the relationship between sedimentary grain size and the slope of river beds during this period[26].

From the Late Miocene through Pliocene to the Early Pleistocene, the inner Qinghai-Xizang Plateau was in the period of tectonic isostatic adjustment under a tensional stress field. There was not a large change in the altitude of extensional basins in a state of aggradation. The plateau climatic effect may be inensified through the uplift of boundary mountains and the reduced relief of the inner plateau between 3.4 and 2.6 Ma BP. Since 2.6 Ma BP, after Qilian and Chaidamu Massifs joined the Qiangtang Massif, the plateau spatial area increased by about 20%. If we take into account the further rapid uplift of the boundary mountains of the northern plateau (the West Kunlun-Arjin) and the uplift of the Himalaya in the south boundary of the Plateau, the climatic effect would be more striking. Since about 1.5 Ma BP, the Qinghai-Xizang Plateau started its episodic integral uplift. The average altitude of the plateau surface of 2500 m or so started to uplift till the present 5000 m[23]. During this period, the increase of the Qinghai-Xizang altitude and the change in the nature and state of related underlying boundary conditions became one of the major factors influencing climate.

4 Discussion and conclusion

4.1 Initial occurrence of East Asian monsoon reflected by the Late Cenozoic eolian deposition sequence.

East Asian monsoon circulation characterized by the combined winter and summer monsoons is a powerful linkage between the Qinghai-Xizang uplift and the global climatic change. The eolian loess-red clay sequences from the Loess Plateau form a valuable geological record reflecting the formation and evolution of the East Asian monsoon system. The Lingtai record shows that starting from 7.2 Ma BP, large-scale eolian deposition which occurred on the east of the Qinghai-Xizang Plateau and the north of the Qingling Mountains marked a major differentiation of the East Asian environment system. The onset of aridity in Northwest China can be viewed as the beginning of the establishment of the winter monsoon system as the power of dust transportation. Considering the formation of high-latitude and polar glaciers or ice caps in the Northern Hemisphere[14,15], the occurrence of eolian deposits from the Loess Plateau is not strange. It is the product of the coupling process between land, sea and atmosphere in the Northern Hemisphere, and the major driving force for this will be discussed in terms of tectonic uplift. We would like to point out that the SUS of the red loess-paleosol sequences also reflect summer monsoon intensity to some extent. The SUS record of eolian red clay between 7.2 and 3.4 Ma BP has characteristics similar to deep sea $\delta^{18}O$ records in that there is a small amplitude with low average values (fig. 3). During this period, the sedimentation rate is also very low (fig. 4).

Based on this we can clearly see that during the precursor stage of the East Asian monsoon system, winter and summer monsoons were not strong. The annual temperature differences were still low, and pollen assemblages from lacustrine sediments of the same period at the east margin of the Loess Plateau indicate a lot of *Picea*, and a small amount of *Abies*, with some needle-leaved forest pollen, though the major pollen assemblage belongs to subtropical and temperature broad-leaved deciduous forests and there is a small amount of subtropical evergreen tree pollen[39]. This provides strong evidence for the precursor stage of East Asian monsoons when both winter and summer monsoons were weak.

4.2 East Asian monsoon change at the initial stage of Great Glaciation in the Northern Hemisphere

Within the upper portion of the red loess-paleosol sequences, SUS values and their amplitude gradually increased between 3.4 and 2.6 Ma BP (fig. 3). The sedimentation rate began to increase from 3.4 Ma BP as well (fig. 4). This indicates the in-phase characteristics of increase of intensification of winter and summer monsoons during this period. It seems that the theories of solar radiation and global ice volume cannot give a reasonable explanation for this in-phase change. Therefore, we need to postulate the driving force leading to the intensification of simultaneous winter and summer monsoon variation from a new point of view.

The oxygen isotope record from deep sea cores (fig. 3) shows that the initial stages of the Great Glaciation in the Northern Hemisphere occurred within the period from 3.4 to 2.6 Ma BP. Global ice volume increased significantly, further indicating that a large extension of higher-latitude and polar ice sheets occurred. At the same time continental mountain glaciers were developed in the mid latitude areas including the Qinghai-Xizang Plateau and North America[17,18]. When in the Late Cenozoic, global cooling occurred, especially at the beginning of Great Glaciation in the Northern Hemisphere, the cooling amplitude is larger in higher latitudes than in the low-latitude areas, the pressure gradient increased between polar regions and the equator leading to the intensification of the mid-latitude westerly circulation. Simultaneously, the south of the Qinghai-Xizang Platesu and the Himalaya Mountains were being uplifted, with its basin altitude reaching 2500 mn and the average mountain altitude ranging from 3500 to 2500 m. This uplift caused the westerly jet to mechanically separate when passing through the plateau, providing suitable conditions for the formation of the Mongolian high-pressure system on the north side of the plateau, and the southward outbreak of cold air in the state of anticyclone on the east side of the plateau, resulting in a significant increase in East Asian winter monsoon conditions. Beginning at about 3.4 Ma BP, the eolian quartz sedimentation flux in the northern Pacific Ocean increased rapidly[21], and the eolian sedimentation rate within the Loess Plateau speed up (fig. 4). This provides sedimentary evidence for westerly circulation and Ease Asian winter monsoon intensification during the initial stages of the Great Glaciation in the Northern Hemisphere.

The intensity of the East Asian summer monsoon mainly relies on the sea-land thermal contrast between Eurasian and the Pacific Ocean. The Qinghai-Xizang Plateau uplift strengthens sea-and-land thermal contrast together with longitudinal vapour and heat transportation. This promotes the development of the East Asian summer monsoon and significantly increases precipitation in monsoon areas. At about 3.4—2.6 Ma BP, the lake basins were formed and lakes developed widely in North China, Loess Plateau and Yunnan-Guizhou Plateau[40], reflecting abundant precipitation conditions to some extent. Such a phenomenon is in good agreement with the rapid strengthening of summer monsoon indicated by SUS signals from the dust deposits on the Loess Plateau. Besides, the paleovegetation changes of the same period possesses a transitional characteristic. The spore pollen assemblage from lacustrine sediments at the Loess Plateau[39,41] and North China[42] show that although the component of dark coniferous forest increased, the major component was still the pollen of temperate broad-leaved deciduous forest, and a small amount of subtropical pollen component remained.

In a word, at the initial stage of the Great Glaciation, i.e. 3.4—2.6 Ma BP, a successive intensification of both winter and summer monsoons in East Asia took place. This characteristic of transition of winter and summer monsoon strengthening simultaneously can only be interpreted by the accelerating uplift of the Qinghai-Xizang Plateau and its reaching a certain altitude and dimensions during this period. The climatic modeling results[43] also show that the existence of the Qinghai-Xizang Plateau is one of the decisive factors for the formation of Asian monsoons, especially the East Asian monsoon. Starting from about 2.6 Ma BP, when global cooling and ice volume increased to the threshold values, the Great Glaciation characterized by Milankovich glacial-interglacial cycles started. The eolian deposits on the Loess Plateau, a typical loess-paleosol sequence, marked the predominant period of the East Asian monsoon, forming a complementary pattern of winter and summer monsoon climate on a large scale. During this period, under the influence of episodic uplift of the Qinghai-Xizang Plateau, monsoon climatic frequent and lower-amplitude abrupt changes such as those around 1.3 and 0.6 Ma BP occurred successively[3,5].

4.3 Qinghai-Xizang Plateau uplift and its driving force to the onset of the Great Glaciation

The Qinghai-Xizang Plateau uplift not only strengthened the East Asian monsoon but also influenced the global climate and environment. In addition to the formation of fault basins and elevation of mountains caused by tectogenesis between 8 and 7 Ma BP, around 3.4 Ma BP the West Kunlun Mountains-West Qinling at the north margin of the Qinghai-Xizang Plateau started to uplift dramatically. Meanwhile, on the Yunnan-Guizhou Plateau adjacent to the southeast part of the Plateau there were many fault basins formed[40]. The fission track age of the tectonic movement of the East Himalaya shows that since 3 Ma BP the Qinghai-Xizang Plateau accelerated its uplift[44]. It is clear that the outskirt mountains and regions of the Qinghai-Xizang Plateau were within a strong tectonic activity period from 3.4 to 2.6 Ma BP. We estimate that the average altitude in the low land in the south of the Plateau was above 2500 m at least. The average altitude of the mountains has reached 3000 to 3500 m. It is worth mentioning that around 3.4 Ma BP was just the onset of the Northern Hemisphere Great Glaciation transitional period. Such corresponence between the increase of global ice volume and the Plateau uplift is not coincidental.

In recent years Ruddiman et al.[2] proposed the hypothesis of climatic change caused by Cenozoic tectonic uplift forcing. He pointed out that the uplift of the Qinghai-Xizang Plateau in the Northern Hemisphere and that of Altiplano and East Cordillera from the Southern Hemisphere has had a large influence on the atmosphere and oceanic circulation leading to atmospheric CO_2 concentration decrease through weathering and erosion, thus causing global cooling. He also pointed out that in the process of global cooling driven by structural uplift, the Qinghai-Xizang uplift may be a major source area of driving. On the basis of analysis from this understanding, the onset and development of the Cenozoic Great Glaciation in the Northern Hemisphere, including the arrival stage of 7.2 to 3.4 Ma BP, the initial stage of 3.4 to 2.6 Ma BP, and the Great Ice Age since 2.6 Ma BP, are all driven by the tectonic uplift of the Qinghai-Xizang Plateau. Although the hypothesis of tectonic uplift and global climatic change has not been finally verified, the $^{87}Sr/^{86}Sr$ of the foraminifera from the Indian Ocean show a significant increase around 2.5 Ma BP indicating the strengthening of chemical weathering and exhausing of CO_2 in atmosphere. This is not only in agreement with the onset of the Great Glaciation[2] but also is the fingerprint of dust deposits transformed from red clay to loess in the Loess Plateau. Loess-paleosol sequences contain on average 10% carbonate[4], which indicates a certain amount of carbon has been fixed and buried, and would not take part in the global carbon cycle. This indicates that such a type of geological process is also a possible cause of atmospheric CO_2 concentration decrease. We would like to emphasize that because in the period from 3.4 to 2.6 Ma BP, the Qinghai-Xizang Plateau's accelerating uplift strengthened winter monsoon, dust-increased atmospheric dust flux or loading indicated by the deposition rate of the Loess Plateau may have resulted in the global cooling and onset of the Great Glaciation to a certain extent.

Based on the above we believe that in the coupling system of land-sea-atmosphere, under solar radiation conditions controlling the global climatic system especially during 3.4 to 2.6 Ma BP, the uplift of the Qinghai-Xizang Plateau and that of the mid-latitude mountains of the Northern Hemisphere act as the driving force for the Great Glaciation onset of the Northern Hemisphere, the development of the East Asian monsoon, the global climatic cooling in terms of weathering, erosion, dynamic and themodynamic.

From dust deposits of the Loess Plateau adjacent to the Qinghai-Xizang Plateau we should be able to extract climatic information of the response in tectonic uplift[45]. This will be very important to understanding the long-term global and East Asian climatic change and its dynamic mechanism. The eolian dust records from 7.2 Ma BP as recorded in the Lingtai profile of the Loess Plateau provide important evidence for demonstrating the onset and evolution process of the Great Glaciation in the Northern Hemisphere. In the attempt to theorize the hypothesis of the climatic change driven by tectonic uplift we should focus on scientific questions such as global carbon cycle chemical weathering intensity, the mechanism from cold to warm on a greater than orbital scale, and make deep studies on the tectonic uplift of the Qinghai-Xizang Plateau and dust deposits on the Loess Plateau.

Acknowledgement The mammal fossil identification for this study has been guided by Prof. Xue Xiangxi at the Geological Department, Northwest University. Some of the environmental magnetic measurements were carried out with assistance from Dr. Zhu Rixiang, Institute of Geophysics, Chinese Academy of Sciences, and Dr. Yang Shanlin, Liverpool University, UK. The authors wish to thank them all.

References

1 Ruddiman, W. F., Kutzbach, J. E., Forcing of Late Cenozoic Northern Hemisphere climate by plateau uplift in southern Asia and the American West, *Journal of Geophysical Research*, 1989, 94(D15): 18409.

2 Ruddiman, W. F. (ed.), *Tectonic Uplift and Climate Change*, New York: Plenum Press, 1997, 1—515.

3 An Zhisheng, Liu Tungsheng, Lu Yanchou et al., The long-term paleomonsoon variation recorded by the loess-paleosol sequence in central China, *Quaternary International*, 1990, 7/8: 91.

4 Liu Tungsheng (ed.), *Loess and Environment* (in Chinese), Beijing, Science Press, 1985, 1—481.

5 Wu Xihao, An Zhisheng, Loess-paleosol sequence on the Loess Plateau and the uplift of Qinghai-Xizang Plateau, *Science in China*, Ser. D, 1996, 39(2): 121.

6 Sun Donghuai, Liu Tungsheng, Chen Mingyang et al. Magnetic stratigraphy of red clay sequence of Loess Plateau of China and

climate change, *Science in China* (in Chinese), Ser. D, 1997, 27(3): 265.
7 Ding Zhongli, Sun Jimin, Zhu Rixiang et al., The origin of red clay from the Loess Plateau and Late Pliocene aridification of North China, *Quaternary Sciences* (in Chinese with English abstract), 1997, (2): 147.
8 Sun Donghuai, Chen Mingyang, Shaw, J. et al., Magnetostratigraphy and paleoclimatic record of Late Cenozoic eolian sequences on the Loess Plateau, *Science in China* (in Chinese), Ser. D, 1998, 28(1): 79.
9 Shackleton, N. J., Hall, M. A., Pate, D., Pliocene stable isotope stratigraphy of site 846, in *Proceedings of the Ocean Drilling Program*, *Scientific Results* (eds. Pisias, N. G. et al.), College Station TX: Ocean Drilling Program, 1995, 138: 227.
10 Kukla, G., An Zhisheng, Loess stratigraphy in central China, *Paleogeography*, *Plaeoclimatology*, *Paleoecology*, 1989, 72 (2): 203.
11 Chen Xiaofeng, Stratigraphy and large mammals of the "Jinlean" stage, Shanxi, China, *Quaternary Sciences* (in Chinese with English abstract), 1994, (4): 339.
12 Kennett, J.P., Cenozoic evolution of Antarctic glaciation, the circum-Antarcitc Ocean and their impact on global paleoceanography, *Journal of Geophysical Research*, 1977, 82(27): 3843.
13 Zachos, J. C., Lohmann, K. C., Walker, J. C. G., Abrupt climate change and transient climates during the Paleogene: a marine perspective, *The Journal of Geology*, 1993, 101: 191.
14 Mangerud, J., Jansen, E., Landvik, J. Y., Late Cenozoic history of the Scandinavian and Barents Sea ice sheets, *Global and Planetary Change*, 1996, 12: 11.
15 Larsen, H. C., Saunders, A. D., Clift, P. D. et al., Seven million years of glaciation in Greenland, *Science*, 1996, 264: 952.
16 McDougall, I., Wensink, H., Paleomagnetism and geochronology of the Pliocene-Pleistocene lavas in Iceland, *Earth Planet. Sci. Lett.*, 1966, 1: 232.
17 Curry, R. R., Glaciation about 3 00 000 years ago in the Sierra Nevada, *Science*, 1966, 154: 770.
18 Wu Xihao, Li Yongzhao, Moraines and environments in Qinghai-Xizang Plateau, *Quaternary Sciences* (in Chinese with English abstract), 1990, (2): 146.
19 Shackleton, N. J., Opdyke, N. D., Oxygen isotope and palaeomagnetic evidence for early Northern Hemisphere glaciation, *Nature*, 1977, 270: 216.
20 Cande, S. C., Kent, D. V., Revised calibration of the geomagnetic polarity time scale for the Late Cretaceous and Cenozoic, *Journal of Geophysical Research*, 1995, 100: 6 093.
21 Leinen, M., Heath, G. R., Sedimentary indicators of atmospheric activity in the Northern Hemisphere during the Cenozoic, *Palaeography*, *Palacoclimatology*, *Palaeoecology*, 1981, 36: 1.
22 Wu Xihao, Wang Fubao, An Zhisheng et al., Uplift stage and elevation of Tibet Plateau over the late Cenozoic, in *Loess Quaternary Geology and Global Change* (in Chinese) (eds. Liu Tungsheng, An Zhisheng), Beijing: Science Press, 1992, 1—13.
23 Wu, Xihao, A preliminary study on the uplift amplitudes of Qinghai-Xizang Plateau, in *Loess Quaternary Geology*, *Global Change* (in Chinese) (eds. Liu Tungsheng, An Zhisheg, Wu Xihao), Beijing: Science Press, 1996, 1—17.
24 Tao Junrong, Du Naiqiu, Miocene flora from Markam County and fossil record of Betulaceae, *Acta Botanica Sinica* (in Chinese), 1987, 29(6): 649.
25 Qian Fang, Preliminary study of horizontal tectonic movement in Arli, Tibet since Pliocene using pateomagnetic stratigraphy technique, in *Petrospheric Tectonic Evolution of Himalaya and Qinghai-Xizang Geophysics* (in Chinese), Beijing: Geological Publishin House, 1990, 198—206.
26 Wang Fubao, Li Shengfeng, Shen Xuhui et al., Formation, evolution and environmental changes of the Gyirong Basin and uplift of the Himalaya, *Science in China*, Ser. D, 1996, 39(4): 401.
27 Burbank, D. W., Johnson, G. D., Intermontane-basin development in the past 4 Myr. in the north-west Himalaya, *Nature*, 1982, 298: 432.
28 Chen Huahui, Lin Xiulun, Guan Kangnian et al., Early Pleistocene deposits and its lower boundary (Q/N) in Tianshan Mt., Xinjiang region, *Quaternary Sciences* (in Chinese with English abstract), 1994, (1): 38.
29 Wu Xihao, Zhu Yizhi, The Neotectonic framework of the boundary of the Qinghai-Xizang Plateau, in *Proceedings of the First Symposium on Qinghai-Xizang Plateau* (in Chinese) (ed. CGQXP Editorial Committee), Beijing: Science Press, 1992, 272—279.
30 Wu Xihao, Qian Fang, Pu Qinyu, Quaternary glaciogeology of East Kunlun Mts, in *Contribution to the Geology of Tibet Plateau* (4) (in Chinese) (ed. CGQXP edition committee), Beijing: Geological Publishing House, 1982, 1—18.
31 Qian Fang, Zhang Jinqi, Study on the magnetic stratigraphy of the Qiangtang Formation and the neotectonism, *Journal of Geomechanics* (in Chinese with English abstract), 1997, 3(1): 50.

32 Fan Xiaomin, Li Jijun, Zhu Junjie et al., Cenozoic stratigraphic dating and subdivision of Lingxia Basin, Gansu Province, *Chinese Science Bulletin*, 1997, 42(14): 1 457.

33 Li Jijun, Fang Xiaomin, Ma Haizhou et al., Geomorphologic and environmental evolution in the upper reaches of the Yellow River during the Late Cenozoic, *Science in China*, Ser. D, 1996, 39(4): 380.

34 Qian Fang, Xu Shujin, Chen Fubin et al., Study on the paleomagnetism of the Xigeda Formation, *Mountain Research* (in Chinese with English abstract), 1984, 2(4): 275.

35 Qian Fang, The Gravel chronology and environment of Gongba Formation in Dingri, Tibet, in *Quaternary Glacial and Environment in the Western China* (in Chinese) (ed. Chinese Quaternary Glacial and Environmental Center, the Commission of Chinese Quaternary), Beijing: Science Press, 1991, 285—291.

36 Chen Jie, Lu Yanchou, Ding Guoyu, Subdivision of Quaternary tectonic movement of west part of Qilian Mountain and Jiuxi Basin, *Quaternary Sciences* (in Chinese with English abstract), 1996, (3): 263.

37 Li Binyuan, Wang Fubao, Zhang Qinsong et al., *Quaternary Geology in Xizang* (in Chinese), Beijing: Science Press, 1983, 110-171.

38 Zhang Rongzu, Zhen Du, Yang Qinye, *Natural Geography of Xizang* (in Chinese), Beijing: Science Press, 1982, 1—178.

39 Shi Ning, Cao Jiaxin, Kongsson, L. K., Late Cenozoic vegetation history and the Pliocene-Pleistocene boundary in the Yushe Basin, SE Shanxi, China, *GRANA*, 1993, 32: 260.

40 Nanjing Institute of Geography and Lake, *Fault Lake Deposition and the Environment in Yunan* (in Chinese), Beijing: Science Press, 1989, 16—53.

41 Tong Guobang, Zhang Junpai, Liu Minjian et al., Palaeovegetation (2—3 Ma BP) and lower boundary of Quaternary in Weihe River Basin, Shanxi, *Marine Geology & Quaternary Geology* (in Chinese with English abstract), 1989, 9(4): 86.

42 Wu Xihao, Qian Fang, Lan Chaoyu, Paleoclimatic reconstruction during the early Pleistocene, in Yanqing basin, Beijing, in *Loess Quaternary Geology*, *Global Change* (in Chinese) (ed. Liu Tungsheng), Beijing: Science Press, 1990, 47—61.

43 Kutzbach, J. E., Guetter, P. J., Ruddiman, W. F. et al., Sensitivity of climate to Late Cenozoic uplift in Southern Asia and the America West: numerical experiments, *Journal Geophysical Research*, 1989, 94(D15): 18 393.

44 Zhong Dalai, Ding Lin, Rising process of the Qinghai-Xizang (Tibet) Plateau and its mechanism, *Science in China*, Ser. D, 1996, 39(4): 369.

45 Wu Xihao, An Zhisheng, Some considerations of the Quaternary environmental dynamics of Qinghai-Tibetan and Loess Plateaus, in *Qinghai-Tibetan Plateau and Global Variations* (in Chinese), Beijing: Meteorological Press, 1995, 222—227.