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Linkage between the second uplifting of the Qinghai-Xizang (Tibetan) Plateau and the initiation of the Asian monsoon system*

SHI Yafeng (施雅风),
(Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences, Lanzhou 730000, China)
TANG Maocang (汤懋苍)
(Lanzhou Institute of Plateau Atmospheric Physics, Chinese Academy of Sciences, Lanzhou 730000, China)
and MA Yuzhen (马玉贞)
(Geography Department of Lanzhou University, Lanzhou 730000, China)

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Abstract During the period from 25 to 17 Ma BP, when the second plateau uplifting, i.e. the second phase of the Himalaya movement, occurred, the Qinghai-Xizang Plateau reached an altitude high enough to change the situation of the general circulation. Such an effect of the plateau on the atmospheric circulation was accompanied by the warming of the tropical ocean, the enhancement of the cross equatorial current, the enlargement of the marginal sea basins in the east-southeastern Asia, the westward extending of the Asian continent and the regression of the Paratethys Sea. As a result, the thermal difference was enlarged, and the air currents were enhanced between continents and oceans; finally the Asian monsoon system, mainly the summer monsoon, was initiated. The former planet wind system was then substituted by the monsoon system, and this caused the important environmental changes, such as the large shrinkage of the dry steppe in Central Asia, and the extension of the humid forest zone in East Asia. Those changes have been dated at 21.8 Ma BP on the Lingxia profile in the northeastern border of the Tibet Plateau, when the savanna was transformed into the forest.

Keywords: uplifting of Qinghai-Xizang Plateau, environment change of East Asia, Asian monsoon system.

Since 45—38 Ma BP, when the Indian Plate drifted northwards and collided with the Asian Plate, the crust of the Qinghai-Xizang Plateau has been undergoing a process of shortening, thickening, and uplifting. The large-scale uplifting of the plateau led to a significant change of the atmospheric circulation, strenthening the rock weathering and erosion. Thus the uplifting of the Qinghai-Xizang Plateau was an important driving force to the global change, especially the Asian monsoon system. On the other hand, the Asia monsoon could be affected by some other factors. This paper is designed to discuss the linkage among the second uplifting of the plateau, the initiation of the Asian monsoon system and the related affecting facts.

1 Environmental characteristics of the Qinghai-Xizang Plateau (Tibetan) and the East Asia during the early stage of the plate collision.

About 40 Ma BP ago, the Tethys Ocean between the Indian Plate and the Asian Plate was

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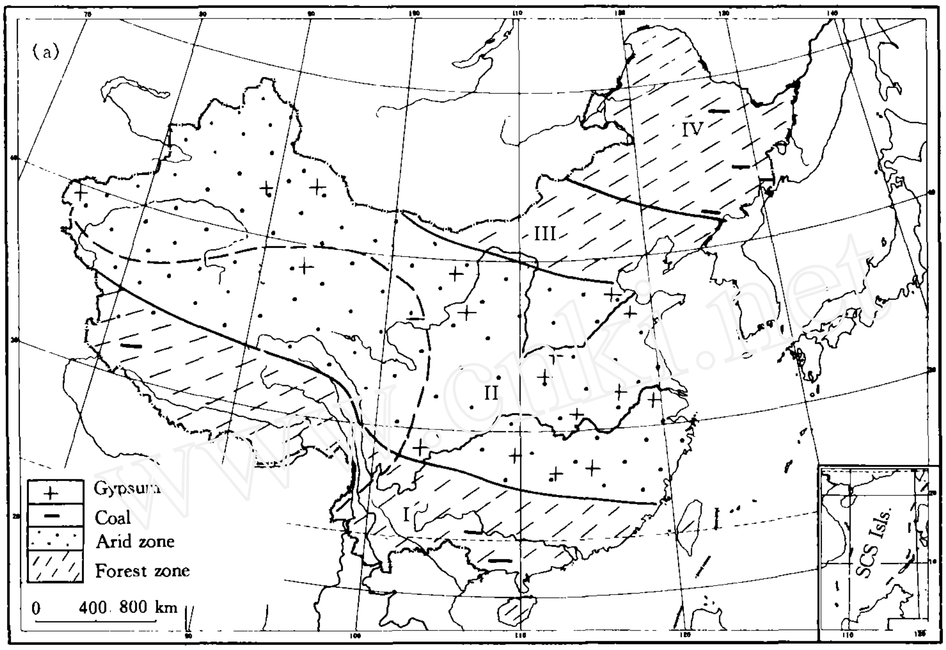
closed finally, while the Paratethys Sea, stretching from the East Europe to West and Central Asia, still occupied a large area to the north of 40°N. The Gangdise belt in the southern part of the Qinghai-Xizang region uplifted due to the jams and the driving of the Indian Plate. The mollasse deposit, as thick as 2000—4000 m, was formed at the south flank of the mountains. This was the first uplifting of the Qinghai-Xizang Plateau, i.e. the first Himalaya movement. It is difficult to estimate the possible altitude of the mountains formed at that time[1]. The northern and eastern parts of the Qinghai-Xizang region had merged with the Asian Plate earlier, and they were subject to denudation. There were several fault-subsidence basins, including the Qaidam Basin, filled with thick alluvial-lacustrine deposits. During the long period of Oligocene (35.4—23.3 Ma BP), the Qinghai-Xizang region was relatively stable. The surfaces of peneplain were developed. Some parts of the surface, preserved now at various mountain summits 5000—6000 m a.s.l., might be formed at that time, and they were named the summit surfaces (Li et al.)[2].

Data of pollen and deposits reconstruct the southern Qinghai-Xizang region located in the tropic-subtropic rain-forest zone with the forming of coal series during the early Tertiary. During the late Oligocene temperature decreased to some extent. The pollen of *Quarcus of folima and palmocarpon sp*. were found in the variegate sandstone in the Zedang Basin. Northwards, it changed into the arid zone, forming the red clastic deposits with gypsum and the pollen of *Chenopociaceae*, *Compositae* and *Ephedra* drought-enduring plants[3]. These two zones were bordered along 32°N. This was also the boundary of the latitudinal natural zones controlled by the planet wind system. The southern zone extended eastwards, joining the evergreen tree belt in the southern part of China. The northern zone, together with the arid area in northwestern China, extended eastwards, occupying the broad area of the lower reaches of the Changjiang and the Yellow Rivers. The red strata with gypsum and halite evaporite were developed widely, forming a subtropical high-controlled arid zone across China (fig. 1). The boundary between these two zones in Qinghai-Xizang region was 5°—6° in latitudes higher than that in eastern China. This reflects the result of the northward jams of the Indian Plate and the shortening of the crust in Qinghai-Xizang region. Perhaps the altitude of eastern China was higher than that of western China during the Paleogene, so the thermal difference between the sea and the land was enlarged, and the preliminary southeast monsoon in southeastern China was induced during the Oligocene[4].

2 A new outlook of natural zones in the Neogene and the time for its transformation indicated by the record from Linxia and Qaidam profile

As shown in fig. 1(b), the natural zones in China had changed significantly from the Paleogene to the Neogene, mainly in the northwestward regression of the arid zone and the extension of the southern humid forest zone. At that time, a broad area from southern to northern China was covered with subtropical evergreen and deciduous forest. The arid zone of the Qinghai-Xizang region also regressed northwards, up to the northern flank of the Kunlun range. The middle part of the Qinghai-Xizang region became the semi-humid and semi-arid forest or forest-steppe. The Hipparion faunal group developed widely then. The obvious increase of humidity in East China and in Qinghai-Xizang regions might indicate that the summer monsoon with a great amount of water vapour from Indian and Pacific Oceans drove and changed the arid environment which had been controlled by the subtropical high in the planet wind system originally. It was one of the most important events in the natural envi-

Paleogene



Neogene

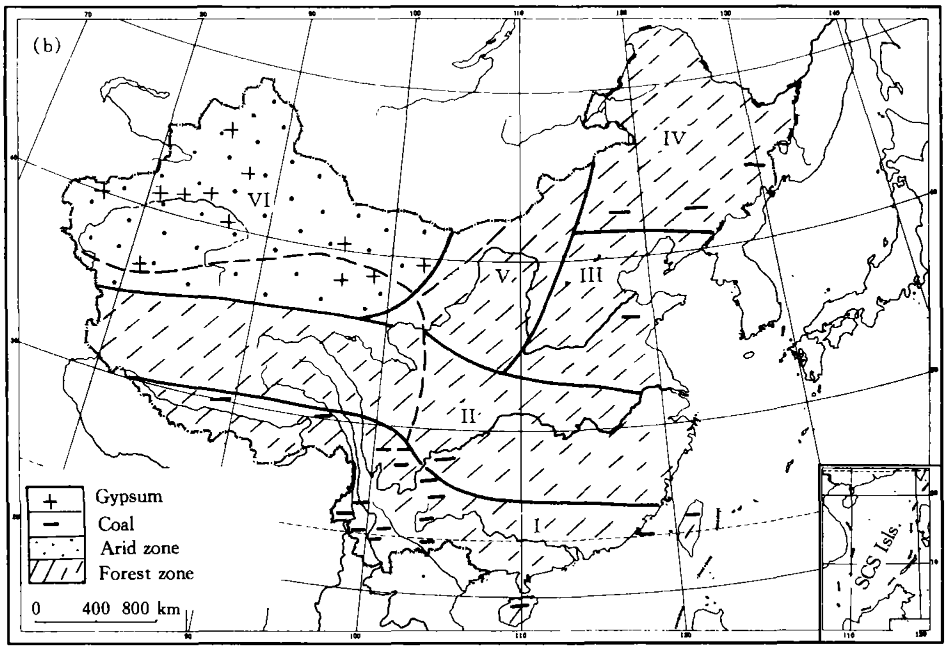


Fig. 1. The environmental change of China during the Middle Tertiary. (a) Broad arid zone across China in Paleogene. I, Tropical and subtropical rainy forest; II, subtropical steppe and desert; III, subtropical forest; IV, warm temperate broad-leaved forest. (b) Northwestward regression of arid zone and the extension of humid forest zone in Neogene. I, Tropical and subtropical evergreen forest; II, subtropical evergreen and deciduous forest and forest steppe; III, subtropical evergreen and deciduous forest; IV, warm temperate deciduous forest; V, subtropical and warm temperate forest steppe; VI, desert and desert steppe (after Pan Baotian).

ronmental change of China during the Cenozoic Era.

Important evidence has been attained by detailed study on the continuous stratigraphic profile since 30 Ma BP in Linxia of Gansu Province, indicating that the above event occurred at 21.8 Ma BP in the paleomagnetic age. It is revealed by the pollen data that during the period from 30 to 21.8 Ma BP, the savanna vegetation, mainly various herbs including *Chenopodipollis*, Polygonaceae and Compositae, was dominant. After 21.8 Ma BP, a large number of broad-leaved and coniferous trees occurred, such as Cupressacaceae, *Taxus*, *Juniperus*, *Quercoidites*, *Betulaepollenites*, *Fraxinoipollenites*, and *Salixipollenites*, some of which were the subtropical components of population. Such a forest vegetation indicates the presence of humid climate until 8.5 Ma BP (fig. 2). On the study of the fauna record, Gu et al.[5] revealed that the grass-eating animals such as *Metexallerix*, *Tataromys*, *Leptotataromys* and *Tsaganomys* were buried in the Oligocene red deposits in the age of 24.1—21.8 Ma BP near the Lanzhou Basin. Then the fauna changed in to elephants, rhinocceras, etc. including *Gomphotherium*, *Dzungaritherium*, Rhinocerotidae and *Paraentelodon* in the lower Miocene bed in the age of 21.8—19.2 Ma BP in the Linxia profile. This indicates that the environment changed to much humid and warm then. The pollen data from western Qaidam Basin also denote a similar trend that a relatively humid climate occurred during the Miocene, following the arid period from the Eocene to the Oligocene. In such a humid stage, the clastic deposits were changed in colour from reddish to grey, grey-green and yellow-green; gypsum and halite disappeared from the sediments (fig. 3), while more pollens of coniferous and broad-leaved trees occurred[6].

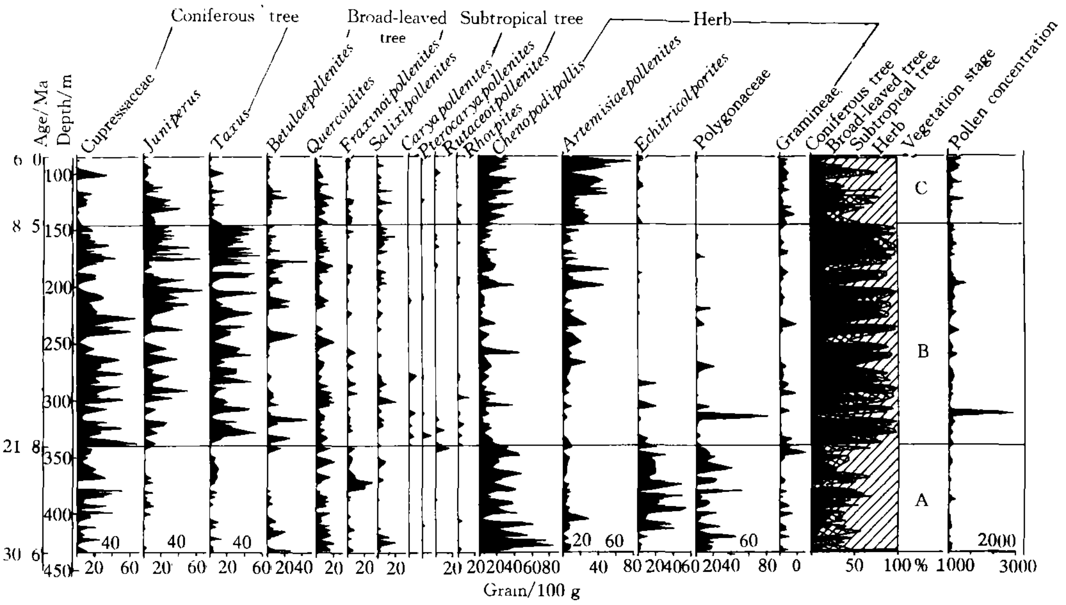


Fig. 2. Major changes of vegetation during 30—5 Ma BP on the Linxia Profile, Gansu Province.

3 The second uplifting of the Qinghai-Xizang region (25—17 Ma BP) and the attained altitude

According to Zhong Dalai and Ding Lin (1996), the Second Uplifting of Qinghai-Xizang region occurred during the period from 25 to 17 Ma BP. Based on the U-Pb age of the zircon in dyke of the strike-slip fault at the Gongrigabuqu in the southern part of the Gangdise Island Arc, it is known that the time of the maximum faulting was at 24.7 Ma BP. A great amount of the biotite was formed during 18—25 Ma BP in K-Ar age, around the time of the strike-slip fault. Through the processes of the quick denudation and uplifting, zircon was raised from the depth of 22 km to 8 km with a rising rate of 4.7 mm $\cdot a^{-1}$[7]. According to Harrison et al.[8], the rising rate of the Qushui Granite near Lhasa was increased from 0.7 to 4.4 mm$\cdot a^{-1}$ during the period of 20—17 Ma BP. The age of the granite and the main central thrust (MCT) of the Central Himalaya demonstrated that the most possible time of this tectonic movement might have started during 21—27 Ma BP[7]. By 18.3 Ma BP, the basal deposit of the Siwalik Group was formed[9]. The variation of the ratio of $^{87}Sr/^{86}Sr$ in the Bengal turbidite fan indicates that the metasedimentary rock of the Himalayas was strongly raised during 20—18 Ma BP[10]. Besides, the rising rate of rock mass in Mt. Xixiabangma was increased to 2.3 mm$\cdot a^{-1}$ during 30—20 Ma BP[11].

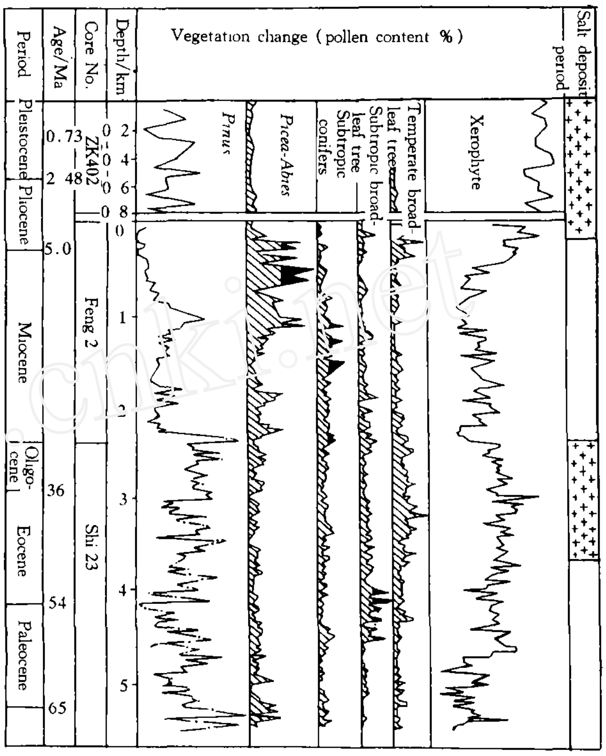


Fig. 3. Cenozoic vegetation changes in the western Qaidam Basin (after Wang et al., 1996)[6].

Only a few data can be offered to reconstruct the tectonic movement in the northern part of the Qinghai-Xizang region during that period. The Paratethys Sea still occupied a considerable area of Central Asia to north of the Kunlun Range at that time. In the northwestern part of the Qaidam Basin, the deposition of conglomerate, 700—900 m in thickness and mainly subangular, indicates a large and steep slope on the hill side between the mountain and basin[12]. The Shulehe Group gravelly deposit in the Hexi Corridor starting at 21 Ma BP indicates the uplifting of the Qilian Range at that time[13]. The planation surface at the top of Tala Group in the Linxia Basin was uplifted by tectonic movement at 21 Ma BP[14]. The current available data can only conclude that the northern part of the Qinghai-Xizang region was raised during the second uplifting. However, the intensity of crust movement seemed not as strong as that in the south then.

It is difficult to estimate properly the altitude of the Qinghai-Xizang region at that time. Chang[11] considered that the Qinghai-Xizang region had risen up to 3000 m a.s.l. before the Miocene due to the northward movement of the Indian Plate as well as the thickening and shortening of the crust. Li Jijun (personal communication, 1997) inferred that most parts of the Qinghia-Xizang region were lower than 2000 m a.s.l. during the second uplifting. According to the altitudinal spectrum of vegetation, it is possible to estimate that the altitude of the Kunlun and the Tangula might have reached 3000 m a.s.l. If the above inference is true, the Himalayas and the Gangdise Island Arc, where the tectonic movements were much stronger, might attain a much higher altitude, and the relief might be steeper than the northern part of the plateau. It is a reasonable estimation that the mean height of the plateau surface would be higher than 2000 m after due consideration of the balance between the higher rising rate of the rock mass (about $4\ \mathrm{mm \cdot a^{-1}}$) and the relative denudation rate. Using a numerial model on the relationship of the plateau uplift and the paleomagnetic polarity, the calculation by Dong and Tang[15] indicates that the plateau possibly rose to 2300 m during 20—18 Ma BP, but its mechanism is still not well understood.

4 Effect of the height and width of the second uplifting on atmospheric circulation and climate change

Tang et al.[16] recognized that the plateau should reach the critical scale of geostrophic adjustment in baraclinic atmosphere to provide a necessary condition of the plateau monsoon. He estimated that the horizontal scale is about 800 km in the middle latitudes and the vertical scale is higher than the vapour condensation height (1.5—2 km in general). The emancipation of condensed latent heat plays an important role in the plateau monsoon[16].

At present, the height for the vapour condensation is 1000—1500 m a.s.l. above the humid plain at the southeast periphery of the Qinghai-Xizang Plateau, and 2000—2500 m a.s.l. above the arid area on its northwestern side[17]. Due to the Second Uplifting, most parts of the Qinghai-Xizang region reached over 2000 m in altitude and 1200 km in width, sensible heat difference between the plateau and the surrounding area, together with the release of latent heat during the vapour condensation at such an altitude, strengthened the effect of the plateau as a heat source. In addition to the tropic zone, the plateau became another heat source leading to the rising and diverging of the air current. This changed the longitudinal Hadley circulation and created a favourable condition for the occurrence of the plateau monsoon. According to Trenberth and Chen[18], in the region with the same latitude as the Qinghai-Xizang Plateau, the eastward air circulation would be affected by the plateau if its mean altitude was higher than 1000—1500 m a.s.l. Thus, the near-surface westlies could be divided into two roundabout currents, i.e. the southern and the northern, and it also caused the northward moving of the middle-latitude high. It could be estimated that at an early time of the Second Uplifting the thermal and mechanical effects of the Qinghai-Xizang Plateau might become important factors to change the circulation from the relatively weak and unstable monsoon to the stable and strong monsoon, i.e. the southwest monsoon might bring a great amount of water vapour across the plateau with medium altitude, resulting in the humidification in the northern and northeastern parts of the plateau. This might be the major reason for the forest vegetation to substitute the savanna at 21.8 Ma BP, as shown in the record of the Linxia profile, and for the occurrence of the coniferous and broad-leaved components in a relatively humid climate in Miocene, as shown in the borehole record in the Qaidam Basin.

5 Other factors strengthening the Asian monsoon

The uplifting of the Qinghai-Xizang Plateau was not the single factor strengthening the Asian monsoon. The significant changes of the thermal conditions in the marine and continental environments also played an important role.

5.1 Changes in marine environment

Based on the data of oxygen isotope in benthic foraminifera, Donglas[19] suggested an oxygen isotope-paleotemperature curve (fig. 4) showing a general long-time cooling tendency of the tropical Pacific since 100 Ma BP or from the Cretaceous to the Cenozoic. Although the temperature decreased during that long period, the fluctuation of warming and cooling occurred obviously. In particular, the warming event with a temperature increase of 5℃ during the Late Paleocene and that of 3℃ from the middle stage of the Late Oligocene to the end of the Early Miocene (about 27—14 Ma BP) are most evident[19]. The latter can be distinguished also in the records of the South Pacific, but less clear in the Atlantic. The Second Uplifting of the Qinghai-Xizang region (25—17 Ma BP) occurred during this warming event. Zubakov and Borzenkova[20] remarked: "During the warming event at 21—25 Ma BP, the temperature had an increase of 3—5℃ at the surface of the Equatorial Ocean and had an increase of 2—3℃ at the bottom of the Antarctic Ocean". The warming of the tropical water enhanced the evaporation of the ocean, while the existence of the Antarctic Ice Sheet and the Circum Antarctic Ocean current increased the longitudinal temperature gradient and strenthened the cold wind of the Southern Hemisphere in winter. It crossed the equater as the energetic source of the summer monsoon in the Northern Hempisphere and brought a large amount of the vapour from the tropical ocean to the Asian Continent.

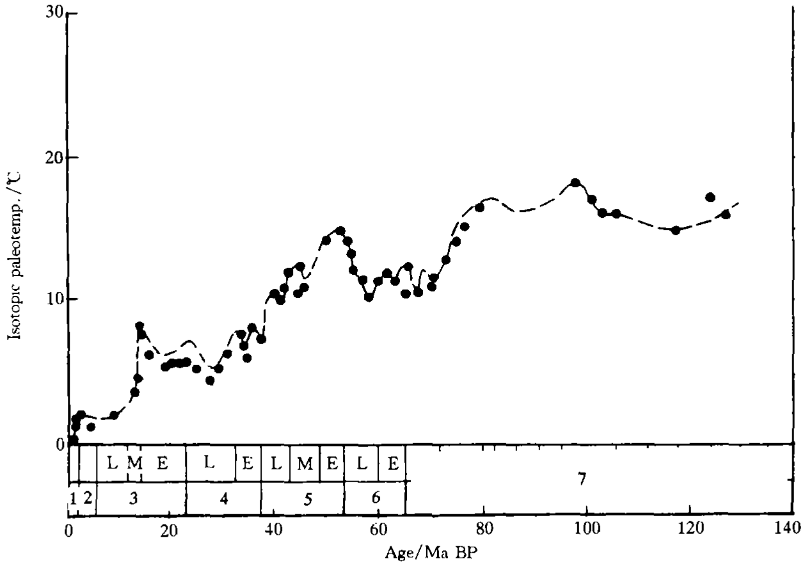


Fig. 4. Paleotemperature of the tropical Pacific Ocean during the Cretaceous to Cenozoic Era based on the oxygen isotopic composition of benthic foraminifera (after Douglas[19]).

According to Jin et al.[21], it was a period for sea basins to extend along the east and southeast margin of Asia from the Late Oligocene to Miocene (32—15 Ma BP), e.g. the Kuril Basin (30—15 Ma BP), the Japan Sea Basin (28—15 Ma BP), the Shikoku Sea Basin (27—13 Ma BP) and the South China Sea Basin (32—17 Ma BP). The enlargement of the marginal sea basins should provide much more water vapour and make its source closer to the East Asian Continent.

5.2 Changes in continental environment

When the marginal sea basins in East Asia were extending, the continent in West Asia was enlarged considerably. The Africa-Arabian Plate moved northwards, and approached closely the Asian Plate. The east end of the Mediterranean Sea had been closed at 23 Ma BP after the blocking up of the Turgai strait, a passage through Asia and Europe to the Arctic. Thus the Eurasian supercontinent was formed. The shrinkage of the Paratethys Sea in the central-west Asia was also an important affecting factor. As shown in fig. 5, the Paratethys Sea had occupied a vast area from 40° to 60°N, west of 90°E with a southeast branch (named the Kashi Bay) extending to the present Tarim Basin, resulting in a humid and temperate climate in the surrounding area during about 30 Ma BP. Afterwards, the Paratethys Sea withered rapidly. At the Mid-Miocene it could only occupy an area of the present Aral Sea, Caspian Sea and Black Sea and their surrounding regions. Thus the central Asia became drier, and strong continental climate appeared. According to the AGCM simulation test by Ramstein et al.[22], when the Paratethys Sea existed in the Oligocene, the annual range of air temperature did not exceed 17℃, and the annual precipitation could be as much as 900 mm. The Kazakhstan was partly covered by broad-leaved trees and bogs. After the westward regression of the Paratethys Sea, the annual range of the temperature increased to 30℃ or more, the mean temperature in winter had a decrease of 10℃, and the summer temperature had an increase of 4℃. Then the precipitation decreased obviously, and the desertification promptly intensified. Certainly the increase of the continentality enlarged the thermal difference between the Asian Continent and the Pacific-Indian Ocean, and enhanced the monsoon system.

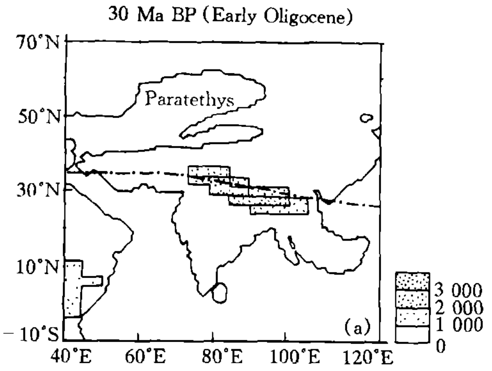


Fig. 5. Asian paleogeography and topography. (a) The Early Oligocene (about 30 Ma BP); (b) the Middle to Late Miocene (about 10 Ma BP) (after Ramsteim et al.)[22].

6 Conclusion and discussion

Under the coupling effect of various factors, the Asian Monsoon System was properly initiated (fig. 6) and strengthened during the Late Oligocene to the Early Miocene as described above. The driving forces are as follows:

1) When the Qinghai-Xizang Plateau reached an altitude of about 2000 m or higher and a width of about 1200 km at the early stage of the Second Uplifting of the Plateau, i.e. the second phase of the Himalaya movement, the thermal and mechanical effects of the Plateau were strong enough to

stimulate the occurrence of the monsoon.

2) The obvious return warming of the tropical Pacific increased the evaporation of the ocean, and also increased the temperature gradient due to the existence of the Antarctic Ice Sheet. This enhanced the winter's cold wind which crossed the Equator, became the summer monsoon in the Northern Hemisphere and brought a large amount of the vapour to the Asian Continent.

3) The drying continental climate of Central Asia was induced both by the westward extending of the Asian Continent due to its combination with Europe and the Africa-Arabian plate and by the shrinkage of the Paratethys Sea in the Western and Central Asia. The thermal difference between the Asia and the Pacific-Indian Ocean was then enlarged.

4) The enlargement of the marginal sea basins in East and Southeast Asia was favourable for more moisture to be transported to the continent nearby.

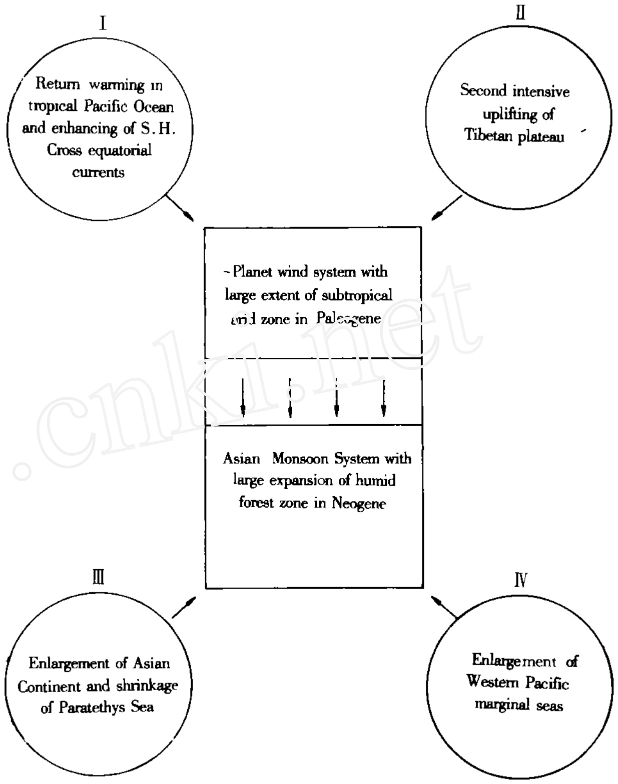


Fig. 6. Speculation upon the driving forces of the Asian Monsoon System in the Middle Tertiary.

The changes of vegetation from the savanna to the forest shown in the Linxia Profile at 21.8 Ma BP, the occurrence of the forest component in the Qaidam Basin and in the middle part of the Qinghai-Xizang region during the Early Miocene all indicate that the drying tendency in Central Asia was restrained by the strong southwest monsoon. Wang[23] stated that this reduction in aridity could be ascribed to a forerunner of the monsoon circulation, when the southeast and southwest monsoons were raging, bringing plenty of water vapour from the ocean to the continent, and therefore changing the surface planet wind system to monsoon system. However, the winter monsoon was much weaker than the strong winter monsoon in the Pleistocene marked by the thick loess deposition.

During the late stage of the Second Uplifting of the Plateau and its succeeding time, the rate of denudation exceeded that of the Uplifting. Thus the peneplains developed gradually, the altitude of the Plateau could decrease, and its effect on the monsoon could also be weakened. The climatic deterioration during the Late Miocene to Pliocene as shown in the Linxia profile caused the forest to chang into steppe at 8.5 Ma BP, later followed by the alternation of steppe and forest (fig. 2). The deterioration was marked by the salt formation during the Pliocene in the Qaidam Basin (fig. 3). The problem of the linkage between the plateau condition and the climatic change in that period still remains to be solved.

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