Uplift of the Tibetan Plateau and environmental changes

LI Jijun and FANG Xiaomin

Department of Geography, Lanzhou University, Lanzhou, Gansu 730000, China

Abstract Major progress, problems, and challenges of recent investigation of the Tibetan Plateau uplift processes and resulting environmental changes are reviewed and summarized briefly, which especially covers the National Tibetan Research Projects of the Chinese Eighth (1992—1996) and Ninth (1997—2001) "Five-Year Projects". The Tibetan Plateau uplift is a complicated multiple cyclic process. The Gangdise and Himalayas began to uplift in the Middle Eocene and Early Miocene respectively, while the main part of the Plateau merely underwent corresponding passive deformation and secular denudation, resulting in two planation surfaces. The third and also the strongest uplift involved the whole Plateau and its marginal mountains commenced at 3.6 Ma. Successive Kunlun-Huanghe movement at 1.1—0.6 Ma and Gonghe movement at 0.15 Ma raised the Plateau to its present height. The Asian monsoonal system and Asian natural environment formed in response to these tectonic uplifts.

Keywords: Tibetan Plateau, uplift process, Asian monsoon.

1 Brief geologic history

AFTER the World War Ⅱ, progress in geoscience was made chiefly in oceanic research. Plate theory and deep sea isotopic research recovered and developed the continental drift hypothesis of Wagner and the astronomical glacial theory of Milankovitch. This basic research made plausible earlier interpretations of the movement and variation of the earth's lithosphere and atmosphere. Undoubtedly this should be regarded as the greatest geoscience progress of this century. However, since the 1980s, the highest raised region on the earth surface, the Tibetan Plateau, gradually became a geoscience focus and a breakthrough area for new theories. This is because (ⅰ) the Plateau, as one of the most typical regions of continental collision on the earth, was an ideal area for testing and developing plate theory and facilitating creation of new geodynamic theories; and (ⅱ) the strong uplift of the Plateau during the late Cenozoic altered the pattern of Asian air circulation a great deal, producing the earth's strongest monsoonal system and even exerting a considerable influence on air circulation of the Northern Hemisphere. Without considering the Tibetan Plateau uplift, it would be very difficult to make a proper interpretation of global change in Cenozoic Era. Without the Tibetan Plateau in China, there would not be a dry Northwest China or a humid East China. Instead, the North Africa- and Arabia-like desert climate would prevail in the lower reaches of Changjiang River (Yangtze River) and South China. Actually, Eocene gypsum deposits in the lower reaches of Changjiang River are evidence of this. Obviously, in Eocene time there were no such summer monsoons as that now. During that time, the Tibetan Plateau eroded down to a planation surface and smooth planetary winds prevailed. The Late Cenozoic (N2-Q) intensive uplift of the Tibetan Plateau broke the latitudinal subtropic high zone over the Plateau, inducing and enhancing the Southern Asian summer monsoon circulation. Besides, with the Plateau uplift, a strong Siberian-Mongolian High formed in northern Asia in the winter. Manabe in the 1970s[1] first demonstrated this by numerical modeling. Meanwhile the Chinese researchers[2] have got the same conclusion.

Asian monsoons profoundly affect the Quaternary environment of North China. The winter monsoons transported dust from the Asian inland Gobi-desert areas to form the Loess Plateau. Studies of loess by Liu *et al*. contributed much to the understanding of loess and in particular established the relationship between loess and monsoons[3]. The Tibetan Plateau, gobi-desert, and Loess Plateau are related in origin and interdependant. The genesis of Huanghe River (Yellow River), the in-filling of the North China Plain, the Yellow and Bohai Seas, and accumulation of dust in the northern Pacific Ocean are all extensions of this coupling system. The uplift of the Tibetan Plateau initiated the system. In fact, uplift of the Tibetan Plateau exerted a great effect on Northern Africa as well as on Eastern and Southern Asia. Earlier in the 1960s Flohn believed that drying of Northern Africa is related to uplift of the Tibetan Plateau[4]. Moreover, some foreign researchers boldly proposed that three times in the Cenozoic global cooling and later global glaciation resulted from uplift of the Tibetan Plateau[5].

However, it is uncertain how the Tibetan Plateau was uplifted. The rate of uplift and the relief and appearance of the developing plateau are also not known. From the coupling system described above, loess deposition in the Loess Plateau is a good record of the Plateau uplift. Thus, the Chinese loess deposition started at 2.6 Ma[3], suggesting that the Tibetan Plateau rose to a critical height and the modern Asian monsoon system began at that time. Numerical general circulation modeling (GEM) confirmed this and showed that the critical height is about half the Plateau height, that is, ca. 2 000 m[6]. Indeed a large body of geological evidence from Chinese researchers demonstrates that intensive tectonisms occurred in West China in the Late Neogene-Early Quaternary. Compressed by the Indian and Eurasian plates the rim of the Tibetan Plateau rose, causing deformation and folding of Cenozoic sediments in the foredeeps and a large-scale accumulation of thick fanglomerates in peripheral areas. The well-known Yumen Conglomerate (in Hexi, Gansu Province) and Xiyu Conglomerate (in South Xinjiang) have thicknesses of over 1 000—3 000 m, indicating a rapid rise of the Plateau during deposition of the conglomerates. Results (National Tibetan Research Project in the Chinese Eighth Five-Year Projects, 1992—1996) demonstrate three major Late Cenozoic uplift phases. The first, the 'Qingzang (Tibet) movement', occurred between 3.6—1.7 Ma and included A, B and C phases commencing at 3.6, 2.5 and 1.7 Ma, respectively[7]. The second, the 'Kunlun-Huang He (abbreviated as Kunhuang) movement' occurred between 1.1—0.6 Ma and included three phases commencing at 1.1, 0.8 and 0.6 Ma, respectively[8]. The third, the 'Gonghe movement' occurred after 0.15 Ma[7]. Environmental changes in China and East Asia have a close relationship with the episodic uplift of the Tibetan Plateau. Phase A of Qingzang movement at 3.6 Ma produced a number of lake basins in and along the Tibetan Plateau and North China. Simultaneously lakes of the Qaidam, Nihewan and Kashimir Basins expanded. This implies that flows of the ocean-derived monsoonal moist air were able to reach the Asian inland. Phase B of the Qingzang movement at 2.6 Ma raised the Plateau to the critical height of 2 000 m, intensifying the Siberian-Mongolian High and triggering the onset of winter monsoons which deposited the loess. Phase C of the Qingzang movement at 1.7 Ma caused a large geomorphological adjustment and produced the present of geomorphic, hydrologic, sedimentologic and tectonic configurations including the large rivers such as the Huanghe River and Changjiang River. The Kunhuang movement uplifted the Plateau to an average height of 3 000 m with mountains up to over 4 000 m, a critical height for glacial development on a large scale. Since then, the Plateau has undergone several glaciations[9]. Dating of the maximum glaciation on the Plateau to not older than 0.8 Ma such as those in Kunlunshan Pass[8] and new data from Guliya ice cap in the western Tibetan Plateau[10], confirmed this. It should be pointed out that periodicity of climate change turned over from 21 000/41 000 a dominated cycles to 100 000 a dominated cycles. This is partly supported by deep sea and loess-paleosol records of events occurring at ca. 0.8 Ma which may be reasonably linked with the Plateau uplift and glaciation in the Kunhuang movement. The Gonghe movement may be the cause for the breaching of the Kashimir Basin by the Jhelum River in northern Pakistan and of Gonghe Basin by Huanghe River in West China. The latter added 130 000 km^2 of drainage area to the reaches of Huanghe River. Through the Gonghe movement, the Plateau was uplifted to its present height. The Himalayas raised to over 6 000 m and became a major barrier for the inflow of the Indian monsoon onto the Plateau, leading to further drying of northwestern China. In the Qaidam Basin there was an old lake with an area up to several 10 000 km^2 before 30 ka, but dried to become a heavy salt lake since then. Currently its changes are synchronized and further intensified by the winter monsoon. This process is evident in the sediments of the Linxia, Xunhua and Gonghe Basins. In the Linxia Basin of Gansu Province, mudstone red beds embedded with gypsum dominate the 29—4.3 Ma time interval. Phase A of the Qingzang movement caused termination, folding and erosion of the red beds. A thick boulder conglomerate as old as 3.6 Ma superimposes the red beds. At ca. 2.6 Ma, the boulder conglomerate bed became offset and deformed, leading to the formation of the Dongshan paleo-lake. Beginning in the

Oligocene this paleo-lake received limnic sediments and subaqueous loess deposits with a minimum of Cl^-, suggesting a strong phase B Qingzang movement and a further enhancement of the Asian monsoon. This paleo-lake ended at 1.8 Ma and the lacustrine deposits were overlain by gravels from the Huanghe River and its tributary Daxiahe. Soon thereafter, the gravel bed was deformed and greatly incised by these rivers (fig. 1). Fig. 2 details the overall pattern of the Tibetan Plateau uplift.

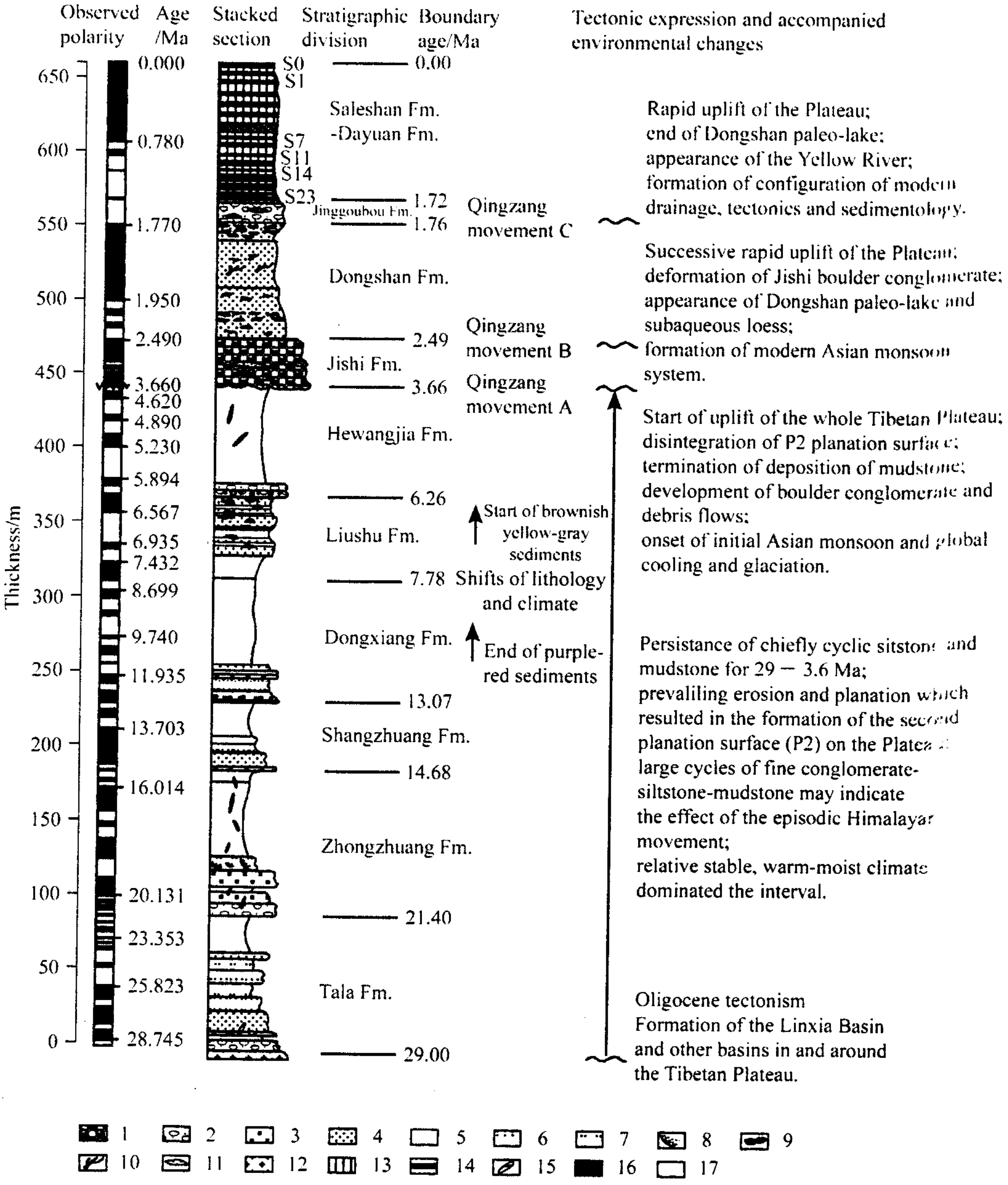

Fig. 1. Paleomagnetic dating of the Cenozoic stratigraphy in the Linxia Basin and the suggested uplift process and environmental changes of the Tibetan Plateau. 1, Boulder conglomerate; 2, fine conglomerate; 3, sandstone; 4, siltstone; 5, mudstone; 6, interbedded siltstone and mudstone; 7, silty mudstone; 8, cross bedding; 9, carbonate nodule; 10, embedded tree; 11, lens; 12, granite; 13, loess; 14, paleosol; 15, gypsum; 16, normal polarity; 17, reversed polarity.

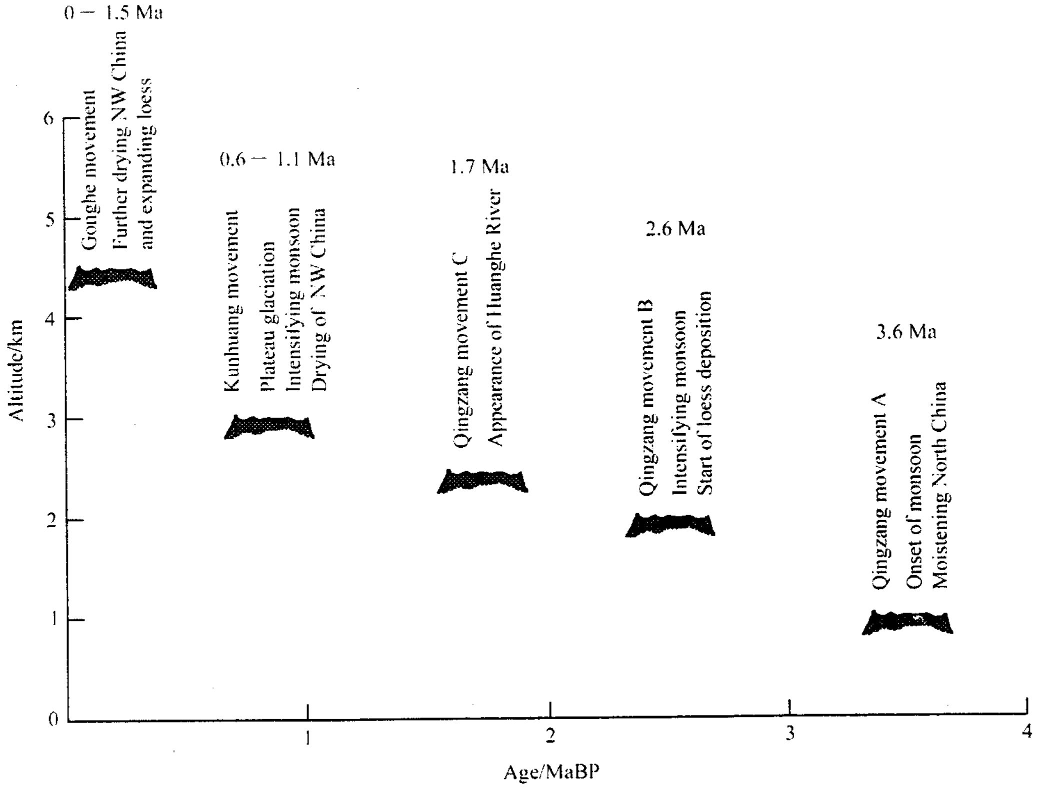

Fig. 2. Schematic diagram showing the uplift process of the Tibetan Plateau.

2 Environmental impact

There are three large physiographical regions in continental China[11], the East China monsoonal region, the Mongolian-Xinjiang arid region and the Tibetan Plateau region. From viewpoint of environmental evolution and differentiation, the uplift of the Tibetan Plateau actually controls this physiographical differentiation. This crustal movement causes large-scale changes in air circulation, climatic zones, large river drainages, and vegetation. Study of the coupling and mutual interaction between these spheres is of great importance for understanding the human living environment and its developmental trends. For instance, recent detailed studies of Antarctic ice core climatic records demonstrated that the Antarctic climate change leads that of Greenland by 1—2.5 ka over the period 47—23 ka BP, and the temperature in millennial climatic events increased and decreased gradually[12] rather than a rapid increase and a gradual decrease in Greenland[13] (fig. 3). Isotopic record from Guliya ice core on the western Tibetan Plateau seems to have somewhat similar phases with the Antarctic climate change, but to show a different pattern of climatic change characterized by a slow warming-rapid cooling and an amplified magnitude[14] (fig. 3). These suggest that cooling of the Tibetan Plateau predated cooling of the other parts of the world. Hence the Tibetan Plateau may act as a trigger and amplifier for regional or global climatic changes.

3 Challenges

There is intense scientific debate about the uplift of the Tibetan Plateau. Since China opened its door to the outside world in 1978, many foreign scholars joined the team to study the Tibetan Plateau. This promoted the scientific exchange between the Chinese and foreign researchers and deepened their investigations on one side, but seriously challenged previous Chinese studies on the other side. The Chinese researchers previously thought that the rapid uplift of the Tibetan Plateau began in the Late Pliocene-Early Quaternary. In the Eocene, crust of the Tibetan Plateau became shorter and thicker as the Indian plate

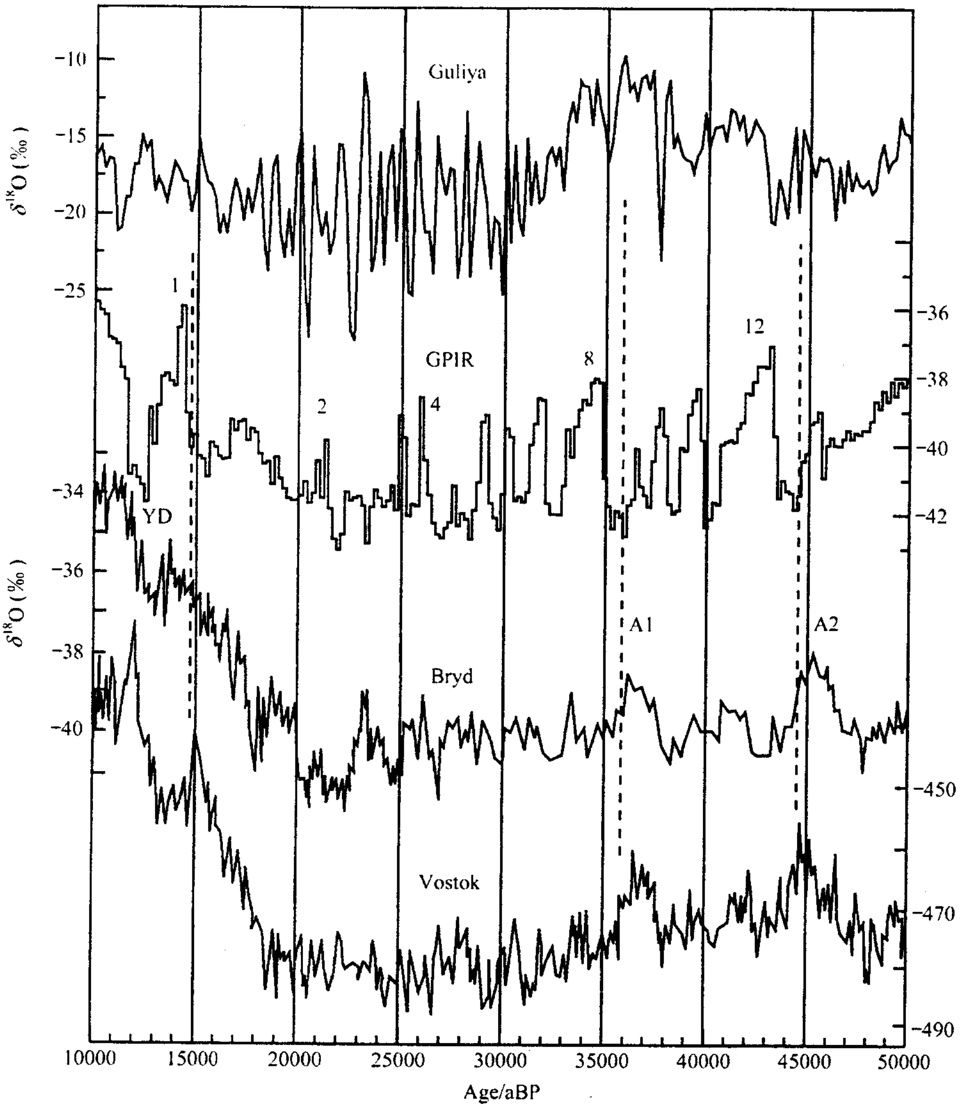

Fig. 3. Isotopic records from ice cores at Guliya on the western Tibetan Plateau[14], GRIP of Greenland[13], and Byrd and Vostok of Antarctic[12] on common timescale. Note warm events A1 and A2 and cold event YD (Younger Dryas) in Antarctic records clearly lead their counterparts in Greenland by 1—2.5 ka[12]. Gradual temperature changes around these events in Antarctic contrast with their counterparts by a rapid warming-gradual cooling in Greenland and a gradual warming-fast cooling on the Tibetan Plateau.

collided with the Eurasian plate. Although other episodes of tectonic uplift occurred (e.g. in the Middle Eocene and Early Miocene), the Plateau twice lowered to a planation surface after long denudation times. Therefore, in the Middle and Late Pliocene (3—4 Ma) most of the Plateau regions, except for the higher mountains such as the Himalayas, was in the late stages of a planation surface (or peneplain), with altitudes generally lower than 1 000 m[15]. This viewpoint was accepted by most researchers, moreover, it was accepted into an American geological textbook[16].

However, at the beginning of the 1990s, foreign researchers challenged the viewpoint mentioned above and preferred a much earlier Tibetan Plateau uplift. Dating of the authigenic minerals along north-south normal faults in the Nepal Himalayas led to the bold hypothesis that the Tibetan Plateau reached its maximum at 14 Ma, accompanied by collapse due to the east-west extension; since then, the Plateau height has decreased[17]. Other researchers thought that the Himalaya-Tibetan Plateau rose to its present height at ca. 8 Ma. The main evidence for their conclusion are: enhanced upwelling in the Arabian Sea at 8 Ma, thus signifying onset of Indian monsoons[18]; drying of the Potwar Plateau in northern Pakistan at ca. 8 Ma along with replacement of forest by grassland[19]; and strong faulting of the Yangbajing Graben in northwestern Lhasa[20] at ca. 8 Ma.

The fundamental point relied on was that the appearance or enhancement of the related monsoon, could happen only at the time when the Tibetan Plateau reached its maximum height. However, this viewpoint is very doubtful. Burbank criticized it, believing that if the Himalaya-Tibetan Plateau experienced an intensive uplift at 8 Ma, sediments in the Siwalik foredeep and deep sea fans (such as the deep sea fan in Bay of Bengal) should record this process with an increase of grain size and deposition rate of the sediments. However, the facts are that grain size and deposition sediment rates have not increased, rather than have decreased[21]. Extensive dating of the grabens on mountains in the Tibetan Plateau shows that the grabens were formed at different times, earlier on the Himalayas, such as the Gyirong and Zhada Basins having an age of ca. 7 Ma, and later in the northern Tibetan Plateau. Two stages of grabens on the Kunlunshan Pass Basin in the northern Tibetan Plateau have been dated, one at 3.6 Ma and the other at 0.7 Ma. The strongest phase of the Kunhuang movement occurred at 0.7 Ma along Kunlunshan Pass Basin. The faults show that they have experienced a large-scale left-rotating strike-slip shift with a total of 30-km horizontal and near 1-km vertical offsets along the east-west strike-slip faults[8]. Therefore, it is a common phenomenon for the lithosphere to fault under tectonic stresses. Compression is often accompanied by extension and even strike-slip. It is quite dangerous to regard the occurrence of tensile fault simply as a judgement for a maximum uplift of the Tibetan Plateau.

Drying of the northern Indian-Pakistan subcontinent has not necessarily linked with the uplift of the Tibetan Plateau and an onset of a monsoon. Comprehensive study of the Linxia Basin near Lanzhou shows that there are two episodes of serious drying of West China, one at the Latest Miocene (ca. 8 Ma) and the other at the Early Pliocene (ca. 5 Ma). Between the two drying episodes, especially at ca. 6 Ma, there was a relatively humid climate (fig. 4). This indicates that the climate fluctuated dramatically. Drying of North and South America at ca. 8 M a was also demonstrated by Quade and his colleagues[22]. Cerling *et al*. thought that there was a fundamental shift for global ecology between 6 and 8 Ma, beginning earlier in lower latitudes[23]. This shift was later than the appearance of Arabian Sea upwelling thought to be an indicator for the Indian monsoon[18,23]. Therefore, it is quite farfetched to regard the climatic/ecological shift in South Asia as a signal for uplift of the Tibetan Plateau and onset of the monsoon. The well-known Bode Red Clay underlying loess in the central Loess Plateau was recently demonstrated as eolian with a paleomagnetic age of 7.2 Ma[24—27]. But it is also doubtful to regard the appearance of the Red Clay as a signal of the onset of the winter monsoon and the rising of the Tibetan Plateau[24,25]. Ding Zhongli and his colleagues have demonstrated a quite homogeneous grain size composition both in spatial and time domains for the Red Clay[26,27]. Obviously, this does not support the thinking of a winter monsoon appearance, which should cause at least a spatial variation of grain size, as this is the case for loess starting at 2.6 Ma[3].

Figure 5 gives a brief summarization of some representative viewpoints on the uplift of the Tibetan Plateau. Our thinking is that the Himalayas had indeed an uplift at ca. 10 Ma, but it could not expand to the whole Tibetan Plateau; the rapid uplift of the whole Tibetan Plateau only commenced at 3.6 Ma[7,15].

It should be pointed out that even after decades of study, the history and uplift processes of the Tibetan Plateau are still far from a final resolution. Future studies should focus on sedimentary basins and stepped planation, erosion, and river terrace surfaces in and along the Tibetan Plateau. Only by reconstructing the uplift history of the Tibetan Plateau through precise dating of the basin sediments and obtaining the accompanying long-term, continuous high-resolution climatic records, could we have opportunities to make a breakthrough in geological theory.

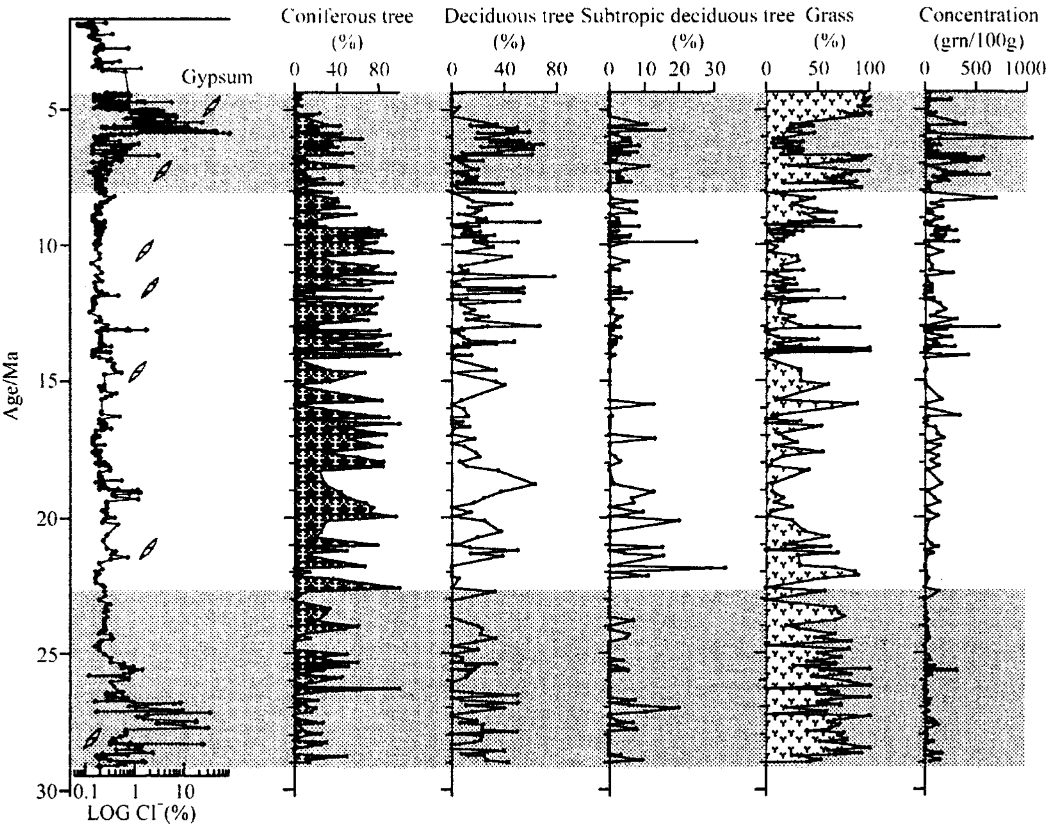

Fig. 4. Climatic change revealed by variations of contents of Cl^- and pollen-spores since 29 Ma in the Linxia Basin.

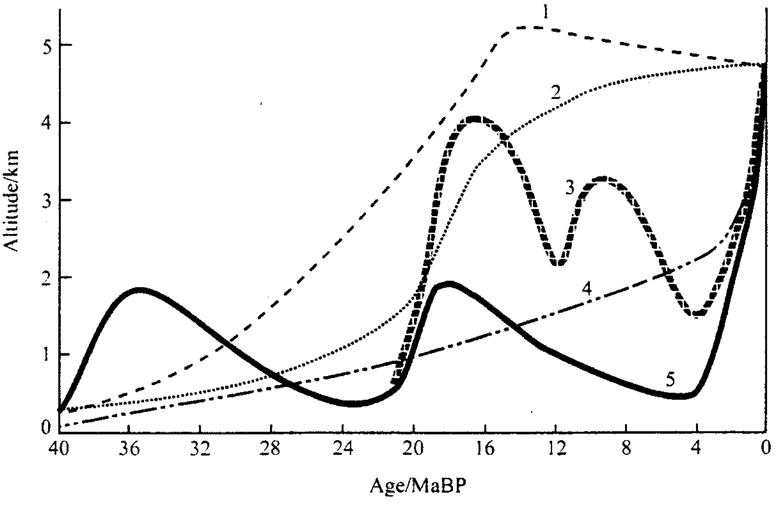

Fig. 5. Diagram summarizing the representative viewpoints of uplift of the Tibetan Plateau. 1, Coleman[17]; 2, Harrison *et al.*[21]; 3, Rea[29] and Zhong *et al.*[30]; 4, Xu[31]; 5, Li *et al.*[7,15].

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References

1 Manabe, S., Terpstra, T. B., The effects of mountains of the general circulation of the atmosphere as identified by numerical experiments, *J. Atmos. Sci.*, 1974, 31: 3.

2 Yie, D. Z., Gao, Y. X., *Meteorology of the Tibetan Plateau* (in Chinese), Beijing: Science Press, 1988.

3 Liu, T. S., *Loess and the Environment*, Beijing: China Ocean Press, 1985.

4 Flohn, H., Contributions to a meteorology of the Tibetan Highlands, Colorado State University, *Ft Collins*, *Colo. Atmosph Sci. Paper Nr*, No. 130, 1968.

5 Raymo, M. E., Ruddiman, W. F., Tectonic forcing of Late Cenozoic Climate, *Nature*, 1992, 359: 117.

6 Kutzbach, J. E., Prell, W. L., Ruddiman, W. F., Sensitivity of Eurasian Climate to surface uplift of the Tibetan Plateau, *J. Geol.*, 1993, 101: 177.

7 Li, J. J., Fang, X. M., Ma, H. Z. *et al.*, Geomorphological and environmental evolution in the upper reaches of Huanghe River during the Late Cenozoic, *Sci. in China*, Ser. D, 1996, 39: 380.

8 Cui, Z. J., Wu, Y. Q., Liu, G. N. *et al.*, On "Kunlun-Yellow River tectonic movement", *Sci. in China*, Ser. D, 1998, 41: 592.

9 Shi, Y. F., Zheng, B. X., Li, S. J. *et al.*, Studies on altitude and climatic environment in the middle and east parts of Tibetan Plateau during Quaternary maximum glaciation *J. Glaciol. and Geocryol* (in Chinese with English abstract), 1995, 17(2): 97.

10 Thompson, L. G., Yao, T. D., Davis, M. E. *et al.*, Tropical climate cycle from a Qinghai-Tibetan ice core, *Science*, 1997, 276: 1821.

11 Huang, B. W., *Comprehensive Division of Chinese Physiography* (1st version) (in Chinese), Beijing: Science Press, 1959, 4—11.

12 Blunier, T., Chappellaz, J., Schwander, J. *et al.*, Asynchrony of Antarctic and Greenland climate change during the last glacial period, *Nature*, 1998, 394: 739.

13 Dansgaard, W., Johnsen, S. J., Clausen, H. B. *et al.*, Evidence for general instability of past climate from a 250-ka ice-core record, *Nature*, 1993, 364: 218.

14 Yao, T. D., Thompson, L. G., Shi, Y. F. *et al.*, Climate variation since the last interglaciation recorded in the Guliya ice core, *Sci. in China.*, Ser. D, 1997, 40: 662.

15 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, *Scientia Sinica*, 1979, 22(11): 1314.

16 Skinner, B. J., Porter, S. C., *Physical Geology*, New York: John & Wiley, 1987.

17 Coleman, M., Evidence for Tibetan uplift before 14 Ma ago from a new minimum age for east-west extension, *Nature*, 1995, 374: 49.

18 Kroon, D., Steens, T. N. F., Troelstra, S. R., Onset of monsoonal related upwelling in the western Arabian Sea, in *Proc. ODP*, *Sci. Results*, 1991, 117: 257.

19 Quade, J., Cerling, T. E., Bowman, J. R., Development of Asian monsoon revealed by marked ecological shift during the Lastest Miocene in north Pakistan, *Nature*, 1989, 342: 163.

20 Harrison, T. M., Copeland, P., Kidd, W. S. F. *et al.*, Raising Tibet, *Science*, 1992, 255: 1663.

21 Burbank, D. W., Derry, L. A., Lanord, C. F., Reduced Himalayan sediment production 8 Ma ago despite an intensified monsoon, *Nature*, 1993, 364: 48.

22 Quade, J., Cater, J. M. L., Ojha, T. P. *et al.*, Late Miocene environmental change in Nepal and the northern Indian sub-continent: Stable isotopic evidence from paleosols, *Geol. Soc. Am. Bull.*, 1995, 107: 1381.

23 Cerling, T. E., Harris, J. M., MacFadden, B. J. *et al.*, Global vegetation change through the Miocene/Pliocene boundary, *Nature*, 1997, 389: 153.

24 Sun, D. H., Liu, T. S., Chen, M. Y. *et al.*, Magnetostratigraphy and climatic record of the Red Clay under the Chinese Loess Plateau, *Sci. in China*, Ser. D, 1997, 40: 337.

25 Sun, D. H., Chen, M. Y., Shaw, J. *et al.*, Magnetostratigraphy and climatic record of the Late Cenozoic eolian depositional sequences in the Chinese Loess Plateau, *Sci. in China* (in Chinese), Ser. D, 1998, 28: 79.

26 Ding, Z. L., Sun, J. M., Zhu, R. X. *et al.*, Eolian origin of the Red Clay in the Loess Plateau and implications for Pliocene climatic changes, *Quat. Sci.* (in Chinese with English abstract), 1997(2): 147.

27 Ding, Z. L., Sun, J. M., Yang, S. L. *et al.*, Magnetostratigraphy and grain size record of a thick Red Clay-loess sequence at Lingtai, the Chinese Loess Plateau, *Quat. Sci.* (in Chinese with English abstract), 1998(1): 86.

28 Fang, X. M., Li, J. J., Zhu, J. J. *et al.*, Chronology and division of the Cenozoic stratigraphy in the Linxia Basin of Gansu Province, *Chin. Sci. Bull.* (in Chinese), 1997, 42(14): 1457.

29 Zhong, D. L., Ding, L., Discussion on process and mechanism of uplift of the Tibetan Plateau, *Sci. in China*, Ser. D (in Chinese), 1996, 39: 389.

30 Xu, R., Vegetational changes in the past and the uplift of Qinghai-Xizang Plateau, in *Proc. Symp. Qinghai-Xizang (Tibet) Plateau (Beijing, China)*, *Geological and Ecological Studies of Qinghai-Xizang Plateau*, Vol. 1, Beijing: Science Press, 1981, 139—143.

31 Rea, D. K., Delivery of Himalayan sediment to the Northern Indian Ocean and its relation to global climate, sea level, uplift, and seawater strontium, *Geophys. Monogr.*, 1992, 70: 387.

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