Loess in Kunlun Mountains and its implications on desert development and Tibetan Plateau uplift in west China

FANG Xiaomin (方小敏)[1,2], LÜ Lianqing (吕连清)[1], YANG Shengli (杨胜利)[1], LI Jijun (李吉均)[1], AN Zhisheng (安芷生)[2], JIANG Ping'an (蒋平安)[3] & CHEN Xiuling (陈秀玲)[1]

1. National Laboratory of Western China's Environmental Systems of Ministry of Education of China and Department of Geography, Lanzhou University, Lanzhou 730000, China;
2. State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710054, China;
3. School of Agriculture, Xinjiang Agriculture University, Ürümqi 830000, China

Correspondence should be addressed to Fang Xiaomin (email: fangxm@lzu.edu.cn)

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Abstract Loess on the northern slope of Kunlun Mountains is the synchronous deposition of the Taklimakan Desert. The paleomagnetism and climatic records of an over 80 m loess-paleosol sequence on the highest river terrace at the foot of Kunlun Mountains show that the loess formed at ~ 880 ka B.P., suggesting a roughly synchronous occurrence of the present-like air circulation and extremely dry climate and the initial desert. The uplift of the Tibetan-Pamir Plateau and Tian-shan Mountains may initiate these events. The rise of the plateau and adjacent mountains caused the drying and desertification of China inland and Tarim Basin, which was dramatically enhanced at ~ 500 ka B.P., leading the desert to expand to its present scale. Global change just overprints this drying trend. Local climate response to global change both in long-term evolution and glacial-interglacial cycles manifests that the stronger the westerlies, the more the precipitation. But the heat-moisture pattern seems still similar to that in the Asian monsoon region.

Keywords: Taklimakan Desert, loess-paleosol, westerly, Tarim Basin, Tibetan Plateau.

China inland is located in the Asian arid and extremely arid regions and develops characteristic temperate deserts including the Asian largest and the world's second largest moving desert, the Taklimakan Desert. These deserts occupy 1/3 of the Chinese continent area. The drying process of the region and the formation and evolution of the deserts not only highly threaten human living environment, but also closely link to Tibetan uplift and global climatic change. Numerical circulation modeling demonstrates that with the uplift of the Tibetan Plateau, the Asian inland will get dry and the strength and fluctuation of air circulation will increase[1]. Dust due to drying and desertification is carried away by the monsoon and westerlies to desert adjacent areas such as the Loess Plateau, and even far away to East China, northern Pacific Ocean and Arctic region[2,3], becoming a key link of land-sea-air coupling change. Particularly, some important related topics have greatly concerned the scientific community and society [4−9], such as, what the drying history and climatic change of the Tarim Basin in the westerlies are and when the Taklimakan Desert appeared, because until the Miocene the Basin was still a part of the northern branch of the Tethys Sea, and what the relationships of the drying with monsoons and Tibetan Plateau uplift are.

Loess on the Kunlun Mountains is so far the thickest loess found in the extremely arid region of China inland. Loess is a roughly synchronous accompanied product of desert process, thus recording continuously the histries of the desert and dust-carrying winds and circulation, providing a good opportunity to study the topics above. Actually, the relationship of the loess and loessic sands in the studied region with the formation of the Taklimakan Desert had been noted as early as in 1950s—60s[4−6]. However, the work at that time was mostly a kind of survey with the following points reached: the Kunlun loess is a synchronous near-source product of the Taklimakan Desert; the loess formed in arid environment; the age of the loess was estimated at the middle[5] or late Pleistocene[6]. The studies since 1980s[10−14] confirmed some inferences of the former work, but the age of the loess remains still uncertain due to failure in searching out paleomagnetic B/M boundary in the loess[11−14].

However, these studies have not dealt with the following two most important problems: the neotectonic (Plateau and Tianshan Mountains uplift) setting of the formation and evolution of the Taklimakan Desert-Kunlun loess and the climatic change pattern of China inland in the westerly zone and its relationships (response and contribution) with Asian monsoon and global change, especially with climatic change in high latitudes of northern hemisphere. Thus, we chose so far the thickest loess section in the region on the highest terrace of Aqqan River to make detailed paleomagnetic and paleoclimatologic studies with an attempt to settle the problems above.

1 Physiographic setting of the studied region

The Taklimakan Desert is surrounded, on the north, west and south, by mountains with altitudes of over 4000 m, with its east end being lower as a wind pass. In the rim of the desert and at the foot of the mountains, sandy loess and/or loessic sands of several to dozens of meters are deposited. On the northern slope of Kunlun Mountains in Hetian-Yutian south of the desert, loess not only distributes in large area and reaches the highest altitudes (on slope from 2500 to 4500 m a.s.l.) but also has the thickest thickness (up to ~ 60—80 m) and coarsest grain size (mostly very fine sands and coarse silts), thus, called commonly loessic sands[4−7]. To the north of the loessic sand and gobi zones is the Taklimakan Desert. To the west of Hetian-Yutian, the desert is characterized by NW aligned barchan dunes and chains, and to the east is NE aligned composite barchan chains and longitudinal dunes. While in Yutian, the desert manifests the most distinguished pyramidal dunes in the basin. Most of the desert dunes are moving obviously southwards[7, 8]. The distributive pattern of the loess and desert dunes just indicates the two major wind directions in the region. They are the NW winds coming from over-Pamir pass currents of the westerlies and the NE and NEE winds of the westerlies from Dabancheng-Hami wind pass flowing by the northern slope of Tianshan Mountains, which finally form an east jet in lower level. The two currents, commonly generating and carrying dust, meet in the Hetian-Yutian area and form very strong convergent uprising flow along the northern slope of Kunlun Mountains [15], downloading coarser dusts there and lifting fine ones up to higher levels and then are carried away by high level westerly jet. This process occurs all the year, especially in spring and summer. Big dust storms occur over 30—40 days a year and the number of mean annual floating dust days reaches 150 days or more, with the maximum being 230 days[7, 15].

2 Stratigraphy

The studied section is situated on a 2900 m altitude of broad flat watershed, between Aqqan River and Suke River at Dabanbaixi of Aqqan Town of Yutian County. The section was dug along the western slope of the watershed. It consists of 81.5 m loess and loessic sands and ~ 4 m river gravel bed at the bottom. At depth 43.3m, the section can be divided by two portions, the upper consisting mainly of sandy loess and paleosols and the lower largely of loessic sands and sandy loess intercalated by paleosols (fig. 1). The loessic sands and sandy loess, except that the former grain size is evidently coarser than the latter, are quite similar, characterized by gray or light grayish yellow, uniform composition, loose texture, massive structure, and less than 1% in area of biological channels. In some parts of the section, loessic sands develop weak wavy beddings or cross beddings. Paleosols are generally very weak. But we still can identify nine layers of paleosol complexes downwards, marked as S_0-S_8 by conventional paleosol numbering in the Chinese Loess Plateau (fig. 1). S_0 is 0.5 m in depth below the top, ~1 m thick, light brownish gray, weak ped structure, with some being rich in organic matter and biological channels, and there are ~ 3% in area of fine carbonate nodules and fleck powder impregnations in its lower part. Paleosols in the middle of Malan Loess are not distinctive and merely manifest some more accumulation of organic matter and carbonates compared with loess. But at depth of 6—6.5 m the carbonate accumulation is quite obvious. At depth of 7.5—10.3 m, there is thick relatively well developed paleosol, being brownish yellow, weak block-ped structure, ~ 3% in area of root and insect channels, ~ 4% in area of fine carbonate nodules and fleck powder impregnations in its lower part. A thermoluminescence (TL) age of 141 ka BP is obtained from the loess right below the bottom of the soil, suggesting that the paleosol is the last interglacial paleosol S_1 (fig. 1). Thick paleosols are observed at depths 16.1—18.4 m, 24—26.2 m, 34.1—36.5 m, 44.6—47.9 m, 50.1—52 m, 56.8—59.1 m, 68.3—70.1 m and 74.9—76.7 m. The developing degrees of these paleosols are weaker than those of S_0 and S_1, but some are deeper in color than loess. Their pedofeatures are light brownish yellow, weak block or massive structure, having ~ 2 % in area of fleck powder carbonate impregnations distributed homogenously in the whole soil horizons. Laminar loess-like thin layers or thin notable stronger paleosol layers (with deeper colors and finer grain sizes) are often found in the paleosols, indicating a high rate of dust deposition and fast climatic changes. According to the pedogenic characteristics and sequence order in the section, these paleosols can be correlated in turn to paleosols S_2 — S_8 on the Chinese Loess Plateau (fig. 1). Besides loessic sands, sandy loess and paleosols, single or interbeddings of thin soil-like layers and sandy loess or loessic sands are often observed in the section, which may reflect fast climatic changes, but make detailed stratification division difficult.

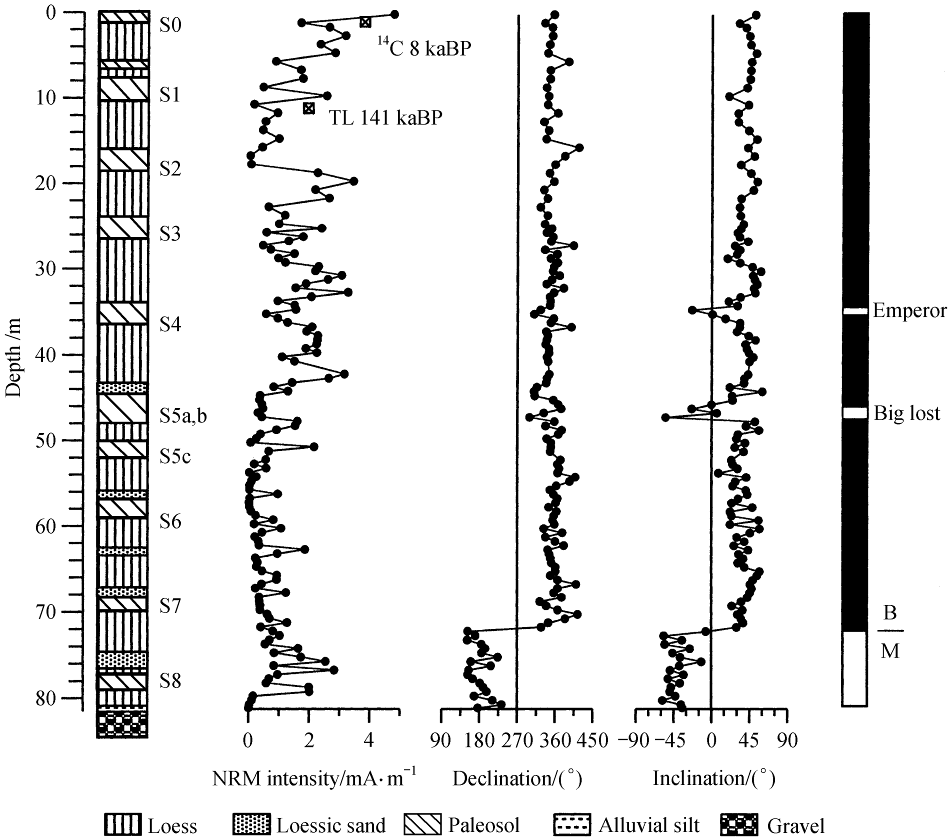

Fig. 1. Soil sequence and magnetostratigraphy of the Dabanbaixi loess section, Aqqan, Yutian.

3 Sampling and laboratory measurement

Paleomagnetic samples were collected at 0.5 m intervals along a 1—2 m deep trench dug in the section. Three oriented sub-samples of 2×2×2 cm were collected at each level, yielding a total of 123 sub-samples. Bulk samples were taken at 5 cm intervals for measurements of carbonate content and grain size, except some coarser parts between depths 0—76 m at 10 cm intervals, yielding a total of 1380 samples each. Grain sizes were measured on the American Mastersizer 2000 laser particle sizer (analytical range: 2mm—0.02 μm), with errors less than 1% at the National Laboratory of Western China's Environmental Systems of Ministry of Education of China, Lanzhou University. Carbonate samples were measured twice by a standard calcimeter with absolute errors controlled under 0.5 wt%. Organic ^{14}C-dating was performed in Lanzhou

University and TL dating was carried out at the Institute of Earth Environment of CAS.

4 Paleomagnetic results

Two sets of parallel sub-samples were systematically analyzed. The first set was measured on an American DSM2 digico spinner magnetometer, and the second was carried out on 2G cryogenic magnetometer in the Institute of Geology and Geophysics of CAS, after 12—13 stepwise alternating field (AF) demagnetizations from 5 to 80/90 mT. The results from the two sets are essentially similar for most of the measured samples, but the remanences obtained on 2G cryogenic magnetometer are more stable than those on DSM2 spinner magnetometer, especially for those samples with coarse grains and weak magnetism. Generally, the intensity of the natural remanent magnetization (NRM) of the loess and loessic sands varies from 2.1 to 4.8 mA/m, averaging 1.13 mA/m (fig. 1), quite similar to that of the Loess Plateau. The systematic demagnetizations demonstrate that there are two clear magnetic directions. A soft magnetic component is observed before 20 mT and decreases rapidly along a direction with the increase of magnetic field (fig. 2). After 25 mT, a hard magnetic component with a stable direction pointing to the origin of the Ziderveld coordinates is observed when its intensity decreases gradually with the magnetic field increasing. So,

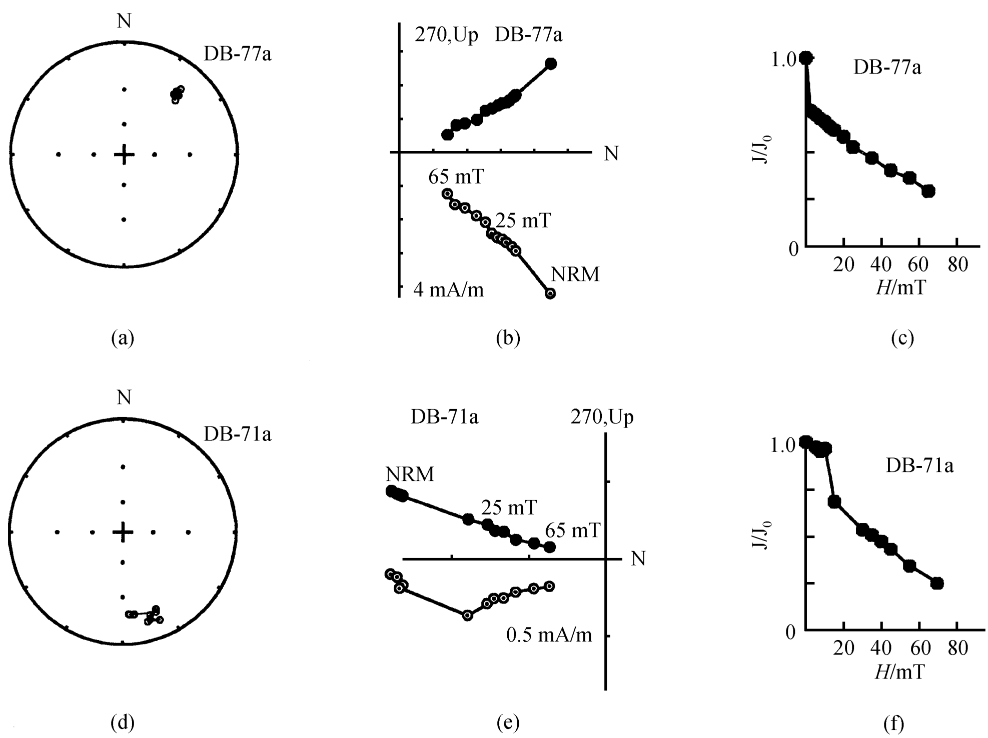

Fig. 2. Stereographic ((a), (d)) and orthogonal projections ((b), (e)) of progressive demagnetization results for representative samples from the Dabanbaixi loess section, along with their respective decay curves ((c), (f)). Solid (open) symbols represent directions in northern (southern) hemisphere in (a) and (d) or projections onto the horizontal (vertical) plane in (b) and (e).

it is the stable primary remanent magnetization (PRM) (fig. 2). Similar demagnetization behavior is observed for most of the samples. The directions of the PRMs were calculated using the principal component method and most of them have passed α_{95} test. Therefore, the PRM directions are reliable. Fig. 1 shows the depth function of the inclinations and declinations averaging from the two sets of the samples.

Clearly, almost normal directions are observed above depth 72 m, except for two brief incomplete reversals at depths 35 m and 47.5 m, and below the depth 72 m are all reversed directions (fig. 1). Since the development of the Holocene topsoil S_0 and last interglacial paleosol S_1, as determined respectively by organic ^{14}C and TL dating (fig. 1), has demonstrated that the loess section is continuous to the present, we correlate the section above depth 72 m with the Brunhes normal polarity chorn and the section blow depth 72m with the uppermost Matuyama reversed polarity chron. The two brief incomplete reversals in the Brunhes chron may be the records of the paleomagnetic Emperor and Big lost events at ~ 460 ka and 550 ka[16], respectively. Thus, the defined B/M boundary is located in loess L8, in good agreement with that of the Loess Plateau. indicating that although monsoonal and westerly climates are quite different, the loess-paleosol sequences in these tow climate regions are quite comparable, suggesting that they all largely respond to global glacial-interglacial climatic changes. Taking B/M boundary at 780 ka BP[17], the averaging sedimentary rate in the Brunhes chron is 9.25 cm/ka, therewith, the age of the section bottom is extrapolated to ~ 883 ka BP.

Based on the above explanation, Fig. 3 illustrates the relationship of depths and ages of the dating points and magnetic zone boundaries. Calculated sedimentary rates are also plotted (fig. 3). A linear age-depth relationship is observed for the plotted points, coincident with the facts that aeolian loess deposits roughly in similar environments. Thus, the dating is successful. The sedimentary rate exhibits a certain extent of variation, the maximal rate occurs between ~ 900 —500 ka, the second occars since ~ 140 ka, and an obvious decrease happens between 500 — 140 ka (fig. 3). These changes quite agree with lithologic variations where before 500 ka BP are mostly loessic sands and sandy loess while after that finer sandy loess becomes dominant.

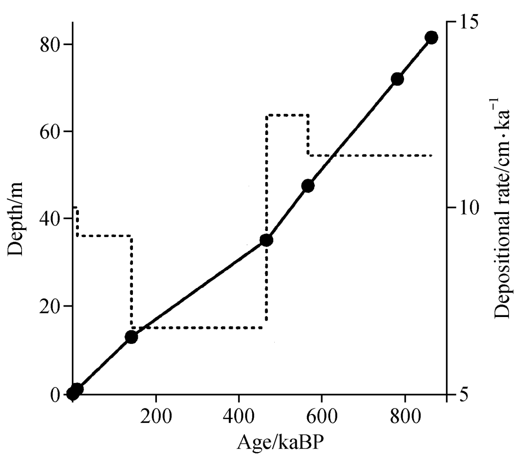

Fig. 3. Age-depth relationship of dates and magnetic (sub-)chrons in the Dabanbaixi loess section and their determined depositional rates.

5 Drying of the Tarim Basin and the formation and evolution of the Taklimakan Desert

Fig. 4 shows the variation of carbonate content and grain size in the section. Two characteristics are evident. Firstly, on the long-term variation, the content of $CaCO_3$ keeps high, the average being 11.3% (11.4% for loess and 11.1% for paleosol) and the variance being very small, just 6.8% (the moving average only 2.4%, c.f. fig. 4). With the decrease of age or depth between 81.3 m and 43.3 m, the content of $CaCO_3$ decreases gradually and the grain size is getting coarser, both showing larger amplitudes. A rapid shift of the content of $CaCO_3$ and grain size occurs at depth 43.3 m (~ 500 ka B.P.), the content of $CaCO_3$ increasing rapidly from ~ 10.5% to 11.5% and the average of grain size decreasing from ~ 70 μm to 40 μm. The coarse fraction > 63 μm reduces rapidly from 57% to 28%, and the clay content increases dramatically from 1.6% to 3.1%. The shift happens within only ~ 5 ka. After that, the content of $CaCO_3$ increases gradually and grain size becomes finer and finer, accompanied by much small variances (fig. 4). Secondly, on the short-term change at the scale of glaciation and interglaciation, like the long-term change, a decrease of grain size corresponds to an increase of the content of $CaCO_3$, which further corresponds to a loess layer in a glacial period. A reversed trend is observed for paleosols in interglaciations (fig. 4).

Since the amount and size of coarse grains reflect the strength of winds or air circulation

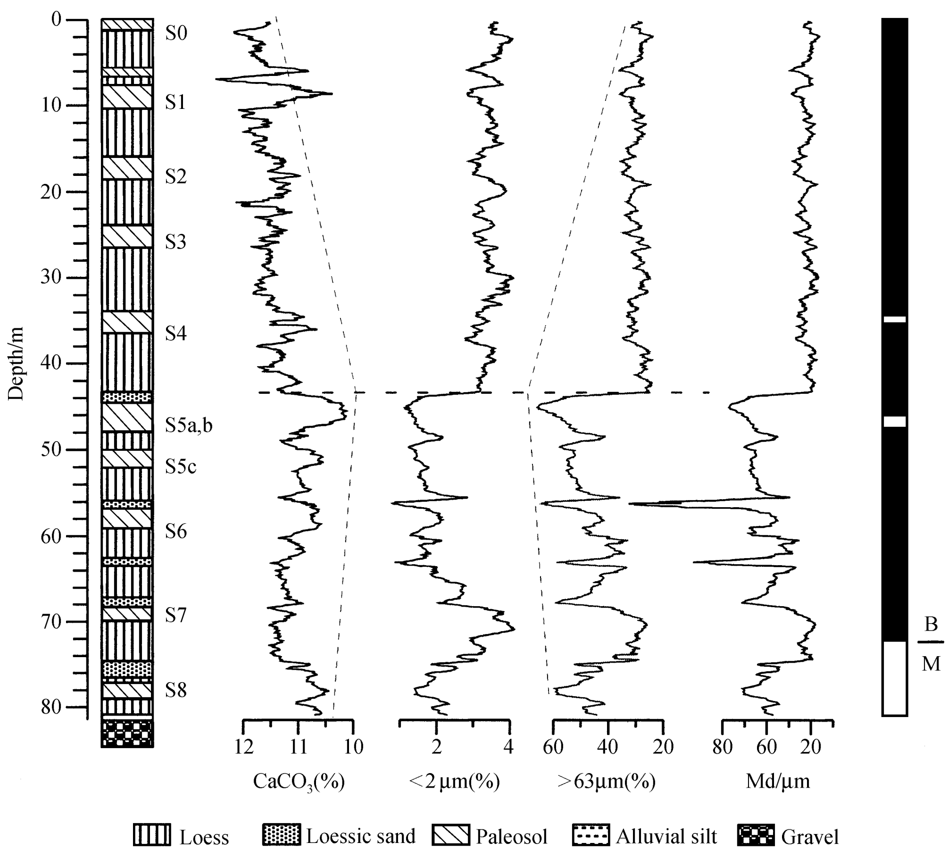

Fig. 4. Depth functions of carbonate content and grain size in the Dabanbaixi loess section. All the data are 11-point moving averaged. Interpreted observed magnetic polarity zones are plotted against the loess-paleosol sequence on the right.

carrying dusts[18], it means that the coarser grains or the more content of coarse fraction indicate the stronger winds or air circulation. Because the change of $CaCO_3$ is largely controlled by eluviation of rain during pedogenesis, that is, the more the rainfall, the stronger the pedogenesis, the more $CaCO_3$ is leached from the upper horizon to its lower ones and precipitates there[2]. If compared with carbonate states in sub-humid region in the central Loess Plateau (the average content of $CaCO_3$ is 11.6%, 11.8% for loess and 3.6% for paleosol, and the variance is 20.9%)[2], in semi-arid region in the western Loess Plateau (the average content of $CaCO_3$ of 1004 samples is 11.3%, 11.5% for loess and 7.3% for paleosol, and the variance is 17.8%), and in the arid region (the average content of $CaCO_3$ of 669 samples is 10.8%, 10.9% for loess and 10.2% for paleosol, and the variance is 8.3%)[19], the variations of the content of $CaCO_3$ and grain size above could be generally interpreted as: (i) The environment in the northern slope of Kunlun Mountains has been very dry since ~ 880 ka B.P., causing very weak eluviation of paleosols; (ii) With this drying background, a stronger or weaker air circulation vs a more or less rainfall (or enhanced aridity) is matched. More interesting is that the former matching happened in glaciation and the latter in interglaciation. This leads to a pattern of warm vs moist in interglaciation and cold vs dry in glaciation. It seems that the central southern Tarim Basin is still influenced somewhat by the monsoon; (iii) Before ~ 500 ka B.P., the air circulation was gradually enhanced, the desert got expanded and the rainfall on the northern slope of Kunlun Mountains increased, after ~ 500 ka B.P., the situation just reversed, i.e, a gradually weakened air circulation resulted in a progressively reduced rainfall and further enhanced aridity and desertification; (iv) While at ~ 500 ka B.P., an abrupt shift of air circulation occurred, manifesting as a rapid reduction of air circulation strength and rainfall and a fast enhancement of aridity (fig. 4); (v) Because the studied section is located on the highest terrace of the river and no thicker loess section is found on the slope of the Kunlun Mountains, the studied section seems to represent the oldest deposit of loess in the region. Thus, the appearance of the loess at ~ 880 ka B.P. suggests a rapid change of air circulation and a fast drying of the environment. We think this drying event may have led to the formation of an initial Taklimakan Desert. And the change and enhancement of air circulation not only facilitated the occurrence of the event but also led to the appearance of a present-like air circulation pattern in the Tarim Basin, causing dusts to be transported from the lower desert region to the terraces of the river and the higher slope of Kunlun Mountains, forming loessic sands and loess.

6 Discussion

The formation of desert and loess needs at least two conditions, i.e. an extremely drying environment that can bare surface to expose fine materials and a certain strength of wind or air circulation that can blow away surface fine materials. Therefore, the formation of the initial Taklimakan Desert suggested by the appearance of the Kunlun loess at ~ 880 ka B.P. may imply that the Tibetan-Pamir Plateau and Tianshan Mountains experienced a rapid uplift at that time, leading the over-plateau-flowing westerly jet to diverge as two byflowing jets and an onset of a present-like air circulation pattern. A combination of the westerly divergence and the hindering of the westerly jet by Pamir Plateau and Tianshan mountains results in a formation of sinking hot-dry flows on lower and higher levels in the Tarim Basin, causing a rapid drying of the basin. Furthermore, the byflowing jet can blow away fine materials on the dried surface, forming desert-loess system. These fast changes in air circulation and environment have been recorded also by the Tibetan loess and Plateau monsoon[20, 21]. Thus, the stop of moisture by the plateau and mountains and the formation of strong sinking flow are the fundamental causes for the formation of the Taklimakan Desert.

At ~ 500 ka B.P., the sudden reduction of air circulation strength and rapid enhancement of aridity may suggest the second obvious uplift of the Pamir Plateau and Tianshan Mountains. This uplift, firstly, may have caused an obvious block of the input of the westerly moisture and weakening of the strength of the lower westerly jet in the basin, and secondly, may have caused a rapid river incision which raised terraces and dust-deposition height. Continuing this process would block more and more input of moisture by lower level currents and enhance basin aridity, giving rise to a persistent expansion and thickening of the Taklimakan Desert and finally to its present scale. The whole process of changes of air circulation and aridity and the formation and evolution of the desert are actually revealed as well by the variation of loess deposition rate (fig. 3).

The air circulation changes in the westerly acted Tarim Basin (strong or weak circulation vs interglaciation or glaciation), as suggested by grain size changes above, just oppose that in the Asian monsoon region[2]. We think it may be related with the special location of southern Xinjiang and the characteristic of air circulation. The present air circulation in winter (November—March) in southern Xinjiang is controlled by the northern branch of the westerly jet and Siberian High. Under this circulation, flow current is quite stable and climate is very cold–dry and lacks big winds, and the lower east jet in the Tarim Basin is the weakest in all the year[15]. In spring (April—May), the northern branch of the subtropic westerly jet appears in southern Xinjiang. In addition, polar front jet and Siberian High still exist in northern Xinjiang, air level and circulation become unstable in this changing season, and the westerly cyclone acts frequently. All these make cold surges strongly break out and the lower east jet become the strongest in the whole year. In summer, the whole basin is controlled by the subtropic westerly jet, and the lower east jet is only slightly weaker than that in spring[15]. As a result, dust storms and dune moving are strongest in spring and summer[7—9]. We estimate that during glaciation, the westerlies would have obvious southward moving, likely leading the northern branch westerly jet to join the southern one and to be kept in the southern side of the plateau in all the year, whereas the southward moving of the polar front jet could be not enough to influence southern Xinjiang. Thus, the resulting air circulation at lower level would be weakened. During interglaciation, the situation would be just reversed. A similar case is the averaged air circulation in February, 1957, i.e. the climate was one of the coldest in China since 1950s, but the north westerly jet disappeared and moved to southern plateau to join the south westerly jet and form a very strong single jet. In contrast to this, the air circulation in southern Xinjiang was relatively weakened[22]. Fig. 4 shows that this process was most evident before 500 ka B.P. and unclear after that. This indicates that besides plateau and mountains uplift weakening the air circulation, there seems to have other factors acting on the circulation and climate.

7 Conclusion

The Kunlun Mountains loess formed at ~ 880 ka B.P., reflecting roughly a synchronous appearance of the present-like air circulation system and extreme dry climate in the Tarim Basin and the initiation of the Taklimakan Desert.

The uplift of the Tibetan-Pamir Plateau and Tianshan Mountains is the fundamental driving force for the extreme dry climate in the Tarim Basin and the formation of the Taklimakan Desert. The air circulation change caused by the plateau uplift is just the mechanism to run drying process. Episodic rapid uplift of the plateau and change of the westerly circulation happened at ~ 880 ka B.P. and 500 ka B.P. With future uplift of the plateau and mountains, the aridity of the Tarim Basin will be further increased; global change is merely superimposing on this trend.

The climate change in the studied region during the Quaternary, either on long-term evolution or at the scale of glacial–interglacial cycle, is the increase of the westerly circulation leading to more rainfall. But the pattern of moisture and heat seems still similar to that in monsoonal Asia.

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