

A major reorganization of Asian climate by the early Miocene

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Abstract. The global climate system experienced a series of drastic changes during the Cenozoic. In Asia, these include the climate transformation from a zonal pattern to a *monsoon-dominated pattern*, the disappearance of typical subtropical aridity, and the onset of *inland deserts*. Despite major advances in the last two decades in characterizing and understanding these climate phenomena, disagreements persist relative to the timing, behaviors and underlying causes.

This paper addresses these issues mainly based on two lines of evidence. First, we compiled newly collected data from geological indicators of the Cenozoic environment in China as paleoenvironmental maps of ten intervals. In confirming the earlier observation that a zonal climate pattern was transformed into a monsoonal one, the maps within the Miocene indicate that this change was achieved by the early Miocene, roughly consistent with the onset of loess deposition in China. Although a monsoon-like regime would have existed in the Eocene, it was restricted to tropical-subtropical regions. The latitudinal oscillations of the climate zones during the Paleogene are likely attributable to the imbalance in evolution of polar ice-sheets between the two hemispheres.

Secondly, we examine the relevant depositional and soil forming processes of the Miocene loess-soil sequences to determine the circulation characteristics with emphasis on the early Miocene. Continuous eolian deposition in the middle reaches of the Yellow River since the early Miocene firmly indicates the formation of inland deserts, which have been constantly maintained during the past 22 Ma. Grain-

size gradients between loess sections indicate northerly dust-carrying winds from northern sources, a clear indication of an Asian winter monsoon system. Meanwhile, well-developed Luvisols show evidence that moisture from the oceans reached northern China. This evidence shows the co-existence of two kinds of circulations, one from the ocean carrying moisture and another from the inland deserts transporting dust. The formation of the early Miocene paleosols resulted from interactive soil forming and dust deposition processes in these two seasonally alternating monsoonal circulations. The much stronger development of the early Miocene soils compared to those in the Quaternary loess indicates that summer monsoons were either significantly stronger, more persistent through the year, or both.

These lines of evidence indicate a joint change in circulation and inland aridity by the early Miocene and suggest a dynamic linkage of them. Our recent sensitivity tests with a general circulation model, along with relevant geological data, suggest that the onset of these contrasting wet/dry responses, as well as the change from the “planetary” subtropical aridity pattern to the ‘inland’ aridity pattern, resulted from the combined effects of Tibetan uplift and withdrawal of the Paratethys seaway in central Asia, as suggested by earlier experiments. The spreading of South China Sea also helped to enhance the south-north contrast of humidity. The Miocene loess record provides a vital insight that these tectonic factors had evolved by the early Miocene to a threshold sufficient to cause this major climate reorganization in Asia.



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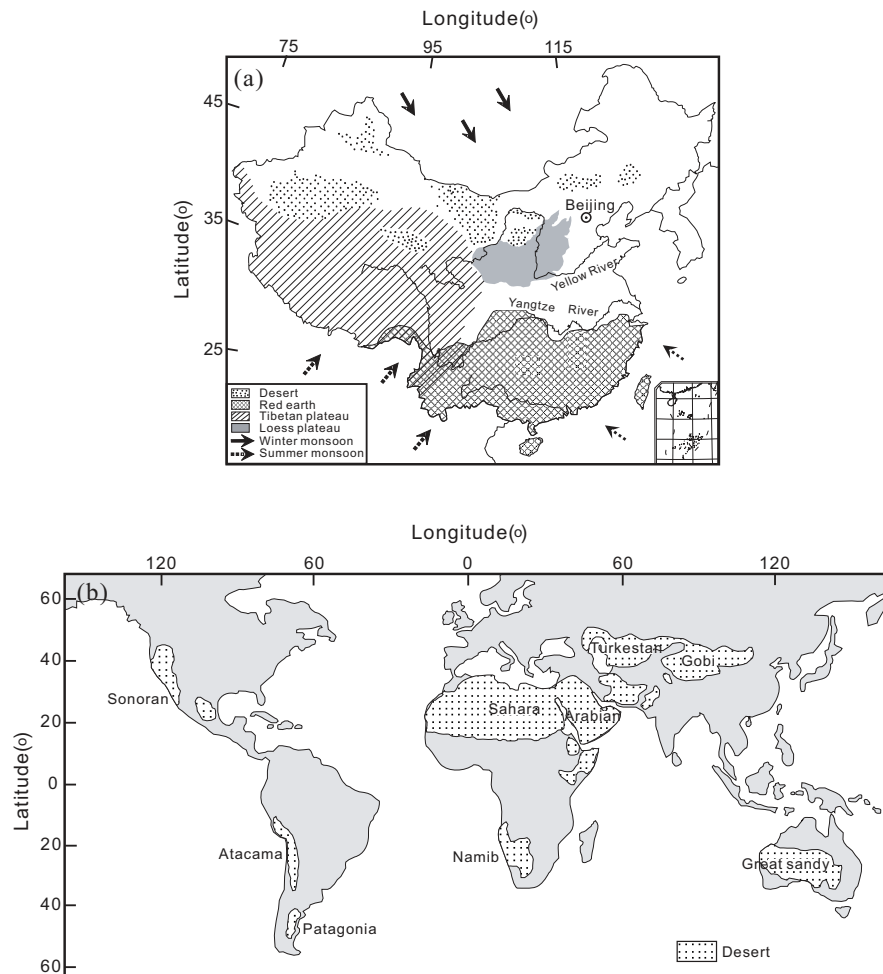


Fig. 1. Sketch maps showing the modern environmental patterns of China and the world. **(a)** Modern environmental pattern in China and the prevailing atmospheric circulations. The Loess Plateau is located in the middle reaches of the Yellow River, with the Tibetan Plateau to the Southwest, inland deserts to the North and Northwest. The subtropical and tropical regions in southern China are covered by so-called red earth (mainly soils formed under tropical and subtropical humid conditions). Dotted arrows indicate the southwest and southeast Asian summer monsoons, solid arrows indicate the Asian winter monsoon. **(b)** Distribution of the world drylands (modified after Meigs, 1953). Most of the subtropical zones are occupied by drylands with the exception of East Asia.

1 Introduction

The modern environment in Asia is characterized by two prominent features: the moist southern part under the influence of the southwest (South Asian) and southeast (East Asian) summer monsoons, the drylands in the central part beyond the monsoon influence (Wang, 2006). These are clearly illustrated by the climate pattern in China (Fig. 1a). In summer, the fronts of the summer monsoons penetrate northwards into China and lead to abundant rainfall and high temperature. In winter, the region is mainly controlled by the northwesterly dry-cold winds, i.e. the Asia winter monsoon related to the Siberian high-pressure cell (Chen et al., 1991). Currently, precipitation in northern China is mostly brought by the southeast summer monsoon (Chen et al., 1991; Fu,

2003). Although modern observations also indicate a contribution of the southwest summer monsoon to the precipitation in northern China (Chen et al., 1991; Wang, 2006), the effect is largely reduced by the barrier effect of the Himalayan-Tibetan complex. During the late Cenozoic, a large amount of eolian dust was transported from the inland deserts by winter monsoon winds to the middle reaches of the Yellow River, leading to the formation of the Loess Plateau (Liu, 1985; An et al., 1990; Ding et al., 1995; Liu and Ding, 1998; Guo et al., 2002). The western part of China is also influenced by the westerlies of the Northern Hemisphere (Wang, 2006), but their contribution to regional rainfall is relatively small because of the long continental trajectory.

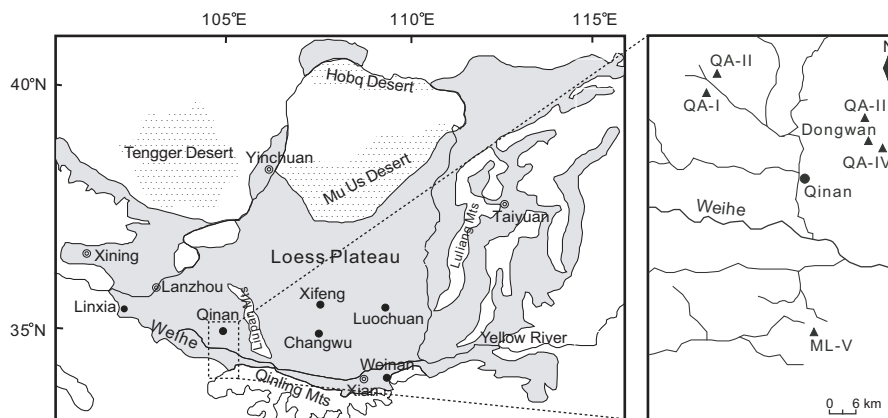


Fig. 2. The Loess Plateau in northern China relative to the inland deserts in northwestern China and various loess sites. The Plateau is delimited by the Liupan Mountains into the eastern and western parts. The right panel corresponds to an expanded part of the western Loess Plateau where the Miocene eolian deposits have been studied.

The very moist conditions in the subtropical zone in Asia, along with the presence of mid-latitude drylands, referred to here as the *monsoon-dominated pattern* (Guo, 2003), are somewhat unusual compared to the widespread drylands in most subtropical regions (Fig. 1b). These include the Australian and South American deserts in the Southern Hemisphere and the Sahara-Arabian deserts in the Northern Hemisphere. The causes of aridity for these two kinds of deserts are also very different. Except for the North American deserts that are primarily the result of rain-shadow development in the lee of mountains (Kutzbach et al., 1989), most low-latitude aridity results from subtropical high-pressure zones related to the descending branches of the Hadley Cells near the equator and the Ferrell Cells at mid-latitudes over both the hemispheres (Houghton, 1984). The subsiding air of the subtropical highs adiabatically warms, causes the air to dry out, and inhibit condensation, leading to dry conditions on the underlying continents.

In contrast, aridity in Central and East Asia is essentially independent of the subtropical highs, and mainly related to the barrier and thermo-dynamic effects of the Himalayan-Tibetan complex, the Siberian high-pressure cell and the remote distance from the oceans (Kutzbach et al., 1989, 1993; Ruddiman and Kutzbach, 1989; Chen et al., 1991; Wang et al., 2006). Consequently, we discriminate between these two kinds of drylands as *planetary* and *inland* deserts. Because subtropical high-pressure zones are a component of the planetary circulation system mainly forced by solar heating (Houghton, 1984), we assume that they can be traced back to much earlier in Earth history. Consequently, the onset of planetary drylands should be primarily dependent on the timing when a continent drifted to subtropical latitudes.

On the contrary, the onset of inland-type deserts and monsoon-dominated climate in Asia is one of the most prominent changes in the climate system of the Cenozoic

Era (Ruddiman and Kutzbach, 1989). Since the late 1970's, many numerical experiments have been conducted to address their causes. Invoked factors have focused on Tibetan uplift and changes in land-sea distribution (Manabe and Terpstra, 1974; Ruddiman and Kutzbach, 1989; Ruddiman et al., 1989; Kutzbach et al., 1989, 1993; Prell and Kutzbach, 1992; Ramstein et al., 1997; Fluteau et al., 1999; Abe et al., 2003; Zhang et al., 2007a, b).

Meanwhile, studies of geological records have led to major advances about the timing of these changes. On the southern side of the Himalayas, a record of planktonic foraminifera from the Arabian Sea that revealed strong upwelling since the late Miocene at ~ 8 Ma was interpreted as an indication of the onset or strengthening of the Indian Ocean (South Asian) monsoon (Kroon et al., 1991). The expansion of plants that use C4 photosynthesis at ~ 8 Ma in South Asia may also be indicative of strengthening of South Asian monsoon (Quade et al., 1989).

On the northern side of the Himalayan-Tibetan complex, examination on the spatial distribution of geological indicators in China revealed a transformation of the dry areas in the Cenozoic from a roughly W-E zonal belt across China to a region restricted to northwestern China (Wang, 1990). Later, six paleoenvironmental maps corresponding to the Paleocene, Eocene, Oligocene, Miocene, late Miocene-early Pliocene and Pliocene were compiled based on various geological and biological indicators (Liu and Guo, 1997). The results showed a roughly zonal climate pattern from the Paleocene to Oligocene, followed by a pattern similar to the present-day for later epochs, suggesting that the reorganization occurred during the Oligocene or Miocene. Broadly similar results have been given by a detailed compilation of paleobotanical evidence (Sun and Wang, 2005). Geological sequences from northern China also revealed more accurate age control on these changes. A pollen record from

the Linxia basin showed a significant increase in the contents of tree pollen, which was interpreted as an indication of the onset of Asian monsoon (Shi et al., 1999).

Recently, study of loess-soil sequences of Miocene ages (Guo et al., 2002) indicated that sizeable deserts in the Asian inlands and a monsoonal pattern had both been established by 22 Ma ago in the Loess Plateau region of eastern Asia. Correlative sequences with high-resolution magnetostratigraphic time control show layered sequences of fully developed soils indicative of south-to-north inflow typical of wet summer monsoons, alternating with loess layers indicative of stronger north-to-south outflow in dry winter monsoons. These alternations attest to cyclical changes of the summer and winter monsoons at the orbital scale (Guo et al., 2002).

Despite these major advances, a number of questions remain to be addressed.

1. Previous paleoenvironmental maps were mainly compiled in intervals of epochs, and hence have rather long time coverage (Liu and Guo, 1997; Sun and Wang, 2005). Because dominant views about the timing of monsoon climate in Asia focused on the late Miocene (Quade et al., 1989; Kroon et al., 1991) or around the Oligocene-Miocene boundary (Liu and Guo, 1997; Sun and Wang, 2005), a more detailed examination on the climate patterns within the Oligocene and Miocene would provide helpful insights about the timing of pattern changes. Over the past ten years, a significant amount of new geological information has been acquired, providing the opportunity to reexamine the spatial patterns in greater detail. Although the climates in Asia in the Paleocene, Eocene and Oligocene are commonly characterized by zonal patterns (Liu and Guo, 1997; Sun and Wang, 2005), their link to Cenozoic global ice-volume and temperature changes as documented by marine $\delta^{18}\text{O}$ records (Zachos et al., 2001) also needs to be discussed.
2. Examination of temporal and spatial variations of the Quaternary and Pliocene eolian deposits have provided a significant amount of information on monsoon and dryland evolution in Asia during the past 8 Ma (e.g. Liu and Ding, 1998; Miao et al., 2004). Their distribution in the Miocene remains unclear because of the insufficient number of Miocene loess sections. Recently, several new sections at different localities have been dated and analyzed. These sections provide an opportunity to further examine climate features prior to 8 Ma. Moreover, specific features of monsoonal loess-soil sequences in China can be compared to those in non-monsoon zones such as Europe and North America (Rousseau and Kukla, 1994; Rousseau et al., 1998; Berger, 2003).

In Sect. 2 of this paper, we summarize Cenozoic changes of climate patterns using paleoenvironmental maps of ten time intervals based on new collection and re-examination of geological indicators from the literature. In Sect. 3, we address the implications of the Miocene eolian deposits in northern China regarding the early stage of Asian inland desertification and monsoon climate. Other relevant geological records are reviewed in Sect. 4. In Sect. 5, we discuss the potential causes of this major change of Asian climate based on the insights from the Miocene loess-soil sequences, the available numerical experiments and tectonic studies.

2 Cenozoic climate patterns in Asia

The data used to compile the paleoenvironmental maps were acquired mainly for studies of stratigraphy, paleontology, paleogeography and paleoclimate, for resource exploration and for geological mapping. The main sources are listed in the Supplementary Material <http://www.clim-past.net/4/153/2008/cp-4-153-2008-supplement.pdf>. Among a larger number of collected records, we have selected 385 for compiling the paleoenvironment maps based on reliability of chronology and clarity of environmental significance. The chronologies of 157 records are based on mammalian fossils, those of 146 records on pollen chronology, and those of 44 records on other biochronological indicators (for example foraminifera, ostracoda). Isotope or magnetostratigraphic ages are available for 38 records.

In China, calibrations of fossil chronology by isotopic and geomagnetic dating are only available for scattered sites. Most investigations used relative chronology assignments, which potentially have large uncertainties. We infer a potential uncertainty of at least several million years for data without isotopic and geomagnetic age controls even with careful selection and examination.

These indicators are classified into three groups (humid, semi-arid and arid) according to their environmental implications. Indicators of humid conditions include coal, pollen and fossil assemblages typical of forest conditions. Arid indicators include saline and alkaline lake deposits, as well as pollen and fossils typical of deserts and desert-steppe environments. Pedogenic carbonates, pollen and fossil assemblages typical of sparse forest-steppe and steppe are used as indicators of semi-arid environments. Because of the potential uncertainty of environmental significance for some mammalian fossils, only carefully studied fauna with modern analogues are used for compiling the maps although most faunal data are useful for chronology. The maps compiled for the ten different intervals are shown in Figs. 3 and 4. The data used in each map are listed in the Supplementary Material.

2.1 Paleogene climate patterns

The Paleocene data are rather sparse, probably due to tectonic changes and erosion, but they are abundant enough to show the dominance of arid and semi-arid conditions in large areas of China. Their spatial distribution defines a broad, roughly W-E dry belt across the country (Fig. 3a). Only the southern-most Hainan Islands and northeastern China were dominated by more humid conditions. The Eocene data are significantly more abundant, showing a pattern essentially similar to that of the Paleocene (Fig. 3b). However, a northwards migration of the southern boundary of the dry belt is evident. A further slight northwards retreat of this boundary is observed for the Oligocene, although the basic environmental pattern remained zonal (Fig. 3c).

We further subdivided the Oligocene data into two groups, one corresponding to the early and mid-Oligocene (Fig. 3d), and the other to the late Oligocene (Fig. 3e). The data are sufficient to show a zonal climate pattern for the early and mid-Oligocene, but the pattern for the late Oligocene is hard to define because of a lack of data in southern China, probably due to tectonic movements and large-scale erosion (Zhang and Guo, 2005). In any case, the map for the late Oligocene does not clearly show a pattern different from that of the early and mid-Oligocene.

These five maps show that climate in Asia during most of the Paleogene was characterized by roughly W-E zonal patterns with dry conditions in southern China where humid conditions prevail today (Fig. 1a). A dry belt existed from the western-most part to the eastern coasts at latitudes similar to the present-day drylands in North Africa (Fig. 1b). The aridity was presumably caused by the subtropical high-pressure zone of the Northern Hemisphere, because of the lack of evidence of mountain ranges (and rain shadows) for the Paleogene. Thus, the zonal climate pattern is largely attributable to a planetary circulation system (Liu and Guo, 1997; Sun and Wang, 2005), rather than a monsoon-dominated regime.

The broad dry zone with a northern boundary at higher latitudes has no modern analog, probably for two main reasons. First, the climate zones within each mapping interval would have experienced significant short-term latitudinal oscillations caused by changes in global boundary conditions, leading to a broader distribution of the arid indicators. This possibility is supported by the scattered humid indicators within the dry belt (Fig. 3). Second, the northeast trade winds had mostly a terrestrial origin, and would have broadened the zone with dry conditions.

The northward migration of the climate zones from the Paleocene to the Oligocene, including the dry belt, appears to be consistent with the Paleogene changes of the global boundary conditions as reflected by marine $\delta^{18}\text{O}$ records (Zachos et al., 2001) (Fig. 5a). The Paleocene Earth is commonly considered ice-free. Glaciations may have started on Antarctica at ~ 43 Ma ago and then expanded in the early Oligocene at ~ 34 Ma (Miller et al., 1987; Zachos et al.,

2001). Ice-volume on Antarctica during the early Oligocene glaciation may have reached $\sim 70\%$ of the present-day volume (Zachos et al., 1992). Although recent evidence of ice-rafting (Moran et al., 2006) revealed nearly synchronous bipolar cooling events during the Cenozoic, impermanent ice, probably mainly mountain and piedmont glaciers in the Northern Hemisphere, only appeared since the late Miocene, ~ 10 – 6 Ma (Lear et al., 2000).

These global scenarios in the Paleogene, characterized by great ice-sheets in Antarctica and ice-free or sporadic ice in Arctic, imply a much greater asymmetry of ice-conditions between the two hemispheres. Under the present-day global boundary conditions, the northern front of the southern hemispheric trade winds, i.e. the ITCZ, penetrates northwards to ~ 22 – 24° N in summer and to $\sim 4^\circ$ N in winter (Lezine et al., 2007) due to hemispheric asymmetry. The development of the Antarctic ice in the Eocene and early Oligocene (Zachos et al., 2001) would have forced global climate zones to migrate northwards, providing a likely explanation for the northward migration of the dry belt in Asia from the Paleocene to the Oligocene (Fig. 3).

Although these interpretations remain hypothetical and need to be tested by climate models, a meridional shift of the atmospheric circulation induced by greater extents of sea ice over the Southern Atlantic and Southern Ocean has been demonstrated by the late Quaternary geological records (Iri-ono, 2000; Markgraf et al., 2000; Stuut and Lamy, 2004; Gersonde et al., 2005; Lambert et al., 2008). A climate model (Cox et al., 2008) shows that reduced aerosol pollution in the Northern Hemisphere also favors a northwards shift of the atmospheric circulation. The much weaker dust intensity during the Paleogene, as evidenced by the lack of loess deposits in China and the low dust accumulation rates in the North Pacific (Rea et al., 1985; Rea, 1994), may also account for the northwards shift of the climate zones.

This explanation is also supported by the increased humidification in the southern part of China from the Eocene to Oligocene (Fig. 3), suggesting the existence of a circulation that brought moisture to the region. It might correspond to the so-called tropical monsoon (Chase et al., 2003) resulted from the penetration of Southern Hemisphere trade winds into the Northern Hemisphere, primarily driven by the seasonal oscillations of planetary circulations (Chase et al., 2003).

In summary, the climate in Asia in the Paleogene was dominated by a zonal pattern attributable to the planetary circulation system. Despite a possible monsoon regime in the tropical regions, its intensity was not strong enough to dominate the climate of the Asian continent.

2.2 Neogene climate pattern

The Miocene climate patterns (Fig. 4) are entirely different from those in the Paleogene (Fig. 3). Indicators of arid conditions are mainly distributed in northwest China.

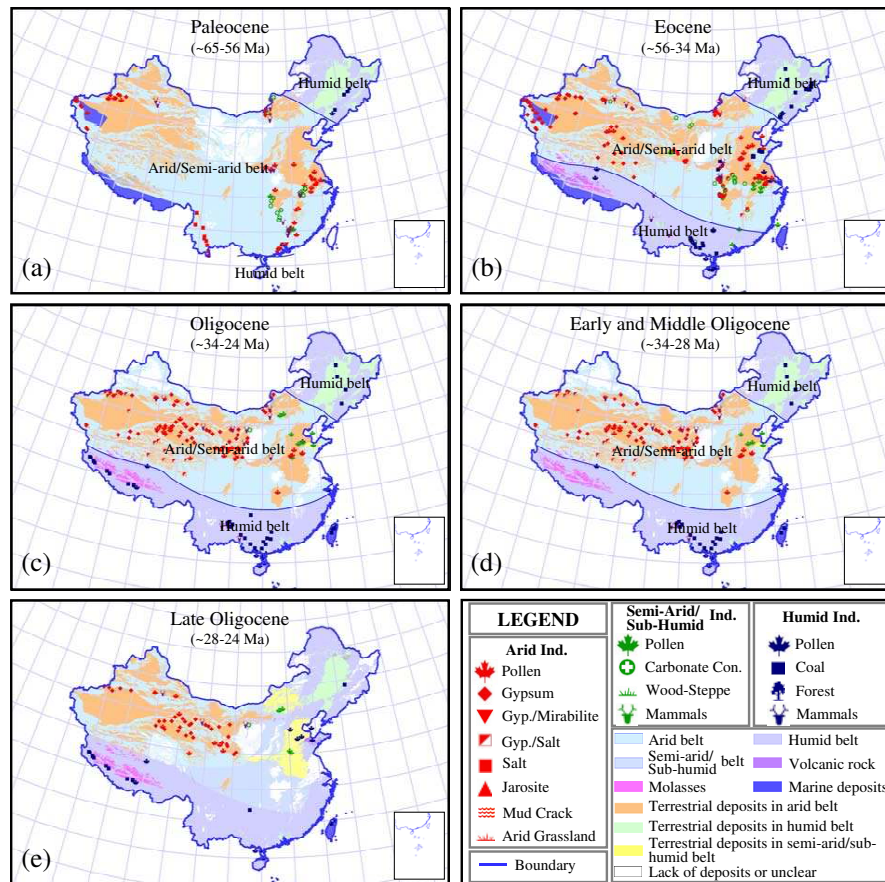


Fig. 3. Paleogene environmental patterns in China. (a) Paleocene; (b) Eocene; (c) Oligocene; (d) Early and middle Oligocene; (e) Late Oligocene. The data sources are given in Supplementary Material <http://www.clim-past.net/4/153/2008/cp-4-153-2008-supplement.pdf>. A geographical information system was used to illustrate the distribution of environmental indicators. The base map is from China Geological Survey (2001). Data on the distribution of the Cenozoic terrestrial deposits are from Chinese Stratum Thesaurus Editorial Board (1999).

The middle reaches of the Yellow River were dominated by semi-arid conditions. In contrast, indicators of humid conditions spread widely across the southwestern and southeastern parts. This spatial pattern is highly similar to the present-day climate pattern in China (Fig. 1a).

Earlier studies inferred two important Miocene boundaries of climate changes in Asia, one in the early Miocene (Shi et al., 1999; Guo et al., 2002) and the other in the late Miocene (Quade et al., 1989; Kroon et al., 1991; An et al., 2001). To more accurately examine this problem, the Miocene data are separated into the early, middle and late Miocene parts (Fig. 4b–d). Data for each interval are abundant enough to define the climate patterns clearly. They show the existence of a pattern similar to the modern one since the early Miocene (Zhang and Guo, 2005). The Pliocene pattern (Fig. 4e) is also similar to the Miocene one, except that the far northeastern part is marked by semi-arid conditions, representing a slight humidification compared to the late Miocene.

The humidification in the southeast and southwest of China since the early Miocene firmly indicates the strong influence of the southeast and southwest summer monsoons. It also supports a notion of synchronous onsets/strengthenings of the two summer monsoons rather than largely diachronous developments. The Neogene location of drylands at much higher latitudes indicates that the aridity was not caused by the subtropical high-pressure zone. Instead, the similar location to the present-day drylands indicates typical inland-type deserts.

In summary, the spatial distributions of the geological indicators clearly reveal that (1) the zonal climate pattern linked to the planetary circulation system was transformed to a monsoon-dominated pattern similar to the present-day one; (2) the low-latitude drylands related to the subtropical high-pressure zone disappeared while inland-type deserts at higher latitudes formed; and (3) both the humidification in southwest and southeast China and the appearance of the northwest drylands were closely coupled, suggesting a joint change of circulation and aridity, and hence, dynamic links

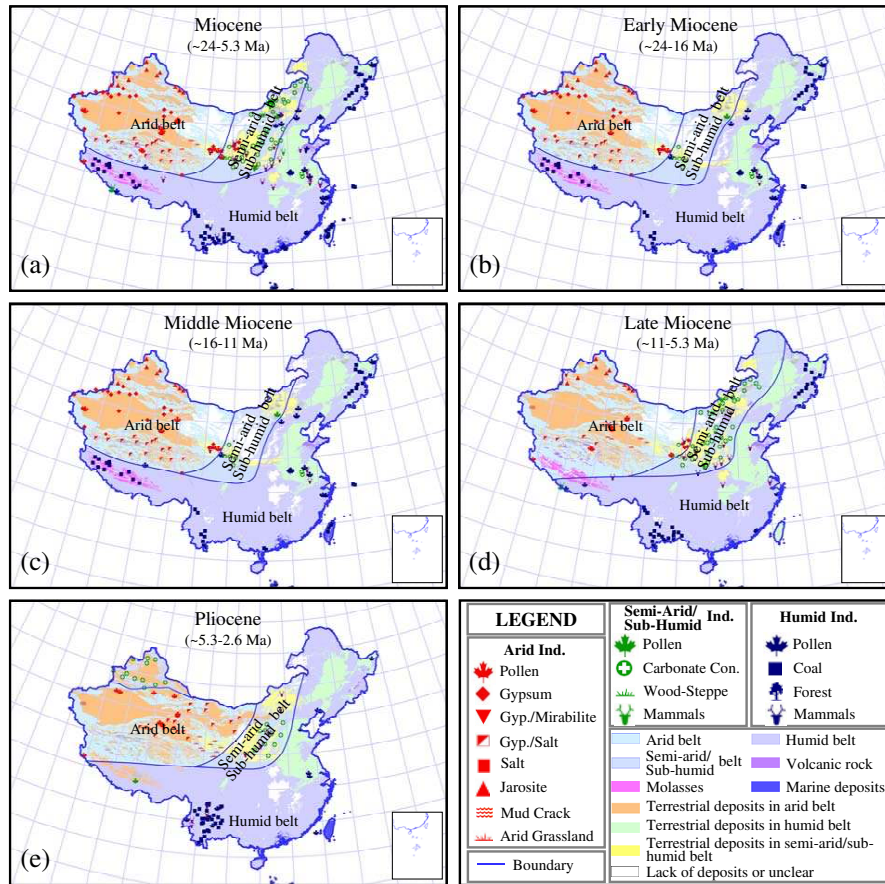


Fig. 4. Neogene environmental patterns in China. (a) Miocene; (b) Early Miocene; (c) Middle Miocene; (d) Late Miocene; (e) Pliocene. Data sources are the same as noted in the caption of Fig. 3.

between them; and (4) these changes had occurred at least by the early Miocene. The climate effects of the subtropical high-pressure zone, which would generate dry conditions at low-latitudes (Houghton, 1984), were largely weakened during the Neogene due to the strong influence of the summer monsoons.

3 Miocene loess-soil sequences as indications of monsoon regime and inland-deserts

Eolian dust deposits spread widely across the middle reaches of the Yellow River in the Loess Plateau (Liu, 1985). The region is delimited by the Liupan Mountains into the eastern and western parts, with the Asian inland deserts to the north and northwest, and the Himalayan-Tibetan Plateau to the southwest (Figs. 1a and 2). Modern observations indicate that eolian dust is mainly derived from inland deserts and transported by the Asian winter monsoon (Liu, 1985) while rainfall in the region is mainly brought by the south-east summer monsoon (An et al., 1990; Liu and Ding, 1998)

and to a lesser extent, by the southwest summer monsoon (Chen et al., 1991).

To date, three main eolian formations have been identified in the Loess Plateau. These include the well-known loess-soil sequences of the last 2.6 Ma (Liu, 1985; Kukla et al., 1990; Ding et al., 1994; An et al., 2001), the Hipparion Red-Earth of eolian origin, also referred to as Red-Clay (2.6–8.0 Ma) and only found in the eastern Loess Plateau (Sun et al., 1997; Ding et al., 1998; An et al., 2001; Guo et al., 2004), and the Miocene and Pliocene loess-soil sequences recently found in the western Loess Plateau with a combined time coverage from 22 to 3.5 Ma (Guo et al., 2002; Hao and Guo, 2004, 2007; Liu et al., 2005). These eolian formations provide a near continuous terrestrial record of paleoclimate for the past 22 Ma.

3.1 Onset of loess deposition roughly coupled with the changes of climate pattern

Miocene loess deposits were firstly found in the western Loess Plateau (Guo et al., 2002) near Qin'an (QA-I and QA-II sections), Gansu Province (Fig. 2). Their eolian origin

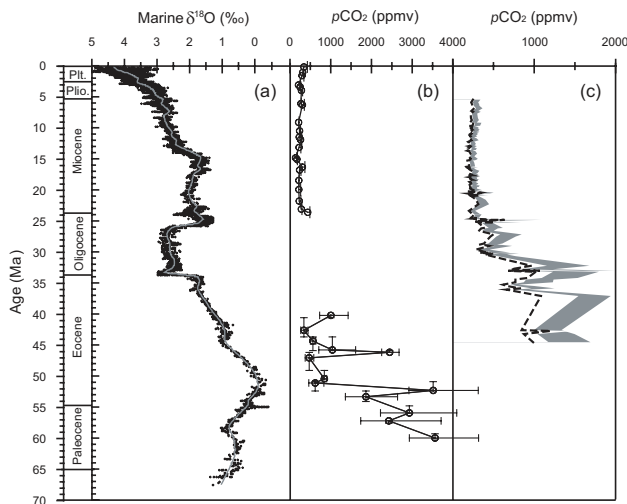


Fig. 5. Variations of global temperature/ice volume and proxy estimates of the Cenozoic atmospheric concentration of CO₂. (a) Marine δ¹⁸O records of benthic foraminifera as an indication of global temperature and ice volumes (Zachos, et al., 2001); (b) Boron isotope-based estimates of atmospheric CO₂ levels for the past 60 Ma (Pearson and Palmer, 2000); (c) Carbon isotope based estimates of Cenozoic atmospheric CO₂ levels (Pagani et al., 2005). The shadowed band indicates the maximum and intermediate estimates and dashed line indicates the minimum estimates.

is attested by (1) the presence of several hundred paleosols and interbedded loess layers that were significantly affected by pedogenesis, indicative of subaerial environments (Guo et al., 2002); (2) the fine silty texture throughout the ~16-Ma sequence with maximum grain-size mostly <120 μm (Guo et al., 2002; Qiao et al., 2006); (3) the angular morphology of quartz grains typical of eolian dust deposits (Guo et al., 2002; Liu et al., 2006); (4) the similar geochemical properties to the Quaternary loess and to the average composition of the upper continental crust (Liang et al., 2006), a basic feature of loess deposits (Jahn et al., 2001); (5) the well-preserved, abundant and randomly distributed land snail fossils in both soil and loess layers, along with the lack of aquatic and amphibian species throughout the sequences (Li et al., 2006a, 2006b); and (6) rock magnetic properties typical of eolian deposits (Hao et al., 2008). Spatial investigations showed that the Miocene eolian deposits mantle the highlands across a broad region of the western Loess Plateau (Yuan et al., 2007).

We have dated five Miocene loess-soil sections (Fig. 2) using magnetostratigraphy. These include the QA-I (22–6.2 Ma) and QA-II (21.6–7.4 Ma) (Guo et al., 2002), QA-III (21.4–11.4 Ma) (Hao and Guo, 2007), QA-IV (Miziwan site, 18.5–11.6 Ma) (Liu et al., 2005) and ML-V (Gaojiazhuang site) in this study (Fig. 6). The variable basal ages of the sections are related to their different topographic locations. A loess section near Xining containing a Miocene portion younger than 14 Ma was also reported (Lu et al., 2004).

These results provide several lines of new information about this unique terrestrial record.

1. These sections have stratigraphies and magnetic susceptibility time series that are spatially correlative (Guo et al., 2002; Liu et al., 2005; Hao and Guo, 2007). This is clear in the correlations between ML-V and QA-I (Figs. 6 and 8), separated by ~75 km. Such high spatial correlative is characteristic of eolian deposits and also attests to the relative continuity of the sequences.
2. The spatial coverage of these sites, as well as our geomorphic investigations (Yuan et al., 2007), reveals widespread Miocene eolian deposition in northern China, and their significance for paleoclimate at larger regional scales. Miocene eolian dust input has also been identified as the main source of fine-grained sediments in some fluvial-lacustrine basins in the region (Garzzone et al., 2005). Recently, a set of fine-grained sediments beneath a 15-Ma basalt sheet near Nanjing has been identified as eolian deposits (Zhang et al., 2007) suggesting that the southern boundary of the Miocene eolian deposition might have reached as far south as the Yangtze River.
3. The lower boundaries of these sections indicate that loess deposition in northern China started at least in the early Miocene. The basal age of the QA-I section, ~22 Ma (Guo et al., 2002), still represents the oldest up to date. This is approximately consistent with the major change of climate patterns in Asia discussed above, confirming a major reorganization of climate regime.

3.2 Miocene loess as direct evidence of inland deserts in Asia

Loess deposits cover ~10% of the land surface and are found in variable environments (Liu, 1985; Tsoar and Pye, 1987; Pye, 1995). Drylands are the most important dust sources and the resulted loess deposits are known as *hot loess* (Obruchev, 1933, but see Liu, 1985). In contrast, loess deposits around glacial areas are referred to as *cold loess*, with distributions spatially restricted to periglacial environments (Liu, 1985). Loess deposits usually cover terraces of large rivers, mostly due to dust deflation from fine-grained fluvial materials during glacial periods (Qiao et al., 2003; Zoller et al., 2004; Johnson et al., 2007). Their distribution is clearly linked to river valleys. Loess deposits are also frequently found in coastal regions where dust was mostly derived from continental shelves exposed to wind erosion during the times of low sea level (Zhao, 1996). Some loess deposits may result from a mixture of sources, such as the unusually thick loess deposits on some river terraces in northern China (Jiang et al., 2004) where local fluvial sources and remoter desert sources would have co-contributed.

Whatever the main sources of eolian dust, the formation of loess fundamentally requires (1) a sustained source of dust,

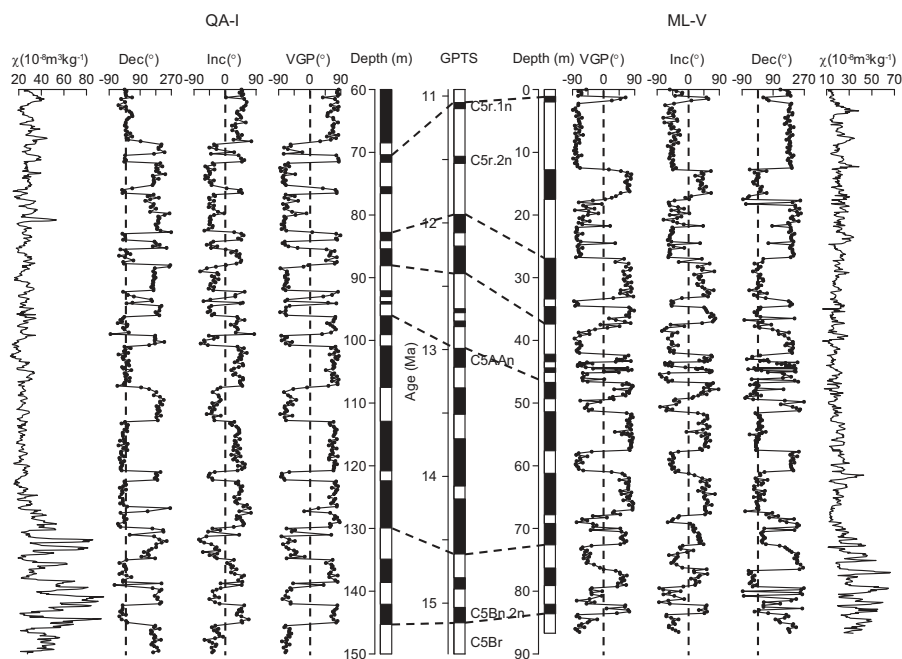


Fig. 6. Magnetostratigraphy and magnetic susceptibility (χ) of ML-V (Gaojiashuang site ~ 75 km south to QA-I, $105^{\circ}43'E$, $34^{\circ}24'N$) Miocene loess-soil sequence and correlation with QA-I. Declination (Dec), inclination (Inc) and virtual geomagnetic pole (VGP) latitudes are shown. Correlation of the ML-V geomagnetic polarity with the standard geomagnetic polarity timescale (GPTS, Cande and Kent, 1995) dates the section from 15.41 Ma to 11.01 Ma. Data of QA-I are from Guo et al. (2002). The ML-V section rests on Devonian phyllite and is overlain by thick colluvia mostly derived from loess materials. Paleomagnetic measurements were made on 376 samples at 20–25 cm intervals in the Paleomagnetism Laboratory of Institute of Geology and Geophysics, Chinese Academy of Sciences using stepwise thermal demagnetization as described in Guo et al. (2002). 94% of the samples gave reliable characteristic remanence directions. Magnetic susceptibility was measured on air-dried samples at 10 cm intervals using a Bartington susceptibility meter.

(2) adequate wind energy to transport the dust, and (3) a suitable accumulation site (Pye, 1995). Dust deflation only occurs in areas with poor vegetation cover (Tsoar and Pye, 1987; Pye, 1995). Although fine-grained material is commonly available in tectonically active regions, dense vegetation cover often prevents the fine materials from being deflated. An example is the humid Yunnan region in southwest China where tectonics and erosions are intense but loess deposition only occurred along river valleys at small scales. The remarkably thick and widespread loess of China and Central Asia results from the long-term persistence of extensive dryland dust sources (Pye, 1995).

The Miocene eolian deposits in northern China are undoubtedly *hot loess* because of their wide distribution and nearly continuous temporal coverage. Their desert origin is also supported by the angular morphology of the quartz fraction extracted from these loess samples (Fig. 7a and b). Scanning electronic microscope (SEM) observations show that a majority of quartz grains are finer than $100 \mu\text{m}$ in diameter, mostly ranging from 10 to $30 \mu\text{m}$. Most grains have irregular and angular shapes and many are characterized by sharp edges and conchiform fractures. The angular grains resulted from mechanical collisions of eolian sandy grains, salt dis-

integration and freeze-thaw weathering in the desert regions (Liu, 1985; Tsoar and Pye, 1987; Pye, 1995). Because dust was transported by wind in suspension, their angular shapes were not abraded.

The elemental geochemistry signatures of the Miocene loess (Liang et al., 2006) are also very similar to the average composition of the upper continental crust, indicating that the dust materials were all derived from well-mixed sedimentary protoliths which underwent numerous upper-crustal recycling processes (Taylor et al., 1983). These compositions suggest that the materials were derived from wide areas, such as desert lands. Local sources of small scale would tend to have more specific geochemical signatures.

Thus, the Miocene loess deposits in northern China provide pertinent evidence on the following crucial features relative to the Cenozoic history of Asian drying.

1. They indicate the existence of sizeable deserts in the Asian inlands by 22 Ma ago as dust sources (Guo et al., 2002). Because the onset of loess deposition matches the reorganization of climate patterns, these deserts must be *inland-type* rather than *planetary-type*. These also indicate a joint change in inland aridity and the atmospheric circulation.

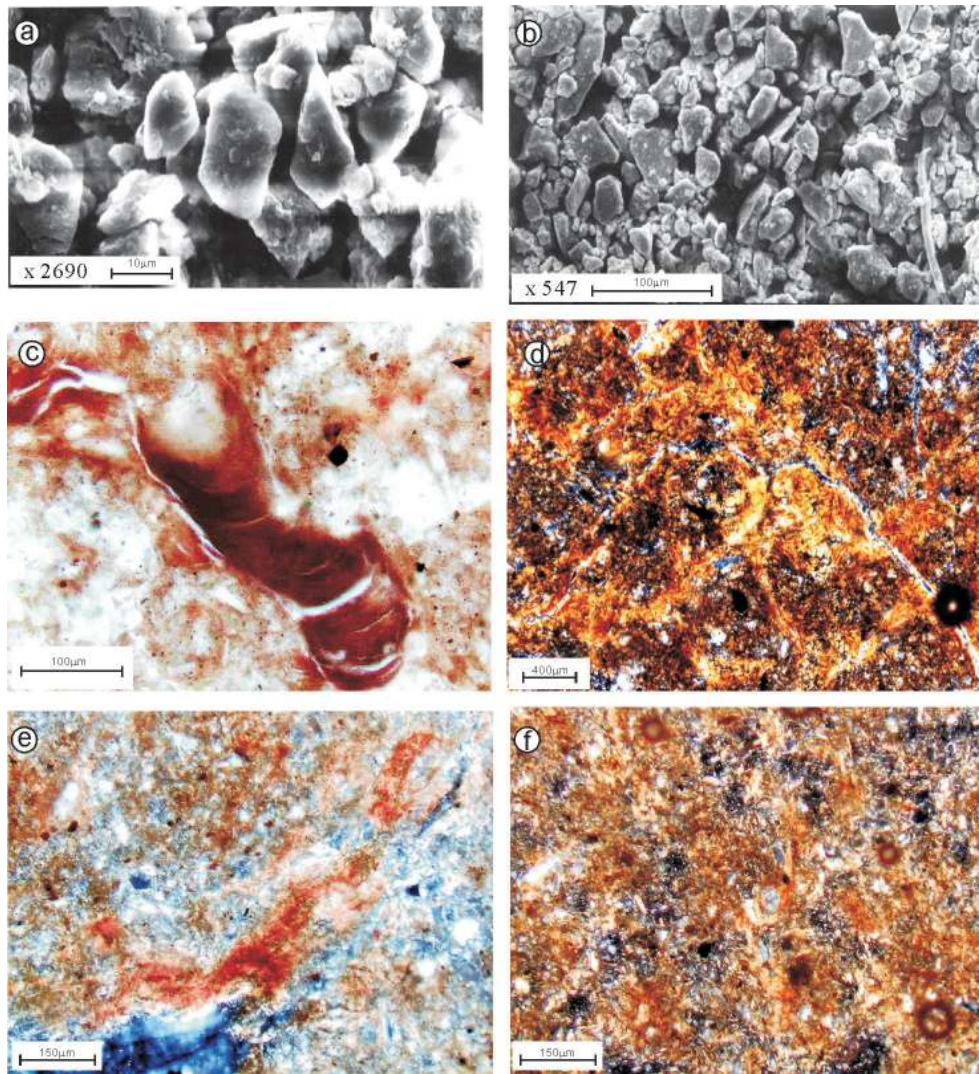


Fig. 7. Quartz grain morphology of early Miocene loess samples and micromorphology of the early Miocene paleosols from QA-I. **(a)** Scanning electronic microscopic (SEM) picture of quartz grains in Miocene loess samples (QA-I, 250 m); **(b)** SEM picture of quartz grains in Miocene loess samples (QA-I, 252.6 m); **(c)** Clay coatings in an early Miocene soil (QA-I, 253.1 m, plain-polarized light); **(d)** Clay coatings and intercalations with high birefringence (QA-I, 253.1 m, cross-polarized light); **(e)** Clay illuvial features in the forms of intercalations within the groundmass (QA-I, 214.8 m, cross-polarized light); **(f)** Groundmass of an early Miocene soil showing the strong argillization (QA-I, 211.8 m, cross-polarized light).

2. The near-continuous development of eolian sequences in northern China, from the early Miocene to the Holocene, implies that inland deserts have been constantly maintained over the past 22 Ma despite drastic changes in global climates during the Neogene and Quaternary (Miller et al., 1998; Zachos et al., 2001).

3.3 Miocene dust transport and Asian winter monsoon

A large collection of observational evidence indicates that the Quaternary loess deposits in northern China were mainly transported by the northwest winds in the Asian winter monsoon (Liu, 1985; An et al., 1990; Ding et al., 1995; Liu and

Ding, 1998). This inference has been confirmed by the spatial variations of eolian grain-size in the Loess Plateau region, ranging from coarser in the northwestern part to finer in the southeastern part (Liu, 1985; Ding et al., 1995). Recent examination on the late Miocene-Pliocene Red-Earth (Miao et al., 2004) revealed a similar pattern of eolian grain-size, indicating a dominant role for the winter monsoon in dust transport since ~ 8 Ma ago.

The onset of eolian dust deposition by 22 Ma ago attests to the presence of a circulation sufficiently energetic to carry eolian dust from the deserts to the Loess Plateau region (Guo et al., 2002). Several lines of evidence suggest that this

circulation was also the winter monsoon.

1. Loess has been continuously deposited in the middle reaches of the Yellow River since at least 22 Ma ago and the location of drylands in Asia (Fig. 4) has been similar to the present-day (Fig. 1). This evidence implies that the dust-carrying winds must have had a northern origin from the available dust sources, consistent with the modern trajectory of the Asian winter monsoon.
2. Although more sophisticated geochemical approaches may discriminate among the relative contributions of different deserts to loess deposits (Chen et al., 2001; Sun, 2002), the similarity in the elemental geochemistry between the Miocene loess and those of the last 8 Ma (Guo et al., 2002; Liang et al., 2006) supports broadly comparable source areas and dust transporting trajectories over the past 22 Ma, and hence the presence of the winter monsoon circulation.

To further address this issue, grain-size analyses were conducted on samples dating from 15.4 to 11.1 Ma at QA-I and ML-V (Gaojiazhang site), ~75 km south to QA-I (Fig. 2). The analyses reveal similar trends of grain-size variations along the two sections, but significantly finer textures at the southern ML-V site (Fig. 8). The average median grain-size at ML-V is $\sim 1 \mu\text{m}$ finer than for QA-I. These new data have three implications.

1. Similar to the magnetic susceptibility time series (Liu et al., 2005; Hao and Guo, 2007), grain-size variations in the Miocene loess-soil sequences are also spatially correlative, again characteristic of eolian deposits.
2. The grain-size gradients indicate that the source areas lie to the north of the Loess Plateau, and thus in the inland deserts.
3. The patterns require north-to-south circulation (the Asian winter monsoon). The establishment of northerly winds is regarded as the main criteria of the Asian monsoon system (Liu and Yin, 2002). Because of the close relationship of the winter monsoon with the Siberian high-pressure center, we believe that the Siberian High would have also formed or greatly intensified by 22 Ma ago.

Unfortunately, available early Miocene sections are not ideally located for examining grain-size gradients prior to 15 Ma.

3.4 Early Miocene soils in loess as evidence of a monsoon climate regime

Loess layers are deposited during relatively dry-cold periods while soils developed during more humid-warm intervals. Because soil formation requires a substantial amount of rainfall, the numerous paleosols in the Miocene eolian sequences

also imply the existence of other circulation branches able to bring moisture from the ocean to the south. Consequently, the alternations between loess and soil layers indicate cyclical orbital-scale occurrences of dry and humid conditions in northern China (Guo et al., 2002).

To further characterize the circulation characteristics, we examined properties of the early Miocene paleosols. Micromorphology examination reveals abundant clay illuvial features (Fig. 7) that are typical of Luvisols (FAO-Unesco, 1974) formed under humid forest environments (Fedoroff and Goldberg, 1982). Their proportions of up to $\sim 30\%$ are approximately comparable to those of the modern Luvisols in the south of the Yangtze River where annual rainfall is more than 1000 mm (Zhang et al., 1999). Moreover, a large fraction of the clay illuvial features are in the form of intercalations within the groundmass (Fig. 7d–e). Such illuvial features, commonly described as vertic due to alternative humidification and shrinkage of soil profiles (Hussein and Adey, 1998; Cao and He, 1999), are typical of soils formed under climates with contrasting seasons (Cao and He, 1999). They suggest a strong seasonality in northern China since the early Miocene.

The intensity of clay illuviation of these early Miocene soils was much stronger compared to the most developed soil Quaternary S5-1 soil (~ 0.5 Ma in age) in the relatively humid southernmost Loess Plateau, for which clay illuvial features amount to $\sim 10\%$ (Guo et al., 1998). Although the relative duration of the seasons may affect pedogenesis, the substantially increased amount of illuvial features in the Miocene soils indicates much more abundant rainfall in northern China during the early Miocene than for the Quaternary. According to the climate patterns since the early Miocene (Fig. 4), most of the moisture must have had a low-latitude origin in the summer monsoons. In view of the rather dry conditions in northwest China (Fig. 4), the westerlies were unlikely to have provided a significant moisture contribution, because of the extremely long continental trajectory from moisture sources.

Under a climate regime without seasonally alternating circulations, a soil largely represents a sedimentary hiatus (Fedoroff and Goldberg, 1982; Cremaschi et al., 1990), as is the case for most loess-soil sequences in non-monsoon regions. In these regions, soil develops on the parent loess deposited during a dry-cold period, such as late-glacial intervals just prior to the soil-forming interglacial period when dust deposition was negligible (Fedoroff and Goldberg, 1982; Cremaschi et al., 1990). In contrast, paleosols in the loess-soil sequences under a monsoonal climate regime have completely different features resulting from interactions between summer and winter monsoons. In summer, the monsoonal rainfall associated with the high temperature favors pedogenesis, but eolian dust continues to be added to the soil surface in winter and early spring, although at lower intensities than during typical loess deposition periods (Guo et al., 1991, 1993). Thus, dust deposition and soil-formation under

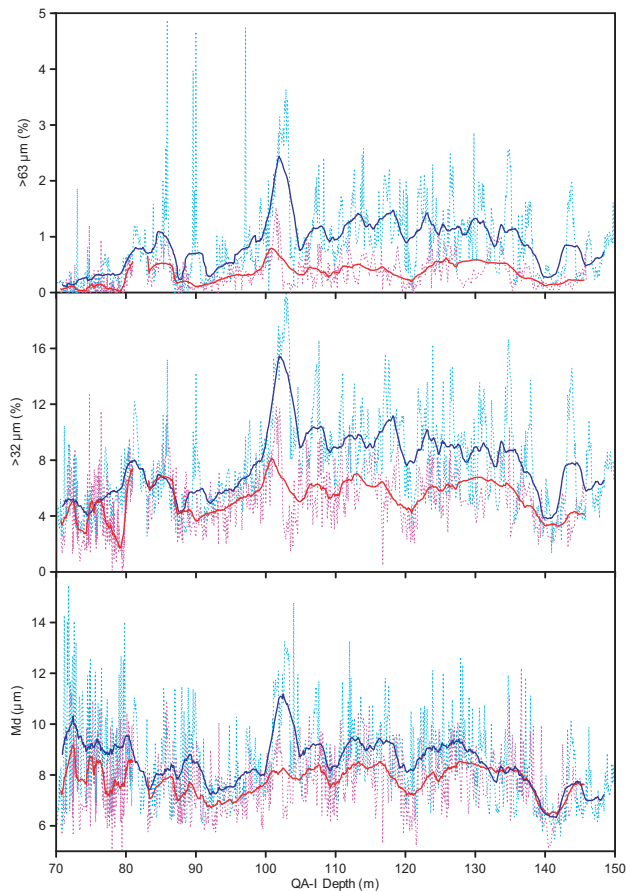


Fig. 8. Comparison of grain-size changes between QA-I (blue lines) and ML-V (red lines). The fine dotted lines represent the data at 10 cm intervals and the thick lines are 30-point moving averages. ML-V is adjusted to the QA-I depth using magnetic reversals as control points. The grain-size changes shown here correspond to the interval from 15.41 to 11.12 Ma. The intervals within ML-V without data correspond to two layers of water-reworked loess with some coarse sands derived from the upper slopes, for which samples were not analyzed. The finer grain-size at the ML-V site indicates northern source locations and northerly dust-carrying winds during the Miocene. Grain-size of 787 samples from QA-I and 868 from ML-V were analyzed using a Malvern Mastersizer-2000 laser particle analyzer with an analytical precision $<1\%$. They were pretreated with hydrogen peroxide to remove the organic matter, then with hydrochloric acid to remove the carbonates, and with sodium hexametaphosphate for dispersion.

a monsoonal climate regime are competing processes, and the presence of a soil implies that the latter process was predominant (Porter, 2001). These interactive processes lead to the formation of the so-called *accretionary soils* (Hovan and Rea, 1991; Kemp, 2001) that can be regarded as a strong evidence of a monsoonal climate regime.

Accretionary soils are characterized by specific features (Guo et al., 1991, 1993), three of which allow quick discrimination from non-accretionary soils. First, eolian dust during the soil-forming intervals is usually significantly finer due to the weakened winter monsoon and relatively smaller/remoter sources. This can be detected by examining the grain-size of the quartz fraction, which is highly resistant to weathering and hence independent of the effects of pedogenesis. The quartz fraction of an accretionary soil has finer grain-size than that of the underlying loess, while that of a non-accretionary soil has similar quartz grain-size to its parent loess. Second, because of the differences in dust grain-size between soil forming and loess deposition periods, the dust composition may also be different, as can be determined using stable elements resistant to post-depositional pedogenesis. Third, accretionary soils usually have highest chemical weathering intensity in the middle of their profiles because of the intensified dust deposition during the late stage of soil development, while non accretionary soils have strongest weathering at the top horizon (Duchaufour, 1983).

To check if the soils in the Miocene loess sequences are accretionary soils, four kinds of analyses were conducted. First, microscopic observations show that the quartz fraction in soils are significantly finer than in the underlying loess layers indicating that the soils were not totally developed from the underlying loess. This conclusion is also confirmed by grain-size analyses on the quartz fraction (Fig. 9a). Second, chemical analyses show an unambiguous difference of chemical composition of the stable elements between the loess and soils that are not affected by the soil-forming processes, indicating a composition differences (Fig. 9b). Finally, the chemical weathering profiles of the soils show stronger weathering intensity in the middle of the profiles (Fig. 9c), followed by decreasing intensity to the top. These properties firmly define the accretionary nature of the paleosols in the Miocene loess deposits, indicating a monsoon climate regime.

In summary, the properties of the Miocene loess-soil sequences require the existence of a typical monsoonal climate in northern China. Still an open question is the relative contribution of moisture from the southeast and southwest summer monsoons to the formation of the Luvisols in the Loess Plateau. Clarification of this question would require several suitably located Miocene loess-soil sections, but these are not yet available. Measurements on the oxygen isotope composition of pedogenic carbonates would also be helpful. Although modern moisture in the Loess Plateau is mostly related to the East Asian summer monsoon due to the elevated Tibetan Plateau to the southwest, a greater contribution from the southwest summer monsoon would be expected during times when the Himalayas and Tibetan Plateau were not as high as it is today, as might be the case for the early Miocene. The results of numerical experiments (Zhang et al., 2007a, b) appear to be supportive to this possibility.

4 Other records of the climate reorganization

Although the onset of loess deposition is roughly consistent in time with the major reorganization of climate patterns, the precise age of this change remains an open question, because the data used for spatial mapping are of coarse resolution and low chronological accuracy while the basal age of the loess sections may depend in part on the tectonic setting of the substrata (Guo, 2003; Hao and Guo, 2004). Also, whether or not this climatic reorganization represents a sudden change or stepwise changes need to be addressed.

During the past five years, we explored for older loess deposits in the Loess Plateau, but did not find any. However, other kinds of records from surrounding regions may provide some insights to this issue. A pollen record from the nearby Linxia fluvial-lacustrine basin (Fig. 10a) showed a drastic increase in the percentage of tree pollen near ~ 22 Ma (Shi et al., 1999). Because the site was located within the planetary-type dry belt during the Oligocene (Fig. 3) and is presently within the monsoon zone, this vegetation shift would indicate humidification of the region, and thus an enhanced influence of the summer monsoon. Similar trends were shown by a slight decrease in the content of xerophytes at ~ 23 Ma (Fig. 10b) in a core from the Qaidam basin (Wang et al., 1999) although the region is currently less influenced by the summer monsoons. In a carbon isotope record of terrestrial black carbon reflective of vegetation changes in South China, the earliest high $\delta^{13}\text{C}$ peaks appeared ~ 20 Ma ago and were interpreted as a support of early monsoon initiation (Jia et al., 2003). A prominent change in the mammalian and floristic regions in China appears to have also occurred in the early Miocene (Song et al., 1983; Qiu and Li, 2005).

A marine eolian record at the LL44-GPC3 site from the North Pacific (Rea et al., 1985; Rea, 1994) shows lower rates of dust accumulation in the Paleogene and roughly doubled rates since ~ 25 Ma (Fig. 10c). This transition, associated with mineralogy and chemistry changes, was interpreted as representing the time when the core site migrated north from the regime of trade winds to that dominated by eolian transport in the westerlies and the influence of Asian dust sources (Rea, 1994). Recently, a comprehensive geochemical analysis shows a major increase in the delivery of Asian dust material since ~ 20 Ma (Fig. 10d) at ODP site 1215 from the central Pacific (Ziegler et al., 2007), which was interpreted as recording the development of East Asian monsoon and formation of Asian loess.

These lines of evidence, associated with the Miocene loess records (Guo et al., 2002), suggest that the major changes in the Asian climate regime occurred between 25 and 22 Ma ago, and most of them support an age close to 22 Ma. From these insights, we speculate that discovery of older loess-soil sections could yet be made in northern China but probably not more than a few million years older.

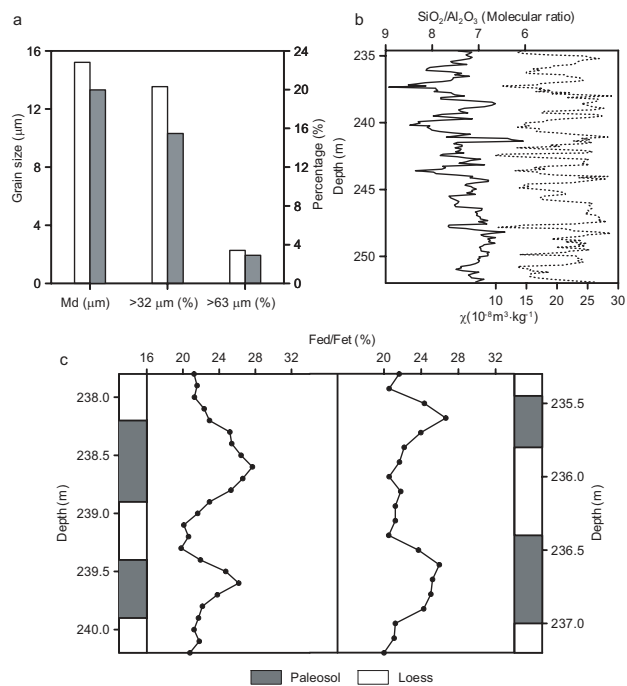


Fig. 9. Accretionary properties of the early Miocene paleosols. **(a)** Comparison of median grain-size (Md) and the proportions of the $>32\ \mu\text{m}$ and $>63\ \mu\text{m}$ fractions of quartz particles between soils and loess layers, showing the accretion of finer eolian dust during soil-forming periods. 30 soil and 30 loess samples were analyzed along QA-I (totally 253.1 m in thickness). The quartz fraction was extracted using the sodium pyrosulfate fusion-hydrofluorosilicic acid method (Xiao et al., 1995). X-Ray diffractions of the extracted fraction indicate a quartz purity of more than 95%. Grain-size of the quartz samples was analyzed using a Malvern Mastersizer-2000 laser analyzer. **(b)** Variations of $\text{SiO}_2/\text{Al}_2\text{O}_3$ molecular ratio along an early Miocene portion of QA-I showing lower values in soils than in loess layers. Because this ratio has been shown to reflect mainly the eolian grain-size prior to pedogenic affection (Peng and Guo, 2001; Guo et al., 2004), its lower values in soils indicate continuous dust deposition during the soil-forming periods, but with finer grain sizes. Alternations between soil and loess layers are illustrated by the fluctuations of magnetic susceptibility, higher in soils and lower in loess. SiO_2 and Al_2O_3 contents were analyzed by X-Ray fluorescence using a Philips PW-1400 unit with an analytical uncertainty of 2%. **(c)** Variations of Fed/Fet ratio along two early Miocene portions at QA-I as examples show highest weathering at the middle of the soil profiles. Fed/Fet is a chemical weathering index (Duchaufour, 1983) that measures the proportion of iron oxides and hydroxides liberated by chemical weathering from iron-bearing silicate minerals and has been successfully applied in the Quaternary loess of China (Guo et al., 1996, 2000).

5 Causes of climate reorganization

The new results therefore confirm previous evidence that the climate in Asia experienced a transition from a zonal climate pattern to a monsoon-dominated one near the Oligocene/Miocene boundary, by 22 Ma ago. This reorganization was marked by the joint onsets/strengthenings of the Asian summer and winter monsoon circulations and inland-type deserts. After this transition, the role of the summer Subtropical High was largely weakened, while that of the winter Siberian High was reinforced. The similarity of climate patterns through the Neogene and Quaternary, and continuous loess deposition over the past 22 Ma indicate that the monsoon-dominated climate and the inland deserts have constantly been maintained since their formation.

The causes of the Asian monsoons and inland desertification have been objectives of numerous studies. Earliest theories emphasized the role of land-sea thermal contrast and its link to monsoon phenomena (Halley, 1986). However, these theories cannot explain the onset of a broad monsoon-dominated regime by the early Miocene. Normal seasonal oscillations of planetary circulations (Flöhn, 1956) such as the inter-tropical convergence zone (ITCZ) may explain the presence of monsoons in tropical regions, but not the deep penetration of the ITCZ and summer monsoons into eastern Asia since the early Miocene as indicated by the presence of well developed soils.

Although the Cenozoic global cooling trends had significant impacts on the Asian monsoon climate in the past 6 Ma (Ding et al., 1995; Guo et al., 2004), they are unlikely to account for the major reorganization of climate pattern by 22 Ma ago because the most prominent changes in global ice-volume and temperature, as documented by the marine $\delta^{18}\text{O}$ records (Miller et al., 1998; Zachos et al., 2001), are not correlative with the major changes in Asia (Fig. 5a). Also, the consistently maintained monsoon-dominated climate pattern and inland deserts in the past 22 Ma, as evidenced by near-continuous eolian sequences in China and the paleoenvironmental maps (Fig. 4), indicate that ice volume changes had not rearranged the basic climate pattern in Asia.

Other possible factors include the decreasing atmospheric concentration of CO_2 , which would cause global cooling, and consequently intensify Asian aridity and the winter monsoon. Proxy estimates (Perason and Palmer, 2000; Pagani et al., 2005) suggested large CO_2 decreases at ~ 50 Ma, 30 Ma and 24 Ma (Fig. 5b and c). Although the fall at ~ 24 Ma is close in time to the Asian climate change, changes in CO_2 level are not likely by themselves to be the main cause of the climate-pattern rearrangement. Consequently, regional factors must have played a dominant role.

Climate model experiments have focused on two main factors: uplift of the Himalayan-Tibetan complex and retreat of the Paratethys Sea, an epicontinental sea still largely opened during the Paleogene (Dercourt et al., 1993). Uplift could shift the Asian climate from a zonal pattern to

a non-zonal one (Manabe and Terpstra, 1974). The growing elevation (Kutzbach et al., 1989; 1993; Ruddiman and Kutzbach, 1989; Ruddiman et al., 1989; Abe et al., 2003) and expansion of Tibetan Plateau along its northern and eastern margin (An et al., 2001) could lead to drying trends in the Asian inlands and enhance both the summer and winter monsoon circulations. The summer monsoon could be triggered when the Tibetan Plateau reached half its present-day elevation (Prell and Kutzbach, 1992). This threshold of half-elevation also seems to apply to the winter monsoon circulation (Liu and Yin, 2002). Continuing uplift and expansion would alter significantly the thermally forced circulation and enhance continental-scale summer and winter monsoons and central Asian aridity (An et al., 2001). In northern China, the formation of the monsoon climate is mainly marked by the establishment of northerly winter winds, and uplift would have had a more significant effect on the winter monsoon than for the summer monsoon (Liu and Yin, 2002).

An alternative view invokes the impact of the Paratethys retreat (Ramstein et al., 1997; Fluteau et al., 1999) in intensifying the South Asian monsoon and shifting the central Asian climate from temperate to continental conditions. Shrinkage of this epicontinental sea could thus have played a major role in large-scale atmospheric changes along with plateau uplift (Fluteau et al., 1999).

Recently, we attempted to discriminate the effects of these two major factors, and to examine the potential roles of other tectonic changes, on the formation of the monsoon-dominated climate in Asia using a nine-layer AGCM (Zhang et al., 2006, 2007a,b). Sensitivity experiments show that a progressively elevated Tibetan plateau intensifies both the Asian summer and winter monsoons, increases the seasonal contrast of precipitation in the monsoon zone, and enhances aridity in northwestern China (Zhang et al., 2006, 2007a, b). These findings confirm earlier conclusions that uplift plays an important role in the formation and development of the Asian climate (Kutzbach et al., 1989; 1993; Ruddiman and Kutzbach, 1989; Ruddiman et al., 1989; An et al., 2001; Abe et al., 2003), and also explain the constant maintenance of the monsoon-dominated climate and inland deserts in Asia in the past 22 Ma.

Our experiments also revealed that a monsoon-dominated climate and inland deserts can be generated by a 3000-m elevated Tibetan Plateau under most of the Paratethys conditions except one in which the Paratethys Sea is connected with the Arctic Ocean (Zhang et al., 2007a, b). These experiments imply that once the Paratethys becomes disconnected from the Arctic Ocean, a sufficiently elevated Tibetan Plateau (~ 3000 m) alone is able to cause formation of both a monsoon-dominated climate and inland deserts in Asia, regardless of the size of the Paratethys. The effects of the plateau are, however, largely weakened when the Paratethys is still connected with the Arctic Ocean.

Experiments with the Paratethys Sea also show that withdrawal of this epicontinental sea increases precipitation in

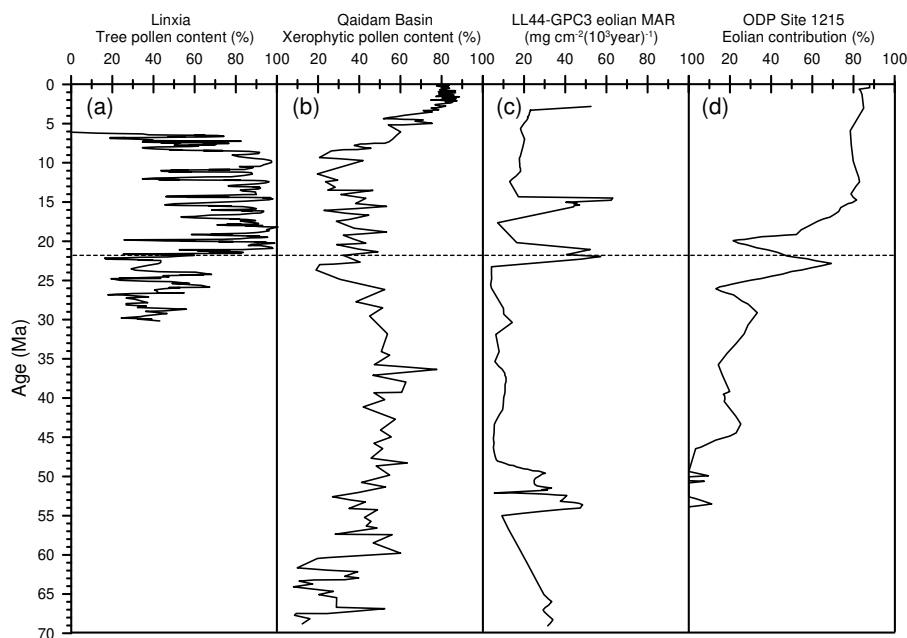


Fig. 10. Relevant geological records of Asian climate changes near the Miocene-Oligocene boundary. **(a)** Increase in the content of tree pollen ~ 22 Ma ago at Linxia (Shi et al., 1999); **(b)** Decrease in the content of xerophytic pollens in the Qaidam Basin at ~ 23 Ma (Wang et al., 1999); **(c)** Cenozoic variations of eolian mass accumulation rate (MAR) at Site LL44-GPC3 from the North Pacific (Rea et al., 1985); **(d)** Estimated Asian eolian contribution at Site ODP 1215 in the central Pacific showing a large increase at ~ 20 Ma (Ziegler et al., 2007).

the monsoon zone and decreases rainfall in northwest China (Zhang et al., 2007a, b). These results reinforce the earlier conclusion about the role of the Paratethys retreat (Ramstein et al., 1997; Fluteau et al., 1999), and meanwhile show that monsoon climate and inland deserts can be generated when the Paratethys retreats to the Turan Plate whatever the elevation of the Tibetan Plateau (1000–3000 m). The results also suggest that widening of the South China Sea enhances the humidity contrast between southern and northern China (Zhang et al., 2007b).

The effects of Tibetan uplift and Paratethys retreat on the seasonal circulation patterns are somewhat similar for northern China (Fig. 11). In summer, both factors deepen the Asian low pressure and cause south-to-north inflow and bring moisture into China (Fig. 11a and c). In winter, uplift intensifies the Asian high-pressure and lead to northwesterly winds in northern China (Fig. 11b). The Paratethys retreat leads to an anticyclonic anomaly circulation centered over Central Asia and a cyclonic anomaly circulation over Mongolia (Fig. 11d) in winter. The coupled anomalies intensify the northwest winter winds from the inland deserts to the Loess Plateau. Although the anomalies also cause a south-to-north winter flow over eastern China, it would be a moisture-depleted flow because of its terrestrial origin. Our results thus suggest different impacts of Tibetan uplift and Paratethys retreat on the winter circulations, but their common effects are the intensification of the Asian high-pressure and the formation of northwesterly winds in northern China

that pick up eolian dust from the inland deserts and transport it to the southeast. These changes are mostly consistent with the seasonal circulation characteristics indicated by the Miocene loess-soil sequences and the Neogene environmental maps (Fig. 4).

As for the geological histories of the three invoked tectonic factors, there is a general consensus about the spreading of South China Sea, which was initiated during the Oligocene and reached a stable spreading state in the early Miocene (Briaies et al., 1993; Li et al., 2005, 2006c). This is broadly consistent with the onset of the monsoon-dominated climate. This factor would have enhanced the south-north contrast of humidity (Zhang et al., 2007b). The collision of India and Asia in South Tibet may have begun ~ 55 Ma or 34 Ma ago (Aitchison et al., 2007) while the subsequent uplift histories of the Tibetan region remain highly controversial. Some views about major uplift focus on several boundaries, including the Eocene and Oligocene at ~ 45 –30 Ma (Chung et al., 1998; Guo et al., 2006; Rowley and Currie, 2006; Wang et al., 2008), the late Oligocene or early Miocene at ~ 26 –18 Ma (Harrison et al., 1992; DeCelles et al., 2007), the mid-Miocene around 14 Ma (Turner et al., 1993; Coleman and Hodges, 1995; Spicer et al., 2003), the late Miocene around 8 Ma (Harrison et al., 1992; Valdiya, 1999; Garzzone et al., 2000; Clark et al., 2005; Molnar, 2005) and the Plio-Pleistocene after 3–4 Ma (Li and Fang, 1999; Zheng et al., 2000). Because the Himalayan-Tibetan Plateau has undoubtedly had a strong effect on moisture transport to the Asian

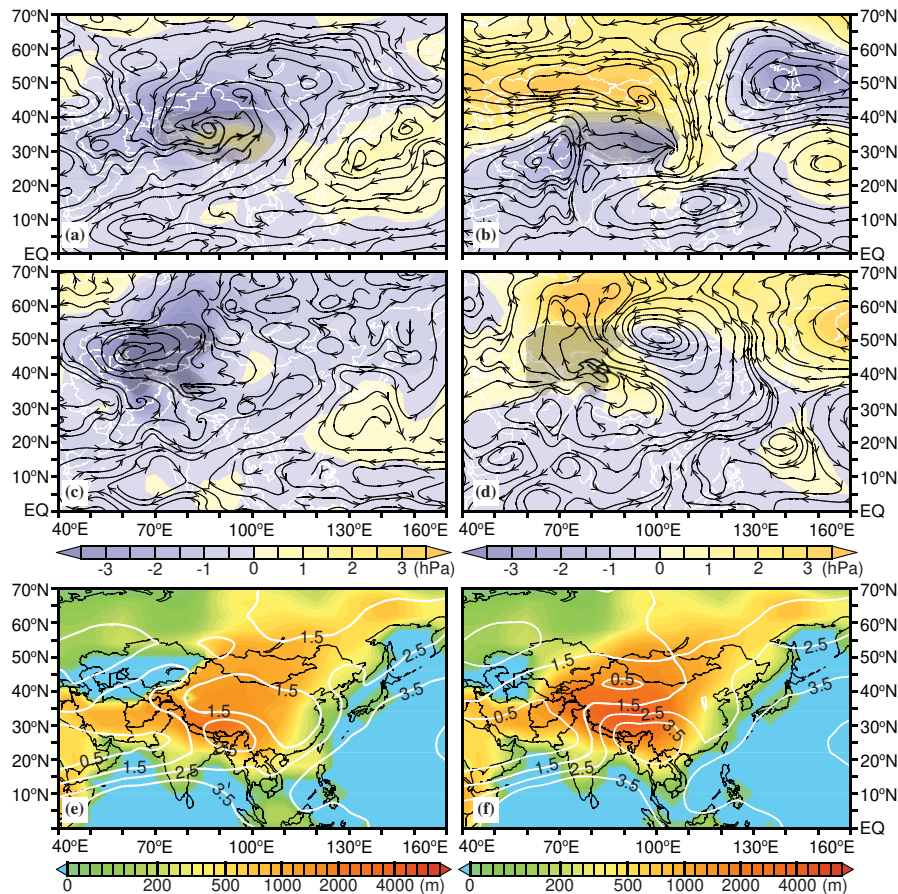


Fig. 11. Effects of Tibetan Plateau uplift and Paratethys retreat on the summer and winter circulation patterns and precipitation fields in Asia (compiled from sensitivity experiments in Zhang et al., 2007b). (a) and (b) show the anomalies of sea-level pressure (color scale, hPa) and 850 hPa wind circulations (stream lines) in summer and winter, respectively, corresponding to uplift of the Tibetan Plateau from half to full elevation. The gray shaded zone indicates the heightened area of the plateau. (c) and (d) show anomalies of sea-level pressure (color scale) and 850 hPa wind circulations (stream lines) in summer and winter, respectively, corresponding to a retreat of the Paratethys Sea from south of Western Siberia to the Turan Plate. The gray shaded zone indicates the sea area that changed into land. (e) and (f) show the comparative precipitation fields under the combined boundary conditions of a low Tibetan Plateau and a large Paratethys Sea, and of a high Tibetan Plateau and a smaller Paratethys Sea, respectively. Color scale shows the elevation of topography with the sea areas in blue. White lines represent isohyets of annual precipitation.

interior, we believe that at least the southern margin of the plateau would have been sufficiently elevated by 22 Ma ago to act as a moisture barrier. This inference is strongly supported by the deposition of debris in submarine fans in the Indian Ocean around this time (Corrigan and Crowley, 1992; Clift, 2006).

During an initial stage of the India and Asia collision, Paratethys would have already separated from the Arctic Ocean (Akhmet'ev et al., 2001; Akhmet'ev and Beniamovski, 2006) while the Tibetan Plateau remained low. Available data suggest shrinkage of this sea from a large extent during the Oligocene and Miocene (Dercourt et al., 1993; Pavelic et al., 2001; Akhmet'ev and Beniamovski, 2006) to a smaller one during the Miocene (Dercourt et al., 1993). This withdrawal is broadly consistent in time with

the suggested chronological ranges of Tibetan uplift and the onsets of monsoon dominant climate and inland deserts in Asia.

The fact that a monsoon-dominated climate and inland deserts were already formed by 22 Ma ago provides an environmental clue for a further evaluation. It suggests that the tectonic conditions had evolved to a threshold by ~ 22 Ma ago sufficient to cause the climate reorganization. Since both Tibetan uplift and Paratethys retreat were linked with plate tectonics in the region, there is a strong possibility that these two factors evolved more or less synchronously. A large collection of data effectively demonstrates a peak range of regional tectonic changes around the early Miocene (Harrison et al., 1993; Hodell and Woodruff, 1994; Ding and Zhong, 1999; Pavelic et al., 2001; Ding et al., 2004; Guo et al.,

2006). Consequently, the combined effect of Tibetan uplift and Paratethys shrinkage probably triggered the major climate reorganization in Asia.

This combined effect is clear in our numerical experiments (Fig. 11e and f). Under the conditions combining a low Tibetan Plateau and a large Paratethys Sea (Fig. 11e), a roughly zonal field of low precipitation occurs at lower latitudes in China, comparable to the zonal dry belt in the Paleogene (Fig. 3). In contrast, the experiment with a high Tibetan Plateau and a smaller Paratethys Sea yield an arid zone at higher latitudes in northwestern China and increased rainfall in southern China (Fig. 11f). These are comparable with the Neogene climate patterns (Fig. 4).

The exact relationship of Asian climate change relative to tectonics remains to be determined because of uncertainties about the timing and extent of Tibetan uplift and Paratethys retreat, and the inability of models to simulate higher-resolution topography. An increasing amount of evidence suggests diachronous uplifts of the plateau (e.g. Chung et al., 1998; Wang et al., 2008) but detailed reconstructions are not yet possible. Models with higher resolution will also be necessary to investigate the effects of regional mountain ranges, such as the Liupan and Qinling Mountains, which were also likely uplifted during the Neogene. In addition, discriminating the effects of tectonics and global climate changes on the Asian paleoclimate remains an important issue.

Recently, paleo-altimeters based on stable-isotopic indices, such as $\delta^{18}\text{O}$ of soil carbonate (DeCelles et al., 2006), ^{13}C - ^{18}O bonds in carbonate minerals (Ghosh et al., 2006), $\delta^{18}\text{O}$ and $\delta^2\text{H}$ of authigenic minerals (Rowley and Currie, 2006; Rowley and Garzzone, 2007), as well as paleobotanical indicators (Lu et al., 2001; Spicer et al., 2003) have been developed to address the elevation history of mountains. Most of the results tend to suggest the existence of high-elevation parts of the Tibetan Plateau by or in the early Miocene (Spicer et al., 2003; DeCelles et al., 2006; Rowley and Currie, 2006; Rowley and Garzzone, 2007). However, an elevation similar to the present-day one during the early Oligocene, as inferred by some studies (Chung et al., 1998; Rowley and Currie, 2006; Rowley and Garzzone, 2007; Wang et al., 2008), may only be local in extent, because an extended plateau at this height would produce the monsoon-dominated climate pattern in Asia according to climate models (Kutzbach et al., 1989; 1993; Ruddiman and Kutzbach, 1989; Ruddiman et al., 1989; Abe et al., 2003; Zhang et al., 2007a, b), yet geological evidence clearly reveals a planetary climatic pattern in Asia during most of the Oligocene (Fig. 3c). These results, associated with the model outputs and geological records, likely support the notion of diachronous uplifts of the plateau.

Chemical weathering of silicate materials is a process that consumes CO_2 (Raymo et al., 1988; Raymo and Ruddiman, 1992). Tectonic uplift may have major impacts on atmospheric CO_2 levels by accelerating chemical weathering and

increasing the burial of organic matter (Raymo et al., 1988; Raymo and Ruddiman, 1992; Derry and France-Lanord, 1996; Ruddiman et al., 1997). Consequently, reconstruction of the Cenozoic atmospheric CO_2 levels might be expected to provide helpful insights about the uplift history if other factors were secondary. Available proxy estimates based on marine boron-isotope (Pearson and Palmer, 2000), marine carbon isotope (Pagani et al., 1999, 2005) and paleobotanical evidence (Royer et al., 2001) consistently suggest a fall of the atmospheric CO_2 level near the Oligocene/Miocene boundary, followed by rather stable CO_2 levels during the Neogene. Whether these suggest an achieved state of major tectonic uplifts of global significance by that time is a worthy question to consider in the future, as it appears to be coherent with the results of paleo-altimetry approaches for the Tibetan region (DeCelles et al., 2006; Rowley and Currie, 2006; Rowley and Garzzone, 2007). It should be noted, however, that proxy estimations of paleo- CO_2 level may be biased by other factors (ex. Lemarchand et al., 2000). Also, the rather stable and near present-day levels of CO_2 through the Neogene suggested by available estimates (Pagani et al., 1999, 2005; Perason and Palmer, 2000; Royer et al., 2001) face the question on explaining the ongoing global cooling since the early Neogene (Zachos et al., 2001).

6 Conclusions

Based on a significant amount of new data, we have examined the spatial distribution of environmental indicators in ten Paleogene-Neogene time intervals, as well as the properties of Miocene loess-soil sequences in northern China. The results led to the following conclusions.

1. Our geobiological data and map compilation confirm the earlier conclusion that the zonal climate pattern of the Paleogene was transformed into a monsoon-dominated pattern similar to the present-day one in the Neogene. These changes are marked by humidification in southwest and southeast China, disappearance of low-latitude aridity related to the subtropical high-pressure zone, and emergence of inland deserts at higher latitudes. Detailed mapping within the Oligocene and Miocene indicates that the reorganization was achieved by the early Miocene, matching the time of onset of widespread loess deposition in northern China. Although the basal ages of the loess sections do not necessarily provide the earliest age of this major climate transition, other terrestrial and marine records tend to suggest an age near the Oligocene-Miocene boundary, at 25–22 Ma.
2. The dated Miocene loess-soil sections in northern China show spatially correlative stratigraphy and climate proxies, similar to younger eolian deposits in the region.

The near-complete time coverage of Neogene and Pleistocene eolian deposits attest to the existence of inland deserts in the Asian interior as persistent dust sources during the past 22 Ma despite major changes of global climate. Spatial gradients of eolian grain-size indicate a source area lying north to the Loess Plateau in the inland deserts. They also provide evidence of strong dust-carrying circulation from the north in the Asian winter monsoon.

3. The well-developed Luvisols present since the early Miocene indicate the existence of a circulation of oceanic origin that brought moisture to northern China, in the Asian summer monsoons. The intensity of these circulations was significantly stronger than for the Quaternary. The accretionary properties of the soils attest to the presence of two seasonally alternating circulations, one from the oceans in the south carrying moisture and the other from the northern deserts carrying dust. These features rightly define a full monsoonal (seasonally reversing) climatic regime.
4. This major reorganization represents a fundamental transformation from a planetary circulation system to a monsoon-dominated system. Following this transition, the effects of the subtropical high-pressure zone in generating dry conditions at low latitudes weakened during the Neogene because of the strong influence of summer monsoons. In contrast, the effects of the winter Siberian High were reinforced. The roughly synchronous humidification in southwest and southeast China suggests a coupled strengthening of the southwest and southeast summer monsoon circulations, rather than largely diachronous developments. In confirming the roles of Tibetan uplift and Paratethys shrinkage as suggested in previous studies, our recent numerical experiments and new geological data suggest a combined effect of these two factors with a contribution from the spreading and opening of the South China Sea. The loess record provides a vital insight that these tectonic scenarios had evolved to a threshold by the early Miocene sufficient to cause this major climate change in Asia.

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