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A major reorganization of Asian climate regime by the early Miocene

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Abstract

The global climate system has experienced a series of drastic changes during the Cenozoic. These include the climate transformation in Asia, from a zonal pattern to a *monsoon-dominant pattern*, the disappearance of subtropical aridity related to a planetary circulation system and the onset of *inland deserts* in central Asia. Despite of the 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. Firstly, we newly collected the available Cenozoic geological indicators of environment in China to compile the paleoenvironmental maps of ten intervals with a more detailed examination within the Oligocene and Miocene. In confirming the earlier observation that a zonal climate pattern was transformed into a monsoonal one, the new maps within the Miocene indicate that this major 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 in the tropical-subtropical regions. The observed latitudinal oscillations of the climate zones during the Paleogene are likely attributable to the imbalanced 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 special emphasis given to 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 has been constantly maintained in the past 22 Ma. Inter-section grain-size gradients indicate northerly dust-carrying winds and source location, as is regarded as the main criteria of the Asian winter monsoon system. Meanwhile, the well-developed Luvisols evidence the existence of circulations from the ocean, which brought moisture to northern China. These imply the coexistence of two kinds of circulations, one from the ocean as moisture carrier and another from the inland deserts as dust transporter. The accretionary properties of the early Miocene paleosols, resulted from interactive soil-forming and dust deposition processes, evidence two seasonally alternative circulations, i.e. a monsoonal climate regime. The much stronger development of the early Miocene soils compared to those in the Quaternary loess indicates significantly stronger summer monsoons.

These lines of evidence indicate a joint change in circulations and inland aridity by the early Miocene, and suggest a dynamic linkage of them. Our recent numerical experiments reconfirm the potential roles of Tibetan uplift and Paratethys shrinkage in triggering this major climate reorganization, as revealed in peer studies, but yielded more details about their combined scenarios. These two factors would have coacted with the help of South China Sea spreading. Although the realistic effects of each factor remain to be further discriminated, probably through more paleoaltimetrical and tectonic approaches, the Miocene loess record provides a vital insight that tectonics had evolved to a threshold by the early Miocene to cause this major climate reorganization in Asia.

1 Introduction

The modern environment in Asia is characterized by two prominent features: the moist southern part under the influence of southwest (South Asian) and southeast (East Asian) summer monsoons, the drylands in the central part beyond the monsoon influence (Wang, 2006). These are clearly illustratable 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

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summer monsoon to the precipitation in northern China (Chen et al., 1991; Wang, 2006), the effect is largely reduced due to the barrier effect of the Himalayan-Tibetan complex. A large amount of eolian dust was transported from the inland deserts by the 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). The western part of China is also influenced by the northern hemispheric westerlies (Wang, 2006), but their contribution to regional rainfall should be relatively small in view of the long continental trajectory.

The strongly moist conditions in the subtropical zone associated with the mid-latitude drylands in Asia, referred to as the *monsoon-dominant pattern* (Guo, 2003), are somewhat unusual compared to the widespread drylands in most of the subtropical regions of our globe (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 of radical difference. Except the orography effects on the aridity of Americas (Kutzbach et al., 1989), the low-latitude aridity are largely attributable to the subtropical high pressure zones over both the hemispheres, which are indeed a component of the planetary circulation system (Houghton, 1984). In contrast, the modern aridity in Central and East Asia are essentially independent of the subtropical highs, but 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). Consequently, these two kinds of drylands could be discriminated into *planetary-type* and *inland-type* deserts. Since subtropical high pressure zone is a component of the planetary circulation system (Houghton, 1984), we guess it could be traced back to a much earlier history of the Earth. Consequently, the onset of planetary-type 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-dominant climate in Asia is one of the most prominent changes in the climate system of the Cenozoic Era

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(Ruddiman and Kutzbach, 1989). Since the late 1970's, a great number of numerical experiments have been conducted to address their causes. Invoked factors focus on the 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).

Meanwhile, studies on geological records 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 revealed strong upwelling since the late Miocene at ~8 Ma and 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 the 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, and 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 suggested more accurate ages about these changes. A pollen record from the Linxia basin showed a significant increase in the contents of tree pollens, which was interpreted as an indication of the onset of Asian monsoon (Shi et al., 1999). Recently, the discovery of the loess-soil sequences of Miocene ages in the western Loess Plateau indicates the existence of sizeable deserts in the Asian inlands and a monsoon-dominant climate in northern China at least since 22 Ma ago

(Guo et al., 2002).

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

(1) Available paleoenvironmental maps were mainly compiled by 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 indicators have been acquired, providing a possibility to reexamine the spatial patterns in greater details. 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), how they were linked to the Cenozoic global ice-volume and temperature changes as documented by the marine δ^{18}O records (Zachos et al., 2001), needs to be further discussed.

(2) Examinations on the temporal and spatial variations of the Quaternary and Pliocene eolian deposits have provided a huge amount of information on the monsoon and dryland evolution in Asia in the past 8 Ma (e.g. Liu and Ding, 1998; Miao et al., 2004). How these were for the Miocene has remained unclear because of the insufficient number of the Miocene loess sections. Recently, several new sections at different localities have been dated and new analyses have been conducted. These offer a possibility to further examine the climate features prior to 8 Ma. Moreover, the specific features of the monsoonal loess-soil sequences in China compared to the loess deposits in non-monsoon zones, such as those in Europe and North America (Rousseau and Kukla, 1994; Rousseau et al., 1998; Berger, 2003) need to be further demonstrated.

In Sect. 2 of this paper, we reexamined the Cenozoic changes of climate patterns based on a recompilation of paleoenvironmental maps of ten time intervals through independent new collection and examination of geological indicators from the literature, including the data acquired during the last ten years. Their spatial distribution patterns within the Oligocene and Miocene are examined in more detail compared to earlier studies (Liu and Guo, 1997; Sun and Wang, 2005). Their possible links with the global climate background are also tentatively analyzed.

In Sect. 3, we address the implications of the Miocene eolian deposits in northern China on the early stage of Asian inland desertification and monsoon climate. Based on the available and new sections dated by paleomagnetic method, their low boundary ages, the texture and geochemical features as well as the inter-section grain-size gradients, we show that the Miocene loess deposits can be regarded as a direct evidence of sizeable deserts in the Asian interior formed by the early Miocene, and that dust was transported by northerly winds, as is regarded as a main criteria of the Asian winter monsoon system (Liu and Yin, 2002). We also show that the properties of the early Miocene soils indicate the existence of strong summer monsoons by 22 Ma ago, and that our evidence suggests a joint change of inland aridity and circulations in Asia. These results, in addition to the other relevant geological records as reviewed in Sect. 4, tend to suggest that this major change would have occurred near the Oligocene/Miocene boundary, close to 22 Ma.

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. These data tend to suggest a joint effect of the Himalayan-Tibetan uplift and land-sea distribution changes on the early Asian desertification and monsoon-dominant climate. The existence of sizeable inland deserts and strong monsoons at least since the early Miocene provides an independent perspective that these tectonic scenarios had evolved to a threshold by 22 Ma ago to cause this major reorganization of climate regime in Asia.

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2 Cenozoic climate patterns in Asia

All the data used for the compilation of paleoenvironmental maps are newly collected from the literature, that were acquired mainly for the purposes of stratigraphy, paleontology, paleogeography and paleoclimate investigations, resources exploration and geological mapping. The main data sources are listed in the Supplementary Material (http://www.clim-past-discuss.net/4/535/2008/cpd-4-535-2008-supplement.pdf). The collection was made as complete as possible to minimize potential missing of important information.

In comparison with our earlier compilation (Liu and Guo, 1997), the data acquired in the last ten years are included. Among the great number of collected records, we have selected only 385 for the compilation of paleoenvironment maps according to their reliability of chronology and clarity of environmental significance. The chronologies of 157 records are based on mammalian fossils, 146 records based on pollen chronology, and 44 records based on other biochronological indicators (ex. foraminifera, ostracoda). Isotope or magnetostratigraphic ages are available for 38 records. We avoided using the data with chronology or stratigraphy contentions.

In China, calibrations of fossil chronology by isotopic and geomagnetic dating are only available for scattered sites. Most of the past investigations used relative chronology assignments, which potentially have large ranges of accuracy. We believe a potential uncertainty in an order of at least several million years for the data without isotopic and geomagnetic age controls despite of the careful selection and examination. Consequently, they would only be statistically valid for illustrating the spatial environmental patterns within an accuracy of several millions of years.

These indicators are classified into three groups (humid, semi-arid and arid) according to their environmental implications. Indicators of humid conditions include coal, all pollen and fossil assemblages of forest conditions. Those of arid conditions include saline and alkaline lake deposits, pollen and fossils typical of deserts and desert-steppe environments. Pedogenic carbonates, pollen and fossil assemblages of sparse forest-steppe and steppe are considered indicators of semi-arid environments. Because of the potential uncertainty of environmental significance for some mammalian fossils, only the most studied fauna and those having modern analogues are used for the compilation of maps while most of the fauna data are considered chronology references. Although some of the data are still, to some extent, of potential uncertainty in environmental significance, they would be statistically reliable for illustrating the climate patterns.

The complied maps for the ten different intervals are shown in Figs. 3 and 4. The numbers and types of data used in each map are given in the Supplementary Material (http://www.clim-past-discuss.net/4/535/2008/cpd-4-535-2008-supplement.pdf). Except some new insights discussed in the following sections, the yielded patterns are essentially consistent with the earlier results (Liu and Guo, 1997; Sun and Wang, 2005), and thus confirm their reliability.

2.1 Paleogene climate patterns

The Paleocene data are rather sparse probably due to tectonic changes and erosion. However, 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 clear. A further slight northwards retreat of this boundary is observed for the Oligocene while the basic environmental pattern remained zonal (Fig. 3c).

We further examine the Oligocene data by two groups according to their chronology assignments; one corresponding to the early and mid-Oligocene (Fig. 3d), and another to the late Oligocene (Fig. 3e). A sufficient number of data explicitly defines a zonal climate pattern for the early and mid-Oligocene while the pattern for the late Oligocene is hard to define because of the lack of data in southern China, probably due to tectonic movements and large-scale erosions.

These five maps, therefore, show that the 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, with a central latitudinal location similar to the present-day drylands in North African and North America (Fig. 1b). The aridity was obviously caused by the subtropical high pressure zone of the northern hemisphere as non evidence of mountain ranges exists for the Paleogene southern China. Thus, the zonal climate pattern is largely attributable to a planetary circulation system, as was already stated in earlier studies (Liu and Guo, 1997; Sun and Wang, 2005), rather than a monsoon-dominant regime. Consequently, the southern boundary of the dry belt would reflect the position of the paleo-ITCZ (inter-tropical convergence zone) in summer.

However, the broad dry zone and their northern boundary at higher latitudes have no modern analogues. These are likely explainable by two main reasons. First, the climate zones within each mapping interval would have experienced significant latitudinal oscillations following the 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 south to the subtropical high pressure zone had a continental origin, and would be able to broaden the zone with dry conditions.

The northwards 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 the marine δ^{18}O records (Zachos et al., 2001) (Fig. 5a). The Paleocene Earth is commonly considered ice-free and glaciations may have started on the Antarctica at ∼43 Ma ago, then expanded in the early Oligocene at ∼34 Ma (Miller et al., 1987; Zachos et al., 2001). Ice-volume during the early Oligocene glaciation, mainly on the Antarctica, may have reached to ∼70% of the present-day volume (Zachos et al., 1992). Although recent evidence of ice-rafting

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(Moran et al., 2006) revealed nearly synchronous bipolar cooling events during the Cenozoic, permanent ice-sheets 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 imbalance between the two hemispheres. The development of the Antarctic ice in the Eocene and early Oligocene (Zachos et al., 2001) would have forced the global climate zones to migrate northwards, providing a likely explanation to the overall northwards migration of the dry belt in Asia from the Paleocene to the Oligocene (Fig. 3). These hypothetic interpretations would need to be tested by climate models.

This explanation is consistent with 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; Ruddiman, 2006) resulted from the penetration of the southern hemispheric trade winds to the northern hemisphere, primarily driven by the seasonal oscillations of planetary circulations (Chase et al., 2003). 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 ~4° N in winter (Lezine et al., 2007). The increased inter-hemispheric imbalance from the Eocene to the Oligocene would favor the northwards penetration of the ITCZ, and consequently, would lead to the observed northwards migration of subtropical dry belt.

In summary, the climate in Asia in the Paleogene was dominated by a zonal pattern attributable to the planetary circulation system. Despite of a possible monsoon regime in the tropical regions, its intensity was not strengthened enough to dominate the climate of the Asian continent. This also implies that the classical theory of monsoon, which emphasizes the predominant role of land-sea distribution in a broad sense (Halley, 1986), could probably only explain the essence of the tropical monsoons, but not fully applicable to the monsoon-dominant climate in Asia.

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2.2 Neogene climate pattern

The Miocene climate patterns (Fig. 4) radically differ from the Paleogene ones (Fig. 3). Indicators of arid conditions mainly distribute in northwest China within an area similar to the present-day drylands. The middle reaches of the Yellow River were dominated by semi-arid conditions. In contrast, indicators of humid conditions widely spread in the southwestern and southeastern parts. This spatial pattern is highly similar to the present-day climate pattern in China (Fig. 1a).

Earlier studies raised two important Miocene boundaries of climate changes in Asia, one is the early Miocene (Shi et al., 1999; Guo et al., 2002) and another is the late Miocene (Quade et al., 1989; Kroon et al., 1991; An et al., 2001). To more accurately examine the spatial patterns of different time intervals within the Miocene, the Miocene data are separated into the early, middle and late Miocene parts according to their chronological assignments (Fig. 4b–d). Data for each interval are abundant enough to define the climate pattern. They explicitly show the existence of a pattern since the early Miocene, similar to the modern one (Fig. 1a). The Pliocene pattern (Fig. 4e) is essentially similar to the Miocene one, but the most northeastern part is marked by semi-arid conditions, hence a slightly humidification compared to the late Miocene.

The humidification in the southeast and southwest country since the early Miocene firmly indicates the strong influence of the southeast and southwest summer monsoons. It also supports a notion of synchronous onset/strengthening of the two summer monsoons instead of largely diachronous developments. The Neogene location of drylands at much higher latitudes indicates that the aridity was no longer caused by the subtropical high pressure zone. Instead, the similar location to the present-day drylands undoubtedly indicates typical inland-type deserts.

In summary, the spatial distributions of the geological indicators clearly revealed that (1) the zonal climate pattern linked to the planetary circulation system was transformed to a monsoon-dominant pattern similar to the present-day one; (2) the low-latitude drylands related to the subtropical high pressure zone were disappeared while inland-

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type deserts at higher latitudes were formed; and (3) the humidification in southwest and southeast China, the appearance of the northwest drylands were closely coupled, suggesting a joint change of circulation and aridity, and hence, dynamic linkages; and (4) these changes occurred at least in 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 influences of the summer monsoons.

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

Eolian dust deposits widely spread in the middle reaches of the Yellow River, i.e. 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, the Himalayan-Tibetan Plateau to the southwest (Figs. 1a and 2). Modern observations indicate that eolian dust is mainly derived from the inland deserts and transported by the Asian winter monsoon (Liu, 1985) while the rainfall in the region is mainly brought by the southeast summer monsoon (An et al., 1990; Liu and Ding, 1998) and to a lesser extent, by the southwest summer monsoon (Chen et al., 1991).

Up 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, also referred to as Red-Clay (2.6–8.0 Ma) of eolian origin 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 are attested by (1) the presence of several hundred of paleosols and the interbedded loess layers that were also significantly affected by pedogenesis, indicative of subaerial environments (Guo et al., 2002); (2) the constant fine silty texture throughout the ~16-Ma sequence with the maximum grain-size mostly $<120\,\mu$m (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, the lack of aquatic and amphibian species throughout the sequences (Li et al., 2006a, b); and (6) rock magnetic properties typical of eolian deposits (Hao et al., 2008). Spatial investigations showed that the Miocene eolian deposits widely spread mantling the highlands within a broad region of the western Loess Plateau (Yuan et al., 2007).

Up to date, we have dated five Miocene loess-soil sections (Fig. 2) using magnetostratigraphic method. 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 with 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 showed that the stratigraphy and magnetic susceptibility time-series are spatially correlative (Guo et al., 2002; Liu et al., 2005; Hao and Guo, 2007). This is also demonstrated by the correlativity between ML-V and QA-I (Figs. 6 and 8),

~75 km in distance. Such a high spatial correlativity in stratigraphy and measured proxies is characteristic of eolian deposits and also attests the relative continuity of these sequences.

(2) The spatial coverage of these sites, as well as our geomorphic investigations (Yuan et al., 2007), revealed a widespread nature of Miocene eolian deposition in northern China, and thus confirm their significance on large regional paleoclimate. Miocene eolian dust input has also been identified as the main source of fine-grained sediments in some fluvial-lacustrine basins in the region (Garzione 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., 2007b) suggesting that the southern boundary of the Miocene eolian deposition might have reached as far as to the region south to 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, indicating 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 distribute under variable circumstances (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*, but their distribution is spatially restricted within the periglacial environments (Liu, 1985). Loess deposits usually cover terraces of large rivers, mostly due to dust deflation from the 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 the dust material was mostly derived from continental shelves which exposed to wind erosion during the times of low sea-level (Zhao, 1996). Some loess deposits may result from mixed 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, (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 covers (Tsoar and Pye, 1987; Pye, 1995), and from this sense, the desertic areas, owing to aridity, low temperature or to other causes. Although tectonic-active regions have commonly a greater availability of fine-grained material, a dense vegetation cover can prevent the fine materials from eolian deflation. A convincing example is the humid Yunnan region in southwest China where tectonics and erosions are intense while loess deposition is essentially unavailable. From this sense, loess can be regarded as a direct evidence of poor-vegetated sources more or less extended. The remarkably thick and widespread loess of China and Central Asia results from an unusual combination of persisted conditions (Pye, 1995), including the presence of extended drylands as dust sources.

The Miocene eolian deposits in northern China are undoubtedly *hot loess* because of their wide distribution and near 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). SEM observations showed that a majority of quartz grains are finer than 100 μm in diameter, mostly ranging from 10 to 30 μm. Most of them 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 disintegration 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 sharps were not abraded.

The elemental geochemistry signatures of the Miocene loess (Liang et al., 2006) are also highly comparable to the average composition of the Upper Continental Crust

(UCC) (Taylor et al., 1983), 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 suggest that the materials were derived from rather 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 deposits is timely consistent with 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 atmospheric circulations.

(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 of the drastic changes of 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 indicated that the Quaternary loess deposits in northern China were mainly transported by the northwest winds, i.e. the Asian winter monsoon (Liu, 1985; An et al., 1990; Ding et al., 1995; Liu and Ding, 1998). This has been confirmed by the spatial variations of eolian grain-size in the Loess Plateau region, coarser in the northwestern part and 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 of the winter monsoon on dust transport since ~8 Ma ago.

The onset of eolian dust deposition by 22 Ma ago attests 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). These imply that the dust-carrying winds must have a northern origin where dust sources were available. This is consistent with the modern trajectory of the Asian winter monsoon.

(2) Although more sophisticated geochemical approaches might be able to discriminate the relative contributions of different deserts for 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 are conducted on samples from QA-I and ML-V (Gaojiazhang site), ~75 km south to QA-I (Fig. 2), to examine the grain-size gradients between the two site. The results reveal similar trends of grain-size variations along the sections, but a significantly finer texture at the southern ML-V site (Fig. 8). The average median grain-size at ML-V is ~1 μm finer than for QA-I for the period from 15 to 11.2 Ma. These new data have three implications.

(1) Similar to the magnetic susceptibility timeseries (Liu et al., 2005; Hao and Guo, 2007), the grain-size variations in the Miocene loess-soil sequences are also spatially correlative, as is characteristic of eolian deposits.

(2) The grain-size gradients indicate a location of the source areas north to the Loess Plateau, and thus attest the inland- type deserts as dust sources.

(3) They firmly evidence a northerly dust-carrying circulation, i.e. 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, we believe that the Siberian High would have also formed by 22 Ma ago.

Unfortunately, available sections with the early Miocene portions are not ideally located for examining the grain-szie 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. Thus, the numerous paleosols in the Miocene eolian sequences also imply the existence of other circulation branches able to bring moisture from the oceans because soil formation requires a substantial amount of rainfall. Consequently, the alternations between loess and soil layers indicate cyclical occurrences of dry and humid conditions in northern China within the orbital scale (Guo et al., 2002). These evidence the existence of at least two branches of circulations, one brought eolian dust and another brought moisture. Moreover, the dust-carrying winds and moist-carrying winds must be timely alternative and significantly different in their directions. Such a circulation configuration rightly defines a monsoon climate regime.

To further characterize the circulation characteristics, properties of the early Miocene paleosols are studied here. Micromorphological 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 amount, up to ~30%, is approximately comparable to those of the modern Luvisols in the south of the Yangtze River where annual rainfall is ~1000 mm (Zhang et al., 1999). Moreover, a large proportion of the clay illuvial features are in the form of intercalations within the groundmass (Fig. 7d and e). Such kind of illuvial features, commonly described as vertic property, resulted from alternative humidifications and shrinkages of soil profiles (Hussein and Adey, 1998; Cao and He, 1999), are typical of soils under climates with contrast seasons (Cao and He, 1999), suggesting 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 S5-1 soil (~0.5 Ma) in the Quaternary loess of which the clay illuvial features amount to ~10% in the southern-most Loess Plateau (Guo et al., 1998) where climate represents the most humid in the region. These indicate 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), the dominant moisture must have low-latitude origins brought by the summer monsoons. In view of the rather dry conditions in northwest China shown by the climate patterns (Fig. 4), the northern hemispheric westerlies were unlikely to have a significant moisture contribution, probably because of its extremely long continental trajectory from the moisture sources.

Under a climate regime without seasonally alternative circulations, a soil largely represents a sedimentary hiatus (Fedoroff and Goldberg, 1982; Cremaschi et al., 1990), as is the case for most of the loess-soil sequences in the non-monsoon regions. In these regions, soil developed on the parent loess deposited during a dry-cold period, such as the glacial time prior to the soil-forming interglacial period while dust deposition was negligible during the soil development (Fedoroff and Goldberg, 1982; Cremaschi et al., 1990). In contrast, paleosols in the loess-soil sequences under a monsoonal climate regime have radically different features resulted from the interactions between summer and winter monsoons. In summer, the monsoonal rainfall associated with the high temperature favors pedogenesis while eolian dust continues to add onto the soil surface in winter and early spring although the intensity is significantly lower than for typical loess deposition periods (Guo et al., 1991, 1993). Thus, dust deposition and soil-formation under a monsoonal climate regime are competing processes at all time and the presence of a soil simply 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 monsoonal climate regime.

Accretionary soils are characterized by a series of specific features (Guo et al., 1991, 1993), but three of them allow a quick discrimination from non-accretionary soils. Firstly, 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 comparing the grain-size of the quartz fraction that is highly resistant to

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weathering, and hence independent of any effect of pedogenesis. The quartz fraction of an accretionary soil has finer grain-size than for the underlying loess while that of a non-accretionary soil has similar quartz grain-size to its parent loess. Secondly, because of the differences of dust grain-size between soil-forming and loess deposition periods, dust composition may also be different as can be determined using some stable elements resistant to post-depositional pedogenesis. Thirdly, accretionary soils usually have highest chemical weathering intensity at the middle profile 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 lines of analyses were conducted. Firstly, 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 on the basis of the underlying loess. This is also confirmed by the grain-size analyses on the quartz fraction (Fig. 9a). Secondly, 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 at the mid-profiles (Fig. 9c), followed by decreased 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 explicitly indicate the existence of a typical monsoon climate in northern China. An open question is the relative contribution of the southeast and southwest summer monsoons to the moisture leading to the formation of the Luvisols in the Loess Plateau. Clarification of this question would need several distant Miocene loess-soil sections suitably located, which are not yet available. Although modern moisture in the Loess Plateau is mostly related to the East Asian summer monsoon due to the elevated Tibetan Plateau, a greater contribution from the southwest summer monsoon would be possible for Miocene times when the Tibetan Plateau was probably not as high as it is today.

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 accurate age of this major change remains an open question, because the data used for spatial mapping are of coarse resolution and low chronology accuracy while the basal age of a loess section is not only dependent of the availability of eolian dust deposition but also the timing of the substratum formation linked to tectonics (Guo, 2003; Hao and Guo, 2004). Also, this climate reorganization represents a sudden change or stepwise changes need to be further addressed.

During the past five years, we attempted to investigate potential older loess deposits throughout the Loess Plateau, but not yet found. However, available records from the surrounding regions may provide some insights to this issue. A pollen record developed from the nearby Linxia fluvial-lacustrine basin (Fig. 5b) showed a drastic increase in the contents of tree pollens near ~22 Ma (Shi et al., 1999). Because the site is located within the planetary-type dry belt during the Oligocene (Fig. 3) and presently within the monsoon zone, the vegetation shift would evidence a humidification of the region, and thus an enhanced influence of the summer monsoon (Shi et al., 1999). Similar trends were shown by the decreased contents of xerophytes at ~23 Ma in a core from the Qaidam basin (Wang et al., 1999). In a carbon isotope record of terrestrial black carbon reflective of vegetation changes in South China, earliest high δ^{13}C peaks appeared ~20 Ma ago and was interpreted as an indication 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) showed overall low rates of dust accumulation in the Paleogene and roughly doubled rates since ~25 Ma (Fig. 5c). This transition, also associated with mineralogy and chemistry changes, was interpreted as representing the time when

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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 approach showed a drastic increase in the delivery of Asian dust material since ~20 Ma (Fig. 5c) at the ODP site 1215 from the central Pacific (Ziegler et al., 2007), and 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 would have occurred between 22 and 25 Ma ago, and most of them tend to support an age close to 22 Ma. From these insights, we speculate that discovery of loess pieces a few million years older than 22 Ma may be possible in northern China, but their eolian properties must be fully examined to clarify this question.

5 Potential causes of the climate reorganization

The climate in Asia therefore experienced a transition from a zonal climate pattern to a monsoon-dominant one near the Oligocene/Miocene boundary, by 22 Ma ago. This major reorganization was marked by the joint onset/strengthening of the Asian summer and winter monsoon circulations and inland-type deserts. After this transition, the role of the Subtropical High was largely weakened while that of the Siberian High was reinforced. The similarity of climate patterns between the Neogene and Quaternary, the continuous loess deposition in a similar region over the past 22 Ma indicate that the monsoon-dominant 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 in broad sense to the monsoon phenomena (Halley, 1986). However, they are unable to explain the onset of the monsoon-dominant regime by the early Miocene as land-sea thermal contrast persisted during the Paleogene. The seasonal oscillations of planetary circulations (Flöhn, 1956), such as the inter-tropical convergence zone (ITCZ), may explain the essence of the monsoons in the tropical regions, such as the African monsoon, but are not fully applicable to the Asian monsoons as the northern fronts of the Asian summer monsoons are presently able to penetrate into a position far deeper north to the ITCZ, and certainly farer in the Miocene in view of the much stronger soils discussed above. 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 δ^{18}O records (Miller et al., 1998; Zachos et al., 2001), are not timely correlative to these major changes in Asia (Fig. 5). Consequently, other factors must have played a dominant role.

Climate models 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. Summer monsoon could be triggered under the solar forcing when the Tibetan Plateau reached to its half elevation of the present-day (Prell and Kutzbach, 1992). This threshold of half-elevation seems to also be applicable to the winter monsoon circulation (Liu and Yin, 2002). Further continuous uplift and expansion are sufficient to alter significantly the thermally forced circulation and establish strong 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 more significant effect on the winter monsoon than for the summer monsoon (Liu and Yin, 2002).

An alternative view invokes the impacts of the Paratethys retreat (Ramstein et al., 1997; Fluteau et al., 1999) that intensifies the South Asian monsoon and shifted the central Asian climate from temperate to continental conditions, and thus would have played a role as important as the Tibetan uplift in driving the Asian monsoon. The shrinkage of this epicontinental sea would have played a major role in large-scale atmospheric changes although the Paratethys shrinkage and plateau uplift were the main causes of monsoon changes (Fluteau et al., 1999).

Recently, we attempted to discriminate the effects of these two main factors, and to examine the potential roles of other tectonic changes on the formation of the monsoon dominant-climate in Asia (Zhang et al., 2006, 2007a, c) using a nine-level AGCM. A series of numerical experiments yielded the following main insights.

(1) A progressively elevated Tibetan Plateau strengthens the Asian monsoons, increases the seasonal contrast of precipitation in the monsoon zone, and enhances the aridity in northwestern China. These confirm the earlier conclusions of the peer studies that uplift plays an important role in the formation and development of the Asian monsoon climate. However, our experiments also revealed an interesting detail that a monsoon-dominant climate and inland deserts can be generated by a 3000-m elevated Tibetan Plateau under most of the Paratethys conditions except one corresponding to the scenario that the Paratethys Sea is connected with the Arctic Ocean. These imply that once the Paratethys is disconnected with the Arctic Ocean, a sufficiently elevated Tibetan Plateau (~3000 m) alone is able to cause the formation of monsoon-dominant climate and inland deserts in Asia whatever the size of the Paratethys. The effects of the plateau are, however, largely weakened when the Paratethys is still connected with the Arctic Ocean.

(2) Shrinkage of the Paratethys Sea increases the precipitation in the monsoon zone and decreases the rainfall in northwest China. The results reinforce the earlier conclusion (Ramstein et al., 1997; Fluteau et al., 1999), and also provide more details that monsoon climate and inland deserts can be generated when the Paratethys retreated to the Turan Plain whatever the elevation of the Tibetan Plateau (1000–3000 m).

(3) In addition to the Tibetan uplift and Paratethys shrinkage, the expansion of South China Sea leads to enhanced humidity contrast between southern and northern China, and hence would have also played a significant role in the formation of monsoon-dominant climate in Asia. The first two factors favor the dynamic conditions while the expansion of South China Sea favors the water vapor condition.

Climate models therefore consistently indicate the major roles of Tibetan uplift and Paratethys shrinkage in the formation of the monsoon-dominant climate and inland deserts in Asia, with the expansion of South China Sea having probably helped this transition.

As for the geological histories of the three invoked tectonic factors, there is a general consensus about the spreading of South China Sea, which initiated during the Oligocene and reached to a stable or end spreading state in the early Miocene (Briais et al., 1993; Li et al., 2005, 2006c). This is in broad consistence with the onset of the monsoon-dominant climate. Also, this factor would have played a role to sharpen the monsoon climate pattern, rather than a role of trigger (Zhang et al., 2007c). Consequently, Tibetan uplift and Paratethys shrinkage remain to be the two main factors to consider (Zhang et al., 2007a).

The collision of India and Asia in South Tibet may have initiated at ~55 or 34 Ma ago (Aitchison et al., 2007) while the subsequent uplift histories of Tibetan region remain highly controversial. Main views about major uplifts focused on several boundaries, including the Eocene and Oligocene at ~45–30 Ma (Chung et al., 1998; Guo et al., 2006; Rowley and Currie, 2006), late Oligocene or early Miocene at ~26–18 Ma (Harrison et al., 1992; DeCelles et al., 2007), mid-Miocene around 14 Ma (Turner et al., 1993; Coleman and Hodges, 1995; Spicer et al., 2003), late Miocene around 8 Ma (Harrison et al., 1992; Valdiya, 1999; Garzione et al., 2000; Clark et al., 2005; Molnar, 2005) and Plio-Pleistocene after 3–4 Ma (Li and Fang, 1999; Zheng et al., 2000). Because the Himalayan-Tibetan Plateau has undoubtedly a strong barrier effect on the moisture transport to the Asian interior, we believe that at least the southern margin of the plateau would have been sufficiently elevated by 22 Ma ago to act as moisture barrier. This is strongly supported by the development of the 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 the shrinkage during the Oligocene and Miocene (Dercourt et al., 1993; Pavelic et al., 2001; Akhmet'ev and Beniamovski, 2006), with probably a large extent during the Oligocene and a gradual shrinkage during the Miocene (Dercourt et al., 1993). These are broadly consistent in time with the suggested chronological ranges of Tibetan uplift and the onsets of monsoon dominant climate and inland deserts in Asia.

Although these contentions and uncertainties left the real causes unresolved, the fact that typical monsoon-dominant climate and inland deserts were already formed by 22 Ma ago provide an environmental clue for further evaluations. Because either Tibetan uplift or Paratethys retreat were linked with plate tectonics of the region, there is a strong possibility that these two factors evolved more or less synchronously. Consequently, a most realistic picture would be the coactions of Tibetan uplift and Paratethys shrinkage that triggered the major climate reorganization in Asia. Their roles would not be mutually exclusive. Although the evolution histories of these two factors are highly contentious or uncertain and the available dating of uplift-related tectonic events in the surrounding regions have a large range, from at least 45 Ma ago to the Quaternary, a large collection of data demonstrated a peak range of 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). These data suggest that the tectonics conditions had evolved to a threshold by ∼22 Ma ago able to cause the climate reorganization. Paleoaltimetrical and tectonic approaches are crucial towards a more advanced discrimination of their impacts.

6 Conclusions

In regards to the onset of monsoon-dominant climate and inland deserts in Asia that are among the most prominent changes of the Cenozoic climate system, we have examined the spatial distribution of environmental indicators at ten time boundaries, the properties of the Miocene loess-soil sequences in northern China based on a significant amount of new data. The results led to the following conclusions.

(1) Our independent collection of geobiological data and map compilation confirm the earlier results that the zonal climate patterns during the Paleogene was transformed into a monsoon-dominant pattern similar to the present-day one. These are characterized by the humidification in southwest and southeast China, disappearance of the low-latitude aridity related to the subtropical high pressure zone and emergence of inland deserts at much higher latitudes. Our more detailed mapping within the Oligocene and Miocene indicates that the reorganization was achieved by the early Miocene, which is timely consistent with the onset of widespread loess deposition in northern China. Although the basal ages of loess sections do not necessarily provide the accurate age of this drastic climate transition, other terrestrial and marine records tend to suggest an age near the Oligocene-Miocene boundary, closer to 22 Ma.

(2) The dated Miocene loess-soil sections in northern China show spatially correlative stratigraphy and climate proxies, as is similar to younger eolian deposits in China. The near-complete coverage of the Neogene and Pleistocene eolian deposits attest the existence of inlands deserts in the Asian interior as dust sources which have been constantly maintained in the past 22 Ma despite of the drastic changes of global climate. The spatial gradients of eolian grain-size indicate a location of the source areas north to the Loess Plateau, and thus attest that the inland-deserts were dust sources. They also firmly evidence a northerly dust-carrying circulation, i.e. the Asian winter monsoon.

(3) The well-developed Luvisols since the early Miocene evidence the existence of circulations of oceanic origin that brought moisture to northern China, i.e. the Asian

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summer monsoons. Their intensity was significantly stronger than for the Quaternary. The accretionary properties of the soils attest the presence of two seasonally alternative circulations, one from the ocean as moisture carrier and another from the northern deserts as dust carrier. These features rightly define a monsoonal climate regime.

(4) This major reorganization thus represents a transformation of climate regime from a planetary circulation system to a monsoon-dominant system, characterized by a joint change of circulations and aridity. Posterior to this transition, the effects of the subtropical high pressure zone, that should generate dry conditions at low-latitudes, were largely weakened during the Neogene due to the enhanced influence of summer monsoons. In contrast, those of the 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. Our recent numerical experiments reconfirm the potential roles of Tibetan uplift and Paratethys shrinkage with probably the help of the spreading of South China Sea. The loess record provides a vital insight that these tectonic scenarios had evolved to a threshold by the early Miocene to cause this major climate change in Asia.

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References

Abe, M., Kitoh, A., and Yasunari, T.: An evolution of the Asian summer monsoon associated with mountain uplift - Simulation with the MRI atmosphere-ocean coupled GCM, J. Meteorol. Soc. Jpn., 81, 909–933, 2003.

Aitchison, J. C., Ali, J. R., and Davis, A. M.: When and where did India and Asia collide?, J. Geophys. Res., 112, B05426, doi:10.1029/2006JB004706, 2007.

Akhmet'ev, M. A., Aleksandrova, G. N., Amon, E. O., Beniamovskii, V. N., Bugrova, E. M., Vasil'eva, O. N., Glezer, Z. I., Zhelezko, V. I., Zaporozhets, N. I., Kozlova, G. E., Nikolaeva, I.

cc BY

A., Oreshkina, T. V., Panova, L. A., Radionova, E. P., Strel'nikova, N. I., and Yakovleva, A. I.: Biostratigraphy of the marine Paleogene in the West Siberian plate, Stratigr. Geol. Correl., 9, 132–158, 2001.

Akhmet'ev, M. and Beniamovski, V.: The Paleocene and Eocene in the Russian Part of West Eurasia, Stratigr. Geol. Correl., 14, 49–72, 2006.

An, Z. S., Liu, T. S., Lu, Y. C., Porter, S. C., Kukla, G., Wu, X. H., and Hua, Y.: The long-term paleomonsoon variation recorded by the loess-paleosol sequence in Central China, Quatern. Int., 7, 91–96, 1990.

An, Z. S., Kutzbach, J. E., Prell, W. L., and Porter, S. C.: Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan plateau since Late Miocene times, Nature, 411, 62–66, 2001.

Berger, G. W.: Luminescence chronology of late Pleistocene loess-paleosol and tephra sequences near Fairbanks, Alaska, Quaternary Res., 60, 70–83, 2003.

Briais, A., Patriat, P., and Tapponnier, P.: Updated interpretation of magnetic-anomalies and Ssea-floor spreading stages in the South China Sea-implications for the Tertiary tectonics of Southeast-Asia, J. Geophys. Res., 98, 6299–6328, 1993.

Cande, S. C. and Kent, D. V.: Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic, J. Geophys. Res., 100, 6093–6095, 1995.

Cao, S. G. and He, Y. R.: Vertisols, in: Chinese Soil Taxonomy, edited by: Gong, Z. T., Science Press, Beijing, 261–323, 1999.

Chase, T. N., Knaff, J. A., Pielke, R. A., and Kalnay, E.: Changes in global monsoon circulations since 1950, Nat. Hazards, 29, 229–254, 2003.

Chen, J., An, Z. S., Liu, L. W., Ji, J. F., Yang, J. D., and Chen, Y.: Variations in chemical compositions of the eolian dust in Chinese Loess Plateau over the past 2.5 Ma and chemical weathering in the Asian inland, Sci. China Ser. D, 44, 403–413, 2001.

Chen, L. X., Zhu, Q. G., Luo, H. B., He, J. H., Dong, M., and Feng, Z. Q. (Eds.): Monsoons Over East Asia, Meteorol. Publ., Beijing, 362 pp., 1991 (in Chinese).

China Geological Survery: Chinese 1,500,000 Geological Map Database 1.0, 2001.

Chinese Stratum Thesaurus Editorial Board: Tertiary Stratum Thesaurus, 1999.

Chung, S. L., Hua, C., Lee, T. Y., Zhang, Y. Q., Xie, Y. W., Li, X. H., Wang, K. L., and Wang, P. L.: Dischronous uplift of the Tibetan Plateau starting 40 Myr ago, Nature, 394, 769–773, 1998.

Clark, M. K., House, M. A., Royden, L. H., Whipple, K. X., Burchfiel, B. C., Zhang, X. B., and

cc BY

Tang, W.: Late Cenozoic uplift of southeastern Tibet, Geology, 33, 525–528, 2005.

Clift, P. D.: Controls on the erosion of Cenozoic Asia and the flux of clastic sediment to the ocean, Earth Planet. Sc. Lett., 241, 571–580, 2006.

Coleman, M. and Hodges, K.: Evidence for Tibetan plateau uplift before 14 Myr ago from a new minimum age for east-west extension, Nature, 374, 49–52, 1995.

Corrigan, J. D. and Crowley, K. D.: Unroofing of the Himalayas-a view from apatite fission-track analysis of Bengal Fan sediments, Geophys. Res. Lett., 19, 2345–2348, 1992.

Cremaschi, M., Fedoroff, N., Guerreschi, A., Huxtable, J., Colombi, N., Castelletti, L., and Maspero, A.: Sedimentary and pedological processes in the Upper Pleistocene loess of northern Italy, The Bagaggera sequence, Quatern. Int., 5, 23–38, 1990.

DeCelles, P. G., Quade, J., Kapp, P., Fan, M. J., Dettman, D. L., and Ding, L.: High and dry in central Tibet during the Late Oligocene, Earth Planet. Sc. Lett., 253, 389–401, 2007.

Dercourt, J., Ricou, L. E., and Vrielinck, B. (Eds.): Atlas Tethys Paleoenvironmental Maps, Gauthier-Villars, Paris, 307 pp., 1993.

Ding, G. Y., Chen, J., Tian, Q. J., Shen, X. H., Xing, C. Q., and Wei, K. B.: Active faults and magnitudes of left-lateral displacement along the northern margin of the Tibetan Plateau, Tectonophysics, 380, 243–260, 2004.

Ding, L. and Zhong, D. L.: Metamorphic characteristics and geotectonic implications of the high-pressure granulites from Namjagbarwa, eastern Tibet, Sci. China Ser. D, 42, 491–505, 1999.

Ding, Z. L., Yu, Z. W., Rutter, N. W., and Liu, T. S.: Towards an Orbital Time-Scale for Chinese Loess Deposits, Quaternary Sci. Rev., 13, 39–70, 1994.

Ding, Z. L., Liu, T. S., Rutter, N. W., Yu, Z. W., Guo, Z. T., and Zhu, R. X.: Ice-Volume Forcing of East Asian Winter Monsoon Variations in the Past 800,000 Years, Quaternary Res., 44, 149–159, 1995.

Ding, Z. L., Sun, J. M., Liu, T. S., Zhu, R. X., Yang, S. L., and Guo, B.: Wind-blown origin of the Pliocene red clay formation in the central Loess Plateau, China, Earth Planet. Sc. Lett., 161, 135–143, 1998.

Duchaufour, P. H.: Pdologie, Tome I: Pdogense et classification, Masson-Paris-New York-Barcelone-Milan, 477 pp., 1983.

FAO-Unesco: Soil Map of the World, 1:5 000 000 Vol. I, Legend, UNESCO, Paris, 20–32, 1974.

Fedoroff, N. and Goldberg, P.: Comparative micromorphology of two late Pleistocene paleosols (in the Paris Basin), Catena, 9, 227–251, 1982.

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Flöhn, H.: Der indische sommermonsun als Glied der planetarischen Zirkulation der atmosphere, Bec. Des D. wd. Bd., 4, 22, 1956.

Fluteau, F., Ramstein, G., and Besse, J.: Simulating the evolution of the Asian and African monsoons during the past 30 Myr using an atmospheric general circulation model, J. Geophys. Res., 104, 11 995–12 018, 1999.

Fu, C. B.: Potential impacts of human-induced land cover change on East Asia monsoon, Global Planet. Change, 37, 219–229, 2003.

Garzione, C. N., Dettman, D. L., Quade, J., DeCelles, P. G., and Butler, R. F.: High times on the Tibetan Plateau: Paleoelevation of the Thakkhola graben, Nepal, Geology, 28, 339–342, 2000.

Garzione, C. N., Ikari, M. J., and Basu, A. R.: Source of Oligocene to Pliocene sedimentary rocks in the Linxia basin in northeastern Tibet from Nd isotopes: Implications for tectonic forcing of climate, Geol. Soc. Am. Bull., 117, 1156–1166, 2005.

Guo, Z. F., Wilson, M., Liu, J. Q., and Mao, Q.: Post-collisional, potassic and ultrapotassic magmatism of the northern Tibetan Plateau: Constraints on characteristics of the mantle source, geodynamic setting and uplift mechanisms, J. Petrol., 47, 1177–1220, 2006.

Guo, Z. T., Fedoroff, N., An, Z. S., and Liu, T. S.: Interglacial dustfall and origin of iron oxides hydroxides in the paleosols of the Xifeng loess section, China, Sci. Geol. Sinica, 2, 91–100, 1993.

Guo, Z. T., Liu, T. S., Guiot, J., Wu, N. Q., Lu, H. Y., Han, J. M., Liu, J. Q., and Gu, Z. Y.: High frequency pulses of East Asian monsoon climate in the last two glaciations: link with the North Atlantic, Clim. Dynam., 12, 701–709, 1996.

Guo, Z. T., Fedoroff, N., and An, Z. S.: Genetic types of the Holocene soil and the Pleistocene palaeosols in the Xifeng loess section in central China, in: Loess, Environment and Global Change, edited by: Liu, T. S., Ding, Z. L., and Guo, Z. T., Science Press, Beijing, 93–111, 1991.

Guo, Z. T., Liu, T. S., Fedoroff, N., Wei, L. Y., Ding, Z. L., Wu, N. Q., Lu, H. Y., Jiang, W. Y., and An, Z. S.: Climate extremes in loess of China coupled with the strength of deep-water formation in the North Atlantic, Global Planet. Change, 18, 113–128, 1998.

Guo, Z. T., Biscaye, P., Wei, L. Y., Chen, X. H., Peng, S. Z., and Liu, T. S.: Summer monsoon variations over the last 1.2 Ma from the weathering of loess-soil sequences in China, Geophys. Res. Lett., 27, 1751–1754, 2000.

Guo, Z. T., Ruddiman, W. F., Hao, Q. Z., Wu, H. B., Qiao, Y. S., Zhu, R. X., Peng, S. Z., Wei,

J. J., Yuan, B. Y., and Liu, T. S.: Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China, Nature, 416, 159–163, 2002.

Guo, Z. T.: Uplift of the Tibetan Plateau and the aeolian deposits in China (in Chinese), in: Formation of Tibetan Plateau, Environment and Development, edited by: Zheng, D. and Yao, T. D., Hebei Scientific and Technical Press, Shijiazhuang, 70–79, 2003.

Guo, Z. T., Peng, S. Z., Hao, Q. Z., Biscaye, P., An, Z. S., and Liu, T. S.: Late Miocene-Pliocene development of Asian aridification as recorded in the Red-Earth Formation in northern China, Global Planet. Change, 41, 135–145, 2004.

Halley, E.: An historical account of the trade winds and monsoons observable in the seas between and near the tropics with an attempt to assign the physical cause of the said wind, Philos. T. R. Soc. Lond., 16, 153–168, 1986.

Hao, Q. Z. and Guo, Z. T.: Magnetostratigraphy of a late Miocene-Pliocene loess-soil sequence in the western Loess Plateau in China, Geophys. Res. Lett., 31, L09209, doi:10.1029/2003GL019392, 2004.

Hao, Q. Z. and Guo, Z. T.: Magnetostratigraphy of an early-middle Miocene loess-soil sequence in the western Loess Plateau of China, Geophys. Res. Lett., 34, L18305, doi:10.1029/2007GL031162, 2007.

Hao, Q. Z., Oldfield, F., Bloemendal, J., and Guo, Z. T.: The magnetic properties of loess and paleosol samples from the Chinese Loess Plateau spanning the last 22 million years, Palaeogeogr. Palaeocl. Palaeoecol., 260, 389–404, 2008.

Harrison, T. M., Copeland, P., Kidd, W. S. F., and Yin, A.: Raising Tibet, Science, 255, 1663–1670, 1992.

Harrison, T. M., Copeland, P., Hall, S. A., Quade, J., Burner, S., Ojha, T. P., and Kidd, W. S. F.: Isotopic Preservation of Himalayan Tibetan Uplift, Denudation, and Climatic Histories of two Molasse Deposits, Geology, 101, 157–175, 1993.

Hodell, D. A. and Woodruff, F.: Variations in the Strontium Isotopic Ratio of Seawater during the Miocene-Stratigraphic and Geochemical Implications, Paleoceanography, 9, 405–426, 1994.

Houghton, J. T.: The Global Climate, Cambridge University Press, Cambridge and New York, 239 pp., 1984.

Hovan, S. A. and Rea, D. K.: Post-Eocene record of eolian deposition at sites 752,754, and 756, Eastern Indian Ocean, Proc. ODP Sci. Res, 121, 219–228, 1991.

Hussein, J. and Adey, M. A.: Changes in microstructure, voids and b-fabric of surface samples

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of a Vertisol caused by wet/dry cycles, Geoderma, 85, 63–82, 1998.

Jahn, B. M., Gallet, S., and Han, J. M.: Geochemistry of the Xining, Xifeng and Jixian sections, Loess Plateau of China: eolian dust provenance and paleosol evolution during the last 140 ka, Chem. Geol., 178, 71–94, 2001.

Jia, G. D., Peng, P. A., Zhao, Q. H., and Jian, Z. M.: Changes in terrestrial ecosystem since 30 Ma in East Asia: Stable isotope evidence from black carbon in the South China Sea, Geology, 31, 1093–1096, 2003.

Jiang, F. C., Wang, S. B., Zhao, Z. Z., and Fu, J. L.: Mangshan loess in Central China and the paleomonsoon variations since the last interglaciation, Acta Geol. Sin-Engl., 78, 813–819, 2004.

Johnson, W. C., Willey, K. L., Mason, J. A., and May, D. W.: Stratigraphy and environmental reconstruction at the middle Wisconsinan Gilman Canyon Formation type locality, Buzzard's Roost, southwestern Nebraska, USA, Quaternary Res., 67, 474–486, 2007.

Kemp, R. A.: Pedogenic modification of loess: significance for palaeoclimatic reconstructions, Earth-Sci. Rev., 54, 145–156, 2001.

Kroon, D., Steens, T., and Troelstra, S. R.: Onset of monsoonal related upwelling in the western Arabian Sea as revealed by planktonic foraminifers, Proc. ODP Sci. Res., 117, 257–263, 1991.

Kukla, G., An, Z. S., Melice, J. L., Gavin, J., and Xiao, J. L.: Magnetic-Susceptibility Record of Chinese Loess, T. Roy. Soc. Edin-Earth., 81, 263–288, 1990.

Kutzbach, J. E., Guetter, P. J., Ruddiman, W. F., and Prell, W. L.: Sensitivity of climate to late Cenozoic uplift in Southern Asia and the American West: Numerical experiments, J. Geophys. Res., 94, 18 393–18 407, 1989.

Kutzbach, J. E., Prell, W. L., and Ruddiman, W. F.: Sensitivity of Eurasian climate to surface uplift of the Tibetan Plateau, J. Geol., 101, 177–190, 1993.

Lear, C. H., Elderfield, H., and Wilson, P. A.: Cenozoic deep-sea temperatures and global ice volumes from Mg/Ca in benthic foraminiferal calcite, Science, 287, 269–272, 2000.

Lezine, A. M., Tiercelin, J. J., Robert, C., Saliege, J. F., Cleuziou, S., Inizan, M. L., and Braemer, F.: Centennial to millennial-scale variability of the Indian monsoon during the early Holocene from a sediment, pollen and isotope record from the desert of Yemen, Palaeogeogr. Palaeocl., 243, 235–249, 2007.

Li, F. J., Wu, N. Q., Pei, Y. P., Hao, Q. Z., and Rousseau, D. D.: Wind-blown origin of Dongwan late Miocene-Pliocene dust sequence documented by land snail record in western Chinese

Loess Plateau, Geology, 34, 405–408, 2006a.

Li, F. J., Wu, N. Q., and Rousseau, D. D.: Preliminary study of mollusk fossils in the Qinan Miocene loess-soil sequence in western Chinese Loess Plateau, Sci. China Ser. D, 49, 724–730, 2006b.

Li, J. J. and Fang, X. M.: Uplift of the Tibetan Plateau and environmental changes, Chinese Sci. Bull., 44, 2117–2124, 1999.

Li, Q. Y., Han, Z. M., and Su, X.: Late Oligocene rapid transformations in the South China Sea, Mar. Micropaleontol., 54, 5–25, 2005.

Li, Q. Y., Wang, P. X., Zhao, Q. H., Shao, L., Zhong, G. F., Tian, J., Cheng, X. R., Han, Z. M., and Su, X.: A 33 Ma lithostratigraphic record of tectonic and paleoceanographic evolution of the South China Sea, Mar. Geol., 230, 217–235, 2006c.

Liang, M. Y., Guo, Z. T., and Gu, Z. Y.: Geochemical characteristics of the Miocene eolian deposits and comparison with those of the Pliocene and Quaternary eolian deposits (in Chinese with English abstract), Quaternary Science, 26, 657–664, 2006.

Liu, J. F., Guo, Z. T., Hao, Q. Z., Peng, S. Z., Qiao, Y. S., Sun, B., and Ge, J. Y.: Magnetostratigraphy of the Miziwan Miocene eolian deposits in Qin'an County (Gansu Province)(in Chinese with English abstract), Quaternary Science, 25, 503–508, 2005.

Liu, J. F., Guo, Z. T., Qiao, Y. S., Hao, Q. Z., and Yuan, B. Y.: Eolian origin of the Miocene loess-soil sequence at Qin'an, China: Evidence of quartz morphology and quartz grain-size, Chinese Sci. Bull., 51, 117–120, 2006.

Liu, T. S.: Loess and the Environment, China Ocean Press, Beijing, 251 pp., 1985.

Liu, T. S. and Guo, Z. T.: Geological environment in China and global change, in: Selected Works of Liu Tungsheng, edited by: An, Z. S., Science Press, Beijing, 192–202, 1997.

Liu, T. S. and Ding, Z. L.: Chinese loess and the paleomonsoon, Annu. Rev. Earth Pl. Sc., 26, 111–145, 1998.

Liu, X. D. and Yin, Z. Y.: Sensitivity of East Asian monsoon climate to the uplift of the Tibetan Plateau, Palaeogeogr. Palaeocl., 183, 223–245, 2002.

Lu, H. Y., Wang, X. Y., An, Z. S., Miao, X. D., Zhu, R. X., Ma, H. Z., Li, Z., Tan, H. B., and Wang, X. Y.: Geomorphologic evidence of phased uplift of the northeastern Qinghai-Tibet Plateau since 14 million years ago, Sci. China Ser. D, 47, 822–833, 2004.

Manabe, S. and Terpstra, T. B.: The effects of mountains on the general circulation of the atmosphere as identified by numerical experiments, J. Atmos. Sci., 31, 3–42, 1974.

Meigs, P.: World distribution of arid and semi-arid homoclimates, in: UNESCO Arid Zone Research, Series No. 1, Arid Zone Hydrology, UNESCO, Paris, 203–209, 1953.

Miao, X. D., Sun, Y. B., Lu, H. Y., and Mason, J. A.: Spatial pattern of grain size in the Late Pliocene 'Red Clay' deposits (North China) indicates transport by low-level northerly winds, Palaeogeogr. Palaeocl., 206, 149–155, 2004.

Miller, K. G., Faribanks, R. G., and Mountain, G. S.: Tertiary oxygen isotope synthesis, sealecel history, and continental margin erosion, Paleoceanography, 2, 1–19, 1987.

Miller, K. G., Mountain, G. S., Browning, J. V., Kominz, M., Sugarman, P. J., Christie-Blick, N., Katz, M. E., and Wright, J. D.: Cenozoic global sea level, sequences, and the New Jersey transect: Results from coastal plain and continental slope drilling, Rev. Geophys., 36, 569–601, 1998.

Molnar, P.: Mio-Pliocene growth of the Tibetan Plateau and evolution of Asian climate, Palaeontol. Electron., 8, 1–23, 2005.

Moran, K., Backman, J., Brinkhuis, H., Clemens, S. C., Cronin, T., Dickens, G. R., Eynaud, F., Gattacceca, J., Jakobsson, M., Jordan, R. W., Kaminski, M., King, J., Koc, N., Krylov, A., Martinez, N., Matthiessen, J., McInroy, D., Moore, T. C., Onodera, J., O'Regan, M., Palike, H., Rea, B., Rio, D., Sakamoto, T., Smith, D. C., Stein, R., St John, K., Suto, I., Suzuki, N., Takahashi, K., Watanabe, M., Yamamoto, M., Farrell, J., Frank, M., Kubik, P., Jokat, W., and Kristoffersen, Y.: The Cenozoic palaeoenvironment of the Arctic Ocean, Nature, 441, 601–605, 2006.

Pavelic, D., Avanic, R., Bakrac, K., and Vrsaljko, D.: Early Miocene braided river and lacustrine sedimentation in the Kalnik Mountain area (Pannonian Basin System, NW Croatia), Geol. Carpath., 52, 375–386, 2001.

Peng, S. Z. and Guo, Z. T.: Geochemical indicator of original eolian grain size and implications on winter monsoon evolution, Sci. China Ser. D, 44 (Suppl.), 261–266, 2001.

Porter, S. C.: Chinese loess record of monsoon climate during the last glacial-interglacial cycle, Earth-Sci. Rev., 54, 115–128, 2001.

Prell, W. L. and Kutzbach, J. E.: Sensitivity of the Indian monsoon to forcing parameters and implications for its evolution, Nature, 360, 647–652, 1992.

Pye, K.: The nature, origin and accumulation of loess, Quaternary Sci. Rev., 14, 653–667, 1995.

Qiao, Y. S., Guo, Z. T., Hao, Q. Z., Wu, W. X., Jiang, W. Y., Yuan, B. Y., Zhang, Z. S., Wei, J. J., and Zhao, H.: Loess-soil sequences in southern Anhui Province: Magnetostratigraphy and paleoclimatic significance, Chinese Sci. Bull., 48, 2088–2093, 2003.

Qiao, Y. S., Guo, Z. T., Hao, Q. Z., Yin, Q. Z., Yuan, B. Y., and Liu, T. S.: Grain-size features of a Miocene loess-soil sequence at Qinan: Implications on its origin, Sci. China Ser. D, 49, 731–738, 2006.

Qiu, Z. D. and Li, C. K.: Evolution of Chinese mammalian faunal regions and elevation of the Qinghai-Xizang (Tibet) Plateau, Sci. China Ser. D, 48, 1246–1258, 2005.

Quade, J., Cerling, T. E., and Bowman, J. R.: Development of Asian monsoon revealed by marked ecological shift during the latest Miocene in northern Pakistan, Nature, 342, 163–166, 1989.

Ramstein, G., Fluteau, F., Besse, J., and Joussaume, S.: Effect of orogeny, plate motion and land-sea distribution on Eurasian climate change over the past 30 million years, Nature, 386, 788–795, 1997.

Rea, D. K., Leinen, M., and Janecek, T. R.: Geologic approach to the long-term history of atmospheric circulation, Science, 227, 721–725, 1985.

Rea, D. K.: The paleoclimatic record provided by eolian deposition in the deep-sea – the geologic history of wind, Rev. Geophys., 32, 159–195, 1994.

Rousseau, D. D. and Kukla, G.: Late Pleistocene climate record in the Eustis loess section, Nebraska, based on land snail assemblages and magnetic susceptibility, Quaternary Res., 42, 176–187, 1994.

Rousseau, D. D., Kukla, G., Zoller, L., and Hradilova, J.: Early Weichselian dust storm layer at Achenheim in Alsace, France, Boreas, 27, 200–207, 1998.

Rowley, D. B. and Currie, B. S.: Palaeo-altimetry of the late Eocene to Miocene Lunpola basin, central Tibet, Nature, 439, 677–681, 2006.

Ruddiman, W. F. and Kutzbach, J. E.: Forcing of late Cenozoic northern hemisphere climate by plateau uplift in southern Asia and the American West, J. Geophys. Res., 94, 18 409–18 427, 1989.

Ruddiman, W. F., Prell, W. L., and Raymo, M. E.: Late Cenozoic uplift in southern Asia and the American West: rational for general circulation modeling experiments, J. Geophys. Res., 94, 18 379–18 391, 1989.

Ruddiman, W. F.: What is the timing of orbital-scale monsoon changes?, Quaternary Sci. Rev., 25, 657–658, 2006.

Shi, Y. F., Tang, M. C., and Ma, Y. Z.: Linkage between the second uplifting of the Qinghai-Xizang (Tibetan) Plateau and the initiation of the Asian monsoon system, Sci. China Ser. D, 42, 303–312, 1999.

Song, Z. C., Li, H. M., Zheng, Y. H., and Liu, G.: Miocene floristic region of China (in Chinese), in: Palaeobiogeographic provinces of China, edited by: Lu, Y. H., Beijing Science Press, Beijing, 178–184, 1983.

Spicer, R. A., Harris, N. B. W., Widdowson, M., Herman, A. B., Guo, S., Valdes, P. J., Wolfek, J. A., and Kelley, S. P.: Constant elevation of southern Tibet over the past 15 million years, Nature, 412, 622–624, 2003.

Sun, D. H., Liu, T. S., Chen, M. Y., An, Z. S., and Shaw, J.: Magnetostratigraphy and palaeoclimate of Red Clay sequences from Chinese Loess Plateau, Sci. China Ser. D, 40, 337–343, 1997.

Sun, J. M.: Provenance of loess material and formation of loess deposits on the Chinese Loess Plateau, Earth Planet. Sc. Lett., 203, 845–859, 2002.

Sun, X. J. and Wang, P. X.: How old is the Asian monsoon system?-Palaeobotanical records from China, Palaeogeogr. Palaeocl., 222, 181–222, 2005.

Taylor, S. R., McLennan, S. M., and McCulloch, M. T.: Geochemistry of loess, continental crustal composition and crustal model ages, Geochim. Cosmochim. Ac., 47, 1897–1905, 1983.

Tsoar, H. and Pye, K.: Dust transport and the question of desert loess formation, Sedimentology, 34, 139–153, 1987.

Turner, S., Hawkesworth, C., Liu, J. Q., Rogers, N., Kelley, S., and Vancalsteren, P.: Timing of Tibetan Uplift Constrained by Analysis of Volcanic-Rocks, Nature, 364, 50–54, 1993.

Valdiya, K. S.: Rising Himalaya: Advent and intensification of monsoon, Curr. Sci. India, 76, 514–524, 1999.

Wang, B.: The Asian Monsoon, Springer, UK, 844 pp., 2006.

Wang, J., Wang, Y. J., Liu, Z. C., Li, J. Q., and Xi, P.: Cenozoic environmental evolution of the Qaidam Basin and its implications for the uplift of the Tibetan Plateau and the drying of central Asia, Palaeogeogr. Palaeocl., 152, 37–47, 1999.

Wang, P. X.: Neogene stratigraphy and paleoenvironments of China, Palaeogeogr. Palaeocl., 77, 315–324, 1990.

Xiao, J. L., Porter, S. C., An, Z. S., Kumai, H., and Yoshikawa, S.: Grain-Size of Quartz as an Indicator of Winter Monsoon Strength on the Loess Plateau of Central China during the Last 130,000-Yr, Quaternary Res., 43, 22–29, 1995.

Yuan, B. Y., Guo, Z. T., Hao, Q. Z., Peng, S. Z., Qiao, Y. S., Wu, H. B., Xiao, G. Q., Ge, J. Y., Sun, B., Zhou, X., Yin, Q. Z., Liang, M. Y., Qin, L., Liu, L., Yao, Z. Q., and Liu, T.

S.: Cenozoic evolution of geomorphic and sedimentary environments in the Tianshui-Qin'an regions, Quaternary Science, 27, 161–171, 2007 (in Chinese with English abstract).

Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K.: Trends, Rhythms, and Aberrations in Global Climate 65 Ma to Present, Science, 292, 686–693, 2001.

Zachos, J., Breza, J. R., and Wise, S. W.: Early Oligocene ice-sheet expansion on Antarctica: Stable isotope and sedimentological evidence from Kerguelen Plateau, southern Indian Ocean, Geology, 20, 569–573, 1992.

Zhang, J. M., Xiao, D. N., Huang, R. J., and Zhang, F. R.: Luvisols, in: Chinese Soil Taxonomy, edited by: Gong, Z. T., Science Press, Beijing, 537–607, 1999.

Zhang, Z. K., He, H. C., Li, S. H., Tian, H. T., and Wang, Y.: The discovery of Miocene aeolian sediments and its paleoenvironmental significance in East China, Acta Sedimentologica Sinica, 25, 116–123, 2007b (in Chinese with English abstract).

Zhang, Z. S., Wang, H. J., Guo, Z. T., and Jiang, D. B.: What triggers the transition of palaeoenvironmental patterns in China, the Tibetan Plateau uplift or the Paratethys Sea retreat?, Palaeogeogr. Palaeocl. Palaeoecol., 245, 317–331, 2007a.

Zhang, Z. S., Wang, H. J., Guo, Z. T., and Jiang, D. B.: Impact of topography and land-sea distribution on East Asian paleoenvironmental patterns, Adv. Atmos. Sci., 23, 258–266, 2006.

Zhang, Z. S., Wang, H. J., Guo, Z. T., and Jiang, D. B.: Impacts of tectonic changes on the reorganization of the Cenozoic paleoclimatic patterns in China, Earth Planet. Sc. Lett., 257, 622–634, 2007c.

Zhao, Q. H.: Microfossils from loess of the Miaodao Islands, Bohai Sea, Sci. China Ser. D, 26, 445–451, 1996.

Zheng, H. B., Powell, C. M., An, Z. S., Zhou, J., and Dong, G. R.: Pliocene uplift of the northern Tibetan Plateau, Geology, 28, 715–718, 2000.

Ziegler, C. L., Murray, R. W., Hovan, S. A., and Rea, D. K.: Resolving eolian, volcanogenic, and authigenic components in pelagic sediment from the Pacific Ocean, Earth Planet. Sc. Lett., 254, 416–432, 2007.

Zoller, L., Rousseau, D. D., Jager, K. D., and Kukla, G.: Last interglacial, Lower and Middle Weichselian – a comparative study from the Upper Rhine and Thuringian Loess areas, Z. Geomorphol., 48, 1–24, 2004.

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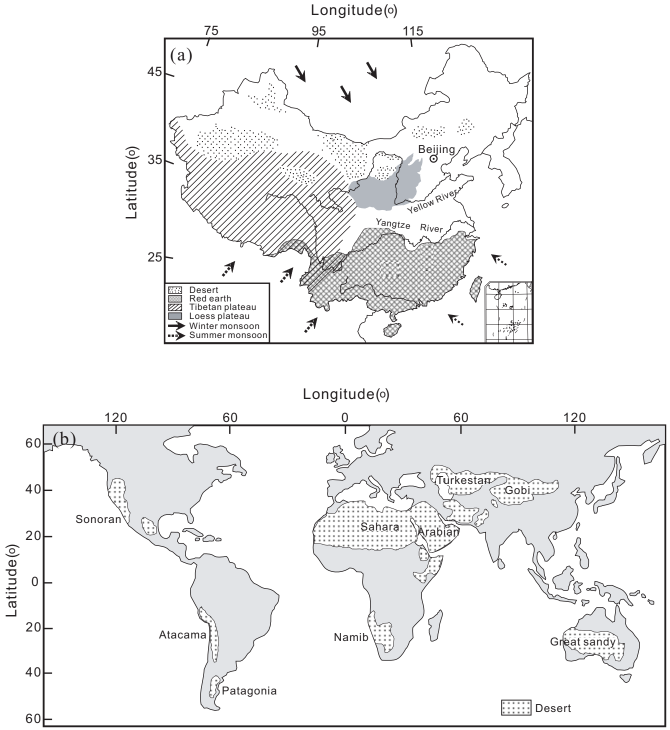

Fig. 1. Sketch maps showing the modern environmental patterns of China and world. **(a)** Modern environmental pattern in China and the prevailing atmospheric circulations. The Loess Plateau locates at the middle reaches of the Yellow River, with the Tibetan Plateau to the Southwest, inland deserts to the North and Northwest while the subtropical and tropical regions in southern China are covered by the 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 world drylands (modified *after* Meigs, 1953). Most of the subtropical zones are occupied by drylands with the exception in East Asia.

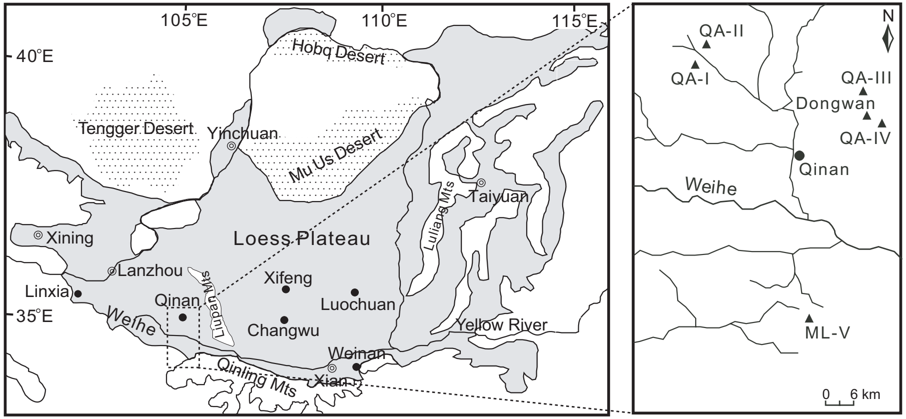

Fig. 2. The Loess Plateau in northern China relative to the inland deserts in northwest China and the mentioned sites. The Plateau is delimited by the Liupan Mountains into the eastern and western parts. The right panel corresponds to a zoomed part of the western Loess Plateau where Miocene eolian deposits are studied.

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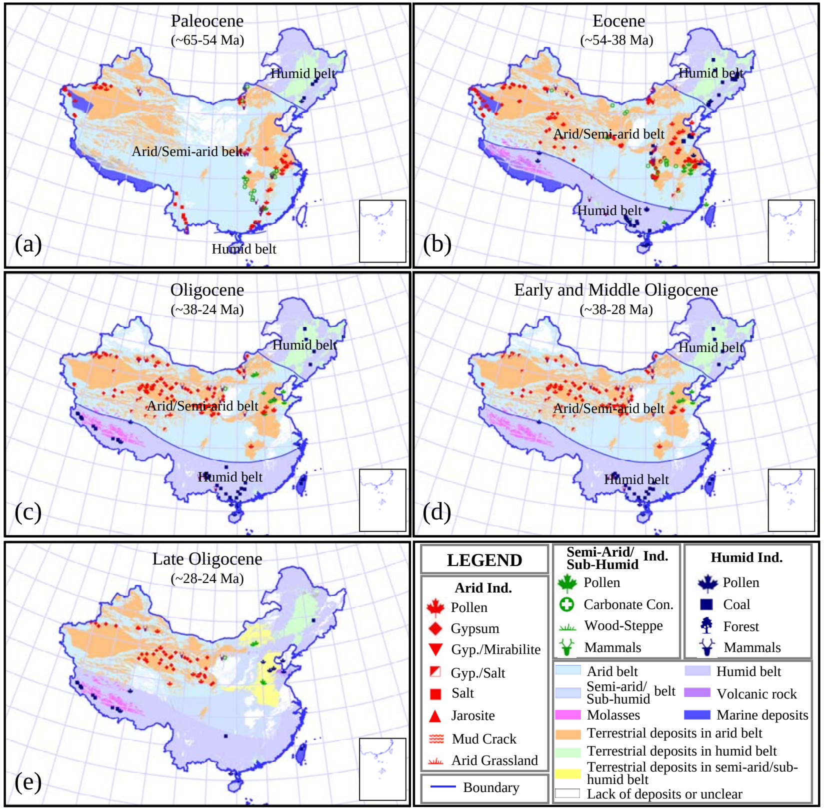

Fig. 3. Paleogene environmental patterns in China. **(a)** Paleocene; **(b)** Eocene; **(c)** Oligocene; **(d)** Early and middle Oligocene; **(e)** Late Oligocene. The data sources are given in Supplementary Material (http://www.clim-past-discuss.net/4/535/2008/cpd-4-535-2008-supplement.pdf). A geographical 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).

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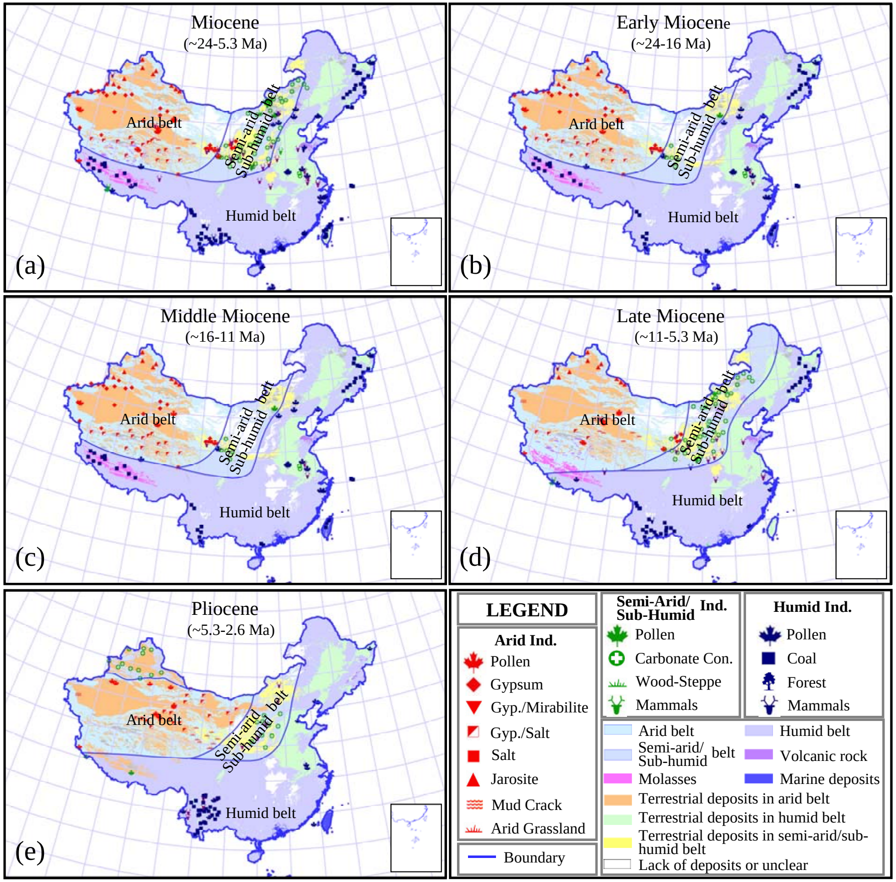

Fig. 4. Neogene environmental patterns in China. **(a)** Miocene; **(b)** Early Miocene; **(c)** Middle Miocene; **(d)** Late Miocene; **(e)** Pliocene. Data sources are the same as noted in the caption of Fig. 3.

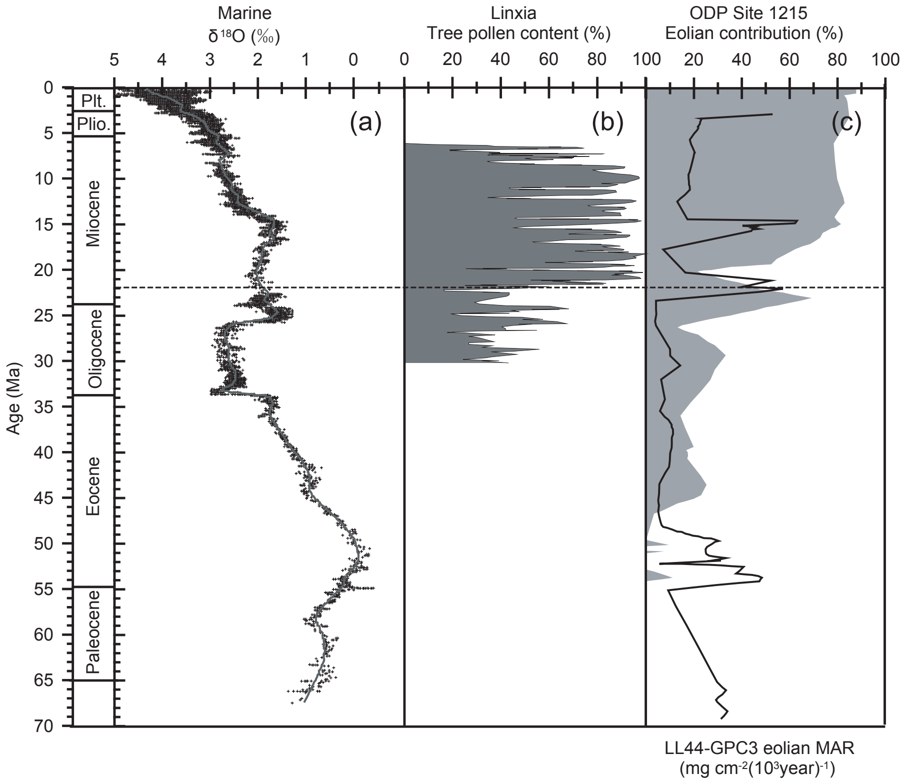

Fig. 5. Variations of global temperature/ice volume in the Cenozoic and relevant proxies of Asian climate changes. **(a)** Marine δ^{18}O records as an indication of global temperature and ice volumes (Zachos et al., 2001); **(b)** Increase in the content of tree pollens around ∼22 Ma ago at Linxia (Shi et al., 1999); **(c)** Cenozoic variations of eolian mass accumulation rate (MAR) at Site LL44-GPC3 (line) from the North Pacific (Rea et al., 1985) and estimated Asian eolian contribution at Site ODP 1215 (shaded zone) in the central Pacific showing the drastic increase at ∼20 Ma (Ziegler et al., 2007).

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Interactive Discussion

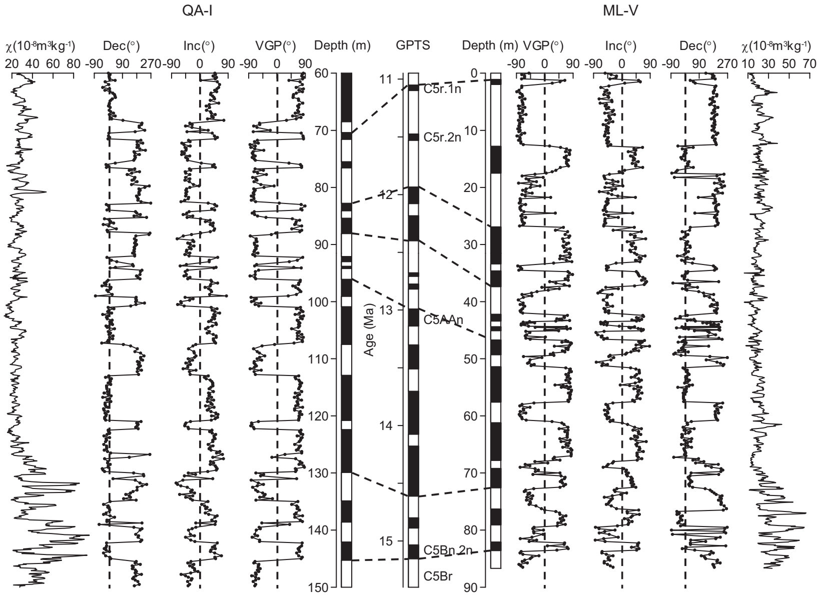

Fig. 6. Magnetostratigraphy and magnetic susceptibility (x) of ML-V (Gaojiazhuang site ∼75 km south to QA-I, 105°43′ E, 34°24′ N) Miocene loess-soil sequence and correlation with QA-I. Declination (Dec.), inclination (Inc) and virtual geomagnetic pole (VGP) latitudes are shown. Correlation of the ML-V geomagnetic polarity with the standard geomagnetic polarity timescale (GTPS, 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 colluviums 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.

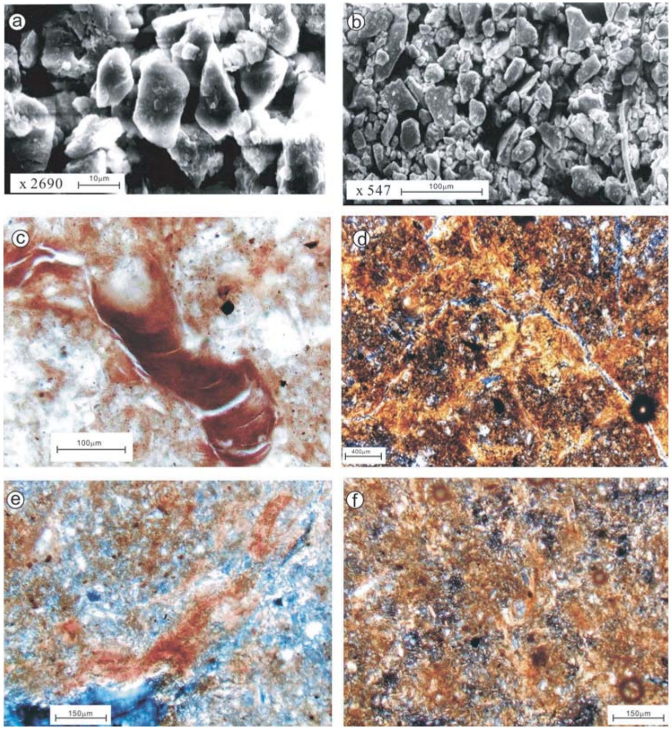

Fig. 7. Quartz grain morphology of the early Miocene loess samples and micromorphology of the early Miocene paleosols from QA-I. **(a)** Scanning electronic microscopic (SEM) picture of quartz grains in the Miocene loess samples (QA-I, 250 m); **(b)** SEM picture of quartz grains in the Miocene loess 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 argilization (QA-I, 211.8 m, cross-polarized light).

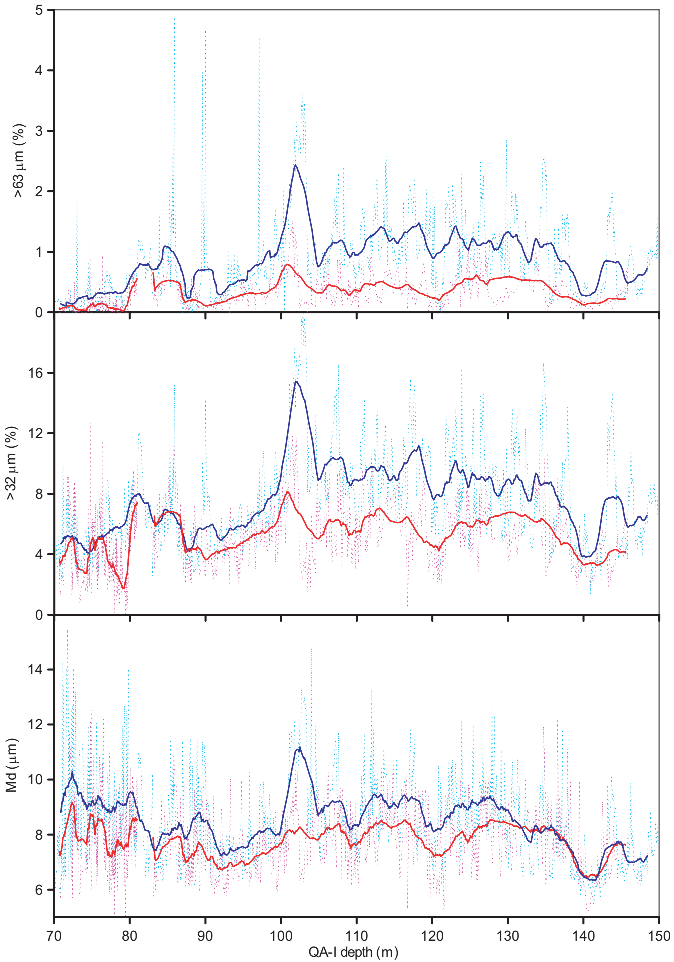
>63 µm (%)
0
1
2
3
4
5
>32 µm (%)
0
4
8
12
16
Md (µm)
6
8
10
12
14
70
80
90
100
110
120
130
140
150
QA-I depth (m)

Fig. 8.

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 the magnetic reversals as control points. The grain-size changes shown here correspond to the interval from 15.41 to 11.12 Ma. Note that the 0–2.0 m and 27.7–31.7 m intervals at ML-V correspond to two layers of water-reworked loess with some coarse sands derived from the upper slopes and thus were not analyzed. The finer grain-size at the ML-V site indicates the 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.

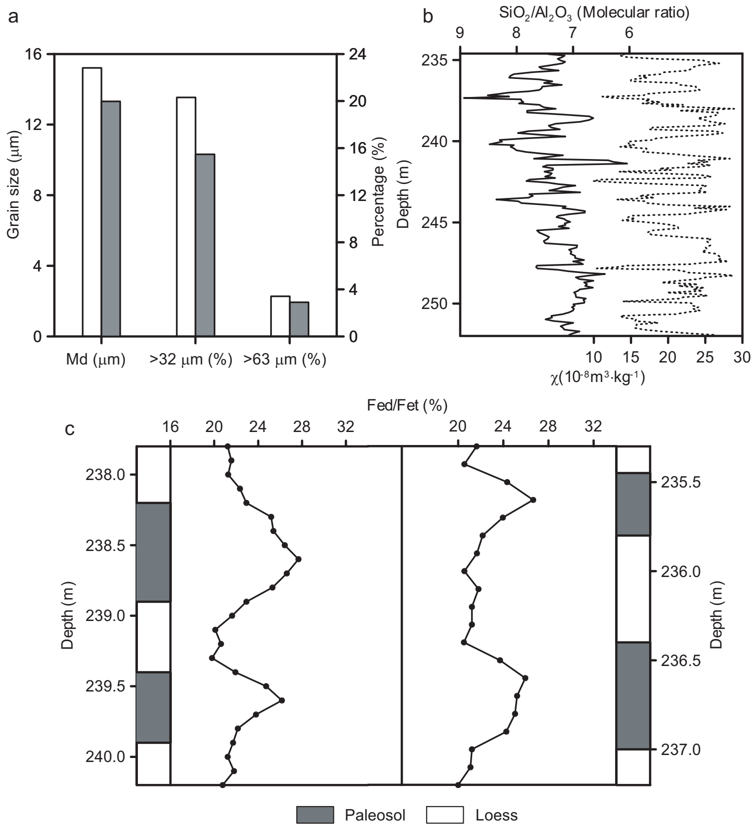
a
Grain size (μm)
16
12
8
4
0
24
20
16
12
8
4
0
Percentage (%)
Md (μm)
>32 μm (%)
>63 μm (%)
b
SiO2/Al2O3 (Molecular ratio)
9
8
7
6
Depth (m)
235
240
245
250
10
15
20
25
30
χ(10⁻⁸m³·kg⁻¹)
c
Fed/Fet (%)
16
20
24
28
32
20
24
28
32
Depth (m)
238.0
238.5
239.0
239.5
240.0
235.5
236.0
236.5
237.0
Depth (m)
Paleosol
Loess

Fig. 9.

Fig. 9. Accretionary properties of the early Miocene paleosols. **(a)** Comparison of median grain-size (Md), the proportions of the >32 μm and >63 μm 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 SiO_2/Al_2O_3 molecular ratio along an early Miocene portion of QA-I showing lower values in soils than in loess layers. Because this ratio was demonstrated to mainly reflect 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-size. The 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 showing highest weathering degree at the middle profiles of soils. Fed/Fet is a chemical weathering index (Duchaufour, 1983) measuring the proportion of iron oxides and hydroxides liberated by chemical weathering from iron-bearing silicate minerals and was successfully applied in the Quaternary loess of China (Guo et al., 1996, 2000).

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