Late Oligocene–Miocene mid-latitude aridification and wind patterns in the Asian interior

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ABSTRACT

The Asian interior has the largest mid-latitude arid zone in the Northern Hemisphere, and so has become increasingly attractive for studying the initiation and the past extent of aridification in this zone. Given the enormousness of the Asian interior, it remains unclear how old and extensive the eolian deposits might have been, and what wind regimes have been responsible for the formation of the mid-latitude arid zone. Here we report new eolian records of widespread Tertiary eolian deposits in a region far from the Chinese Loess Plateau, the giant Junggar inland basin of northwestern China. Our results demonstrate that the earliest eolian deposition initiated ca. 24 Ma. We interpret that the Tertiary eolian dust in the Junggar Basin was transported by westerly winds, possibly from areas in Kazakhstan; the dust differs from the airborne dust transported by winter monsoon winds from the deserts of Mongolia and northern China that accumulated on the Loess Plateau. These results further reveal that the climate pattern, similar to that of the present, has prevailed at least since the latest Oligocene in Central Asia.

INTRODUCTION

Eolian deposits preserved on Earth are geological archives of past climatic changes, especially for wind regimes and arid climates. The world's largest and most extensive airborne deposits occur on the Chinese Loess Plateau (Liu, 1985), where the Quaternary loess-soil successions are discontinuously underlain by the late Tertiary eolian Red Clay, which is usually younger than 8 Ma in most areas (e.g., Ding et al., 1999; Qiang et al., 2001), with the exception of the Qinan section, which extends to 22 Ma (Guo et al., 2002).

Because of the long distance to oceans and the rain-shadow effect of high mountains, an arid to semiarid climate exists in the vast interior of the mid-latitude Central Asia. However, the age, origins, and forcing mechanisms for this aridity are poorly understood.

Here we report on eolian deposits of latest Oligocene–Late Miocene age in the Junggar inland basin, northwestern China, a geographically central area of the Asian interior (Fig. 1). These eolian deposits are widespread in this basin, well constrained chronologically, and richly fossiliferous. The record provides new evidence for the onset of aridification and a new pathway for dust transportation in the Asian interior. The new data contribute to the debates about the effects of the uplifted Tibetan Plateau and the regression of the Tethys Ocean on the atmospheric circulation in Central Asia.

GEOLOGICAL SETTING AND LITHOLOGY

The study area is in the northern part of the Junggar Basin, which is bound by the Altay Mountains to the northeast and the Tianshan Mountains to the south (Fig. 1). The basin has an area of 380,000 km^2 and an average elevation of ~500 m above sea level (Song, 2002), and it is ~2000 km northwest of the Chinese Loess Plateau (Fig. 1A). The Junggar Basin is a structural basin, an extension of the Paleozoic Kazakhstan block, surrounded by Paleozoic folded mountains.

Our study focuses on the Dingshanyanchi and Tieersihabahe sections (Fig. 1B), which are 92.8 m and 190 m thick, respectively. The strata in the studied sections belong to four lithological units, the Tieersihabahe, Suosuoquan, Halamagai, and Dingshanyanchi Formations, which range in age from Late Oligocene to Late Miocene (Figs. 2A and 2B).

The Tieersihabahe and Halamagai Formations are light-colored horizontally bedded fluviolacustrine siltstone and sandstone (R. Zhang et al., 2007), whereas the red bed of the Suosuoquan Formation is predominately ultrafine eolian dust, intercalated occasionally with layers of fluvial sandstones. The lower part of the reddish Dingshanyanchi Formation is also dominated by eolian dust, whereas its upper part consists of reworked (retransported) eolian reddish clay.

The red beds in studied sections consistently show a massive structure with no bedding and commonly contain small carbonate nodules and clay coatings of grains, similar to the Tertiary eolian red clay on the Loess Plateau.

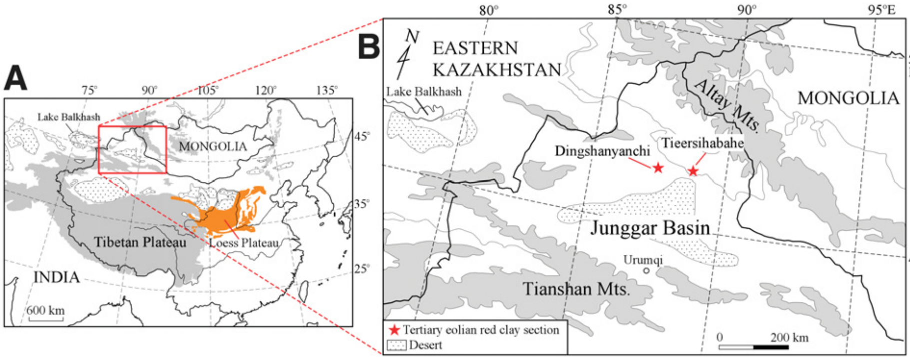

Figure 1. Map showing mid-latitude deserts in China and its neighboring regions and locations of sites mentioned in text. A: Locations of Junggar Basin and the Chinese Loess Plateau. B: Sites of Tertiary eolian red clay within Junggar Basin.

RESULTS

In order to further demonstrate the eolian origin of the red beds in the Suosuoquan and Dingshanyanchi Formations, we analyzed the microelement compositions of the red beds. Both the rare earth element (REE) distributions and the trace element compositions between the Junggar (blue lines) red beds and the Loess Plateau eolian dust (red lines) show nearly identical patterns (Figs. 2C and 2D), supporting an eolian origin for these red beds.

The studied sections are well constrained biostratigraphically and paleomagnetically. At least nine major mammal assemblages (A1–A9) have been collected from the two sections that suggest ages from Late Oligocene to Late Miocene (Meng et al., 2006, 2008; Wu et al., 2009)

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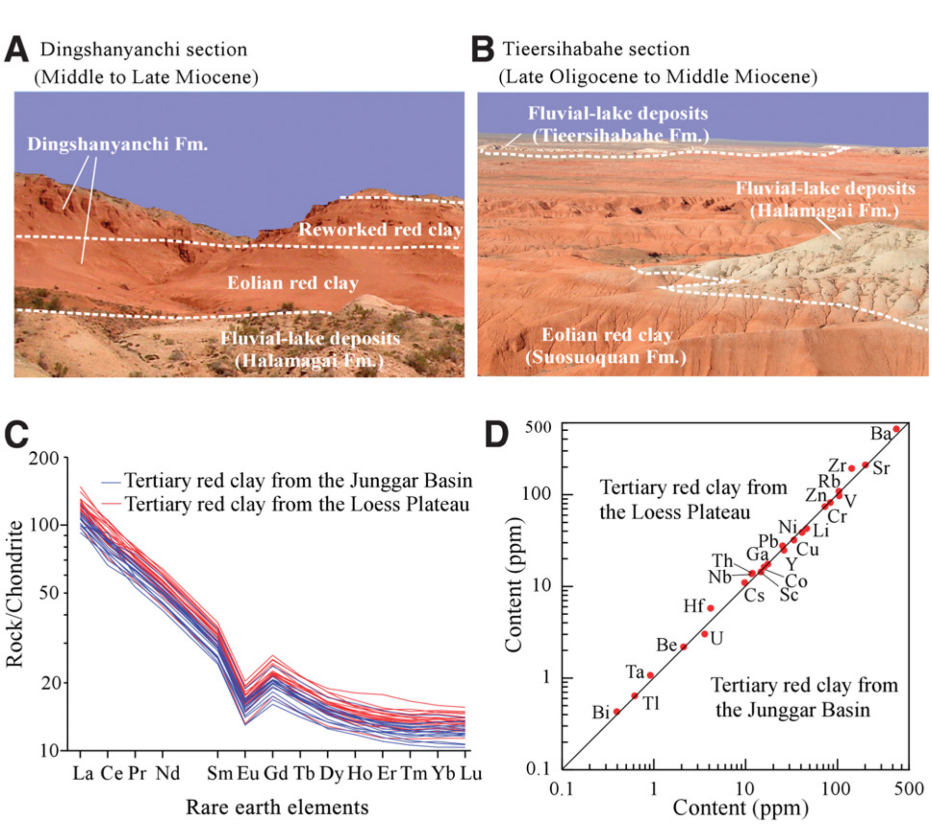

Figure 2. Strata division and geochemical properties of Tertiary deposits in Junggar Basin. A: Dingshanyanchi section. B: Tieersihabahe section. C and D: Comparison of rare earth element distribution patterns and trace element compositions between Tertiary eolian red clay in Junggar Basin (blue lines) and Loess Plateau (red lines).

(Fig. 3). These mammal assemblages form one of the best terrestrial biostratigraphic sequences of the Late Oligocene to Miocene in the Asian interior. The sequential assemblages correlate well with Asian and European land mammal ages (Meng et al., 2008) and provided biostratigraphic age controls for the paleomagnetic sequences of the two studied sections.

The paleomagnetic samples for the Dingshanyanchi section were collected in 2008. A total of 336 oriented specimens were taken, and all samples were subjected to stepwise (averaging 18 steps) thermal demagnetization; the magnetic remanence was measured with a 2G, three-axis, cryogenic magnetometer. The paleomagnetic sequence and correlations for the Tieersihabahe section are based on data from previous studies (Meng et al., 2006; R. Zhang et al., 2007). With the biostratigraphic age controls we are able to correlate the two polarity sequences with the geomagnetic polarity time scale of Cande and Kent (1995) (Fig. 3). The magnetozones of the Dingshanyanchi section correlate with polarity chrons C5En to C3An.1n, an interval of 17.5–6 Ma (Fig. 3A). The magnetic polarity between the top of C5Cn.1n and the bottom of C5AAn are poorly resolved because the coarse fluvial sandstone in the Halamagai Formation is not suitable for paleomagnetic sampling. Although the paleomagnetic chrons are not ideal within the Halamagai Formation, the fossil assemblage correlates well with the European MN6 and probably part of MN5 (Wu et al., 2009). The MN5 to

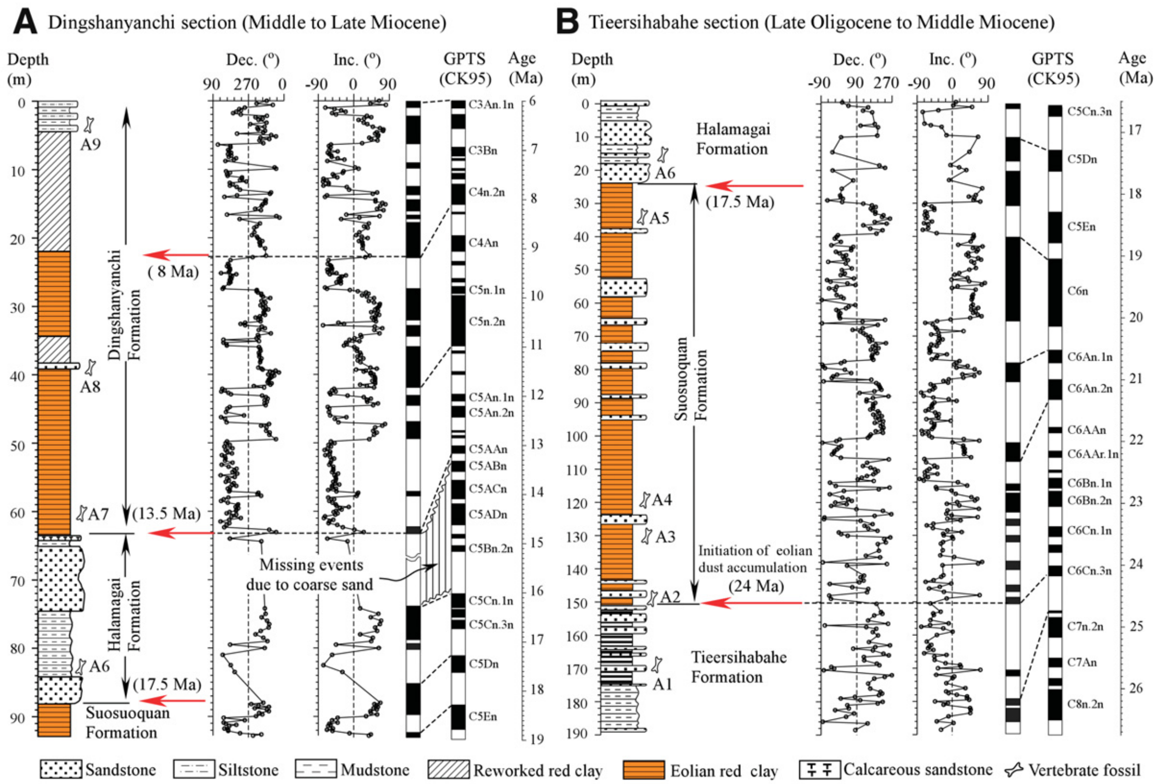

Figure 3. A: Magnetostratigraphy of Dingshanyanchi section. B: Magnetostratigraphy of Tieersihabahe section (declination, Dec., and inclination, Inc., data of this section are from R. Zhang et al., 2007). GPTS—geomagnetic polarity time scale (Cande and Kent, 1995). Red arrows indicate boundary ages of eolian deposition; positions of mammalian fossil assemblages (A1–A9) are also given.

MN6 roughly spans 17 to 14 Ma, so the biostratigraphic correlations of the Halamagai Formation are consistent with the general sequential correlation. The magnetozones of the Tieersihabahe section correlate with polarity chrons from C7n.2n to C5Cn.3n, spanning the interval 25–16.3 Ma (Fig. 3B). However, given the contact observed in the field, there is probably a hiatus between the Suosuoquan and Halamagai Formations (Meng et al., 2008).

The Oligocene-Miocene boundary (23.03 Ma) (Gradstein et al., 2004) is recognized within the basal strata of the Suosuoquan Formation (Fig. 3). The earliest eolian dust layer within the sequence predates the Oligocene-Miocene boundary and is in polarity chron C6Cn.3n, which has a base age of ca. 24 Ma (Fig. 3B). This dust layer marks the onset of a distinctive environmental transition of the region. This earliest episode of eolian deposition lasted from 24 to 17.5 Ma, except for several short-term fluvial events. From 17.5 to 13.5 Ma, eolian deposition was replaced by fluviolacustrine sedimentation. Another eolian deposition period started ca. 13.5 Ma and continued to ca. 8 Ma (Fig. 3A). The deposits dated 8–6.5 Ma are reworked reddish clay, similar in color to the eolian units, but horizontally bedded, indicating they had undergone some transport by surface washing from the nearby sites after initial eolian deposition.

In order to constrain the provenance of the Tertiary eolian deposits in the Junggar Basin, we compared the Sr and Nd isotope compositions of the Junggar eolian sediments with those of the Tertiary and Quaternary airborne materials from the Loess Plateau. These isotopes have been demonstrated to be powerful tools for tracing provenance of eolian deposits (e.g., Taylor et al., 1983; Biscaye et al., 1997; Sun, 2002, 2005). Plots of isotopic data of $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ and $^{87}Sr/^{86}Sr$ versus 1/[Sr] clearly show that the Tertiary samples of the Junggar eolian deposits and those of the Loess Plateau plot into two distinct groups (Figs. 4A and 4B). Despite their different ages, the Sr and Nd data of the Tertiary red clay and Quaternary loess from the Loess Plateau overlap to some extent, suggesting a similar provenance (Figs. 4A and 4B). In sharp contrast, the Sr and Nd isotopic compositions indicate that the Junggar eolian dust must have come from a different source area.

The comparison of particle sizes of the Junggar Tertiary eolian dust with those of the Loess Plateau indicates that the Junggar dust is much finer (Fig. 4C). The sorting versus median size plot differentiates the dusts into two nonoverlapping areas (Fig. 4D). Eolian dust from the Junggar Basin has a median size of 2–4 µm, whereas that from the Loess Plateau has a median size of 4–8.5 µm. In addition, the Junggar eolian dust is better sorted than that of the Loess Plateau, suggesting a longer transport distance and better mixing.

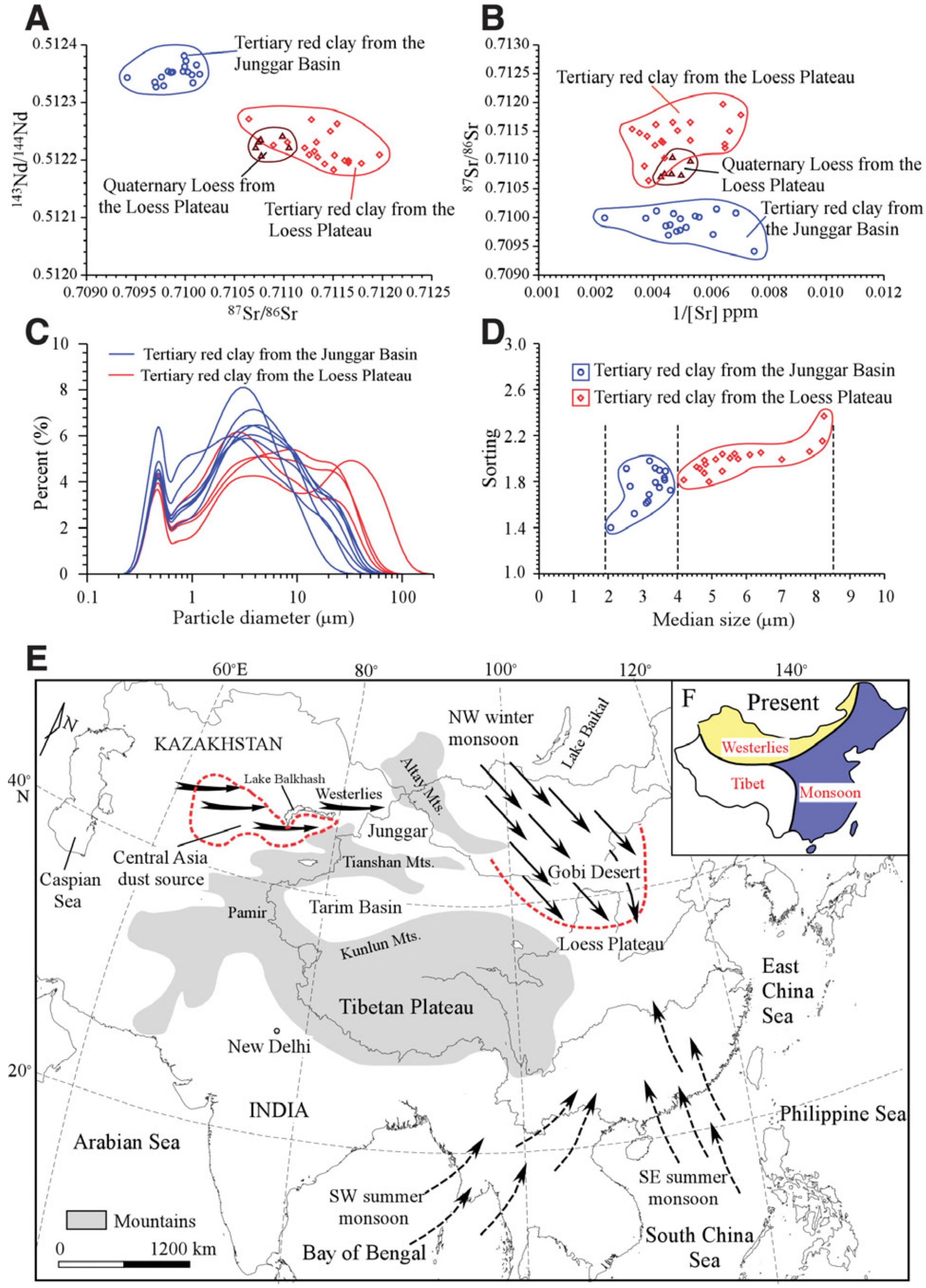

Figure 4. A: Plots of $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ between samples of Tertiary eolian red clay from Junggar Basin (blue circles) and Tertiary (red squares) and Quaternary eolian deposits (black triangle) from Loess Plateau. B: Plots of $^{87}Sr/^{86}Sr$ vs. 1/[Sr]. C: Comparison of particle size distributions between Tertiary eolian red clay in Junggar Basin (blue lines) and those from Loess Plateau (red lines). D: Plots of median size against sorting of Tertiary eolian red clay in Junggar Basin (blue circles) and those from Loess Plateau (red squares). E: Provenance (circled by red dashed lines) and dust pathways of Tertiary eolian red clay in Junggar Basin and on Loess Plateau since latest Oligocene. F: Schematic map showing present climate pattern in China. Note similarity between climate patterns.

DISCUSSION

The Quaternary loess on the Loess Plateau has been demonstrated to be derived from the Gobi Desert, transported by northwest East Asia winter monsoon (Sun, 2002). The similar isotopic compositions of the Tertiary eolian red clay and the Quaternary loess from the Loess Plateau reveal that they have a largely similar provenance (Figs. 4A and 4B). However, the distinctive isotopic composition and the fine and well-sorted nature of the Junggar eolian dust indicate a different source area, a relatively longer transportation distance, and a different wind system for transportation.

The most likely provenance of the Tertiary Junggar eolian deposits is the arid to semiarid area of Central Asia, especially Kazakhstan; therefore, it is necessary to know the past environment in this region. Geological evidence demonstrated that the Paratethys was separated from the Tethys Ocean around the Eocene-Oligocene transition due to the drop of the global (eustatic) sea level and/or tectonic activities (Rögl, 1999; Schulz et al., 2005). The regression of the Tethys Ocean exposed the land of Kazakhstan, which subsequently underwent erosion and aridification in the Early Oligocene (Akhmetyev et al., 2005) and possibly provided dust sources. In these areas, in particular eastern Kazakhstan, are the Sary-Ishikotrau, Taukum, Muyunkum, and Kyzylkum Deserts (Fig. 4E).

Based on the geographical distribution and the nature of the Tertiary eolian deposits in the Junggar Basin, we consider that the Tertiary dust was transported to the Junggar Basin by westerly winds from Kazakhstan, whereas the northwest winter monsoon was responsible for the Tertiary eolian deposits on the Loess Plateau (Fig. 4E). Such a wind pattern is similar to the present wind regime in China, characterized by the monsoon climate prevailing in eastern China and the westerlies prevailing in northwestern China (Fig. 4F). We therefore suggest that the wind pattern, similar to the modern one, has prevailed at least since 24 Ma in Central Asia.

The origins and age of arid regions in the mid-latitude Asian interior have long been discussed (e.g., Trewartha and Horn, 1980; Williams et al., 1998). A distinguishing feature of the modern East Asia monsoon system is its geographic distribution, which disturbed the zonal pattern of the Paleogene planetary climate system (Sun and Wang, 2005; Guo et al., 2008). Climatic modeling results suggest that the Asian climate is affected significantly by the uplift of the Tibetan Plateau (Kutzbach et al., 1989; An et al., 2001). Broccoli and Manabe (1992) demonstrated that the zonal pattern of prevailing climate and the mid-latitude aridity would be absent without the uplifted Tibet Plateau, and that substantial aridity occurs across the mid-latitude interior of Eurasia because of the existence of Tibet. Clift et al. (2006) revealed that initial surface uplift in eastern Tibet occurred no later than 24 Ma. In addition, the stepwise retreat of the New Tethys Ocean during Cenozoic time reduced the moisture transported by westerly winds; this also led to the enhanced aridity in Central Asia. Our results demonstrate that extensive arid to semiarid regions existed in the Asian interior by 24 Ma (Fig. 4E), suggesting that the uplift of the Tibet Plateau and the Paratethys retreat could have had a profound effect on the mid-latitude climate in the Asian interior in the latest Oligocene. This is demonstrated by the most recent atmospheric general circulation modeling result, which confirms that both the uplift of Tibet and/or the Paratethys Sea retreat could have led to the arid climate in western China and monsoonal climate in eastern China (e.g., Z.S. Zhang et al., 2007).

The Junggar eolian deposits indicate that the aridity of Central Asia started at least 24 Ma ago. The Junggar dust was mostly derived from Central Asia and was transported by westerly winds. This indicates a new system for eolian deposits, differing from the one responsible for the Tertiary red clay currently known on the Loess Plateau and other areas. These new data suggest that the history of eolian deposits in Central Asia is more complex than previously thought, and that the transition from the zonal pattern of a planetary climate system to a monsoon climate occurred ca. 24 Ma ago in China.

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