Onset of aridification by 34 Ma across the Eocene-Oligocene transition in Central Asia

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ABSTRACT

Cenozoic climate has changed markedly from a warm, wet climate to the present cool, dry glacial-interglacial cycles. The largest of these cooling steps is thought to have taken place across the Eocene-Oligocene transition. Terrestrial airborne eolian loess is a direct result of land aridification; therefore, the prolonged formation of thick eolian loess deposits provides a key to aridification history in the geological past. However, the oldest eolian loess in the Asian interior has been dated to only 25–22 Ma. Here we present new sedimentological, geochemical, and magnetostratigraphic data from Cenozoic sections in southwestern Mongolia to show that the earliest eolian dust accumulation occurred by 34 Ma, ~10 m.y. earlier than currently believed. We suggest that this oldest eolian dust accumulation provides direct evidence for enhanced aridification across the Eocene-Oligocene transition in Central Asia; this is explicable by reduced moisture transport caused by prevailing westerlies during retreat of the Neotethys Ocean. These climatic changes were related to the changing regional plate configuration as well as to global cooling and ice-sheet growth in Antarctica.

INTRODUCTION

The Eocene-Oligocene transition (EOT) at 34 Ma was the most pronounced climatic cooling event during the Cenozoic Era (Zachos et al., 2001). This event records a dramatic cooling of ~4 °C indicated by deep-sea paleoclimatic proxy records (Liu et al., 2009), and by a large drop of ~8 °C in terrestrial mean annual temperature in North America (Zanazzi et al., 2007). In Europe, one of the largest mammalian faunal turnovers and extinctions, termed the Grande Coupure (great break), was across the EOT (Hooker et al., 2004). A similar mammalian turnover, called the Mongolian remodeling, took place in Central Asia (Meng and McKenna, 1998). However, despite these improvements in understanding the abrupt changes in mammalian fauna and climate across the EOT (Dupont-Nivet et al., 2007; Kraatz and Geisler, 2010; Sun et al., 2014), there is still no direct evidence for terrestrial eolian deposition across the EOT and for the onset of aridification in the Asian interior.

In this study, we focus on the Valley of Lakes in southwestern Mongolia, which is an elongated intermontane depression bound by the Hangay Mountains to the northeast and the Altai and Gobi-Altai Mountains to the southwest (Fig. 1A). The Valley of Lakes provides unique evidence of Cenozoic mammalian evolution and paleoenvironmental changes in two respects. First, Paleogene and Neogene sequences contain the richest mammalian fauna in Asia (Höck et al., 1999; Daxner-Höck, 2000; Daxner-Höck and Badamgarav, 2007), providing biostratigraphic age control of the sediments and important paleoclimatic implications. Second, the Cenozoic strata are intercalated with several basalt flows, the isotopic ages of which constrain the quantitative time of sediment deposition (Höck et al., 1999).

GEOLOGICAL SETTING AND STRATIGRAPHY

In this study we focused on two Cenozoic sections (A and B) in the Taatsyn Tsagaan Nuur area (Fig. 1B), where the strata belong to three lithological units, the Tsagaan Ovoo, Hsanda Gol, and Loh Formations.

In section A (near the TGR-A of Höck et al., 1999), the lower part of the Tsagaan Ovoo Formation is dominated by an alternation of mostly horizontal, grayish-white sandstones and siltstones (Fig. 2A) that represent shore or shallow lacustrine deposits; the upper part is dominated by fluvial cross-bedded gravels and sandstones. Thus the sedimentary environment of the Tsagaan Ovoo Formation as a whole was fluviolacustrine.

The Hsanda Gol Formation is dominated by reddish-brown mudstones (Figs. 2A and 2B); in section A, its lower part is overlain by a basalt (Basalt I of Höck et al., 1999), and in section B, its upper part is overlain by the Loh Formation. Höck et al. (1999) proposed that the Hsanda Gol Formation is an eolian deposit, based on particle size similarity with American dust. However, the precise basal age of the deposit is unknown. The Loh Formation (section B) is dominated by grayish-green siltstones, grayish-white gravels, and intercalated reddish-brown eolian mudstones.

METHODS

Specimens for our magnetostratigraphic analysis were oriented with a magnetic compass in the field. All samples were subjected to stepwise thermal demagnetization. Magnetic remanence was measured with a 2G Enterprises three-axis cryogenic magnetometer housed in field-free space (300 nT) at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS) in Beijing.

Trace element concentrations (including the rare earth elements, REE) were measured with an inductively coupled plasma–mass spectrometer (ELEMENT 1™, previously Finnigan MAT) at IGGCAS. Uncertainties (<5%) were calculated as a percentage using the standard deviation divided by the mean of replicated samples.

Particle size distributions were measured with a SALD-3001 laser microsizer. Before analyzing the particle size, 30% H_2O_2 and 0.5 N HCl were used to remove organic materials and carbonates (Van Reeuwijk, 2002), respectively.

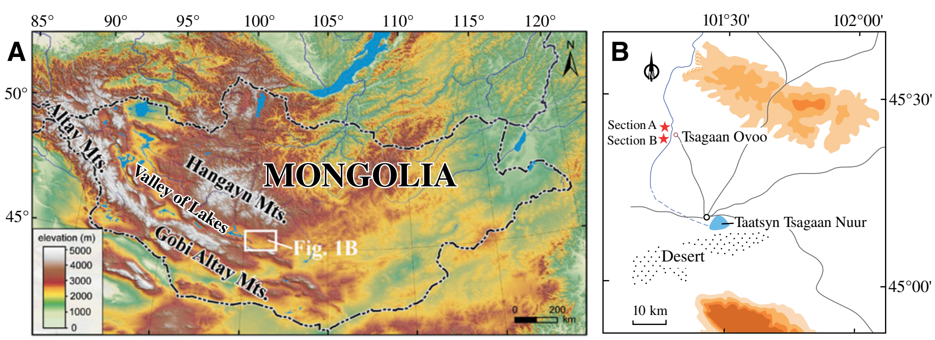

Figure 1. A: Location of the Valley of Lakes (Mongolia), between the Hangay and Altai Mountains. B: The locations of the two studied sections along the Taatsyn Gol.

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Ultrasonic pretreatment involving the addition of 20% $(NaPO_3)_6$ solution was used to disperse the samples before particle measurement.

RESULTS

Red beds of the Hsanda Gol Formation are consistently massive, have no bedding, and commonly contain small carbonate nodules, similar to Neogene eolian red clays on the Chinese Loess Plateau. In order to further demonstrate the eolian origin of these red beds, we analyzed their trace element compositions and particle size distributions. The REE (Table DR1 in the GSA Data Repository[1]) distribution is different from that of lake sediment and glacial moraines, but almost identical to that of Neogene Loess Plateau eolian red clay (Fig. 2C). The trace element compositions (Tables DR2 and DR3) of Mongolian and Chinese red clays are also very similar (Fig. 2D), and their particle size distributions (Tables DR4 and DR5) are comparable (Figs. 2E and 2F). Therefore, these lines of evidence support an eolian origin for the red beds of the Hsanda Gol Formation.

Although the mammalian fossils and the absolute dating of the basalts help to produce a general chronological framework, high-resolution magnetostratigraphy is a better constraint on the chronology. For this study, the magnetostratigraphic analysis of 180 oriented specimens yielded a paleomagnetic polarity sequence (Table DR6; Fig. 3).

In previous studies, rodents in Biozone A, discovered just below Basalt I in section A (Fig. 3), suggest an early Oligocene age, and the ^{40}Ar/^{39}Ar age of Basalt I is 31.5 Ma (Höck et al., 1999). Other rodents in Biozone C from the lower Hsanda Gol Formation in section B indicate an age younger than 28 Ma (Höck et al., 1999).

The mammalian fossils mentioned here and the isotopic age of the basalts help to correlate the measured magnetostratigraphy with the geomagnetic polarity time scale (Gradstein et al., 2004), providing a composite age chronology for the studied area (Fig. 3) that demonstrates that the Eocene and Oligocene transition is the boundary between the Tsagaan Ovoo and Hsanda Gol Formations. Therefore, the eolian dust accumulation of the Hsanda Gol Formation began by 34 Ma. In section A the eolian deposition of the lower Hsanda Gol Formation lasted from 34 to 31.5 Ma (Fig. 3), and in section B the eolian deposition of the upper Hsanda Gol Formation corresponds to the paleomagnetic polarity chrons of C9n–C8n.1n, an age range of 27.8–25.3 Ma (Fig. 3); the age of 27.8 Ma is consistent with the maximum age of 28 Ma of Biozone C suggested by Höck et al. (1999).

This study indicates that the oldest eolian loess deposition had started by 34 Ma in the Valley of Lakes, Mongolia. This is the oldest eolian deposit in Asia, 10 m.y. older than the previously reported oldest Chinese loess (Guo et al., 2002; Sun et al., 2010; Qiang et al., 2011).

DISCUSSION

Early eolian deposits have important paleoclimatic implications, especially for the initiation of aridification in Central Asia. Based on the data reported here, we conclude that the Tsagaan Ovoo Formation has a late Eocene age, and that the lithologies and sedimentary facies represent a fluvial-lacustrine environment (Fig. 4A). However, the environment changed at 34 Ma, from fluviolacustrine in the late Eocene to eolian dust accumulation (Fig. 4B) in the Oligocene; this indicates enhanced aridification across the EOT.

Although enhanced aridification began at 34 Ma, the climatic condition was semiarid rather than hyperarid, indicated by the following lines of evidence. First, dust particles, which settle on a bare, smooth surface in a hyperarid climate, are susceptible to resuspension, resulting in no net deposition (Pye, 1995). In the Valley of Lakes, the thickness of the eolian dust reached tens of meters, and such a long-term vertical accretion of dust requires a vegetated surface on which the particles could be permanently trapped, the most suitable environment being a semiarid grassland perhaps with lowland playas (Fig. 4B). Second, paleosols and carbonate nodules occur within the eolian red beds of the upper Hsanda Gol Formation. Such secondary carbonate nodules are affected by chemical leaching, which is impossible in a hyperarid climatic condition (Pye, 1995). Third, the rich

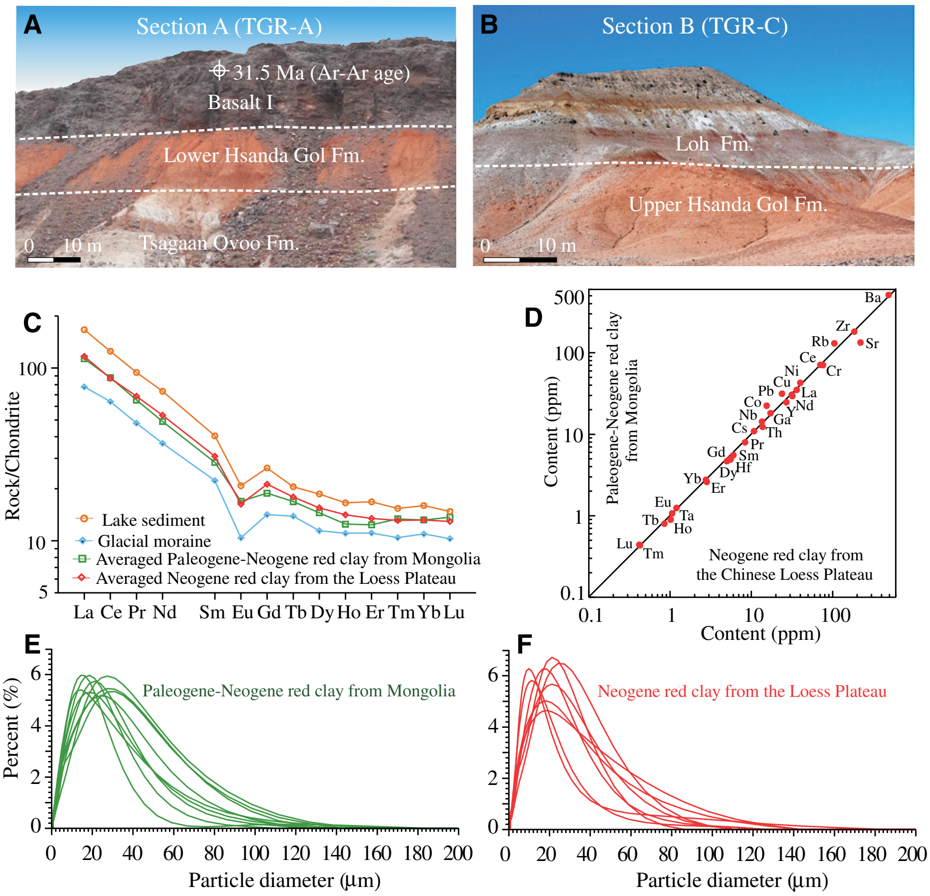

Figure 2. Stratigraphic divisions and geochemical and sedimentological properties of the Paleogene–Neogene deposits in the Valley of Lakes, Mongolia. A: The stratigraphic divisions in section A, consisting of the Tsagaan Ovoo and Lower Hsanda Gol Formations as well as the overlying Basalt I (Höck et al., 1999; from bottom to top). B: The stratigraphic divisions in section B, consisting of the upper Hsanda Gol and Loh Formations (from bottom to top). C: Comparison of rare earth element distribution patterns of the Paleogene–Neogene Mongolian and Chinese eolian red clays, lake sediment (Tanaka et al., 2007), and glacial moraines (Chang et al., 2000). D: Comparison of trace element compositions of the Paleogene–Neogene Mongolia and Chinese eolian red clays. E: Particle size distributions of Paleogene–Neogene eolian red clays in the Valley of Lakes. F: Particle size distributions of Neogene eolian red clays in the Chinese Loess Plateau.

[1]GSA Data Repository item 2015340, rare earth elements, microelements, and particle size data of the Paleogene–Neogene red clay in Mongolia and China (Tables DR1–DR5), and paleomagnetic polarity data of the studied sections (Table DR6), is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

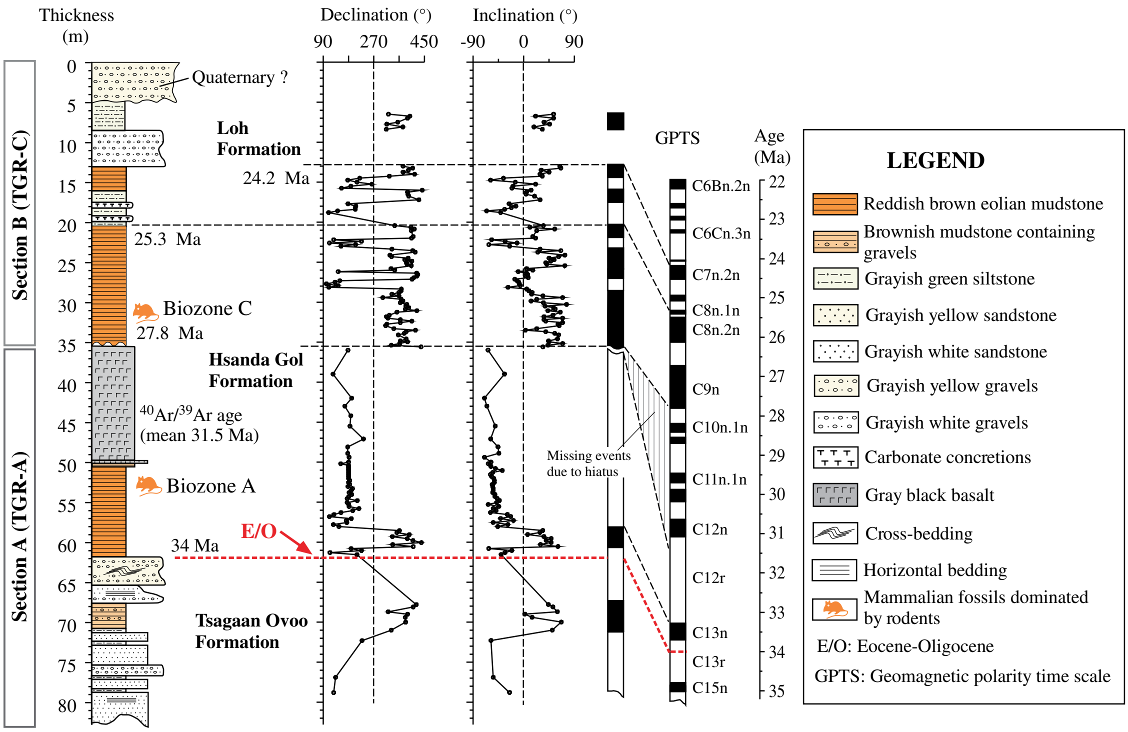

Figure 3. Composite magnetostratigraphy and mammalian fossils zones of the studied sections. Biozones (dominated by rodents) A and C and the ^{40}Ar/^{39}Ar age of Basalt I are from Höck et al. (1999). The Eocene-Oligocene transition is located at the contact between the Tsagaan Ovoo and Hsanda Gol Formations.

mammalian fossils in the Hsanda Gol Formation are dominated by small animals, such as rodents, the most favorable environment for which are open grasslands in a semiarid ecosystem (Meng and McKenna, 1998).

It has been more than a century since the eolian origin of loess was proposed by Von Richthofen (1882). The most common hypotheses for the formation of loess are glacial loess and desert loess. According to the former, glacial grinding plays an important role by producing great quantities of silt-sized materials necessary for the formation of thick loess deposits (Smalley, 1966). This hypothesis is supported by the fact that extensive loess deposits are a Quaternary phenomenon, showing a clear spatial relationship with areas of Pleistocene continental glaciation (Smalley and Leach, 1978). The desert loess hypothesis was suggested by Obruchev (1911) to explain nonglacial mechanisms of silt production by eolian abrasion in deserts.

However, our new age of 34 Ma for the eolian loess in Mongolia predates the Quaternary glaciation of ca. 2.6 Ma in the Northern Hemisphere (Jansen and Sjøholm, 1991). Therefore, the glacial loess origin can be excluded. Moreover, both our geological investigations and previous research (Höck et al., 1999) in the Valley of Lakes found no evidence of Oligocene eolian sand dunes or deserts, and accordingly the desert loess origin can also be eliminated. We require another viable model to explain the formation of Oligocene loess in Central Asia.

The Valley of Lakes is between the Hangay and Altai (also Gobi-Altai) Mountains (Fig. 4A). In the Eocene there was a warm-humid fluviolacustrine environment with rivers, lakes, lowland marsh, and montane forests (Fig. 4A). However, by the Oligocene the climate had changed to semiarid with ephemeral rivers, playas, and open steppe (Fig. 4B). The large quantities of sediment produced by rock denudational processes of the Hangay and Altai Mountains were transported to the lowland basin of the Valley of Lakes by ephemeral rivers in fluvial channels and alluvial fans. Deflation of the dried fluvial channels (wadis), outwash fans, and playas by mid-latitude westerlies generated east-moving dust storms, the dust accumulating as eolian loess in the southeastern Valley of Lakes (Fig. 4B). In this model the Oligocene loess in the Valley of Lakes is neither glacial loess nor desert loess, but mountain loess. The dried-up fluvial channels and alluvial fans, which periodically receive new supplies of sediment from tectonically active areas in Central Asia resulting from the ongoing India-Eurasia collision (Cunningham, 2013), produce large amounts of silt-sized sediment, maintaining the long-term accumulation of eolian loess.

The transition from fluviolacustrine to eolian sedimentation in southwestern Mongolia across the EOT can be explained by reduced moisture transport by the prevailing westerlies from the Neotethys Ocean. First, since the early

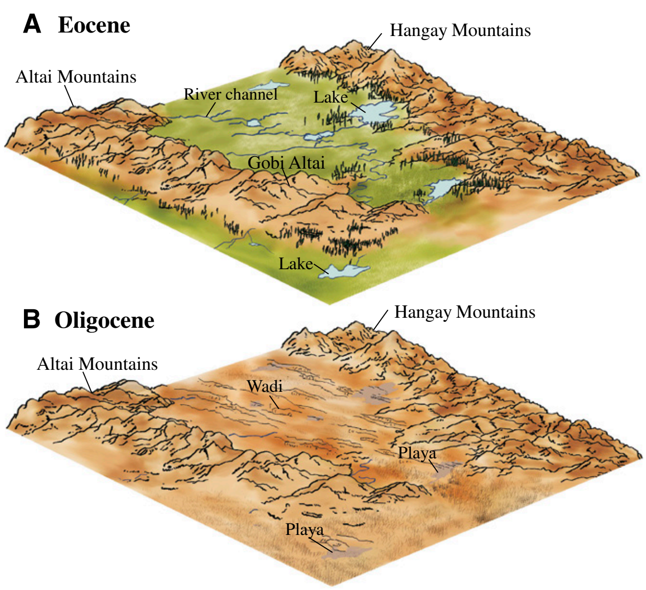

Figure 4. Schematic models showing the ecosystems in the Valley of Lakes (southwestern Mongolia) during the Eocene and Oligocene. A: In the Eocene, there was a warm-humid fluviolacustrine environment with rivers, lakes, lowland marsh, and montane forests. B: The Oligocene ecosystem was marked by a semiarid environment with dried-up fluvial channels (wadis), playas, and open steppe. Eolian dust entrained from the wadis, playas, and outwash fans within the Valley of Lakes was trapped in the downwind steppe terrane, where it accumulated as thick eolian loess.

Cenozoic the ongoing India-Eurasia collision has resulted in the uplift of a series of mountain chains (e.g., Pamir, Kun Lun, Hindu Kush, and Tian Shan) along the southern rim of Eurasia (Molnar and Tapponnier, 1975), leading to the regression of the Neotethys Ocean (Popov et al., 2004). Second, the EOT was characterized by a major drop in the global eustatic sea level and an abrupt cooling of global climates (Zachos et al., 2001). The combination of tectonic uplift and a drop in sea level resulted in westward retreat of the Neotethys Ocean. Therefore, the onset of eolian sedimentation in the Asian interior across the EOT was largely controlled by Neotethys regression, which reduced moisture transport by the westerlies to the Asian interior.

CONCLUSIONS

New magnetostratigraphy and geochemical analyses provide a novel insight into the aridification history of Central Asia. Our results indicate that the earliest eolian dust accumulated by 34 Ma in Mongolia, ~10 m.y. before the oldest reported loess in Asia. This oldest eolian dust deposit provides direct evidence for enhanced aridification across the EOT, for which a new explanation is required. The data can be explained well by reduced moisture transport by prevailing westerlies from the retreated Neotethys Ocean. The overall environment was related to the changing regional plate configuration as well as to global cooling and ice-sheet growth in Antarctica.

ACKNOWLEDGMENTS
This work was supported by the Strategic Priority Research Program of the Chinese Academy of Science (XDB03020500), the National Basic Research Program of China (2013CB956400), and the National Nature Science Foundation of China (41290251 and 41272203). We thank T. Nyambayar, K. Baatarkhuu, N. Buyankhishig, G. Ganbat, Z. Wang, G. Sun, F. Tan, and Z.H. Tian for help in field sampling.

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Manuscript received 16 July 2015
Revised manuscript received 15 September 2015
Manuscript accepted 16 September 2015

Printed in USA