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Thick Miocene eolian deposits on the Huajialing Mountains: The geomorphic evolution of the western Loess Plateau

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The geomorphic evolution of northwestern China during the Cenozoic has been a subject of much geological interest because of its link with the uplift of the Himalayan-Tibetan complex. Much information about these changes is recoverable from the sedimentary sequences of the region. We report here on the thick eolian deposits mantling the Huajialing Mountains, a relatively flat mountain range in the western Loess Plateau. Correlation of magnetic susceptibility stratigraphy with the QA-I Miocene eolian sequence dates a 134.7 m section (NL-VII) for the interval from 18.7 to 11.8 Ma, as confirmed by micromammalian fossils. These eolian deposits demonstrate a much wider distribution of the Miocene eolian deposits, and also indicate that the topography contrasts in the western Loess Plateau, including the uplifts of the Huajialing Mountains and the bedrock highlands in the Qinan region, were formed by the early Miocene. The near-continuous Miocene eolian sequence from 18.7 to 11.8 Ma indicates that the substratum of Huajialing had not experienced any intense tectonic changes during this time interval, which suggests further, the relative tectonic stability of the nearby Tibetan Plateau.

Miocene, eolian deposits, Huajialing, Tibetan Plateau, Cenozoic geomorphic evolution

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The Quaternary loess deposits of northern China have long been regarded to contain one of the best terrestrial records of Asian and global climates [1]. Identification and dating of the underlying eolian red clay in the region east to the Liupan Mountains, i.e., the eastern Loess Plateau, extends the eolian record in China to ~8 Ma [2, 3]. Investigations in the western Loess Plateau in the past 10 years have further extended the eolian history in China to the early Miocene [4–8]. In fact, the combination of these eolian formations provides a unique and near continuous climate record for the past ~22 Ma.

Eolian deposits require sizeable source regions to provide dust, circulation processes to transport dust, and moisture circulation to form paleosols. In accordance with this, the Miocene loess-soil sequences from the western Loess Plateau contain indications of the onsets of the Asian inland deserts and the monsoon-dominated climate by the early Miocene, temporally consistent with a major reorganization of climate patterns in Asia [5]. These prominent changes have been dynamically linked by numerical modeling to the uplift of the Himalayan-Tibetan complex [9–11], and/or to the retreat of the Paratethys Sea [10–12]. The presence of near-continuous eolian formations in northern China indicates that the inland deserts and monsoon-dominated climate in Asia have been constantly maintained since their

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formation around the Oligocene/Miocene boundary [5].

In addition to climate implications, eolian deposits are also good tracers of regional geomorphic or tectonic changes. This is based on two rationales: (1) the formation of loess requires a positive, relatively flat topography of the substratum that must be formed prior to the deposition of the overlying loess sequence; and (2) loess is extremely sensitive to erosion, such that any significant tectonic/geomorphic change would cause extensive erosion. Accordingly, investigations on the distribution, chronology and completeness of the eolian deposits from the various geomorphic units in the western Loess Plateau may provide reliable information relative to the geomorphic evolution of northwestern China during the Neogene. The latter would have a strong link with the uplift history of the Himalayan-Tibetan complex.

In the Loess Plateau west to Liupan Mountains, eolian deposits of Miocene age were reported from the intermontane basins on the southern slope (NL-VI) [8] and top (ML-V) [5] of the West Qinling Mountains, and in the Qinan region [4, 6, 7]. How they are distributed in the more northern regions remains to be addressed. However, we recently carried out investigations on the Huajialing Mountains (Huajialing) and found extensive eolian deposits mantling this mountain range. An examination of a representative section (NL-VII, 134.7 m thick) shows that these eolian deposits are of Miocene age, and that their magnetic susceptibility stratigraphy can be fairly correlated with the QA-I Miocene eolian sequence, at both over-orbital and orbital timescales. These provide helpful insights for understanding the Neogene geomorphic evolution of the western Loess Plateau, as discussed in this report.

1 General setting and methods

The Huajialing Mountains are a relatively flat rocky mountain range in the western Loess Plateau (Figure 1), with elevations varying between 2100 and 2500 m. It is usually regarded as the northern boundary of the 'Longzhong Basin'. It is tectonically within the southern part of the Qilian orogenic zone [17, 18], which is bounded in the south by the northern frontal fault zone of the West Qinling (NFFWQ) [13–15] near Wushan and Tianshui. The Haiyuan fault belt and NFFWQ are considered to be important boundary faults related to the northeastward growth of the Tibetan Plateau [19, 20]. Since the late Cretaceous, this region has been constrained by the southward rotation of the Ordos block and by the eastern lateral push of Qinling, resulting in strong compressive deformation, with a series of NW-SE oriented folds and faults [21].

The substratum of Huajialing is mainly composed of Variscan granite and metamorphic rocks of Sinian age [22], with a series of NW-SE striking compressional faults in the northeast, which separate the mountain from the Jingning Basin. Neogene eolian deposits of variable thickness mantle the flat parts of the mountains, and then are mostly covered with Quaternary loess.

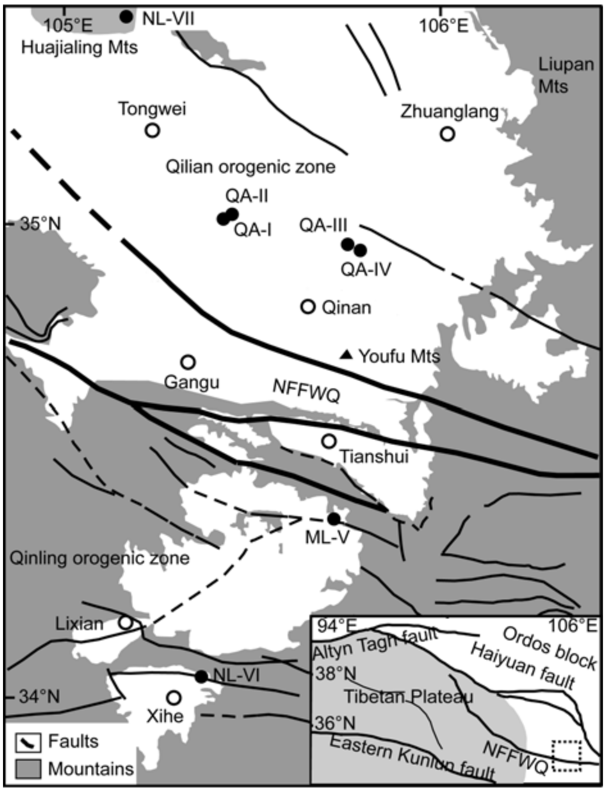

Figure 1 Maps showing the location of the NL-VII section and tectonic settings of the study region (drawn according to refs. [13–16]). The rectangle in the inset shows the scope of the main map. NFFWQ, northern frontal fault zone of the West Qinling.

A representative section (NL-VII, 35°26′N, 105°10′E) of these eolian deposits was established near Dongjiazhai, with an upper elevation of ~2170 m. From this location, it is ~51 km north to the QA-I site where the first Miocene eolian sequence was reported [4], and ~154 km to the southernmost NL-VI site [8] near Xihe (Figure 1). The section was described in detail in the field. Micro-mammalian fossils were collected for controlling the approximate age of the section. A total of 1347 bulk samples were taken at 10-cm intervals for measurements of magnetic susceptibility. Oriented samples were taken from representative soil and loess layers for the fabrication of microscopic thin sections. Particle analyses were carried out on 134 samples at 1-m intervals along the section to characterize the grain-size distributions. The analytical protocols and instruments are the same as described in ref. [4].

2 Morphology and grain-size features

The studied NL-VII section is characterized by clear alterations between paleosols and loess layers (Figure 2(a)). In total, 110 soils can be visually defined in the outcrop. Loess layers are massive in structure and mostly yellowish-brown in color (10YR 5/4-8) with thicknesses varying between 0.3 and 1.3 m. Paleosols have prismatic structure and mostly dark brown in color (7.5YR 3/2-4) with thicknesses varying between 0.3 and 1.0 m. The weathering (B-horizon) or argillic (Bt) horizons for most of the soils are underlain by a calcareous horizon (Ca), nodular or calcrete in form with high carbonate contents.

Microscopic examinations of samples from the loess layers show that the coarse fraction (>10 μm) mainly consists of quartz (50%–60%), feldspar and micas (>30%), followed by pyroxene, hornblende, goethite and hematite. The mineralogical composition of the coarse fraction is thus comparable with that of Pleistocene [1, 23] and Miocene loess from the other sites [4, 8]. All the quartz grains are angular (Figure 2(b)) with the particle size generally finer than 100 μm. This kind of angular grain morphology is characteristic of eolian dust particles [24]. The groundmass of the loess layers contains 4%–5% detrital calcium carbonate, as indicated by its random distribution. The porosity is dominated by channels. Some biotubules are also observed in the groundmass. Pseudomycelia of carbonate are seen under the microscope as hypo-coatings in connection with the channels (Figure 2(c)). These features, typical of pedogenic origin, indicate that the loess layers were significantly affected by pedogenesis, and thus confirm their subaerial deposition.

The mineral composition and grain morphology of the coarse fraction in the soil layers are identical to the loess layer, but the average grain-size is visibly finer. The groundmass of their B horizons is mostly free of detrital carbonate. The fine fraction (<10 μm) is brownish and contains abundant iron oxide or hydroxide particles, similar to those of Pleistocene paleosols. The porosity is dominated by channels. Secondary carbonate is frequently seen under the microscope as hypo-coatings, coatings and infillings in connection with the channels. Clay illuvial features, generally in the forms of intercalations, are observed for most of the soils, with the maximum content up to 5% (Figure 2(d)) in the lower section. The groundmass of the calcareous horizons is moderately or strongly impregnated by micritic carbonate leading to high carbonate content. These features confirm that the reddish layers are paleosols and can be classified as Luvisol [25] formed under semi-humid conditions.

The grain-size distribution of loess (Figure 3(a)) is bimodal, with the dominance of the silty fraction, as is similar to the Quaternary and Neogene loess samples from the other sites (Figure 3(b)). The median grain-size (Md) of the analyzed loess samples varies from 6 to 16 μm. The content of the >63 μm fraction accounts for a maximum of 6%, and 1.4% on average (Figure 3(c)). In the C-M plots (Figure 4), the loess samples from NL-VII, the Quaternary loess and the QA-I loess samples section distribute in parallel with the

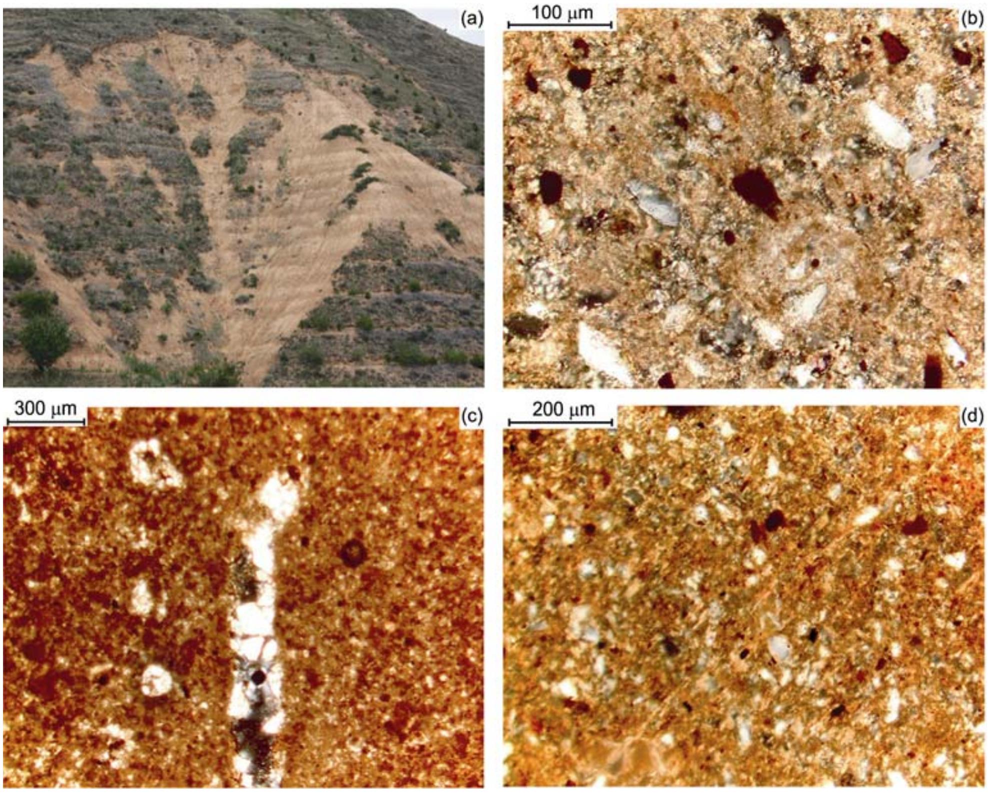

Figure 2 Field and micromorphological features of the NL-VI section. (a) Field picture of the NL-VII section; (b) morphology of mineral grains from loess (38.6 m depth, polarized light); (c) microscopic image showing calcitic infillings in channels (33.6 m depth, polarized light); (d) microscopic image showing clay illuvial features in a paleosol (110.4 m depth, polarized light).

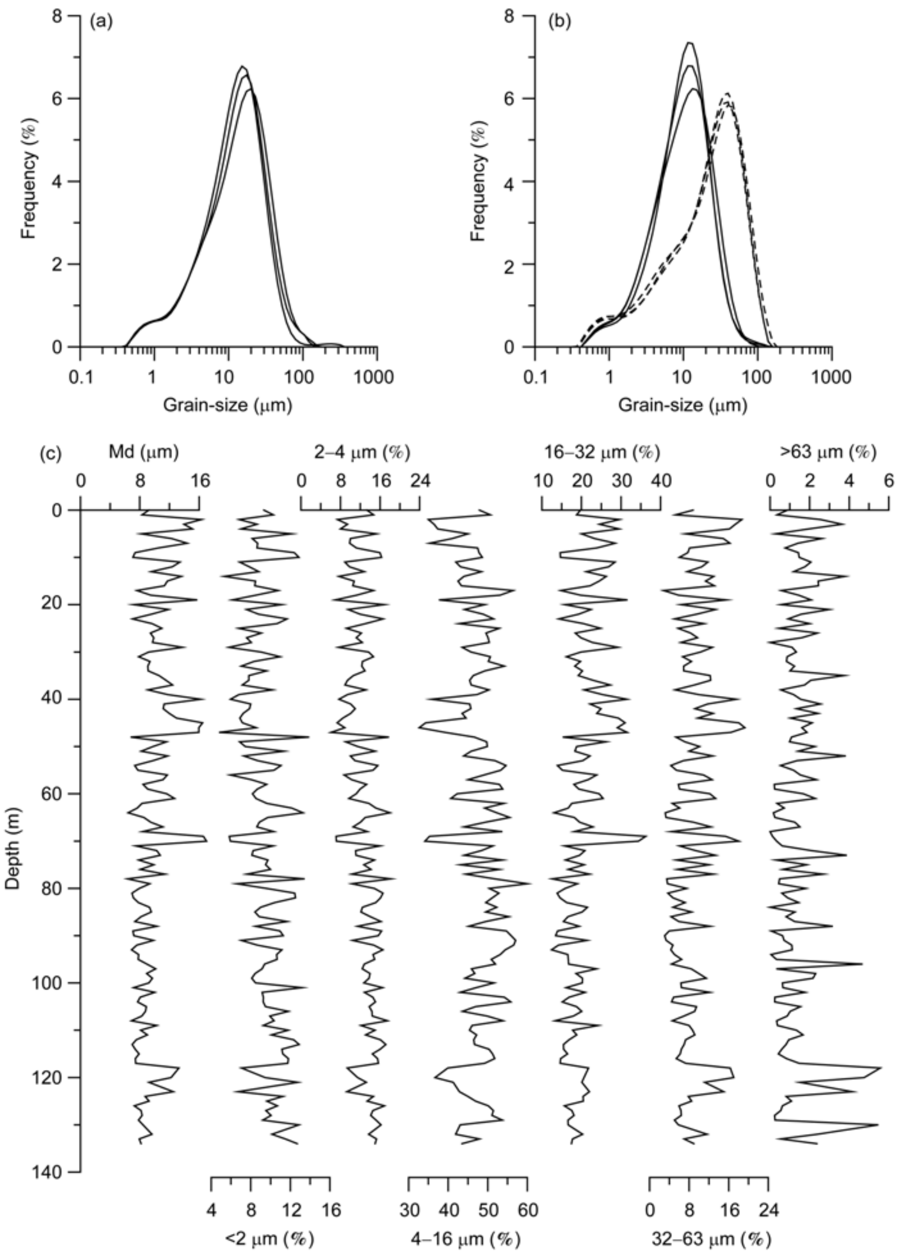

Figure 3 Grain-size features of the NL-VII section and comparison with eolian samples from the other sites. (a) Grain-size distribution of loess samples from NL-VII; (b) grain-size distribution of loess samples from the QA-I section [4] (solid lines) and the Quaternary loess section at Xifeng [4] (dotted lines); (c) median grain-size (Md) and contents of the different size fractions in the NL-VII section.

C=M baseline, also indicating an eolian origin for the NL-VII sequence.

The lithology, mineralogy, grain-morphology and micro-pedofeatures, therefore, confirm that the NL-VII section studied here is a typical loess-soil sequence.

3 Stratigraphy of magnetic susceptibility and chronology

The micro-mammalian fossils from NL-VII are listed in Table 1. *Alloptox gobiensis* and *Plesiodipus leei* at a depth of 42.1 m were mainly found in middle Miocene strata [26, 27] with an approximate age of ~14–12 Ma. *Tachyoryctoides* sp.1 and *Tachyoryctoides* sp.2 at depths of 76.1 and 100 m were reported inform the Aoerban Formation in Sonid Zuoqi in Inner Mongolia, with an early Miocene age (~19–16 Ma) [27]. They were correlated with MN3-MN5 in the European Neogene Mammal Chronology (ENMC) [28]. These fossils, therefore, suggest an approximate age of the NL-VII sequence ranging from the early to mid-late Miocene.

To date, six eolian sequences of Miocene age have been dated [4–8]. These include two pairs of parallel sections,

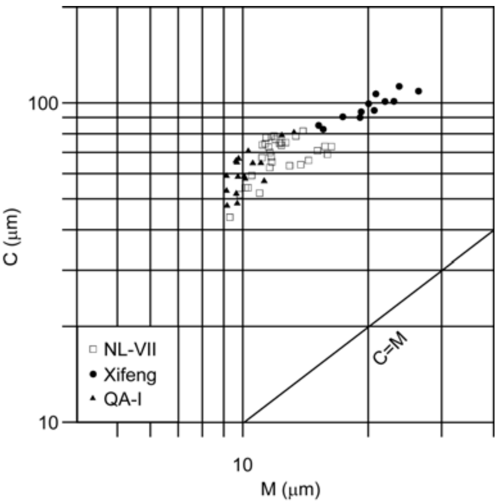

Figure 4 C-M plots of loess samples from the NL-VII, Xifeng Quaternary [4] and QA-I Miocene loess sections [4].

Table 1 Micro-mammalian fossil assemblages from the NL-VII section

Depth (m)	Fossil
42.1	*Alloptox gobiensis*
	Plesiodipus leei
75.2	Cervidae indet.
75.6	*Tachyoryctoides* sp.1
76.1	Erinaceidae indet.
78.6, 78.7	Ochotonidae indet.
100	*Tachyoryctoides* sp.2

QA-I/QA-II [4] near Guojia, QA-III [6]/QA-IV [7] near Lianhua, ML-V [5] from an intermontane basin in the West Qinling Mountains, and NL-VI [8] from the southern slope of the West Qinling (Figure 1). The magnetic susceptibility of these sections from different geomorphic units shows a high spatial correlativity [4–7], proving it a reliable tool for stratigraphic correlation. Susceptibility values are higher in soil layers than in the surrounding loess layers whereas the grain-size of the soil layers is finer than for the surrounding loess layers. This pattern is similar to that of Quaternary loess-soil sequences in northern China.

According to the well-dated Miocene sequences, the portion older than 18.3 Ma is characterized by moderate values of susceptibility with explicit cyclicity. This is followed by a low value interval from 18.3 to 17.1 Ma with lower fluctuation amplitudes. The interval from 17.1 to 16.7 Ma and that from 14.2 to 10 Ma have similar features overall to the portion older than 18.3 Ma. The most spectacular features are the high susceptibility values from 16.7 to 14.2 Ma with extremely large fluctuation amplitudes.

Variations of magnetic susceptibility in NL-VII display exactly similar features (Figure 5(a)). These provide several crucial time controls, and allow the construction of a preliminary timescale for the NL-VII section. Further refining of the timescale can be made through correlating some spectacular high/low peak values (Figure 5(c)), as well as their structure, to the QA-I time series of magnetic susceptibility (Figure 5(d)). The obtained timescale indicates an age span for the NL-VII section from 18.7 to 11.8 Ma. These are highly coherent with the chronology indication of the micro-mammalian fossils (Table 1), confirming the reliability of the timescale.

4 Paleogeographic implications

Our study thus defines typical Miocene eolian deposits

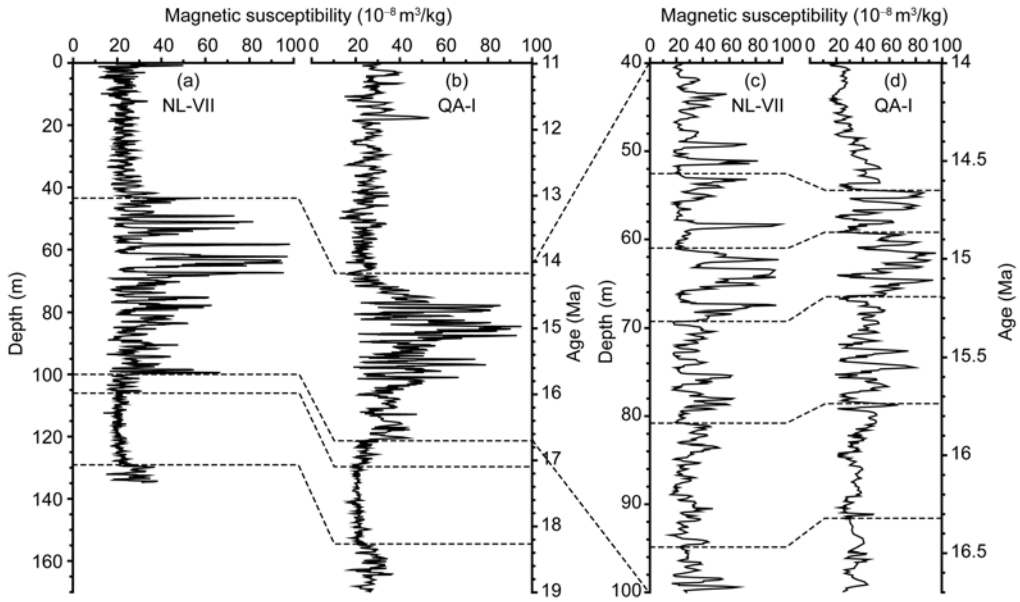

Figure 5 Correlation of magnetic susceptibility stratigraphy between NL-VII and QA-I. (a), (c) Magnetic susceptibility in the NL-VII section versus depth; (b), (d) the QA-I time series of magnetic susceptibility.

mantling Huajialing. Their magnetic susceptibility stratigraphy can be correlated, nearly at a cycle-by-cycle level, with the previously reported QA-I sequence. This demonstrates that magnetic susceptibility can be used as a reliable tool for stratigraphic correlations of the Miocene eolian deposits among well-separated sites. The presence of near-continuous eolian sequences on Huajialing has several implications for the Neogene paleogeography of the western Loess Plateau.

In addition to the previously reported sites from the Qinling Mountains [5, 8], Qinan region [4, 6, 7], the eolian deposits on Huajialing provide additional support for the widespread nature of eolian dust deposition in the western part of the Loess Plateau during the Miocene, with the inter-site distance between NL-VI [8] and NL-VII being about 154 km (Figure 1). They indicate that an embryonic Loess Plateau, covered by interbedded layers of reddish loess and soils, was already formed by the early Miocene in the region west of the Liupan Mountains. They further confirm the presence of sizeable deserts in inland Asia that acted as dust sources, and the existence of seasonally alternating monsoon circulations for dust and moisture transport since the early Miocene. Any local eolian sources would not produce such eolian deposits that are so extensive in both time and space.

The region west to the Liupan Mountains between the Qinling and Huajialing is usually referred to as Longzhong region, with Huajialing being its northern boundary. This vast region consists of three distinct tectonic/geomorphic units of Mesozoic origin, clearly defined in earlier studies [13–15]. These are the Qinling orogenic zone in the south (including the Xihe and Lixian intermontane basins), the NFFWQ including the Tianshui basin, and the Qilian orogenic zone in the north including the Qinan region (Figure 1).

The distribution of Neogene sediments in the region shows a high consistency with these tectonic settings, suggesting that tectonic reactivation during the Cenozoic has not significantly reorganized the spatial tectonic pattern. In the Qinling orogenic zone, the intermontane basins are filled with fluvial-lacustrine deposits whereas the highlands surrounding the basins are mantled by eolian deposits of Miocene (ML-V, 15.41–11.01 Ma) [5] and Miocene-Pliocene (NL-VI, ~10–4 Ma) [8] ages. In the Qilian orogenic zone, thick eolian deposits have mantled the bedrock highlands since the early Miocene, e.g., the QA-I (22–6.2 Ma) [4] and QA-II (21.6–7.6 Ma) [4], QA-III (19.6–11.35 Ma) [6] and QA-IV (18.5–11.6 Ma) [7], whereas the inter-ridge basins have been filled with fluvial-lacustrine sediments [29]. Because of the lower elevations, the zone of NFFWQ near Tianshui is mainly dominated by lacustrine-fluvial sediments and secondary (water-reworked) loess deposits [29]. These different geomorphic/sedimentary units are clearly separated by higher rocky ridges, such as the Youfu Mt. between the Tianshui basin and Qinan region.

The distribution of the Neogene sediments, therefore, indicates a clear control of the Mesozoic tectonic framework on the Neogene tectonic/geomorphic patterns of the studied region. They also provide strong evidence that the topographic contrasts of the substratum north of the NFFWQ, including the uplift of Huajialing and the formation of the bedrock highlands in the Qinan region, occurred by the early Miocene, because typical loess-soil sequences can only be formed on positive topographies.

In assuming a common basin setting for the Miocene, some authors [30] argued that the Longzhong Basin was filled with fan/distal fan and shallow lake deposits including QA-I with the Qinling or Huajialing being the source mountains of the sediments. This model [30] is strongly contrasted by the presence of sedimentary sequences similar to QA-I on the southern slope (NL-VI in the Yangtze catchment) [8] and top (ML-V) [5] of the Qinling Mountains, on the bedrock highlands near Qinan (QA-II, QA-III and QA-VI) [4, 6, 7] and on the top of Huajialing (NL-VII in this study), because mudflat/distal fan and shallow lake sediments cannot be deposited on their source mountains.

Clearly, their model [30] erroneously correlated deposits of different origins and small lateral extent into a fan-distal fan system due to the lack of necessary documentation of distribution, contacts, sedimentology and chronology. It was mainly based on some descriptions on remote fluvial-lacustrine sequences or reworked-loess near QA-I, but ignored extensive evidence for the presence of eolian deposits [4–8, 29, 31–36]. Their descriptions, as well as the visible evidence supporting the descriptions, are mostly ambiguous and confusing, because of the lack of location and depth information for evaluation. Consequently, they are hard to be considered an efficient basis for sedimentary geology interpretations. We have indeed documented the distribution of the different sediments in the studied region [29, 35]. The Neogene eolian sequences from the northeastern margin of the Tibetan Plateau [31] and Junggar Basin [36] beyond the Loess Plateau are also strong evidence against this model.

Although terrestrial water-laid deposits are also correlative, our reported long sedimentary sequences mantling the highlands of different geomorphic units and elevations (the southern slope [8] and top [5] of the Qinling Mountains, Qinan region [4, 6, 7] and top of Huajialing), highly correlative in lithology, chronology, magnetic susceptibility (Figure 5) and grain-size timeseries [5], can only be eolian in origin. In association with the fluvial-lacustrine sediments at lower topographic positions [29], they indicate a high variability of the Miocene topography in the Longzhong region. This is somewhat similar to the geomorphic complexity of the Quaternary Loess Plateau, with eolian deposits on highlands and subaqueous deposits in depressions. There has not been a common Longzhong basin at least since the early Miocene.

Because loess is extremely sensitive to erosion, the presence of near-continuous eolian deposits covering the interval from 18.7 to 11.8 Ma on Huajialing has also two other implications. First, this indicates the relative stability of the tectonic conditions for the substratum of Huajialing during this time interval, such that the NL-VII loess-soil sequence did not experienced significant erosion until the late Miocene. Second, the possibility of intense folding deformation of the substratum from the early Miocene to the present is ruled out. Otherwise, these thick eolian deposits would have mostly been reworked and/or eroded. The relatively stable tectonic environments of Huajialing from 18.7 to 11.8 Ma do not support intense uplift and growth of the northeastern Tibetan Plateau during this interval because of their proximity.

The present-day Huajialing is marked by hilly topography. The investigated hilly bodies around Dongjiazhai mainly consist of Miocene eolian deposits similar to NL-VII, mantled with incomplete Quaternary loess. Younger Neogene eolian deposits were not seen in the many investigated outcrops, although the possibility of their presence in some specific positions cannot be excluded. These indicate an event of loess erosion postdating the top age of NL-VII, ~11.8 Ma. Similar loess erosion around the late Miocene was observed for all the Miocene eolian sequences from the Qinling Mountains [5, 8] and the Qinan region [4, 6, 7], indicating its strong regional significance. We attribute this late Miocene loess erosion to the tectonic instability of the northeastern Tibetan Plateau at that time [37–39].

5 Summary

The examination of the NL-VII section that is representative of the thick Miocene eolian deposits mantling Huajialing in the western Loess Plateau has led to the following conclusions.

(1) Field and micromorphology features, grain-size properties and variations of magnetic susceptibility explicitly indicate an eolian origin for the studied sequence. Its magnetic susceptibility stratigraphy can be correlated, at a cycle-by-cycle level, with a previously reported QA-I sequence [4], dating the NL-VII sequence for the interval from 18.7 to 11.8 Ma, as is also confirmed by micromammalian fossils.

(2) The thick Miocene eolian deposits on Huajialing add new constraints on their widespread extent, and reconfirm their origin and significance concerning the distribution of inland deserts and monsoon-dominated climate since the early Miocene. They also indicate that significant topography contrasts in the western Loess Plateau, including the uplifts of Huajialing and bedrock highlands in the Qinan region, occurred by the early Miocene.

(3) The relative completeness of the NL-VII section indicates the relative stability of tectonic conditions of Huajialing from 18.7 to 11.8 Ma. This would not support intense uplift and growth of the northeastern Tibetan Plateau during this interval in view of their close proximity to each other. Significant loess erosion occurred around the late Miocene, postdating the most recent age of NL-VII, ~11.8 Ma. This is attributable to the tectonic instability of the northeastern Tibetan Plateau in the late Miocene.

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