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Late Cenozoic uplift of the Liupan Mountains: Evidence from the Neogene loess deposits

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Abstract The Liupan Mountains, one of the important mountain ranges in western China, are located on the boundary between the northeastern Tibetan Plateau and the Ordos Block. The uplift history of the Liupan Mountains remains controversial. Loess deposits are good tracers of regional tectonic and geomorphic changes, because loess is sensitive to erosion and the formation and preservation of loess requires relatively flat highlands and relatively stable tectonic environments. We investigated the distribution of Neogene loess deposits on the western piedmont of the Liupan Mountains and examined a near-continuous loess section (Nanping section) on the piedmont alluvial highlands. Correlation of magnetic susceptibility stratigraphy with the QA-Ⅰ Miocene loess sequence dates this 56-m section covering the interval from ~8.1 to 6.2 Ma. The lower boundary age of this section, together with previously reported Zhuanglang red clay (sand-gravel layers with intercalated loess during ~9–8 Ma and near-continuous loess during ~8–4.8 Ma) and Chaona red clay (~8.1–2.58 Ma), indicates that the Liupan Mountains were uplifted in the late Miocene (~9–8 Ma) and basically formed by ~8 Ma, attesting to no intense mountain building since that time. In addition, based on the information from the Zhuanglang core and the QA-Ⅰ section, we infer that sizable parts of the Liupan Mountains were uplifted during the late Oligocene–early Miocene and did not experience intense uplift during ~22–9 Ma.

Keywords Liupan Mountains, Mountain building, Neogene Loess, Chinese Loess Plateau, Late Miocene, Late Oligocene–early Miocene

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1. Introduction

The uplift history of important mountain ranges in China during the Cenozoic is a scientific question of broad interest because such uplift is related to deep and surficial Earth processes, as well as to climate evolution (e.g., Yin et al., 2002; Tang et al., 2012; He et al., 2019; Clinkscales et al., 2021; Yu et al., 2022). The Liupan Mountains, located on the boundary between the northeastern Tibetan Plateau and the Ordos Block, along with the Lüliang Mountains in the east,

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divide the Chinese Loess Plateau into western, central and eastern parts. The uplift history of the Liupan Mountains is of great significance to understand the expansion of the northeastern Tibetan Plateau (i.e., India-Asia-Pacific interaction), geomorphic evolution and Neogene loess deposits on the Chinese Loess Plateau, and evolution of the Yellow River system.

Numerous studies have investigated the uplift of the Liupan Mountains (e.g., Zheng et al., 2006; Wang et al., 2017; Wu et al., 2019). However, the uplift history of the Liupan Mountains remains uncertain. An early study based on analysis of geological structure suggested that deformation in the Liupan Mountains began in the late Pliocene–early Quaternary (Zhang et al., 1991). On the basis of aeolian red clay and fluvial-lacustrine sections in the Liupan Mountains region, Song et al. (2001) proposed that the Liupan Mountains underwent initial uplift at ~8 Ma and pronounced uplift since ~3.8 Ma. Shi et al. (2015) used fault kinematic analyses to infer significant mountain building since the late Miocene (~9.5 Ma). Studies based on provenance and sediment accumulation rate have suggested initial uplift at ~11.5–9.5 Ma (Lin et al., 2010; Wang et al., 2011; Wang et al., 2017). Other studies based on thermochronology have proposed that the Liupan Mountains underwent initial uplift-denudation and rapid cooling at late Miocene (~8 or ~7 Ma) (Zheng et al., 2006; Peng et al., 2019) or ~24 Ma (Yu et al., 2021). In addition, a study based on analyses of anisotropy of magnetic susceptibility has argued for mountain building during the early-middle Miocene (Wu et al., 2019). The possible reasons for these differences in timing include different study sites and methods, as well as different interpretations. Thus, a comprehensive review of previous results and more evidence are needed to constrain the uplift history of the Liupan Mountains.

Loess deposits are useful tracers of regional geomorphic changes or tectonic deformation. Dating of loess deposits could be expected to provide significant information regarding the chronology of substrate topography. This is based on two rationales: (1) in addition to a sustained source of dust and adequate wind energy to transport dust, the formation and preservation of loess requires a positive, relatively flat substrate topography (e.g., bedrock highlands and alluvial highlands) that must pre-exist the deposition of overlying loess deposits, based on the normal laws of stratigraphy; and (2) loess is loose and porous and extremely sensitive to erosion, such that any significant tectonic deformation or geomorphic changes would cause extensive erosion of loess (Guo et al., 2008; Zhan et al., 2011; Ge et al., 2012; Guo, 2017).

Therefore, the distribution and chronology of Neogene loess deposits mantling the Liupan Mountains may provide reliable information on its tectonic uplift. In this study, we investigated the distribution and chronology of Neogene loess deposits on the western piedmont of the Liupan Mountains and studied a representative Neogene loess section (Nanping section), combined with previously reported evidence, to constrain the uplift history of the Liupan Mountains.

2. Geological setting

The Liupan Mountains, a NNW–SSE-trending mountain range with elevations varying between 2000 and 2900 m, constitute a significant tectonic boundary between the northeastern Tibetan Plateau and the Ordos Block (Figure 1a). The Qilian Orogenic Belt is located in the western part, where numerous active strike-slip and thrust faults have contributed to the growth of the northeastern Tibetan Plateau, and the Ordos Block is located in the eastern part.

The Liupan Mountains region has undergone a long and complex geological evolution. During the early Cretaceous, a fault basin developed in this region along a localized area of extension (Shi et al., 2006). The region subsequently underwent tectonic inversion and long-term exhumation during the late Cretaceous–Paleocene (Li W et al., 2013; Liu et al., 2008). Following this exhumation, the region experienced an E–W-oriented extension and marked subsidence that resulted in the deposition of a thick tertiary sedimentary succession, which was followed by another stage (late Cenozoic) of intense folding that formed the Liupan Mountains (Li W et al., 2013; Peng et al., 2019).

Stratigraphic units exposed in the Liupan Mountains region range from the early Ordovician to the Quaternary, but Cretaceous and Tertiary strata form the most extensive outcrops (Figure 1b; Zheng et al., 2006). Lower Cretaceous sediments of the Liupan Shan Group, which overlie the pre-Triassic basement, are the most widely exposed units in the region and form the main body of the Liupan Mountains. The Liupan Shan Group comprises conglomerate, red sandstone, yellow/grey mudstone, grey limestone, and shale, with a total thickness of 3000–4000 m. Tertiary (Eocene to Pliocene) rocks unconformably overlie Cretaceous rocks and consist predominantly of reddish brown mudstone, siltstone, sandstone, and conglomerate (Gansu Geological Bureau, 1989; Zhang et al., 1991; Zheng et al., 2006).

3. Materials and methods

We conducted field investigations on the western piedmont of the Liupan Mountains to ascertain the distribution of Neogene loess deposits. A representative section (Nanping section; 35.22°N, 106.12°E) of Neogene loess deposits on piedmont alluvial highlands was established in Nanping Town of Zhuanglang County (Figure 1), ~5 km east of the

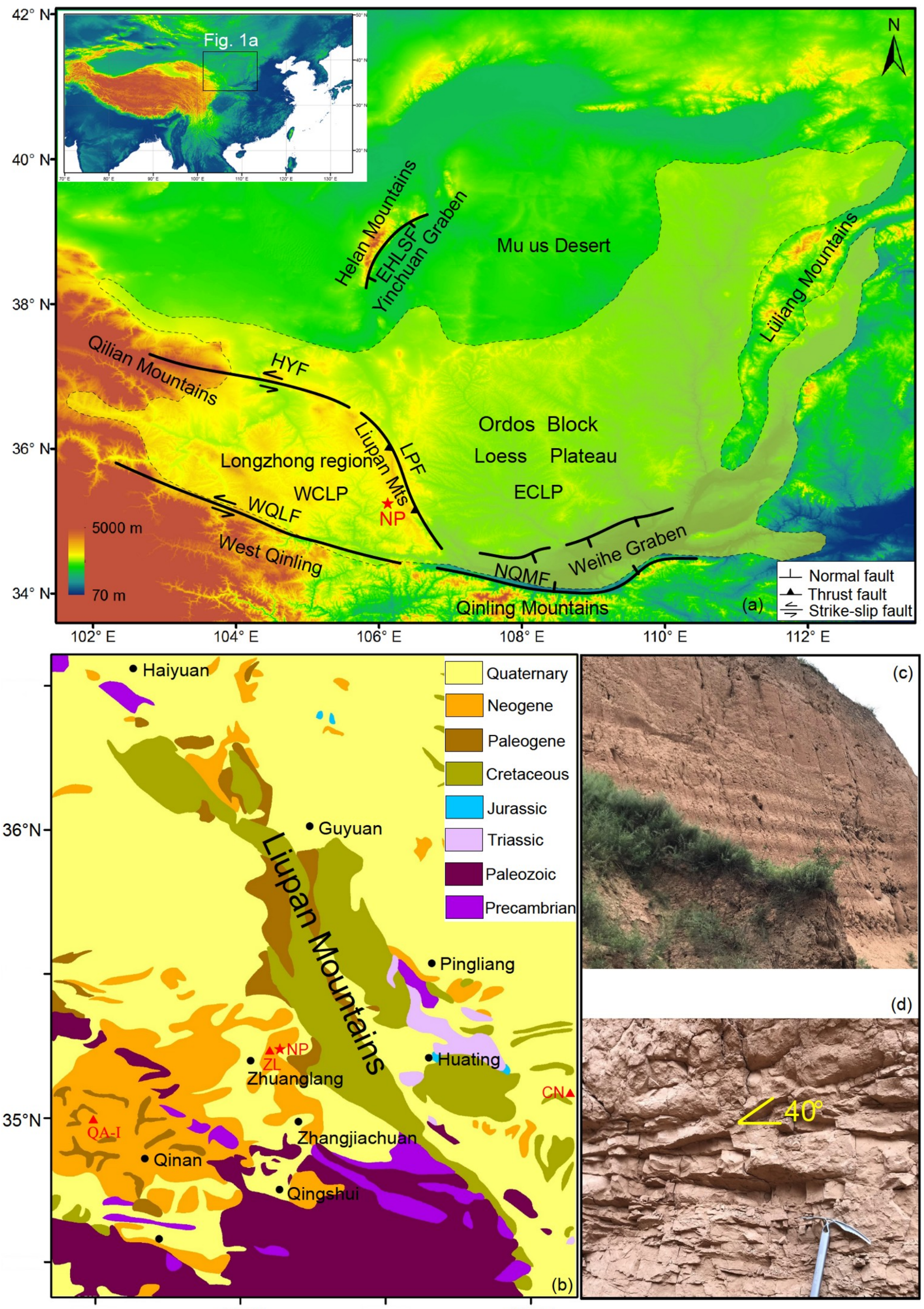

Figure 1 Maps showing the location of the Nanping section (NP) and geological setting of the study region. (a) Physiographical map showing the Liupan Mountains and the Chinese Loess Plateau. LPF, Liupanshan fault; HYF, Haiyuan fault; WQLF, West Qinling fault; NMQLF, northern Qinling margin fault; EHLSF, eastern Helanshan fault; WCLP, western Chinese Loess Plateau; ECLP, eastern Chinese Loess Plateau. (b) Geological map of the Liupan Mountains and its adjacent areas. NP, Nanping section; ZL, Zhuanglang core (Qiang et al., 2011), QA-Ⅰ section (Guo et al., 2002); CN, Chaona section (Song et al., 2001). (c) Field photograph of Nanping Neogene loess-paleosol sequence. (d) Field photograph of the alluvial highlands underlying the Nanping loess section, showing sedimentary beds dipping ~40° to the southwest.

Zhuanglang core site (Qiang et al., 2011) and ~60 km northeast of the QA-Ⅰ section (Guo et al., 2002). The Neogene loess strata are not deformed (Figure 1c), but the strata of alluvial highlands are deformed with an inclination of ~40° (Figure 1d). The Nanping section is composed of alternating reddish paleosol layers and light-brown loess layers. Considering the elevation of the loess ridge where the Nanping section is located and the exposed Neogene loess in the upper part of the opposite side of the gully, the complete Nanping Neogene loess-paleosol sequence is about 100 m thick, with several meters of Quaternary loess at the top. Samples were collected from a 56-m thick section in the middle-lower part of the Nanping loess sequence, but not from the ~40 m thickness of Neogene loess in the upper part of the sequence, which is basically covered by Quaternary loess and slope wash. A total of 560 bulk samples were taken at 10-cm intervals for the determination of magnetic susceptibility (χ), which were measured using a Bartington Instruments MS3 meter at a frequency of 470 Hz.

4. Results and discussion

4.1 Stratigraphy of magnetic susceptibility and chronology of the Nanping Neogene loess

To date, our research group has reported several Neogene loess-paleosol sequences from the western Chinese Loess Plateau, covering the interval from the early Miocene to the Pliocene (~22–3.5 Ma) (Guo et al., 2002, 2008; Hao and Guo, 2004, 2007; Liu et al., 2005; Zhan et al., 2011; Ge et al., 2012). These include QA-Ⅰ, QA-Ⅱ, QA-Ⅲ, QA-Ⅳ, and Dongwan sections near Qinan County, ML-Ⅴ section from an intermontane basin in the West Qinling, NL-Ⅵ section on the southern slope of the West Qinling, and NL-Ⅶ section in the Huajialing Mountains in Tongwei County. In addition, Qiang et al. (2011) reported Zhuanglang red clay (ZL core) from the western piedmont of the Liupan Mountains, seemingly covering the interval from ~25 to 4.8 Ma. The overall characteristics and variation trends of magnetic susceptibility of these loess sections from different geomorphic units are spatially correlative (e.g., Hao and Guo, 2007; Guo et al., 2008; Zhan et al., 2011), indicating that this indicator is a reliable tool for stratigraphic correlation.

Higher values of magnetic susceptibility are observed in paleosol layers of Nanping section compared with interbedded loess layers. Variations in magnetic susceptibility of the Nanping section display similar features to those of the QA-Ⅰ Miocene loess-paleosol sequence (Guo et al., 2002; Figure 2). The magnetic susceptibility of the upper 0–30 m segment of the Nanping section shows an overall decreasing trend, in which the 0–10 m segment exhibits high values and the 10–30 m segment exhibits low values with some fluctuations. Similarly, the interval for ~6.2–7.2 Ma of the QA-Ⅰ section follows a comparable variation trend, in which the ~6.2–6.6 Ma period (corresponding to the 0–10 m segment of the NP section) displays high values and the ~6.6–7.2 Ma period (corresponding to the 10–30 m of the NP section) exhibits low values. The variation in magnetic susceptibility of the 30–56 m segment of the Nanping section is similar to that of the interval for ~7.2–8.1 Ma of the QA-Ⅰ section (Figure 2). This stratigraphic correlation allows the construction of a timescale for the Nanping section. Accordingly, the Nanping section (56 m thick) spans the interval from ~8.1 to ~6.2 Ma (Figure 2). The inferred lower boundary age (~8.1 Ma) of the Nanping section is roughly consistent with that of the near-continuous loess deposited on thick sand-gravel layers in the upper part of Zhuanglang core, indicating that this inferred age is relatively reliable. Furthermore, with the addition of the upper ~40 m thickness of Neogene loess, the complete Nanping Neogene loess-paleosol sequence is about 100 m thick, which is approximately equal to the thickness of loess deposits in the upper part of Zhuanglang core for the interval ~8–4.8 Ma (Qiang et al., 2011), suggesting that age of the top boundary of Nanping Neogene loess-paleosol sequence is estimated as the early Pliocene (~4.8 Ma).

4.2 Neogene loess deposits mantling the piedmont of the Liupan Mountains

We conducted field investigations of the western piedmont of the Liupan Mountains and found Neogene loess deposits ~10–100 m thick on bedrock highlands or alluvial highlands in Qingshui, Zhuangjiachuan, and Zhuanglang counties (Figure 3). Of these deposits, the Nanping Neogene loess-paleosol sequence overlies the piedmont alluvial highlands in Zhuanglang. Our fieldwork indicates that the late Miocene loess strata are not deformed but that the underlying alluvial strata, which consist of reworked loess and sand-gravel, are deformed. To the west of Nanping section, Zhuanglang core consists of relatively continuous loess deposits in most part and several thick layers of sand-gravel with intercalated loess in lower (~25–22 Ma) and upper (~9–8 Ma) parts (Qiang et al., 2011; Figure 3b), indicating that the loess deposits were strongly eroded during ~25–22 Ma and ~9–8 Ma. On the eastern piedmont of the Liupan Mountains, previously reported Chaona section contains a continuously accumulated sequence of loess deposited since ~8.1 Ma (Song et al., 2001; Figure 3b).

4.3 Implications for the uplift and formation of the Liupan Mountains

In addition to climate implications, loess deposits have an indicative significance for regional tectonic/geomorphic changes. The formation and preservation of loess requires a pre-existing positive, relatively flat substrate topography (e.g., bedrock highlands and alluvial highlands) (Guo et al., 2008; Guo, 2017). Because loess is extremely sensitive to erosion, significant tectonic uplift or geomorphic changes would cause extensive erosion of loess and continuous loess deposits indicate relatively stable tectonic conditions (Zhan et al., 2011; Ge et al., 2012; Guo, 2017). In addition, previous studies have demonstrated that continuous loess deposits have been accumulating in the Loess Plateau since ~22 Ma (Guo et al., 2002; Guo, 2017). Therefore, the age of loess

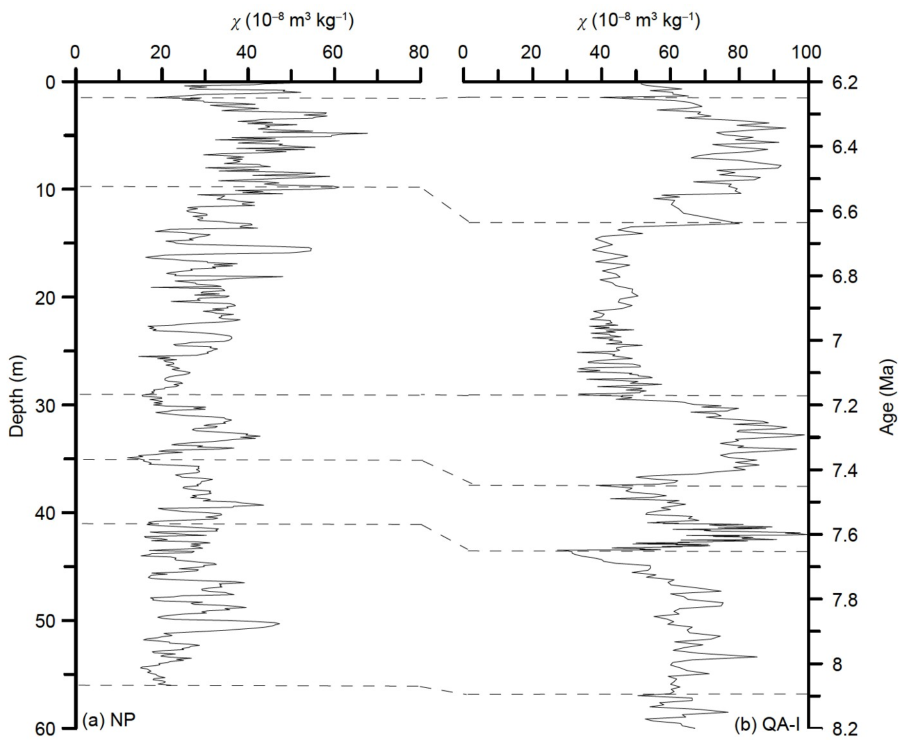

Figure 2 Correlation of magnetic susceptibility (χ) between (a) Nanping section (NP) and (b) QA-Ⅰ Miocene loess sequence (Guo et al., 2002).

deposits on alluvial highlands could be expected to provide valuable information on the timing of the formation of these highlands and therefore on the timing of associated mountain building processes.

The lower boundary age (~8.1 Ma) of the Nanping loess sequence on the western piedmont of the Liupan Mountains, together with the information from the Zhuanglang core (sand-gravel layers with intercalated loess during ~9–8 Ma and near-continuous loess deposits during ~8–4.8 Ma) and the Chaona red clay (~8.1–2.58 Ma) (Figure 3b), indicates that substrate topography (i.e., piedmont alluvial highlands) suitable for the late Miocene loess deposition was formed by that time (~8 Ma), implying that the Liupan Mountains were uplifted during the late Miocene (~9–8 Ma) and basically formed by ~8 Ma (Figure 4). The inferred late Miocene uplift of the Liupan Mountains is supported by other evidence (Zheng et al., 2006; Li Y et al., 2013). Apatite fission-track data of the northern Liupan Mountains suggest a rapid uplift-cooling event at ~8 Ma (Zheng et al., 2006). In addition, high accumulation rate and thick fluvial sands and conglomerates occurred at ~9–8 Ma in Huating section in an intermontane basin of the Liupan Mountains, implying uplift and erosion of the Liupan Mountains at ~9–8 Ma (Li Y et al., 2013).

Furthermore, we infer that the Liupan Mountains, especially the main body of the southern Liupan Mountains, underwent significant uplift during the late Oligocene–early Miocene and did not experience intense uplift during ~22–9 Ma (Figure 4) on the basis of the following arguments: (1) The lower part (~25.6–22 Ma) of Zhuanglang core, which unconformably overlies the Proterozoic bedrock, consists of the late Oligocene alluvium and overlying loess interbedded with thick layers of sand-gravel (Qiang et al., 2011), indicating significant uplift of the Liupan Mountains and erosion of loess during this period; (2) the middle part (~22–9 Ma) of Zhuanglang core consists of near-continuous loess deposits and nearly continuous loess sequences in the western Loess Plateau began at the earliest Miocene (~22 Ma) (Guo et al., 2002), indicating that the Liupan Mountains did not experience intense uplift during ~22–9 Ma and that uplift of the southern Liupan Mountains in the late Miocene was insufficient to cause intense erosion of the early-middle Miocene loess deposits; (3) thermochronological dating has suggested that a rapid uplift and cooling event in the southern Liupan Mountains commenced in the late Oligocene–early Miocene (Lin et al., 2011; Yu et al., 2021); and (4) detrital zircon U-Pb ages of samples from the Sikouzi section show that the late Oligocene–middle Miocene sediments were mainly from the southern Liupan Mountains, indicating that the southern Liupan Mountains probably initiated uplift in the late Oligocene (Wang et al., 2013). This is consistent with the suggested significant deformation and uplift of the northeast Tibetan Plateau in the late Oligocene–early Miocene (e.g., He et al., 2019; Yuan et al., 2007).

It was proposed that the Liupan Mountains underwent pronounced uplift during the Pliocene (e.g., Song et al.,

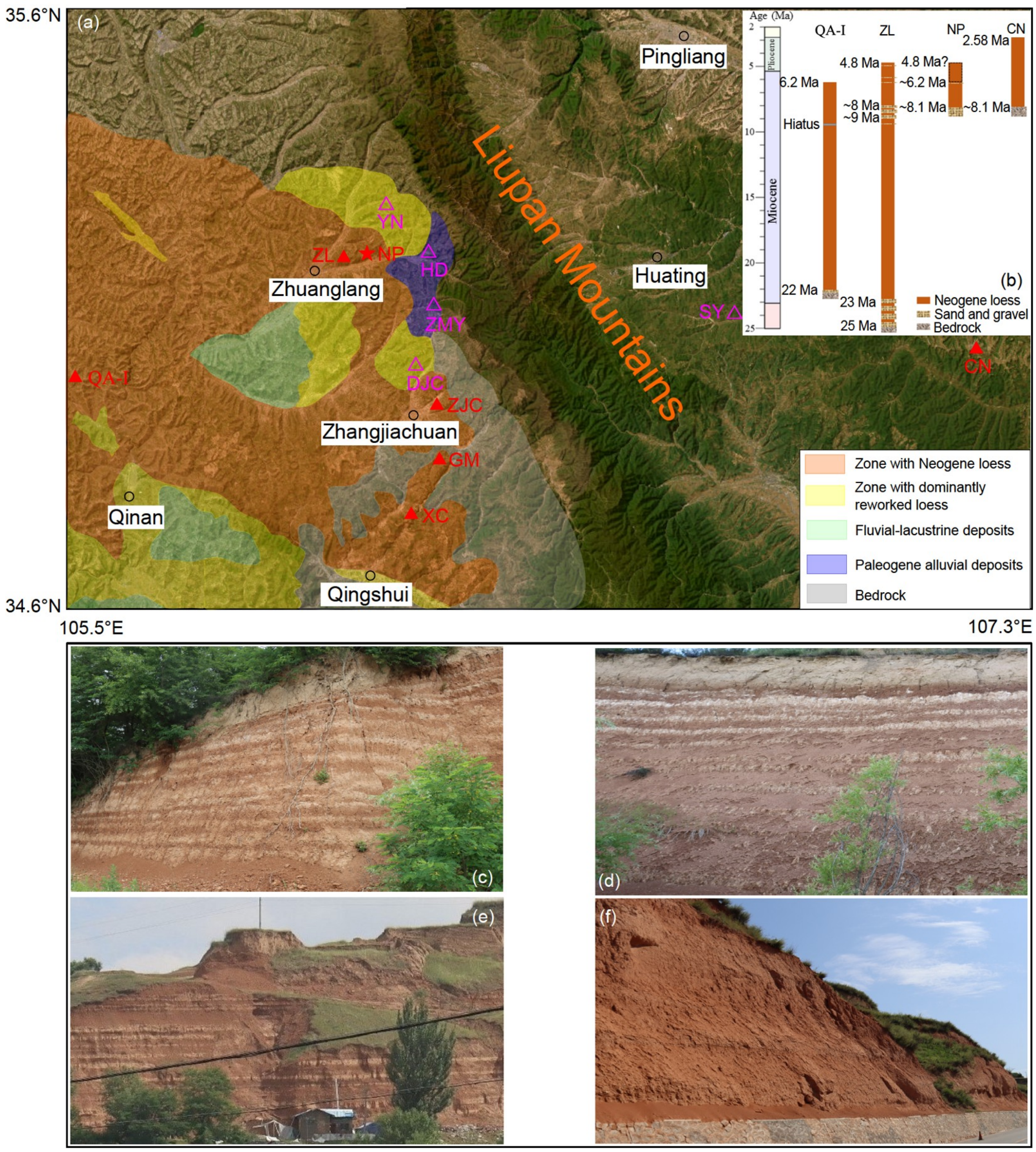

Figure 3 The distribution of the Cenozoic sediments in the Liupan Mountains region. (a) Google Earth image showing the Liupan Mountains and surrounding alluvial highlands. The distribution of Cenozoic sediments in the area to the west of the Liupan Mountains is modified from Figure 1 of Guo et al. (2010) on the basis of our field investigations. Neogene loess sections or cores: NP, Nanping section; ZL, Zhuanglang core; ZJC, Zhuangjiachuan section; GM, Gongmen section; XC, Xincheng section; CN, Chaona section. Alluvial sediments or reworked loess sections: YN, Yongning section; HD, Handian section; ZMY, Zhangmianyi section; DJC, Dongjiacun section; SY, Shenyu section. (b) Chronology and lithology of QA-Ⅰ, Zhuanglang core (ZL), Nanping section (NP), and Chaona section (CN). (c)–(f) Field photographs of Xincheng (c), Gongmen (d), Zhuangjiachuan (e) loess sections, and Zhangmianyi (ZMY) section (f).

2001). Our results do not support this view as such intense tectonic uplift would have caused destruction of the previously formed topographic pattern, surface denudation, and extensive erosion of loess deposits. However, the complete preservation of the late Miocene–Pliocene loess deposits, such as the Nanping section, the upper part (~8–4.8 Ma) of Zhuanglang red clay, and Chaona red clay (~8.1–2.58 Ma), which are near-continuous and undeformed. In addition, no new alluvial highlands were formed in the piedmont of the Liupan Mountains after the late Miocene, as evidenced by the Nanping section and Zhuanglang red clay being covered by the Quaternary loess. Moreover, there is no direct evidence of tectonic deformation indicating intense uplift of the NE Tibetan Plateau during the Pliocene (e.g., Zhang et al., 2006). These lines of evidence preclude the possibility of intense uplift of the Liupan Mountains during the Pliocene–Quaternary. Admittedly, there were some relatively small-scale tectonic activities during this period (Shi et al., 2015; Li et al., 2018).

The Nanping section and Zhuanglang core lack the late Pliocene–Quaternary loess, which is roughly consistent with the Neogene loess deposits (e.g., QA-Ⅰ and Dongwan sec-

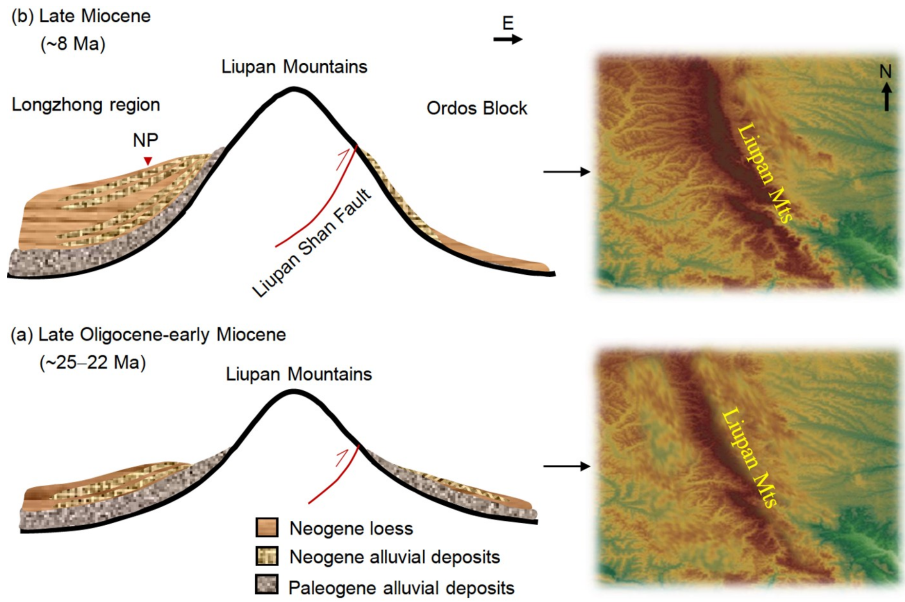

Figure 4 Schematic diagram of the Liupan Mountains uplift and the sedimentary patterns on both sides of the Liupan Mountains during the late Oligocene–early Miocene (a) and the late Miocene (b), based on previously published evidence (e.g., Guo et al., 2002; Qiang et al., 2011; Song et al., 2001).

tions) on the western Loess Plateau, whereas the Chaona section on the eastern piedmont of the Liupan Mountains has been accumulating loess deposits continuously since ~8.1 Ma. This probably indicates an erosion period in the western Loess Plateau during the Pliocene, potentially attributed to tectonic activity and/or climate change (Yuan et al., 2007). On the one hand, some small-scale tectonic activities still occurred in the Longzhong/Liupan Mountains region during the Pliocene (e.g., strike-slip activities; Shi et al., 2015). On the other hand, global cooling during the late Pliocene, characterized by the development of ice sheets, led to a significant drop in global sea levels by tens of meters (Miller et al., 2020), lowering the base level of erosion, and climate-vegetation changes in the Loess Plateau (i.e., a significant ecological shift at ~4.5–3.7 Ma, involving the reduction of forest plants and the formation of typical grassland and even desert steppe) (Guo et al., 1999; Wang et al., 2006). In addition, by the late Miocene, the western Loess Plateau had accumulated over 250 meters of Neogene loess and loess tablelands had been partially destroyed due to the erosion during this period, rendering loess deposits more susceptible to erosion. These combined factors likely lead to the intensification of river downcutting, gully erosion, and slope erosion in the western Loess Plateau, ultimately resulting in additional destruction of loess tablelands and formation of present pattern of loess ridges in the western Loess Plateau from the late Pliocene. The severely fragmented topography of the region since then has not been favorable for subsequent loess deposition.

The dynamics of uplift of the Liupan Mountains have commonly been attributed to the northeastward expansion of the Tibetan Plateau caused by India-Asia convergence (e.g., Guo et al., 2015; Wu et al., 2019; Tian et al., 2021). Additionally, Shi et al. (2015) proposed that the late Miocene tectonic activity of the Liupan Mountains region was controlled by the expansion of the Tibetan Plateau and partially influenced by the subduction of the Pacific plate. During the Neogene, several subduction zones formed in the western Pacific, and these subduction initiation events clustered around 10 Ma (Li et al., 2023), around the same time as the uplift of the Liupan Mountains. In addition, based on a global plate model, Liu et al. (2017) analyzed the influence of western Pacific subduction on northeast Asian deformation and the results showed that southwestern margin of the Ordos Block (i.e., Liupan Mountains region) underwent little stress and other margins of this block and northeast Asia underwent obvious extension during the Cenozoic. Geodynamic experiments further show that the subduction rollback of the Pacific plate plays an important role in Asian continental deformation, including Tibetan extension and eastward extrusion (Schellart et al., 2019), which could be conducive to the northeastward expansion of the Tibetan Plateau. Thus, we infer that convergence between Longzhong region and the Ordos Block generated the Liupan Mountains under the influence of a broad tectonic regime involving northeastward expansion of the Tibetan Plateau and subduction rollback of the Pacific plate.

5. Conclusions

To constrain the uplift history of the Liupan Mountains, we investigated the distribution of Neogene loess deposits in the Liupan Mountains region. We found ~10–100 m thick

Neogene loess deposits overlying bedrock highlands or alluvial highlands on the western piedmont of Liupan Mountains. We examined a Neogene loess section (Nanping section) mantling the deformed piedmont alluvial highlands of the Liupan Mountains. Correlation of magnetic susceptibility stratigraphy with the QA-Ⅰ Miocene loess sequence dates the 56-m section (Nanping section) for the interval from ~8.1 to 6.2 Ma.

The lower boundary age (~8.1 Ma) of the Nanping Neogene loess sequence, together with the data from the upper part of Zhuanglang core (sand-gravel layers with intercalated loess for the interval ~9–8 Ma and near-continuous loess deposits for the interval ~8–4.8 Ma) and Chaona red clay (~8.1–2.58 Ma), indicates that the underlying topography (e.g., piedmont alluvial highlands) suitable for loess deposition was formed at that time (~8 Ma), implying that the Liupan Mountains were uplifted in the late Miocene (~9–8 Ma) and basically formed by ~8 Ma, after which there was probably no intense mountain building. In addition, based on previously published evidence, we infer that the Liupan Mountains underwent significant uplift in the late Oligocene–early Miocene, especially the southern Liupan Mountains, followed by a relatively stable tectonic period during ~22–9 Ma.

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Conflict of interest The authors declare that they have no conflict of interest.

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