Rock magnetic and grain size evidence for intensified Asian atmospheric circulation since 800,000 years B.P. related to Tibetan uplift

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Abstract

Paleomagnetic, rock magnetic, and grain size studies of a thick loess sequence in the West Qin Ling (mountain range) show that loess deposition there began about 800 ka. The data reveal a progressively increasing coarse grain size fraction upwards into the Holocene. The averages of these coarse size fractions are higher than in the central Loess Plateau, which was apparently farther from the source area, and slightly lower than those of the western Loess Plateau and the eastern Tibetan Plateau, which were therefore closer to the source area. The coarsening and source area location suggest (1) that Asian air circulation may have changed and intensified at about 800 ka resulting in dust deposition in West Qin Ling; (2) that dust-carrying winds were driven not only by the Asian winter monsoon, but included also the westerlies and a winter monsoon caused by the Tibetan Plateau High, and (3) that intensification of all these air circulation systems continues to the present. Increased elevation of the Tibetan Plateau so that it reached into the cryosphere by about 800 ka and a subsequent persistent uplift of the plateau may have been the mechanisms to trigger a change and intensify the air circulation system. Moreover, this circulation shift and intensification, simultaneous with a shift in Milankovitch periodicity, may have contributed to large global climate changes such as the 15% increase in global ice volume at ca. 800 ka. © 1999 Published by Elsevier Science B.V. All rights reserved.

Keywords: Brunhes Epoch; Matuyama Epoch; loess, grain size; Asia; monsoons; circulation; Qinghai-Xizang Plateau; uplifts

1. Introduction

The Asian monsoonal circulation system is one of two key atmospheric systems that control much of northern hemispheric climate change, the other being the North Atlantic air–ocean circulation system.

Numerical modeling has demonstrated that initiation and evolution of the Asian monsoons are closely coupled to uplift of the Tibetan Plateau and that these monsoons have great influence on global climate change [1–3]. Knowledge of the long-term evolutionary history of the Asian circulation system, therefore, can provide important information to improve our understanding of ocean–continent air systems, the timing of the uplift of the Tibetan
Plateau, and the mechanisms that force Asian and global climate changes.

Large areas of Central and East Asia are covered by loess. These deposits offer a unique opportunity to trace past air circulation paths, because loess materials are transported and deposited by Asian winter monsoons and other coupled circulation systems of the westerlies and the Tibetan winter monsoon [4]. Grain size variation in loess has proven to be an excellent indicator for this purpose [4–8]. Spatial grain size variation within the Loess Plateau has clearly delineated three NE-oriented loess belts (the sand, silt and clay loess belts). The sequence of these belts indicates a principal NW wind direction, caused by a combination of Asian winter monsoons and the westerlies, with the loess derived from multiple Asian inland dust source areas [4]. In contrast, Tibetan loess is much coarser than that of the Loess Plateau, with grain-size analysis showing a westward-coarsening trend [5]. This demonstrates that the Tibetan loess was derived chiefly from glacial and peri-glacial source areas in the central and western parts of the Tibetan Plateau.

The relative abundance of coarse grains (>63 μm or >32 μm) has been demonstrated to be proportional to the strength of the wind and the intensity of the Asian winter monsoon [4,7,8]. Here, we use grain size evidence to explore the history of Asian air circulation during the last 800,000 years. Our sampling has been carried out in the Zhaodaisuogou loess section at Wudu in the Qin Ling mountains (Fig. 1) because of its large thickness and its location in an area that is sensitive to circulation change.

2. Geological setting and stratigraphy

The Qin Ling mountains, striking W–E, form an important natural boundary that divides temperate and subtropical zones in China and make up the southern boundary of the Loess Plateau. The study section is located at Wudu (104°55′E, 33°25′N) in southern West Qin Ling and is close to the north-eastern margin of the Tibetan Plateau to the west (Fig. 1). West Qin Ling has elevations ranging from over 3.5 km in the west to ca. 1.5 km in the east, rising about 1–1.5 km above the Loess Plateau (Fig. 1). Further east, in central Qin Ling, the altitude increases again to over 3 km. Thus, the east end of West Qin Ling is actually a wind pass as well as a divide between Jialing Jiang (River), a tributary of the Yangtze River (Chang Jiang), and Wei He, a tributary of the Yellow River (Huang He) (see Fig. 1). Modern winter air circulation patterns show that lower level (<3 km) northerly and northwesterly winds proceed southward only through the pass, and then enter the Bailong Jiang valley in the eastern Tibetan Plateau and West Qin Ling (see Fig. 1) from a southeasterly direction. In contrast, winds above 3 km are northwesterly throughout the map area [9]. The lower-level winds are generated mainly by the Asian winter monsoon driven by the Siberian–Mongolian High and by the northern branch of the circum-Plateau westerlies. High-level winds are derived from a combination of the Tibetan Plateau winter monsoon and higher levels of the westerlies [9–12] (Fig. 1, inset).

The study section at Zhaodaisuogou in Wudu is situated on the fourth terrace (T4) of the Bailong Jiang (River), a tributary of Jialing Jiang, and is one of the thickest loess sections in the West Qin Ling (Figs. 1 and 2). It consists of two parts, with the upper part consisting mainly of 55 m of loess, which contains 18 individual paleosols that can be grouped into 8 paleosol complexes (S0–S7), as well as a layer of debris flows in the middle (Figs. 2 and 3). Six thin reworked loess layers are observed in the sequence. The lower part consists of about 25 m of alluvial silt, alluvial gravels and debris flows.

The uppermost paleosol is a well developed, brownish dark (10YR 6/3-2) distinctive paleosol. At a depth of approximately 12–13 m, a second well developed brownish (7.5YR 6/4) paleosol complex is found. Between these two well developed paleosols is brownish yellow (10YR 7/3), coarse and loose Malan Loess (L1) and its four embedded weakly developed yellowish brown (10YR 6/4) paleosols. By analogy with other pedostratigraphic models [4,13–15], these paleosols are correlated with pedo-complexes S0, Sm, and S1 in the Loess Plateau (Figs. 2 and 3). Between 14 to 23 m three well developed soil complexes are correlated to paleosols S2 to S4 in the Loess Plateau (Fig. 3). At depths of 27 to 41 m the three best-developed paleosols of the section occur, characterized by clear horizons of Bt–Bk–C. The Bt horizon has distinct vivid brown colors (7.5
Fig. 1. Location map of the area near the Wudu section in Qin Ling (Mts.), with elevations and loess distribution. The inset shows the configuration of large landforms and wind streamlines at the 1500 m level (arrow-headed solid lines) and 5000 m level (arrow-headed dashed lines) during January (averaged for 1961–1970) [9]. The divergence of the westerlies into north and south branches at the west end of the Tibetan Plateau and convergence at its east end and in East China occurs for winds on the lower (1500) as well as the higher (5000 m) levels. The north branch of the westerlies passing around the plateau is largely responsible for the lower-level formation and intensity of several anticyclones (A) in the Asian inland, such as the Siberian–Mongolian High centered at 100°E, 50°N.

to 5YR 6/4, medium–fine granular structure, many clay channel coatings and infillings, abundant biologic remains, and very low contents of carbonate (8–0.5 wt%) [16]. In the Loess Plateau, paleosol complex S5 consists of three welded or individual soils that are the most strongly developed in the entire loess–paleosol sequence of the last 2.5 Ma [4,13–15]. We correlate the three most strongly developed paleosols in our section with the S5 complex of the Loess Plateau [16]. Consequently, the lowermost two paleosol complexes in our section are S6 and S7 (Fig. 3). Interspersed with these paleosols are loess layers L1–L8 (Figs. 2 and 3), including reworked loess, which is recognized by its weak bedding structure and transported soil relics.

3. Sampling and laboratory measurements

Paleomagnetic samples were taken in the Zhao–daisuogou section (T4) at 0.5–1 m intervals within the paleosol–loess sequence and at variable inter-
vals in lenses within the alluvial gravels and debris flows, wherever sampling was possible. One oriented block sample of $10 \times 10 \times 10$ cm was taken at each site (level), from which three to four oriented cubic sub-samples of $2 \times 2 \times 2$ cm were cut, yielding a total of 260 sub-samples. A parallel section on an older terrace (T7) was similarly sampled at Dazhaicun in Wudu, in order to confirm the location of the Brunhes–Matuyama boundary. Here a total of 520 sub-samples was collected. The Dazhaicun section is located near the Zhaodaisuogou section, but is about 200 m higher in elevation; the two sections have very comparable stratigraphies (Figs. 3 and 4).

Frequency-dependent magnetic susceptibility ($X_{fd}$) was calculated from measurements of bulk susceptibility using a Bartington MS2 susceptibility meter at low (0.47 kHz) and high (4.7 kHz) frequencies corrected for the weight of the sample and is expressed as a percentage of low frequency susceptibility [17]. The natural remanent magnetization (NRM) of the samples was measured using a DIGICO magnetometer and was demagnetized with stepwise alternating fields (AF) from 5 to 50 mT in ten increments of 5 mT at Lanzhou University. One sub-sample from each site in the lower part of the two sections was subjected to thermal demagnetization from 100 to 700°C in fifteen steps varying between 10 and 50°C, and measured with a 2G cryogenic magnetometer in a magnetically shielded room at the University of Michigan.

Demagnetization diagrams demonstrate that AF and thermal demagnetization on the same sam-
Fig. 3. Lithology, frequency-dependent magnetic susceptibility ($\chi_{fd}$), declination, inclination, and NRM intensity in the Wudu loess section at Zhaodaisuogou. The available age dates, obtained with $^{14}$C, thermoluminescence (TL) and optical stimulated luminescence (OSL) techniques, are shown next to the lithological column. The dashed lines indicate an anomalous intermediate magnetic direction obtained in thermal demagnetization. For the locations marked by asterisks, representative demagnetization diagrams are shown in Fig. 5.

A lower-coercivity or lower-blocking temperature component is removed by about 20 mT or 250°C, whereupon characteristic directions become clearly revealed in trajectories to the origin below 50 mT or 700°C (Fig. 5). While
thermal demagnetization shows a contribution of hematite (or maghemite?) to the remanence in the interval 580–700°C, most of the magnetization is removed in fields or temperatures that are rather characteristic of magnetite.

Paleomagnetic directions were obtained using principal component analysis for each sub-sample. Mean directions for each site were obtained by averaging the three or four sub-sample directions from each level. Site-mean declinations and inclinations are plotted alongside the stratigraphic column of Fig. 3.

Additional bulk samples were collected at similar intervals as for the paleomagnetic sites, but at increased intervals in soil horizons. Samples were divided into two portions. One portion was used to measure coarse (sand) size fraction $< 4 \phi (> 63 \mu m)$ by using a wet-sieve method. The other was prepared.
treated by H$_2$O$_2$ to remove organic matter and by calgon solution (3.3% sodium hexametaphosphate and 0.7% sodium carbonate) and subjected to 10 minutes of ultrasonic vibration to scatter fine particles (clays) for homogeneous emulsion. Then the emulsion was moved onto a Sedigraph 500ET laser sizer for analysis of fine grades (>4 μm). The system of Pettijohn [18] was used for grain size classification, which bins sand, silt and clay as particles <4 μm (>63 μm), 4–9 μm (63–2 μm) and >9 μm (<2 μm). Common statistic parameters (mean and sorting coefficient = standard deviation (σ)) were calculated by matrix methods [18].

4. Chronology

4.1. Paleomagnetic and rock magnetic stratigraphy

Stepwise AF- and thermal demagnetizations of loess and paleosols show that there are no clearly reversed directions observed in the upper 60 m of the Zhaodaisuogou section, although one sub-sample from a depth of 52 m in paleosol S7 has an intermediate (westerly and shallowly inclined) direction (Fig. 3). The oldest loess is L8 in this section and is still of normal polarity. Below L8, between 60 and 85 m, sampling was hampered by the poorly suited lithologies, but the few paleomagnetic directions obtained in this part (not shown) were all of normal polarity, with only one exception that has little credibility. In the parallel Dazhaicun section, sampled about 200 m higher than the Zhaodaisuogou section, on the seventh terrace (T7) of the Bailong Jiang at Wudu, the samples are reversed in the bottom 3 m in Paleosol S8 and Loess L9 (Fig. 4 and Fig. 5d). The Brunhes–Matuyama boundary therefore occurs in the lowermost part of L8 or the top of S8. We conclude that the loess–paleosol sequence (upper 60 m) on the terrace T4 at Wudu was formed entirely during the Brunhes Chron, in agreement with the pedostratigraphic division mentioned above and magnetostratigraphic determinations elsewhere for S1–S7 and L8 [4, 22, 23].

The frequency-dependent magnetic susceptibility ($\chi_{fd}$) of the sequence shows a clear magnetic en-

Fig. 5. Lower-hemisphere stereographic projection and orthogonal projections of progressive demagnetization results for representative samples of loess and paleosol from the T4 terrace, Zhaodaisuogou section (a–c), and from (d) the T7 terrace, Dazhaicun section, in Wudu, along with their respective intensity decay curves (e–h). Solid (open) symbols (in b–d) represent projections onto the horizontal (vertical) plane. The positions of the samples shown are marked by asterisks in Figs. 3 and 4.
hancement in the paleosols and sharp decreases in loess (Fig. 3), as has also been found elsewhere in China [17,19,23]. The reworked loess generally also shows higher values of $\chi_{rd}$ (Fig. 3). This may suggest that slope processes have caused an accumulation of some fine-grained magnetic minerals eroded from the upper part of the slope. Except for this minor deviation caused by the reworking of loess, the variation pattern of $\chi_{rd}$ in the section can be easily correlated with that of loess–paleosol sequences on the Loess Plateau [4,17] and with the nineteen MIS stages during the last 800 ka [24]. In summary, the evidence collectively indicates that the age of the bottom of the Zhaodaisuogou section is best placed at about 770 ka, whereas the somewhat older bottom part of the Dazhaicun section is reversely magnetized and estimated to be about 830 ka.

4.2. Radiocarbon and TL/OSL dating

Three bulk samples collected from the top and bottom of the Bw horizon of paleosol S0 and the top of paleosol Sm-1 were used for carbon dating on diffuse organics, yielding ages of 2 to 27 ka (Fig. 3). Five thermoluminescence (TL) and optical stimulated luminescence (OSL) samples collected at depths of 8 to 14 m yielded ages ranging from 54 to 141 ka (Fig. 3). Although the TL and OSL ages have large errors, they suffice to constrain the ages of the upper 14 m of section. Here, the youngest and second-youngest well developed paleosol complexes (S0 and S1), as well as the weakly developed (Sm) paleosol complex between them, are located with ages of about 2–10 $^{14}$C ka (S0), 91–141 ka (S1a and S1b) and 27–54 ka (Sm-1 to Sm-3), respectively (Fig. 3). These ages confirm our pedostratigraphic correlations and are further supported by a good correlation between the $\chi_{rd}$ data in our section (Fig. 3) and $\chi_{rd}$ records from the Loess Plateau [17,19]. Further, marine isotope-stage climatic records (MIS) confine the Holocene (MIS1), last interglacial (MIS5) and last mega-interstadial (MIS3) to ages of 0–12, 74–130 and 24–59 ka, respectively [20]. This, largely, agrees with our data. The radiocarbon and TL/OSL ages also guide age estimates for the lower parts of the section. Based on our ages, the inverse sedimentation rate of the late Pleistocene Malan Loess L1 and the Holocene loess L0 (Fig. 3) is calculated at ca. 75.8 years/cm, assuming no erosion. It has long been known that the Malan and Holocene loesses in China have higher rates of sediment accumulation than the older loesses below [4,13,14]. This is also true for deposits in the North Pacific Ocean [25]. On the central Loess Plateau (e.g., at the Heimogou section in Luochuan), inverse sedimentation rates of loess L1–L0 and loess between L1 and L8 at the Brunhes–Matuyama boundary (780 ka [21]) are ca. 74.5 and 166.3 years/cm, respectively [4]. On the western Loess Plateau (e.g., at the Jiuzhoutai section in Lanzhou), the corresponding rates are 23.9 and 58.9 years/cm, respectively [13,14], averaging to an increase in sedimentation rate by a factor of 2.35 for the Loess Plateau. Taking the same factor of 2.35 for the Wudu area, and subtracting the 5 m of debris flow in the loess section at Wudu, yields an age for the bottom of the Zhaodaisuogou loess section of ca. 770 ka. This estimate agrees well with the paleomagnetic results. Moreover, ages of paleosols S2–S7 estimated by this model are consistent with those on the Loess Plateau [4], suggesting a reasonable pedostratigraphic division for the lower part of the Wudu section.

5. Grain size results, and areal and vertical extent of the loess

The clay-size fraction is greater in paleosols and smaller in loess, while the sand-size fraction just shows the opposite tendency (Fig. 6). Not surprisingly this indicates a high degree of pedogenesis in paleosols. The fluctuation of clay-sized grains agrees well with the $\chi_{rd}$ curve. However, grain sizes of loess and paleosols in our section reveal two other striking characteristics. The first is that grain size shows a progressively coarsening upward trend since ca. 800 ka, especially if the debris flow intervals are discounted. Moreover, this trend appears to be somewhat accelerated since the last interglacial (74–130 ka [20]) (Fig. 6). The coarsening is manifested as an increase in the sand-size and coarse silt-size fractions (>32 $\mu$m, Fig. 6). This trend is equally well indicated by the plot of mean $\phi$ (Fig. 6).

The second characteristic that we observe is that the average grain size in the Wudu Brunhes-age
loess is larger than that in the central Loess Plateau, which is surprising given the closer proximity of the (lower-elevation) central Loess Plateau to Asian inland dust sources. Although stronger northwesterly winds would result in comparably larger grain sizes in the Qinling, such winds would have deposited even larger grains in the central Loess Plateau. This indicates that additional source areas may need to be identified. At Wudu, the average grain size is only slightly smaller than those in the western Loess Plateau and in East Tibet (Table 1), which suggests that these additional source areas may be located in the Tibetan Plateau. This last observation implies that there must have been a shift, either gradual or sudden, in the air circulation at about 800 ka that allowed different winds to bring coarser dust into West Qin Ling than to the central Loess Plateau.

A simple intensification of the previously existing air circulation system can not have accomplished this, for several reasons. First, as already mentioned, the central Loess Plateau is closer to Asian inland dust source areas and has a much lower average elevation than West Qin Ling (Fig. 1), so it would have received coarser loess in greater quantities than the Qin Ling. Second, the previously existing winter monsoon was chiefly transporting coarser dust near the land surface (<2 km) [9,12,26], so it would have been largely stopped by the higher-elevation West Qin Ling. Third, there are no likely local dust sources in West Qin Ling. The wind pass in the eastern end of West Qin Ling (Fig. 1) could have allowed dust from Central Asia (e.g., the Gobi Desert) into the area, as occurs today with the dominant low-level northerly winter winds, but this would only lead to

Fig. 6. Lithology and variation of grain size parameters (see text for explanation) in the loess–paleosol sequence of the Zhaodaisuogou section at Wudu.
Fig. 7. A model proposed for the air circulation resulting from Tibetan Plateau uplift at times (a) well before, and (b) largely after the Brunhes–Matuyama boundary at about 800 ka. Before 800 ka and after 2.5 Ma, the average height of the Tibetan Plateau is assumed to be lower than the threshold height of 3 km but higher than 1.5 km [12,33,45], so that lower-level flow passed mainly around the plateau, but higher-level (‘Main westerly’) flow passed directly over the plateau [44]. The north branch of the low-level westerlies was much weaker than at present and did not yet move in a south–southeasterly direction towards Central China. The Asian and plateau winter
Table 1
Average grain sizes of loess in Qin Ling and other parts of China

<table>
<thead>
<tr>
<th>Stratigraphy</th>
<th>Sand (wt% &lt;4 φ)</th>
<th>Silt (4–9 φ wt%)</th>
<th>Clay (&gt;9 φ wt%)</th>
<th>Mean (φ)</th>
<th>Sorting coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xuancheng (118.8°E, 31°N), Anhui Province, East China [28]</td>
<td>4.1</td>
<td>56.6</td>
<td>39.3*</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>ULL</td>
<td>3.1</td>
<td>45.1</td>
<td>51.9*</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>LLL</td>
<td>2.1</td>
<td>36.0</td>
<td>61.9*</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Luochuan (109.5°E, 35.5°N), Central Loess Plateau [4]</td>
<td>6.8</td>
<td>65.8</td>
<td>27.4</td>
<td>6.00</td>
<td>2.98</td>
</tr>
<tr>
<td>ULL</td>
<td>10.0</td>
<td>63.7</td>
<td>26.0</td>
<td>5.92</td>
<td>2.68</td>
</tr>
<tr>
<td>LLL</td>
<td>5.3</td>
<td>62.6</td>
<td>31.2</td>
<td>6.34</td>
<td>2.97</td>
</tr>
<tr>
<td>Wudu (105°E, 33.5°N), western Qin Ling (this study)</td>
<td>8.2</td>
<td>69.1</td>
<td>22.7</td>
<td>6.71</td>
<td>2.58</td>
</tr>
<tr>
<td>ULL</td>
<td>5.5</td>
<td>65.3</td>
<td>29.2</td>
<td>7.44</td>
<td>2.77</td>
</tr>
<tr>
<td>Lanzhou–Linxia (103.5°E 36°N), western Loess Plateau [14]</td>
<td>11.6</td>
<td>70.0</td>
<td>18.5</td>
<td>6.35</td>
<td>2.71</td>
</tr>
<tr>
<td>ULL</td>
<td>9.1</td>
<td>66.6</td>
<td>24.3</td>
<td>7.08</td>
<td>3.02</td>
</tr>
<tr>
<td>LLL</td>
<td>5.3</td>
<td>72.8</td>
<td>20.7</td>
<td>5.9</td>
<td>2.56</td>
</tr>
<tr>
<td>Eastern Tibetan Plateau</td>
<td>17.9</td>
<td>64.1</td>
<td>18.0</td>
<td>6.64</td>
<td>3.01</td>
</tr>
<tr>
<td>ULL (this study)</td>
<td>13.7</td>
<td>62.9</td>
<td>23.4</td>
<td>7.12</td>
<td>3.34</td>
</tr>
</tbody>
</table>


* Sizes >8 φ.

the deposition of thicker and older, not coarser, loess at the pass [27].

The areal and vertical extent of loesses of different ages provides another line of evidence for a shift in regional atmospheric circulation at ca. 800 ka. Loess deposited during the Brunhes normal-polarity Chron (hereafter called Brunhes loess) has a much wider distribution than loess deposited during the Matuyama Chron between 0.78 and 2.5 Ma [4,22, 23]). Matuyama-aged loess is confined to the Loess Plateau to the north of ca. 34°N in central North China (north of the double dotted line in Fig. 7a; see also fig. 2.1 in [4]), but Brunhes loess extends much farther to the southeast to the lower reaches of the Yangtze River and the coastal area of East China north of 30°N [4,28–30] and even into Japan [31] (Fig. 7b). The increase of dust influx into the northern Pacific Ocean since ca. 800 ka [32] may...
Table 2
Eastward changes in grain size of Malan Loess from the eastern Tibetan Plateau to West Qin Ling

<table>
<thead>
<tr>
<th>Locality</th>
<th>Latitude, longitude</th>
<th>Sand (&lt;4 ϕ) (wt%)</th>
<th>Mean (ϕ)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tibetan Plateau</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Henan</td>
<td>101°30’E, 34°20’N</td>
<td>34.5</td>
<td>5.80</td>
<td>This study</td>
</tr>
<tr>
<td>Luqu</td>
<td>102°40’E, 34°5’N</td>
<td>18.7</td>
<td>6.19</td>
<td>This study</td>
</tr>
<tr>
<td>Longmusi</td>
<td>102°30’E, 34°35’N</td>
<td>17.7</td>
<td>7.31</td>
<td>[5]</td>
</tr>
<tr>
<td>West Qin Ling</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tewo</td>
<td>103°13’E, 34°5’N</td>
<td>10.0</td>
<td>6.50</td>
<td>This study</td>
</tr>
<tr>
<td>Wudu</td>
<td>104°55’E, 33°25’N</td>
<td>8.2</td>
<td>6.71</td>
<td>This study</td>
</tr>
<tr>
<td>Huixian</td>
<td>106°5’E, 33°45’N</td>
<td>7.5</td>
<td>6.8</td>
<td>This study</td>
</tr>
</tbody>
</table>

The eastward decreasing grain sizes of Malan Loess can be traced from the westernmost location on the Tibetan Plateau (top) to the easternmost location in West Qin Ling (bottom).

also be related to this phenomenon. At the same time, at about 800 ka, loess began to be deposited at higher elevations than before, and high Asian loess appeared in Tibet at about 800 ka [33–36].

In the last 90,000 years, loess deposits show yet a further expansion, both horizontally and vertically. Malan and Holocene loess reaches 2–3° southward beyond the limits of the earlier Brunhes loess (to the combined solid–dotted line in Fig. 7b), has higher rates of deposition, is coarser in grain size, and is found at higher elevations than older Brunhes loess [4, 13, 14, 28–30] (Table 1). Modern dust distributions and historical records show dust storms reaching to 23.5°N in China in some cases, as well as southern Japan (e.g., at Chichijima at 27°N [4, 37, 38]. Malan and Holocene loess occurs up to 2.8 km in the western Loess Plateau and up to 2.9 km at the northern slopes of the West Qin Ling, whereas the maximum elevations of older Brunhes loess in these areas were 2.5 and 2.3 km, respectively. The younger loess is found to extend over a larger area in the Himalayas and Tibetan Plateau and adjacent southern Asia than older Brunhes loess [5, 33–36, 39, 40]. The latter area is presently controlled by the Tibetan monsoon, the westerlies, easterlies and Indian monsoon [9–12], a ‘Tibetan’ system that is very different from the air circulation system operating in Central and East China (Fig. 1 and Fig. 7b). Without the ‘Tibetan’ system, High Asian loess would not be deposited.

We argue that it is only because of this ‘Tibetan’ system that coarse dust could have been transported to West Qin Ling and other areas adjacent to the plateau. The higher-level winds of the Tibetan winter monsoon (Fig. 1 inset) pass over Tibetan sand-dunes, providing a ready source area in the western and central plateau, and over loess deposits in the eastern plateau [5, 41]. The mineralogical and chemical similarities between Tibetan, West Qin Ling and Lanzhou area loesses [5, 42, 43] and their eastward decreasing grain sizes (Tables 1 and 2), lend further support to this idea.

6. Discussion

The grain-sizes, and the changes in the temporal, areal, and vertical distributions of the loess in Asia, suggest that atmospheric circulation conditions changed at about the Brunhes–Matuyama boundary and further continued to intensify during the Late Pleistocene and Holocene. The change in grain size has been observed in the Qin Ling as well as the central and western Loess Plateau [4, 14, 23]. We argue that these patterns are due to changes in the orography of the Tibetan Plateau and 100 k-year orbital power dominating the paleoclimate. We will describe, in the following, a conceptual model that aims to explain them. Fig. 7 illustrates the conditions we hypothesize as prevailing well before and largely after the Brunhes–Matuyama boundary at about 800 ka, but we must note that we cannot be definitive about whether the transition was sudden or gradual.

Modern dust is transported by two important air circulation systems, as already mentioned. One is
the Tibetan monsoon, which, combined with the high-level westerly winds that pass over the plateau and the southern branch of the lower-level westerlies, deposits loess in Tibet and adjacent southern Asia [5,9–12] (Fig. 7b). The other system consists of the Asian winter monsoon and the northern branch of the westerlies, which deposit loess in Central and East China [4,9]. The existence of the two air circulation systems, of course, depends critically on the elevation of the Tibetan Plateau, and the first appearance of the Tibetan circulation system is a key to explain the observed features of Brunhes loess.

Theoretical studies have shown that a critical height exists that determines whether flow tends to go over or around the Tibetan Plateau [44]. When the elevation of the Tibetan Plateau is less than half the critical height, most of the flow tends to pass directly over the plateau, whereas when elevations are about twice the critical height (called ‘threshold’ below), much of the flow tends to go around it. Between these two elevations, flow will go over the plateau at the higher level and around the plateau at lower levels. Estimates of threshold height are complicated, but center around mean elevation values of about 3 km [44], which is also a threshold height for the plateau to become glaciated [45]. Studies of Tibetan glaciations have shown that the plateau reached the cryosphere at about 800 ka [33,45,46]. These observations and theoretical considerations are generally consistent with modeling using numerical GCMs (general circulation models), which show that without a Tibetan Plateau above a certain height, there would be no subtropical easterly jet and no Siberian High, whereas only a weak high would be found near the northern margin of the Tibetan Plateau (causing a much weaker Asian winter monsoon); in such a situation, the Eurasian landmass would be mostly influenced by smooth and weaker westerlies [1,2]. Kutzbach and his co-workers have further demonstrated that above a certain average elevation (‘critical height’) of the plateau, a circulation system is configured that begins to resemble, in general, that of today. It must be noted that their ‘critical height’, estimated as ca. 1.5 km, includes averaging of elevations between the plateau and adjacent areas, and so is low for the plateau proper. With further progressive uplift of the plateau, the system is linearly intensified, and when full uplift to ca. 2.6 km has occurred (again this is on the low side), a modern circulation pattern is fully established [2]. Refinements in this GCM modeling using more precise landform data [3], together with detailed past plateau monsoon records [46], have further demonstrated that the Tibetan Plateau monsoon develops in concert with the Asian monsoon, such that a stronger Tibetan High (depending on plateau height) enhances the strength of the Asian winter monsoon, as well as the intensity of the westerly and easterly jets. This means that the two systems are closely coupled and directly linked with uplift of the plateau.

Based on these models, we propose that uplift of the Tibetan Plateau above a critical threshold of some 3 km average height may have triggered a shift in air circulation in Asia, at about 800 ka, and, in turn, may have caused expansion of Brunhes loess to more southerly locations in China and facilitated the first appearance of the Tibetan loess.

Fig. 7a illustrates the situation as we envision it well before the Tibetan Plateau reached a 3 km threshold height. At that time, the Indian monsoon could move directly into and over much of the plateau during the summer, bringing moisture to the surface area of the plateau and the present-day dry areas to the north and east [47–50]. The plateau was then covered by forests and grass, with relatively low albedo. Few possible Tibetan source areas for dust existed, therefore, at that time. The main westerly flow ran directly over the plateau, resulting in weak Tibetan and Siberian Highs (compare their symbolized sizes in Fig. 7a,b), although at lower levels a weak diversion occurred, around the plateau to the north or south. This air circulation system could generate only small dust storms, and transport of dust would be limited in distance, as observed for the Matuyama loess (2.5–0.8 Ma), which is confined to the Loess Plateau north of about 34°N (Fig. 7a).

In contrast, after the plateau reached the threshold height, it began to force the main westerly flow to go principally around it [44] (Fig. 7b). This diversion of the westerlies causes (1) intensification of the Siberian and Tibetan Highs, (2) a strengthened westerly flow, with inherently increased instability, and (3) a much more south-directed orientation of the northern branch of the westerlies after its passage around the plateau [1–3,9–12]. This last charac-
teristic causes a displaced convergence of the two branches of the westerlies towards lower latitudes, e.g., towards the Yangtze River (Chang Jiang) north of 27°N (Fig. 7b), and changes the direction of the lower level flow of the Asian and plateau winter monsoons from eastward to southeastward. The increased instability of the westerlies facilitates the formation of cyclones and troughs in the middle and upper troposphere, which in turn create cold fronts and trigger a release of accumulated Siberian cold air masses that generate the dust storms of the Asian winter monsoon [9–11].

That the plateau reached the cryosphere at the same time at about 800 ka, may have further enhanced the processes described above. The disappearance of vegetation and increase in snow cover of the glacial and periglacial plateau environment during the Brunhes Chron must have increased albedo, produced cooler near-surface air, enhanced the Tibetan High during winter, and very importantly, created a large and new source area of dust. As a corollary, feedback mechanisms associated with the loss of heat and a strengthened Tibetan High will enhance global cooling, and enlarge the temperature gradient between high-latitude areas and the equator, thereby further strengthening the westerlies and the Asian winter monsoon.

In Tibet, stronger currents generated sand dunes and dust [41] and transported dust to eastern and southern parts of the plateau, as well as nearby areas such as West Qin Ling and the western Loess Plateau [5]. Continued Late Pleistocene uplift of the Plateau caused further intensification of the Asian air circulation system and aridity in enlarged Asian inland dust-source areas. We believe that this caused the grain size coarsening in the loess at Wudu and the further expansion of loess in the Late Pleistocene–Holocene (Fig. 7b).

If further research confirms the likelihood of this plateau–air circulation coupling model, the global cooling, enhanced seasonality, and magnified summer monsoons (well known to occur during interglacials [4,7,8]) or winter monsoons (during glacial intervals) [51] may have made important contributions to the increased global ice volume in the Mid-Pleistocene [52], approximately contemporaneous with the Milankovitch climatic periodicity shift at ca. 800 ka [53].

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References

Heavily cited works from various fields, including geology, environmental science, and climate studies, are referenced throughout the document. These works cover topics such as Quaternary dust-fall accumulation, paleoclimatic records, and the physics of blown sand and desert dunes. The references span a wide range of publication dates, indicating the document's comprehensive scope and depth in the field. The cited works range from well-known scientific journals to more specialized research papers, highlighting the interdisciplinary nature of the research.


