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Climatic implications of loess deposits from the Beijing region

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ABSTRACT: Variations in magnetostratigraphy, pedostratigraphy, grain size and magnetic susceptibility of the loess deposits near Beijing have been studied at two sections. The sections are about 400 km east of the main loess deposits in China, have a maximum thickness of 100 m and extend back to 1.1 Ma. The sequence consists of 14 loess–palaeosol couplets (S0-S14), which correlate well with sequences in the Loess Plateau. Susceptibility records from the sites near Beijing are comparable to the Xifeng, Luochuan and Baoji sections located in the middle part of the Loess Plateau; however, the down-core variations in the grain size in the Upper Lishi Formation exhibit some differences. The median grain size increases by about 25–30 μm from L4 to L2, with the sandy grains (>63 μm) increasing from 10–20 wt% to 40–50 wt% . This implies that the depositional environment of the dust sources in the Beijing loess section is different in some aspects from the Loess Plateau. The Beijing loess may have had a different dust source than the Loess Plateau. Copyright © 2001 John Wiley & Sons, Ltd.

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KEYWORDS: loess; Beijing; susceptibility; grain size; desert.

Introduction

Chinese loess is an important archive of climatic and environmental changes over East Asia during the Quaternary (Liu *et al.*, 1985; Kukla *et al.*, 1988; Liu and Ding, 1998; Kukla and An, 1989; Rutter *et al.*, 1990; An *et al.*, 1991; Ding *et al.*, 1992, 1994; Xiao *et al.*, 1995). The main body of information about Chinese loess stratigraphy and palaeoclimatology is from the Loess Plateau in the central part of northern China (Liu *et al.*, 1985; Kukla and An, 1989; Rutter *et al.*, 1990; Ding *et al.*, 1992). Studies during the last two decades have revealed that climatic cycles, represented by the loess–palaeosol alternations, are dominated by variations in monsoon circulation over East Asia, which show a coherent variability with respect to global ice-volume cycles (An *et al.*, 1991; Ding *et al.*, 1992, 1994, 1995). The loess deposits in the Loess Plateau commonly are believed to be derived from deserts west and/or north of the plateau (Liu *et al.*, 1965, 1982, 1985; Zhang *et al.*, 1994; Ding *et al.*, 1999). Thus the Loess Plateau and the deserts can be regarded as a coupled environmental system in terms of a sediment source and sink relationship.

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Previous studies have shown that loess deposits are widely distributed in China, within and beyond the Loess Plateau (Liu *et al.*, 1965, 1985). The study of loess deposits outside the Loess Plateau should enhance our understanding of loess depositional processes and palaeoclimatology outside the Loess Plateau, and the connection between the loess depositional regions and the deserts. However, little attention has been paid to the loess deposits beyond the Loess Plateau.

Here we investigate the loess deposits in the Beijing region. The Beijing region is an important site of loess deposition east of the Loess Plateau (von Richthofen, 1882; Andersson, 1939; Barbour, 1929; An and Lu, 1984; Liu *et al.*, 1985; Lu *et al.*, 1987). Based on magnetostratigraphic, pedostratigraphic and sedimentological approaches, a correlation between the loess near Beijing and that in the Loess Plateau is made here. In addition, palaeoclimatic implications and the connections with the desert source areas are also discussed.

Geological setting

The study area is located in the northwest part of Beijing, in the eastern part of North China (40°30′N, 115°10′E; Fig. 1). The mean annual precipitation is approximately 500–680 mm, and primarily occurs during summer. The mean annual temperature is approximately 8–12.1°C, with the highest temperature occurring during July and the lowest temperature in January. Geomorphologically, the Bejing region is marked by an alternation of mountains and sedimentary basins.

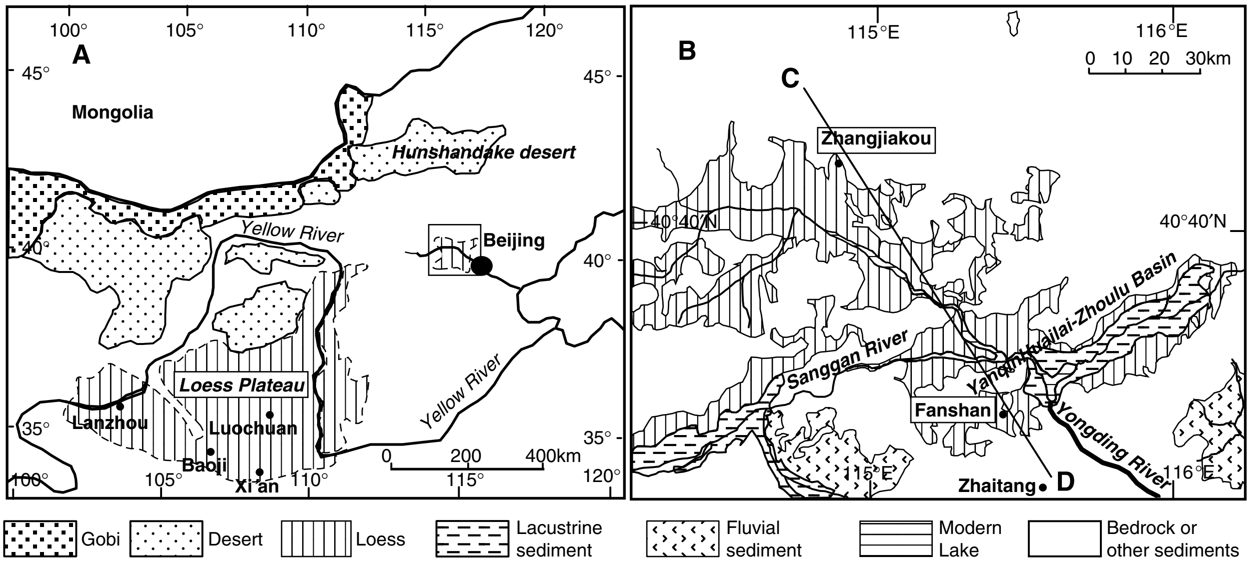

Figure 1 Location map for Beijing (A) with an inset map (B) showing loess distribution near the Beijing region (cross-section C–D is shown in Fig. 2)

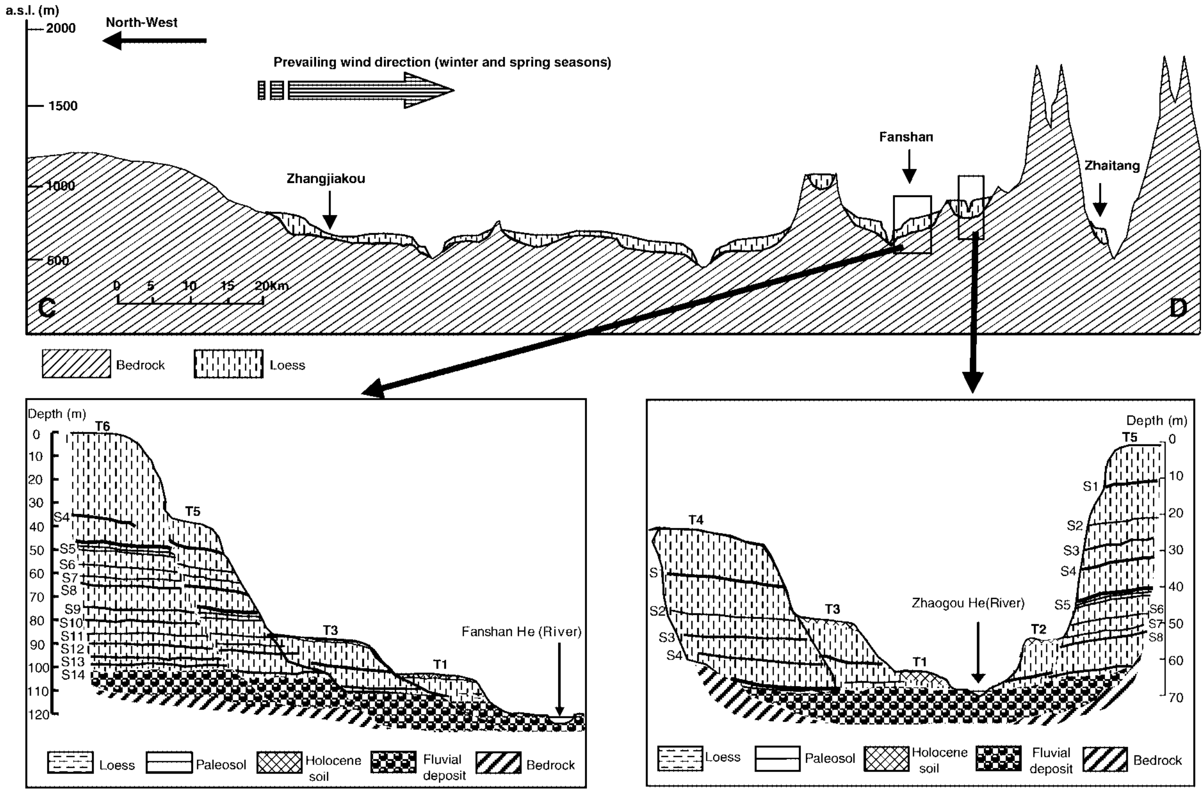

Figure 2 A transect from northwest to southeast across the loess deposits in the Beijing region

The largest basin is the Yanqin-Huailai-Zhoulu Basin (YHZ basin). The most proximal desert is the Hunshandake desert (21 400 km^2), which lies to the northwest.

The present margin of the Hunshandake desert is about 180–200 km northwest of the loess deposits in the Beijing region. Most of the sand dunes in the Hunshandake desert are inactive or have been anthropogenically reactived at present. Holocene sandy soils are present near the centre of the desert. However, during glacial periods the Hunshandake desert probably was covered by shifting dunes and was a source of dust for the loess deposits (Sun *et al.*, 1998). Six terraces have been recognised in the loess-covered area of the Beijing region (Fig. 2). These loess-mantled terraces can be used for reconstructing the history of the river aggradation and downcutting (Porter *et al.*, 1992). The terraces are designated T_1 to T_6, with the oldest one being T_6. The T_6 terrace is found on the margin of the YHZ basin. The top of this terrace is covered by loess units L15 to L1. Terrace T_5 also is found on the margin of the YHZ basin as well as adjacent to some river banks. It is covered by loess units S9 to S0. Terraces T_4, T_3, T_2 and T_1 are widely distributed, and are overlain by S5, S2, S1 and L1, respectively.

Typical loess features are observed in deposits 180–280 km southeast of the Hunshandake desert, whereas transitional aeolian sandy–loess deposits were observed about 90 km south of the desert. The loess occurs mainly on uplands along the piedmonts of the mountains and covers terraces of different heights. The loess is commonly about 10–20 m thick, with a maximum thickness of about 100 m. The loess deposits thin from the YHZ basin in the north towards the south. Loess sections were described and sampled at numerous localities on the oldest terrace (T6) in the Beijing region. The thickest loess deposit, the Fanshan section, is located in the southern part of the YHZ basin. This section consists of 14 loess–palaeosol couplets and is underlain by fluvial pebbly conglomerates. Other loess sections, including the Zhaitang section, located 70 km northwest of Beijing (the type section of the Malan Loess formation), also have been investigated.

Methods

The recognition of distinct palaeosol units has been used to differentiate the loess–palaeosol units in the Beijing sections (Rutter *et al.*, 1991; Ding *et al.*, 1992). The Si–Li system was used to label the alternations of palaeosols and loess (Liu *et al.*, 1985; Rutter *et al.*, 1991).

Palaeomagnetic measurements were made at the Paleomagnetism Laboratory, Institute of Geology and Geophysics, Chinese Academy of Sciences, with a 2-G three-axis cryogenic magnetometer; a total of 110 samples was measured. Some of the samples were thermally demagnetised at 50 °C steps up to 600 °C. Almost all of the samples obtained a stable magnetic component above 300–400 °C, and we used this demagnetisation level to determine the natural remanent magnetisation (NRM) directions for all the samples. Magnetic susceptibility was measured with a Bartington MS2 susceptibility meter.

Particle size distribution was determined with a Sald-3001 diffraction particle analyser after the samples had been ultrasonically treated in a 20% $(NaPO_3)_6$ solution.

Magnetostratigraphy and pedostratigraphy

The magnetic reversal stratigraphy of the Fanshan section is illustrated and correlated with the well-established geomagnetic polarity time-scale (Cande and Kent, 1995) in Fig. 3. The section covers the Brunhes normal and part of the Matuyama reversed polarity zone. The magnetic reversal sequence is similar to that determined previously at Luochuan (Heller and Liu, 1982; Liu *et al.*, 1985; Kukla and An, 1989), Xifeng (Liu *et al.*, 1987; Kukla and An, 1989), Xi'an (Zheng *et al.*, 1992) and Baoji (Rutter *et al.*, 1990; Ding *et al.*, 1993). The Brunhes–Matuyama magnetic reversal is observed in soil unit S8 (66.5 m). The upper and lower reversals of the Jaramillo subchron are assigned respectively within soil unit S9 (74 m) and S12 (88 m). A few data points apparently yield normal polarity above the Jaramillo (Fig. 3). This feature also can be seen in the magnetostratigraphy of the Baoji section (Rutter *et al.*, 1991); the normal polarity data points may be overprinted samples that have not responded to laboratory cleaning (Heller and Evans, 1995). By linear extrapolation, the age of the base of the Fanshan section is about 1.18 Ma.

Most of the sections are composed of the Malan Loess Formation and the Upper Lishi Loess Formation, whereas the Fanshan section consists of the Malan Loess, the Upper Lishi Loess and the Lower Lishi Loess.

The upper unit at Fanshan section is S0, termed the Black Loam, and has a maximum thickness of about 2–3 m. Owing to extensive agricultural activity, however, the unit generally is absent or only preserved as a residual layer at most localities. Typically, S0 exhibits a fine to medium granular to fine subangular structure, common to many rhizomyceliums, and contains rare to common root tubules (commonly <1 mm in diameter). Below S0 is the Malan Loess (L1). In the Beijing region, the Malan Loess is composed of silt and silty clay, with very weak pedogenic modification (Table 1). It exhibits a subangular blocky to very coarsely prismatic structure, rare to common rhizomycelium, and rare root tubules. No primary sedimentary structures have been

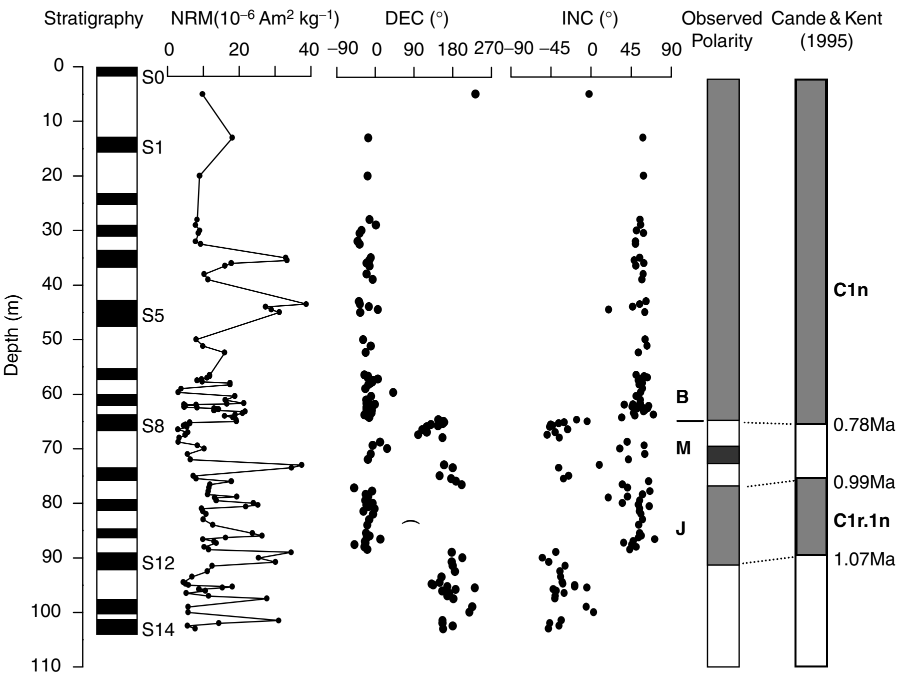

Figure 3 Pedostratigraphic column, magnetic polarity, natural remanent magnetisation (NRM), declination (DEC) and inclination (INC) of the Fanshan loess section

Table 1 Correlation of the pedogenic characteristics between the Beijing loess with the loess in the Loess Plateau (data are from Baoji (Rutter *et al.*, 1991; Ding *et al.*, 1993), Luochuan (Kukla and An, 1989) and Lanzhou (Chen and Zhang, 1993): A, clay skins (✱✱✱) and ferromanganese coatings (▲▲▲); B, carbonate nodules (◎◎◎), carbonate impregnation (⌒⌒⌒), gypsum crystals (✧✧); C, palaeosol color hue (➡➡ 7.5YR; ➡➡➡ 5YR)

	Beijing section			Baoji section			Luochuan section			Lanzhou section		
	A	B	C	A	B	C	A	B	C	A	B	C
Black Loam												
S0												
Malan Formation												
L1												
Upper Lishi Formation					◎◎◎			◎◎◎				
S1	✱✱✱ ▲▲▲		➡➡	✱✱✱		➡➡	✱✱✱		➡➡	✱✱?	⌒⌒⌒	➡➡
L2												
S2	✱✱✱		➡➡	✱✱✱		➡➡	✱✱✱		➡➡➡			➡➡
L3		◎◎◎						◎◎◎				
S3	✱✱✱		➡➡	✱✱✱		➡➡			➡➡		⌒⌒⌒	➡➡
L4		◎◎◎			◎◎◎			◎◎◎				
S4	✱✱✱ ▲▲▲		➡➡➡	✱✱✱		➡➡➡	✱✱✱		➡➡➡		⌒⌒⌒ ✧✧	➡➡➡
L5		◎◎◎						◎◎◎				
Lower Lishi Formation												
S5-1	✱✱✱ ▲▲▲		➡➡➡			➡➡➡	✱✱✱ ▲▲▲		➡➡➡		⌒⌒⌒	➡➡
S5-2			➡➡	✱✱✱		➡➡➡	✱✱✱					➡➡
S5-3	✱✱✱		➡➡	✱✱✱ ▲▲▲		➡➡➡	✱✱✱					➡➡
L6		◎◎◎			◎◎◎			◎◎◎				
S6	✱✱✱ ▲▲▲		➡➡	✱✱✱ ▲▲▲		➡➡			➡➡			➡➡
L7		◎◎◎						◎◎◎				
S7			➡➡	✱✱✱ ▲▲▲		➡➡➡						➡➡
L8		◎◎◎						◎◎◎				
S8	✱✱✱		➡➡	✱✱✱ ▲▲▲		➡➡➡	✱✱✱		➡➡		⌒⌒⌒ ✧✧	➡➡
L9		◎◎◎						◎◎◎				
S9			➡➡	✱✱✱ ▲▲▲		➡➡						➡➡
L10		◎◎◎			◎◎◎			◎◎◎			✧✧	
S10			➡➡	✱✱✱ ▲▲▲		➡➡						➡➡
L11		◎◎◎			◎◎◎			◎◎◎				
S11			➡➡	✱✱✱ ▲▲▲		➡➡➡						➡➡
L12		◎◎◎			◎◎◎			◎◎◎				
S12			➡➡	✱✱✱ ▲▲▲		➡➡						➡➡
L13		◎◎◎			◎◎◎			◎◎◎			✧✧	
S13	✱✱✱ ▲▲▲		➡➡	✱✱✱ ▲▲▲		➡➡➡	✱✱✱					➡➡
L14		◎◎◎						◎◎◎				
S14	✱✱✱ ▲▲▲		➡➡	✱✱✱ ▲▲▲		➡➡➡						➡➡
L15		◎◎◎			◎◎◎			◎◎◎			✧✧	

recognized in the Malan Loess. In the study area the Malan Loess is up to 12–15 m thick. The median grain size (Md) ranges from 35 to 50 μm, with a sandy loam to loamy loess texture.

The Upper Lishi Formation (Table 1) consists of four loess–palaeosol couplets (S1–L5) in the Beijing region. The loess within this formation is light yellowish brown to brownish yellow (10YR 6/4 to 10YR 6/6), and exhibits a coarse blocky to coarse prismatic structure, common to many rhizomycelium and rare to common root tubules. No primary sedimentary structures have been observed in the Upper Lishi Formation. There are four buried palaeosols in the Upper Lishi Formation, designated S1, S2, S3 and S4. The palaeosols typically are brown to strong brown (7.5YR 5/4 to 5YR 4/6), and exhibit fine prismatic to fine subangular blocky structure, rare to common rhizomycelium and rare to common root tubules. Units S1 to S4 are considered buried argillic horizons (Bt) with common, to many, clay skins. A layer of $CaCO_3$ nodules 30–50 cm thick is developed below S3 and S4.

The Lower Lishi Formation (Table 1) comprises 10 loess–palaeosol couplets (S5–L15) in the study region. The loess in this formation is strong brown to yellowish brown (7.5YR 5/6 to 10YR 5/6), with blocky to prismatic structure, rare rhizomycelium and rare root tubules. The palaeosols exhibit a yellowish red to dark brown colour (5YR 4/6 to 7.5YR 3/4), with prismatic to blocky structure, rare to common rhizomycelium and rare to common clay skins. Below most of the palaeosols, there is a layer of pedogenic $CaCO_3$ nodules with diameters of about 5–20 cm.

As in the Loess Plateau, the Malan Loess and Lishi Loess Formations are characterised by numerous buried argillic palaeosols with leaching of $CaCO_3$. The soil 'A' horizons are not well preserved in most cases, and below the Bt or Bw horizons, there commonly is a layer of $CaCO_3$ nodules, indicating leaching and transportation of $CaCO_3$ within the sequence. The most developed palaeosol, S5, however, has no layer of $CaCO_3$ nodules below the base, perhaps implying extreme pedogenesis. Some of the palaeosols are polygenetic. For example, S5 consists of three palaeosols, whereas S1, S2, S6 and S9 consist of two palaeosols. These features are similar to those observed in the Loess Plateau, and imply widespread and stable environments during these periods of time.

Variations in the climatic proxies during past 1.1 Ma

Last interglacial–glacial cycle

The Zhaitang section comprises the Malan Loess (Fig. 4) and soil unit S1 (the upper part of S1 was dated as 84 ± 9 ka by a thermoluminescence technique, Lu *et al.*, 1987). The grain size profile displays frequent oscillations superimposed on the trend of orbital-scale cyclicity, as evidenced in other loess sections (Liu and Ding, 1998) (Fig. 4). The median grain size of palaeosol S1 (equivalent to marine oxygen isotope stage (OIS) 5) and a poorly developed soil within loess L1 (marine OIS 3) is finer than 15 μm, whereas the sediments in L1 are coarser than 35 μm. The percentage of grains larger than 63 μm generally tracks the Md curve and demonstrates similar glacial–interglacial variability, with 0–10% >63 μm by weight in soils, and 15–30% in the Malan Loess. The variation in the >63 μm grains may be an indicator of proximity to the source (Ding *et al.*, 1999) in addition to variations in transporting wind speed and/or lack of pedogenesis. The magnetic susceptibility indicates enhanced pedogenesis during interglacial and interstadial periods (Liu *et al.*, 1988; Zhou *et al.*, 1990) (Fig. 4). At the same time, the proximal dust source areas also may have been influenced by the summer monsoon circulation and no longer provide a major part of dust particles to the downwind regions.

Last1.1 MA

The sequential variation of proxies in the Fanshan section is shown and correlated with the oxygen isotope record of ODP site 846 (Mix *et al.*, 1995) and orbitally tuned ages for Baoji loess (Ding *et al.*, 1994) (Fig. 5). In general, the variation in magnetic susceptibility tracks the loess and palaeosol alternations, with palaeosols corresponding to the peaks and the loess to the troughs. No long-term trends, or shifts in the overall mean, are displayed in the susceptibility record. Over the past 1.1 Ma grain sizes are larger in loess units than in palaeosols. A notable trend is that the median grain size (Md) and the percentage of coarse grains (>63 μm) increases abruptly from the lower part to the upper part of L3, corresponding to about 265 ka by correlation with the oxygen isotope record of ODP site 846 (Mix *et al.*, 1995) and the age model of the Baoji loess (Ding *et al.*, 1994). The median diameter of loess from L15 through L4 is about 20–30 μm,

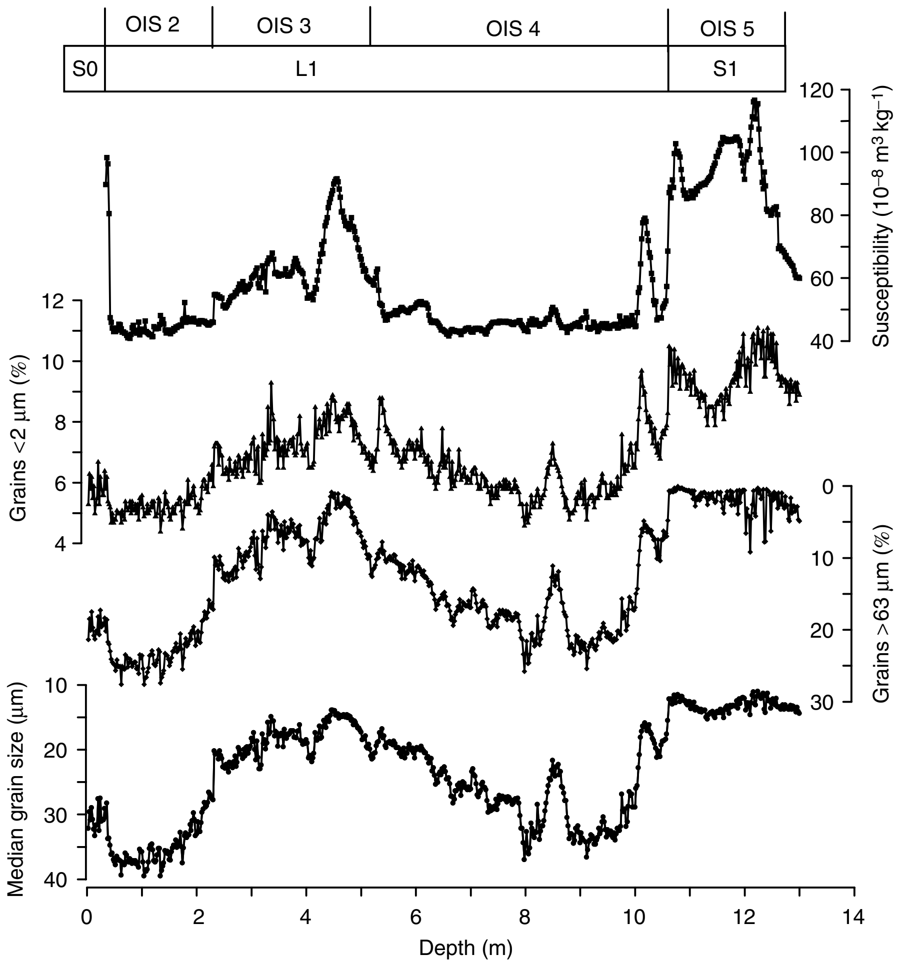

Figure 4 Variations in magnetic susceptibility and grain size during the last interglacial–glacial cycle in the Zhaitang section

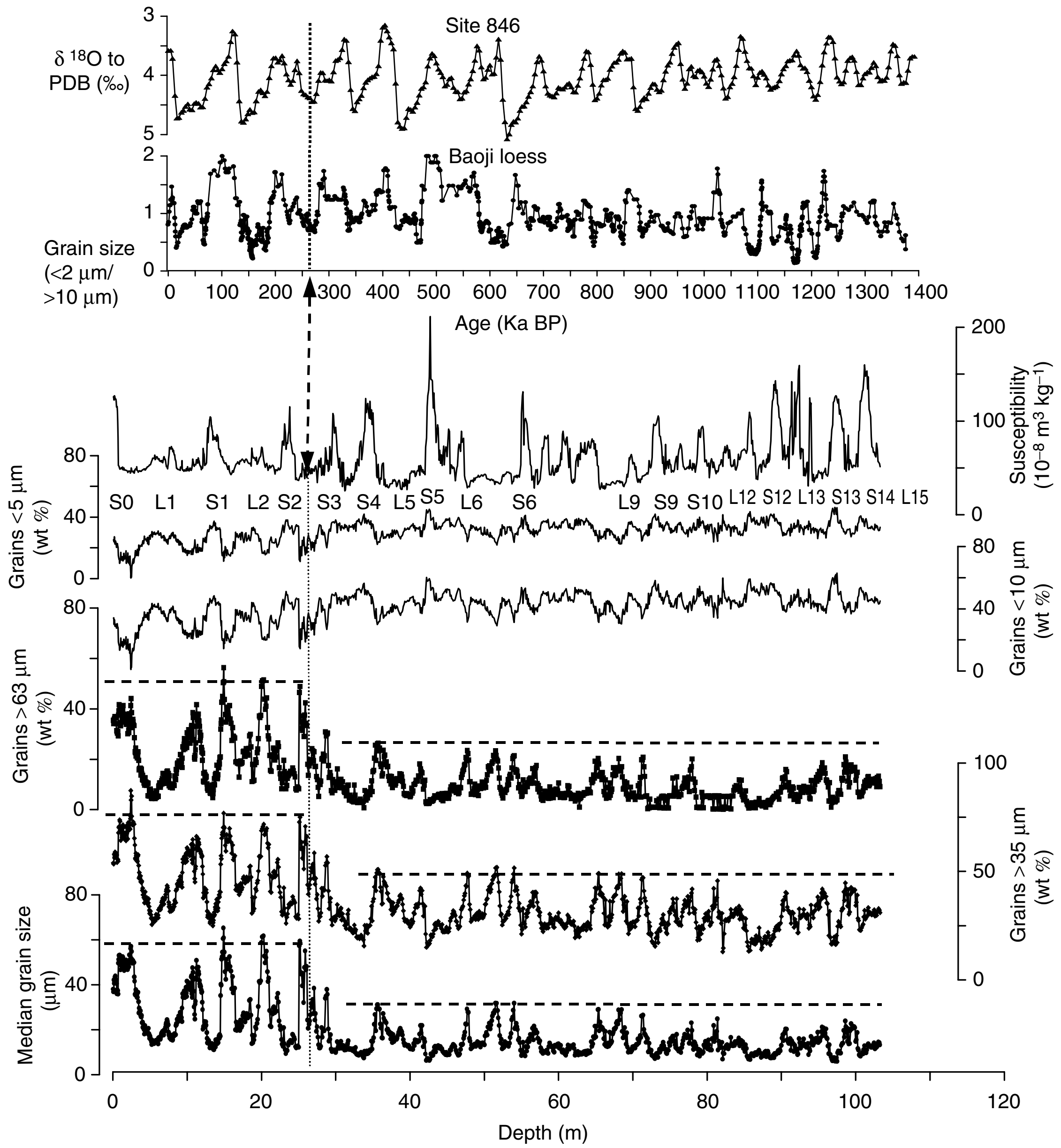

Figure 5 Correlation of the susceptibility and grain size of the Fanshan loess with oxygen isotope data for ODP site 846 (Mix *et al.*, 1995), © Ocean Drilling Program. Reproduced with permission; and the orbitally tuned ages for the Baoji loess section (Ding *et al.*, 1994). © Elsevier Science. Reproduced with permission. An abrupt shift in grain size is observed at 265 ka and is marked with a dashed line

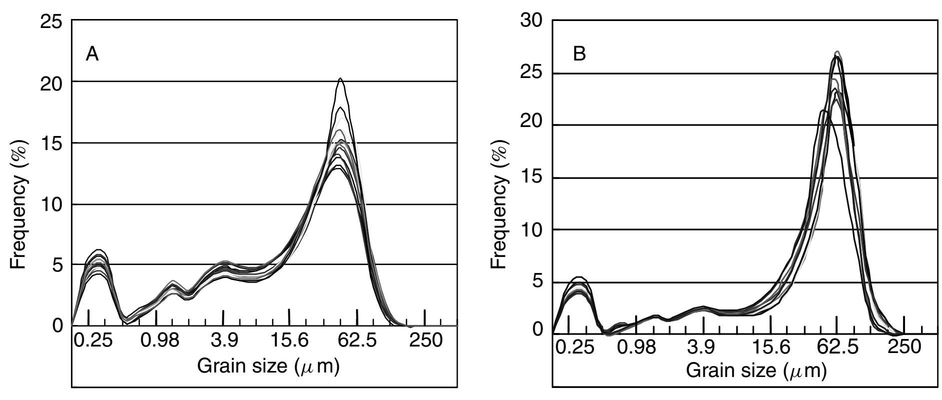

Figure 6 Typical grain-size distributions of the loess before (A) and after (B) the abrupt shift in the grain size throughout the Fanshan loess section

whereas from L3 to L1 it is 45–60 µm. The percentage of the grains >63 µm increased at the same time from 10–20 wt% to 40–50 wt%.

Before and after the abrupt shift the grain-size distributions have changed. Below L3, typical distributions of grain size are finely skewed with a modal size of about 44 µm.

Above L3, the distributions is characterised by a modal size of 62.5 μm (Fig. 6). For palaeosol horizons, the grain-size distributions are similar from the top to the base in the Fanshan section.

Correlation with Luochuan, Lanzhou and Baoji sections

Thickness of loess and pedogenic intensity in palaeosols in the Beijing region are similar to corresponding loess units and palaeosols at sites in the Loess Plateau.

The thickness of the loess–palaeosol couplets in the Beijing region seems similar to that in the middle part of the Loess Plateau, but is thinner than that in the Lanzhou section (Chen and Zhang, 1993). For example, the Lishi Loess Formation in Beijing (S5–S14; L15 is not preserved) is about 60 m thick, slightly thicker than that in the Baoji (S5–S14, 46.9 m; Rutter *et al.*, 1991; Ding *et al.*, 1992, 1993) and Luochuan sections (S5–S14, 38.6 m; Liu *et al.*, 1985; Kukla and An, 1989), whereas in the Lanzhou section it increases to 134.7 m (S5–S14). The thickness of the Malan Loess Formation in the Beijing region is about 12 m, slightly thicker than that in the Baoji section (6.8 m) and Luochuan section (8 m), but much thinner than that in the Lanzhou section (51.5 m). It seems that the average loess deposition rate in the Beijing region is similar to that in middle part of the Loess Plateau.

A comparison of the pedogenic properties of the palaeosols between the Beijing section and other sections in the Loess Plateau was undertaken and is shown in Table 1. The Beijing section compares well with the Baoji and Luochuan sections in the following aspects:

1 there is an apparent decreasing trend in pedogenic development from S5 to S1, based on the development of the clay skins and the variation in magnetic susceptibility;
2 the pedocomplexes, S5 and S2, are composed of three and two subunits, respectively—for S2 the upper subunit is more strongly developed than the lower subunit, for S5 the most developed subunit is S5-1 whereas S5-2 is the most poorly developed and S5-3 is moderately developed;
3 the Bt horizons of the more developed palaeosols are rich in clay skins and ferromanganese coatings, and at the bases of most palaeosols carbonate nodules are present.

In general, the pedogenic intensity for the palaeosols in the Beijing section is between that of Baoji and Luochuan, based on the development of the clay skins and the soil structures. These three sections show much more pedogenic development than the Lanzhou section.

The variations in grain size and susceptibility throughout the Beijing section are consistent with those of the Luochuan and Baoji sections, where systematic differences in proxy data are attributable to glacial–interglacial cyclic variations in the intensities of the summer and winter monsoons. The most significant difference in climatic proxies between the Beijing section and the sections in the central Loess Plateau is that there is an abrupt increase in the grain size in the Upper Lishi Formation (L3) in the Beijing section, whereas this increase is not observed in the Luochuan and Baoji sections. This may imply the influence of a different regional factor for loess deposition in the Beijing region.

Discussion and conclusions

Previous studies have shown that the pedostratigraphy of different loess sections in the middle part of the Loess Plateau are well correlated (Ding *et al.*, 1992, 1994). Loess deposits are inferred to have accumulated during times of strengthened winter monsoon and weakened summer monsoon, whereas the palaeosols developed when these conditions were reversed (An *et al.*, 1991; Ding *et al.*, 1992, 1994). Spectral analyses have suggested that the first-order Pleistocene climate variations recorded in the loess–palaeosol sequence exhibit orbital periodicities, and that the 100 kyr cycle was restricted to loess deposited during the past 1.2 Myr (Ding *et al.*, 1994). This implies astronomical control and/or ice-volume forcing of the monsoonal climatic changes over the Loess Plateau.

The similarity in pedostratigraphic and sedimentary properties between the Beijing loess and the Loess Plateau implies that they are similar in mode of deposition and source and in pedogenic environment. We infer that the same climatic processes found in the middle part of the Loess Plateau also may have controlled the dust deposition and the soil formation in the Beijing region. As in the Loess Plateau, deposition in the Beijing region occurred during glacial periods when the winter monsoon was strengthened, whereas the palaeosols were developed during interglacial periods when the summer monsoon dominated. The number of loess–soil cycles in the Loess Plateau is identical to those in the Beijing region. There are nine major soils recognized above the Brunhes–Matuyama reversal in both regions, with three subunits for the S5 soil complex and two subunits for the S2 soil complex. The sequential pattern of pedogenic strength is also the same for deposits in both regions. However, the loess deposits in the Beijing region differ from those in the Loess Plateau with respect to susceptibility and grain-size variations. In the Loess Plateau, the dust source areas are the deserts to the northwest of the plateau, with a concomitant decrease in grain size towards the southeast (Liu *et al.*, 1965, 1985; Ding *et al.*, 1999). On the other hand, pedogenic development is controlled by the summer monsoon climate, which produces a decreasing gradient from southeast to the northwest (Kemp, 1999). Thus, grain size is coarsest in the sections where the pedogenic development is weakest, whereas maximum palaeosol development is associated with the finest grain size. For example, loess in the Lanzhou section (Chen and Zhang, 1993) is much coarser than in the Baoji section (Ding *et al.*, 1994), whereas the palaeosols in the former are much weaker than in the latter. The Beijing section, however, exhibits pedogenic development as strong as Luochuan and Baoji, whereas the grain size at Beijing is as coarse as the Lanzhou section, but with a lower accumulation rate. This implies that the mode of deposition and source in the Beijing loess section is different from the Loess Plateau.

In addition, variations and shift in grain size (median diameter and wt% of the grains >63 μm) at Beijing do not coincide with the changes in magnetic susceptibility and pedogenic characteristics. This effectively rules out the possibility of variations in pedogenesis in controlling the variations in grain size. Meanwhile, the abrupt shift in grain size is not observed in other loess sections in the middle part of the Loess Plateau. This indicates that a variation in regional atmospheric circulation (for example, variations in wind speed), which would influence a large area, is not the main factor controlling the changes in grain size. Previous studies suggested that grains >63 μm cannot be transported long distances even in extreme dust storm conditions (Pye, 1987), and may be used as an indication of proximal dust sources (Ding *et al.*, 1999). The variations in the percentage of the >63 μm grains in the Zhaitang loess during the last interglacial–glacial cycle and the abrupt increase in the coarse grains at about 265 ka in the Fanshan section thus imply fluctuations in dust provenance, such as the areal expansion of the desert and the reactivation of dunes during the glacial periods. This also implies that the Beijing loess may have different, more proximal, dust source regions than those in the Loess Plateau.

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