Long-term Pleistocene aridification and possible linkage to high-latitude forcing: New evidence from grain size and magnetic susceptibility proxies from loess-paleosol record in northeastern China

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Loess deposits are regarded as good indicators of the inception and development of arid and semi-arid climate in central Asia and northern China during the late Cenozoic. In northeastern China extensive loess deposits are found surrounding the Horqin and Otindag sand fields, and they have great potential for reconstructing the long-term aridification history of the region. However, these loess deposits are currently poorly understood. Here, we present a high-resolution magnetic susceptibility (MS) and grain-size record spanning the last 1.0 Ma from a 36.6-m-thick loess-paleosol sequence at Niuyangzigou site (NYZG) in NE China. The grain-size record reveals a long-term drying trend in NE China since ca. 1.0 Ma, punctuated by two significant abrupt drying events at ~0.65 Ma and ~0.3 Ma. These results demonstrate a process of stepwise intensification of drying in NE China over the past 1 Ma, and lend support to the hypothesis that global ice volume/temperature changes were the major driver of the long-term aridification of Asian dust source areas. However, unlike the widely studied loess deposits on the central Chinese Loess Plateau (CLP), the MS record in paleosol units S1, S2 and S4 from the NYZG site do not show evidence of enhanced monsoon precipitation resulting from decreased global ice volume and the prolonged episodes of interglaciation after the Mid-Pleistocene Transition evident in the ice volume record. We hypothesize that this may be due to differences in the climatic sensitivity of the MS of Chinese loess deposits on a regional scale, rather than to regional differences in monsoon intensity.

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1. Introduction

The extensive Gobi and sandy deserts in the continental Asian interior have long been considered as major candidates for the main provenance of eolian dust in northern China (e.g. Liu, 1985; Ding et al., 2005; Guo et al., 2002b; Nugteren and Vandenberge, 2004; Zhang et al., 2016). The loess of the Chinese Loess Plateau (CLP) is the best-known example of this quasi-accumulating dust archive (Lu et al., 2004, 2006), preserving a record of the influence of both the arid and semiarid climates of the northwest as well as the humid summer monsoon climate in the southwest (Fig. 1a). A range of climate proxies, such as the grain size and accumulation rate of loess deposits on the CLP, have been interpreted as reflecting the progressive drying of the Asian interior during the late Cenozoic era (Lu and An, 1998; Lu et al., 2010; Ding et al., 2005).

In addition to the extensively studied deposits of the CLP, loess deposits in Northeastern (NE) China are also widely distributed, especially in eastern Inner Mongolia, downwind of the Horqin and Otindag sandy deserts (Fig. 2a). These semi-stabilized and stabilized sandy deserts mark the transition zone between loess and shifting sandy desert (Gobi, which is equivalent to the current northern margin of the East Asian Summer monsoon (EASM). This semi-arid zone is geographically close to the densely populated plains in eastern China, where desertification and dust storms have become a serious environmental problem affecting the human livelihood and health (Wang et al., 2008). Thus, research into the drying process and forcing mechanisms in this region are of relevance from both paleoclimatic and human welfare perspectives.

Provenance studies using both using Nd-Sr isotopic composition (Chen and Li, 2011; Zhao et al., 2014) and detrital zircon U-Pb age analyses (Xie et al., 2012) have demonstrated that the major source areas of the loess deposits in NE China are likely to be the upwind Horqin and Otindag sandy deserts. Therefore, the loess and adjacent sandy deserts

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in NE China can be regarded as a coupled system, with dust source and sink formed under a semi-arid climate, which is quite distinct from the loess deposits of the CLP and their corresponding sources areas in northwestern and central China. Thus, the loess deposits in this area should have great potential for revealing the development and variability of aridity and dust emission in NE China.

There has been considerable research on the origin and aridity history of the sandy deserts in the northwest and central China (Guo et al., 2008; Lu and Guo, 2014). For example, the Taklimakan Desert was recently dated back to the Late Oligocene-early Miocene based on loess deposits preserved in the Cenozoic strata along the margin of the Tarim Basin (Zheng et al., 2015), although this result is still in debate (Sun et al., 2015). In addition, work on the Red Earth formation in the western CLP has revealed that desertification of the Asian interior was initiated at least by the late Oligocene (Guo et al., 2002b, 2008; Qiang et al., 2011); and work on the loess-paleosol sequence in the northern part of CLP has documented the stepwise expansion of the Mu Us Desert in the past 3.5 Ma (Ding et al., 2005). However, at the easternmost

Fig. 1. (a) Distribution of deserts and loess in China and the locations of the Niuyangzigu (NYZG), Fanshan (FS), Jingbian (JB), Luochuan (LC) loess sections, shown on the shaded relief map. (b) Simulated springtime dust emissions flux between 1960 and 2002, indicating the primary Asian dust sources (revised from Zhang et al. (2003)). The bold blue line is the modern 400 mm annual average isohyet, representing the approximate boundary of the arid zone and East Asian monsoon zone. EASM: East Asian summer monsoon; EAWM: East Asian winter monsoon; ISM: Indian summer monsoon; CLP: Chinese Loess Plateau.
portion of the arid zone in the inland Asia, the aridity history of NE China is still poorly documented. Thus, without the reconstruction of the long-term paleoclimatic record of NE China, our understanding of the history of aridity in the interior of Asia remains incomplete.

Although several early paleomagnetic studies were conducted on the loess deposits in NE China, the sampling resolution was low and stepwise thermal demagnetization was not conducted (Wu et al., 1984; Xia, 1989); and thus the inferred age of the loess deposits is questionable. In addition, several loess sections in the region were recently dated by optically-stimulated luminescence measurements (Yi et al., 2012, 2015, 2016). However, because of the maximum age limit of luminescence dating, the technique can only be applied to the uppermost parts of these sections. Thus, owing to the lack of reliable paleomagnetic results and the absence of detailed investigation of the pedostratigraphy, long and well-dated paleoclimatic proxy records from loess deposits in NE China are scarce; and consequently, knowledge of the evolution and mechanisms of climate aridification in NE China remains poor. In our previous work (Zeng et al., 2011), a high-resolution magnetostratigraphic record was obtained from a ~37-m-thick section near Chifeng city (Fig. 2a), which revealed that the basal age of the loess deposits in NE China extended to at least ca. 1.0 Ma. This section exhibits an unusually distinct and relatively complete stratigraphic loess-paleosol sequence, and can be regarded as one of the most important loess sections in the region.

Here, we present high-resolution magnetic susceptibility (MS) and grain-size records from the loess deposits of NE China and use the results to investigate climatic changes in the region since ~1.0 Ma. We also use the results of a detailed pedostratigraphic analysis to support our interpretation of the MS and grain-size records, and in addition present a revised chronology for the section based on both new luminescence dates and the previously published magnetostratigraphy (Zeng et al., 2011). Finally, based on extensive comparison of these new proxy records from NE China and other representative loess records from the CLP and central Asia, and deep-sea sediment records, we discuss the mechanisms and processes involved in dust generation from Asian dust source areas and how they responded to ice volume variability in northern high latitudes on glacial-interglacial time scales.

2. Setting and sampling site

Based on a long-term and extensive field survey of the loess deposits in NE China, we have determined that the thickest and most representative eolian loess deposits are mainly distributed in the Chifeng region, in southeastern Inner Mongolia (Fig. 2a). The present climate of the area is semi-arid and mainly controlled by the dynamics of the East Asian Monsoon circulation - characterized by seasonal alternations between cold/dry winters and warm/wet summers. In winter the prevailing wind direction is northwesterly, generated by the Siberian–Mongolian high-pressure zone; while in summer the dominant direction is southeasterly, driven by the pressure gradient between the Subtropical High and the Asian Continental Low. The mean annual precipitation ranges from 600 mm in the southeast to 200 mm in the northwest, and most of the precipitation falls during the boreal summer. As illustrated in Fig. 2a, the Horqin and Otindag sandy deserts are respectively located to the north and west of the Chifeng region.

The Niuyangzigou (NYZG) section (41°55′ N, 118°43′ E, 774 m.a.s.l.) is located in the southern part of the Chifeng area (Fig. 2a), in a landscape characterized by hills comprised of the bedrock and with valleys mantled by eolian loess deposits. The study site consists of a 26-m-thick brickyard exposure (Fig. 2b) and a 10.6-m-deep excavated pit below (Fig. 2c). The lithology can be roughly divided into two parts: an upper part (0–21.8 m) consisting mainly of light brown sandy-silt loess layers interbedded with light reddish brown paleosols or weakly-developed paleosols; and a lower part (21.8–36.6 m) which exhibits stronger pedogenesis, with both the colour of the loess and paleosol becoming progressively more reddish with depth and with the contrast between them becoming weaker. In addition, the texture of the lower part becomes a more homogeneous silt. As shown in Fig. 3, a prominent feature of the lower part of the sequence is the presence of nine...
carbonate nodule horizons intercalated within the loess–paleosol sequence, indicating significant leaching and precipitation of carbonate minerals.

3. Materials and methods

3.1. Sampling and measurements

A total of 367 bulk samples were taken at a 10-cm-interval for grain size and MS measurements. In addition, three samples for luminescence dating were collected from the top of the section by hammering steel tubes into the cleaned face.

For the luminescence dating, the coarse-grained quartz (63–90 μm) and K-rich feldspars were extracted after removal of carbonates and organic matter under subdued red light conditions. All of the luminescence measurements were performed using an automated Risø TL/OSL-DA-20C/D reader (Bøtter-Jensen et al., 2010). In order to verify the reliability of the results, both quartz SAR OSL (Murray and Wintle, 2003) and K-feldspar post-IR infrared stimulated luminescence (post-IR IRSL, pIRIR290) (Buylaert et al., 2012; Thiel et al., 2011) were used to measure the equivalent doses (De) for the same sample. The procedures used for mineral extraction, environmental dose rate measurement and luminescence age calculation are described in Yi et al. (2015, 2016). The luminescence dating results are listed in Table 1.

Low field-magnetic susceptibility (470 Hz) was measured using a Bartington Instruments MS2 magnetic susceptibility meter and MS2b sensor. Samples of 10 g mass were used, following drying at a temperature below 40 °C. The values were normalized by the sample mass in order to obtain the mass-specific magnetic susceptibility.

The grain-size distribution was determined using a Malvern Mastersizer 2000 laser particle-size analyzer with a measurement range of 0.02–2000 μm and a relative error of <2%. The pre-treatment procedure consisted of the removal of organic matter and carbonates by the addition of 10% H2O2 and 10% HCl, respectively, followed by dispersal using 10 ml of 0.05 mol/l (NaPO3)6 and treatment in an ultrasonic vibrator for 10 min (Lu and An, 1997). Grain-size statistics were calculated using the GRADISTAT (v8.0) program developed by Blott and Pye (2001).

3.2. Selected representative CLP loess records for correlation with the NYZG section

We selected MS and grain-size records from several other representative loess sections from the classic CLP for comparison with the NYZG section (Fig. 1a). In order to facilitate the stratigraphic correlation, a conventional CLP stratigraphic unit numbering procedure (Liu, 1985; Kukla and An, 1989) was used to define all of the loess and paleosol layers in these selected representative sections. In this numbering scheme, the loess and paleosol layers are labeled ‘L’ and ‘S’, respectively, and numbered in order of increasing depth.

The Luochuan (LC) section (35° 49’ N, 109° 30’ E, ~1220 m.a.s.l) is located in the central CLP, and an independent timescale has been developed using a grain-size sediment-accumulation-rate-based age model (Porter and An, 1995) applied to the interval between the top of the section (0 ka), the base of paleosol S1 (130 ka), dated by the luminescence dating, and the paleomagnetic reversal boundaries (the Brunhes/Matuyama, the top of Jaramillo subchron, the top and the bottom of the Olduvai subchron, and the Matuyama/Gauss) (Lu et al., 2004). The Jingbian (JB) section (37° 30’ N, 108° 54’ E, ~1700 m.a.s.l) is located at the northern margin of the CLP, and the age model is based on correlation to the Chinese Loess Particle Time Scale (Chiloparts) (Ding et al., 2015). The Fanshan (FS) section (40° 11’ N, 115° 24’ E, ~820 m.a.s.l) is located on the northeastern margin of the CLP and a detailed magnetostratigraphy and pedostratigraphy are available (Xiong et al., 2001). Here, we obtain an age model for the FS section by directly correlating the MS curve to the LR04 stacked benthic δ18O record (Lisiecki and Raymo, 2005), performed using the Match 2.3.1 program (Lisiecki and Lisiecki, 2002). The age model developed for the NYZG section is explained in detail below.

3.3. Pedostratigraphic analysis of the NYZG section

Luminescence dating is an essential technique for determining the age of the standard loess unit L1 and paleosol S1 on the CLP (Buylaert et al., 2015; Lai, 2010; Lu et al., 2007). In NE China, Yi et al. (2015) used both coarse-grained quartz SAR OSL and the K-feldspar post-IR infrared stimulated luminescence (post-IR IRSL; pIRIR290) method to date L1 and S1 in the Sanbahuo section (42° 18’ N, 118° 41’ E, 677 m.a.s.l), which is located about 40 km northwest of the NYZG section. The dating results demonstrate that the quartz OSL and feldspar pIRIR290 ages are in good agreement back to ~44 ka, but that the quartz OSL increasingly underestimates older ages. In contrast, feldspar pIRIR290 ages are in satisfactory agreement with the expected age of S1. As illustrated in Fig. 3, the dating results from the two methods in

![Fig. 3. Pedostratigraphic column, magnetic susceptibility (MS), quartz OSL ages, and feldspar pIRIR290 ages for the top of NYZG section. The ages are plotted against section depth. The blue squares represent quartz ages and red circles represent pIRIR290 ages.](image-url)

Table 1

| Sample | Depth (m) | U (ppm) | Th (ppm) | K (%) | H2O (%) | Q-dose rate (Gy/ka) | FK-dose rate (Gy/ka) | Q-De (Gy) | FK-De (Gy) | Aliquots | Q-Age (ka) | FK-Age (ka) |
|--------|----------|---------|----------|-------|---------|---------------------|---------------------|-----------|-----------|---------|----------|------------|
| A      | 0.6      | 2.11 ± 0.11 | 10.50 ± 0.37 | 1.95 ± 0.05 | 11.22 | 3.04 ± 0.15 | 3.39 ± 0.16 | 96.39 ± 2.40 | 108.61 ± 3.15 | 66/9 | 31.63 ± 1.90 | 32.08 ± 1.75 |
| B      | 2.2      | 2.23 ± 0.10 | 5.86 ± 0.31 | 2.09 ± 0.05 | 11.71 | 3.08 ± 0.16 | 3.42 ± 0.16 | 180.07 ± 7.68 | 207.02 ± 3.30 | 16/9 | 58.50 ± 2.99 | 60.54 ± 2.99 |
| C      | 2.8      | 1.76 ± 0.09 | 11.60 ± 0.34 | 2.02 ± 0.05 | 12.62 | 3.00 ± 0.15 | 3.34 ± 0.16 | 217.98 ± 14.32 | 297.96 ± 6.72 | 15/9 | 72.58 ± 6.20 | 80.11 ± 4.23 |

Note: a. Aliquot numbers using quartz SAR protocol (Q-De); b. Aliquot numbers using the pIRIR290 protocol (FK-De).
the NYZG section are compatible with the results of Yi et al. (2015). The quartz OSL and feldspar pIRIR290 ages in sample A almost overlap within their error limits, while in samples B and C the divergence between the two ages increases significantly with increasing depth. In addition, the feldspar pIRIR290 age (80.11 ± 4.23 ka) of sample C, taken from the paleosol, is in better agreement with the expected ages of S1 (formed during the MIS5 interglacial) than the quartz OSL age (72.58 ± 6.20). In this study, therefore, we used the feldspar pIRIR290 data as preferred ages for L1 and S1, given that the quartz OSL ages of the loess deposits in NE China systematically underestimate the expected ages beyond ~44 ka (Yi et al., 2015). The luminescence ages also indicate that the uppermost dark-gray Cinnamon soil (Fig. 3) is likely to be L1S1, which accumulated during the relatively warm and wet MIS 3 interstadial.

In the field, we preliminarily divided the loess and paleosol units based on visual soil colour and structure contrasts (Fig. 4). The loess layers have a light brown colour and a massive microstructure, and the paleosol units are readily identified by their light reddish brown colour and weak biological microstructures in the loess outcrop (Fig. 2b). However, due to the relatively weak contrast between the units and the lack of sunlight in the sampling pit excavated at the base of the section, it is unlikely that we obtained accurate boundaries between the stratigraphic units in the lower part of the section. In most Chinese loess-paleosol sequences, the MS values of paleosols are higher than in the adjacent loess layers. It has been suggested that MS is the most accurate and objective method of delimitating the separate units in loess-paleosol sequences and has been widely used in previous studies (Kukla and An, 1989). Fig. 4 demonstrates that the depth variations of MS in the NYZG section are well correlated with the paleosol sequences and has been widely used in previous studies (Kukla and An, 1989). The MIS5 interglacial) than the quartz OSL age (72.58 ± 6.20). In this study, therefore, we used the feldspar pIRIR290 data as preferred ages for L1 and S1, given that the quartz OSL ages of the loess deposits in NE China systematically underestimate the expected ages beyond ~44 ka (Yi et al., 2015). The luminescence ages also indicate that the uppermost dark-gray Cinnamon soil (Fig. 3) is likely to be L1S1, which accumulated during the relatively warm and wet MIS 3 interstadial.

The detailed magnetostratigraphic results for the NYZG section have been reported previously (Zeng et al., 2011), and only a summary is given here. As shown in Fig. 4, the Brunhes/Matuyama boundary (B/M) is located at a depth of 27 m, and the top of Jaramillo subchron (TJS) is located at 35.9 m, based on the normal polarity of palaeomagnetic samples at the base. The basal age is estimated to be about 1.0 Ma through extrapolation of the average sedimentation rate during the Brunhes (Zeng et al., 2011). Many paleomagnetic investigations on the CLP have indicated that the B/M and TJS are generally located around L8–S8 and L10–S10, respectively (Guo et al., 2002a; Kukla and An, 1989; Liu et al., 1986; Pan et al., 2002; Wang et al., 2006; Zhu et al., 1994). These discrepancies in the positions of the geomagnetic reversal boundaries among Chinese loess sections has been primarily attributed to local variations in sediment accumulation rate and pedogenesis causing varying degrees of directional smoothing; loss of resolution due to non-continuous sampling strategies; and dissimilar demagnetization/analytical techniques used in different studies (Wang et al., 2006). In spite of these uncertainties, the B/M and TJS provide the key stratigraphic control for pedostratigraphic subdivision in the Chinese loess-paleosol sequence. As shown in Fig. 4, the B/M boundary is located in a loess unit within an interval of low MS; and TJS is located in a paleosol unit corresponding to a MS peak. Therefore, we assigned the stratigraphic units including the B/M and TJS boundaries to L8 and S10, respectively.

Finally, according to the MS curves combined with the positions of the paleomagnetic reversal boundaries, luminescence dates and identified paleosol layers in the field, the conventional CLP stratigraphic unit numbering procedure (Liu, 1985; Kukla and An, 1989) was used define all of the loess and paleosol layers in the NYZG section. These results indicate that the section has preserved loess deposits from the top of S10 to L1, and the diagnostic marker layers S2 (characterized by twofold paleosol layers separated by a thin loess bed) and S5 (with the strongest degree of pedogenesis) are prominent. However, it is noteworthy that in contrast to the classical stratigraphy of the CLP, S5 is composed of a single distinct paleosol, and the L9 unit (‘sandy loess’ marker bed) is not characterized by the highest proportion of coarse silt and fine sand (see Section 4.1, below). These differences in loess stratigraphy may simply be the result of regional climatic differences in NE China, or they may reflect site-specific depositional conditions such as topography, sedimentation rate variations and erosional hiatuses (Lu et al., 2006; Stevens et al., 2007).

### 3.4. Chronology of the NYZG section

The initial chronology of the NYZG section was established by linear interpolation using the ages of the B/M boundary (0.78 Ma) and TJS (0.99 Ma), together with K-feldspar pIRIR290 ages, as control points. The ages for older sediments were estimated by linear extrapolation...
of the sediment accumulation rate of the nearest interval which had been absolutely dated. Fig. 5 illustrates the MS curve for the NYZG section (with the initial chronology) compared to the MS curve for the representative LC section on the CLP (Lu et al., 2004) and the LR04 stacked benthic δ^{18}O record (Lisiecki and Raymo, 2005). This comparison reveals that the MS record of the NYZG section can generally be correlated with the MS record of the LC section and the benthic δ^{18}O record, at least on the scale of glacial-interglacial cycles – which provides justification for our preliminary chronology for the NYZG section. However, it is clear that, based on this initial chronology, there are some phase differences for the NYZG section and the benthic δ^{18}O record, and this may hamper both a detailed analysis of the evolution of the regional climate and comparison with other paleoclimatic proxy records. Here, we use the traditional age model derivation approach based on the correlation of Chinese loess-paleosol sequences with the benthic δ^{18}O record (Lisiecki and Raymo, 2005). In this approach, the MS maxima (minima) are directly correlated to the interglacial (glacial) stages represented by the lower (higher) values of benthic δ^{18}O. The midpoints between the start and end of an interval of rapid change from low to high MS represent transitions from glacial to interglacial periods and are used as age control points (Table 2, Fig. 5). They are used to represent glacial stage terminations defined by the MIS boundaries in the benthic δ^{18}O record. However, we took the midpoint of change between L4 and S5 in the MS record to correspond to the MIS 12/13 boundary as the control point for the S5 paleosol. This contrasts with the other tie points, because sub-paleosols S5–2 and S5–3 are indistinct in the NYZG section compared to the representative loess-paleosol sequence from the CLP (Fig. 4).

In addition to the selected MIS boundaries, the K-feldspar OSL dates and the top and bottom ages of the initial chronology (see above) were used as age control points. A grain-size sedimentation-rate age model (Eq. (1), below) was then used to interpolate the age at each sampling level between these age control points (Porter and An, 1995):

\[
T_m = T_1 + (T_2 - T_1) \left( \sum_{i=1}^{m} A_i^{-1} \right)^{-1} \left( \sum_{i=1}^{n} A_i^{-1} \right)^{-1}
\]

where \(T_1\) and \(T_2\) are the age control points; \(A_i\) is the accumulation rate at level \(i\), which is assumed to be proportional to the content of the >30 μm grains; \(n\) is the total sampling level between \(T_1\) and \(T_2\); and \(m\) is a given sampling level between \(T_1\) and \(T_2\). The one modification of our age model to that of Porter and An (1995) is the use of the >30 μm fraction rather than >40 μm fraction (Lu et al., 2004). Our model assumes that the occurrence of coarser grain-sizes in the loess-paleosol sequence corresponds to the increased capability of dust-bearing winds, and a higher sedimentation rate. The content of the >30 μm grains is believed to be more strongly associated with the strength of the East Asian winter monsoon (EAWM) (Lu et al., 1999). This calibrated chronology is thought to be more reliable than that obtained by linear interpolation because assumed changes in dust accumulation rate are considered in the age model (Hao et al., 2012).

As illustrated in Fig. 6, while there are several differences in the approach used to produce the different chronologies of these representative loess records, the MS time series for the NYZG section is, in

### Table 2

| Depth (m) | Age (ka) | Calibration |
|----------|----------|-------------|
| 0        | 21.41    | Initial chronology |
| 0.6      | 32.08    | pIRIR290 age |
| 2.2      | 60.54    | pIRIR290 age |
| 2.8      | 80.11    | pIRIR290 age |
| 3.3      | 130      | MIS 5/6 |
| 7.3      | 243      | MIS 7/8 |
| 10       | 337      | MIS 9/10 |
| 13.7     | 424      | MIS 11/12 |
| 16.3     | 478      | MIS 12/13 |
| 23       | 712      | MIS 17/18 |
| 24.6     | 790      | MIS 19/20 |
| 30.3     | 866      | MIS 21/22 |
| 36.6     | 1006     | Initial chronology |
general, consistently in-phase with the other records on glacial-interglacial time scales, and the overall structures of the MS curves are well correlated. This suggests that our refined time scale for the NYZG section is valid on orbital timescales and that we can use it for comparison with other palaeoclimatic time series. However, we emphasize that the chronology can only be regarded as reliable over long (orbital) time scales. Over shorter timescales it has been demonstrated by high-resolution OSL dating that the loess record is prone to site-specific influences, and that the sediment accumulation is highly variable (Stevens et al., 2007).

4. Results and discussion

4.1. New evidence for the aridification of NE China during the Pleistocene

Several researchers have argued that the loess deposits on the CLP are predominantly composed of silt-sized dust particles transported from dryland regions: either sandy or Gobi deserts, dry lake beds, or alluvial fans and plains in central Asia and northern China (Chen et al., 2007; Liu, 1985; Stevens et al., 2013; Sun, 2002; Tsoar and Pye, 1987; Zhang et al., 2016). The particles are then mobilized and transported during dust storms, especially in spring (Kurosaki and Mikami, 2003; Roe, 2009; Sun et al., 2001). Observations on contemporary dust falls indicate that the grain size of the dust generally decreases with decreasing wind strength and increasing distance from the dust source areas (Derbyshire et al., 1998; Sun et al., 2003; Yang and Ding, 2008). This is in line with grain-size analysis results of the loess deposits, which indicate that the bulk loess deposits are progressively finer-grained with increasing distance southeastwards across the CLP - changing from sandy loess to silty loess and then to clayey loess (Liu, 1985; Nugteren and Vandenberghe, 2004). Systematic study of the last glacial loess along three transects across the CLP demonstrates that the sand-sized particle content (>63 μm) decreases rapidly from north to south, and that a markedly high proportion of sand-sized particles occurs only in the zone of sandy loess deposition in the northern part of the CLP (Ding et al., 2005). The sand-sized particles are usually transported by saltation or modified saltation near the ground surface during the frequent dust storms (Tsoar and Pye, 1987; Pye and Tsoar, 2009). Thus, the variation of the sand-sized particle fraction in loess deposits near the desert margin is closely linked to the expansion and contraction of areas of sand dune mobility in northern China. Moreover, because the migration of the desert margin is primarily controlled by the amount of monsoon precipitation (Lu et al., 2005; Mason et al., 2009; Sun et al., 1998), the sand-sized particle content in the loess deposits near the desert margin can serve as a useful proxy for the aridity of the dust source areas (Ding et al., 2005).

One of the methods for determining the palaeoclimatic significance of the grain-size of loess sections is to determine the variations of specific grain-size fractions with depth (Lu and An, 1998). The grain size of loess usually ranges from clay to sand, and the grade scales can be used to divide the total grain-size distribution into different size classes. In the present study, we used the Udden-Wentworth scale (Udden, 1914; Wentworth, 1922), modified by Blott and Pye (2001). The content variations of each size fraction can be illustrated as a stacked area chart, and the mean content and standard deviation of each size fraction can be presented as a bar chart (Fig. 7). The loess samples of the NYZG section mainly consist of silt-sized particles (2–63 μm), as is the case for typical loess deposits on the CLP. However, the LC section is located in the zone of silty-loess deposition (Liu, 1985; Nugteren and Vandenberghe, 2004), and compared to the NYZG section it is characterized by a higher very fine sand (63–125 μm) content and a lower clay content (<2 μm). In addition, there is a fine sand component (125–250 μm) in the upper part of the NYZG section which is absent from the LC section. Moreover, the very fine sand fraction in the NYZG section has the highest standard deviation, while in the LC section the very coarse silt component (31–63 μm) has the highest standard deviation. Thus, the results suggest that overall the grain-size characteristics of the NYZG section are very similar to those of the sandy loess in the northern CLP, and that the sand-sized component dominates the grain-size record of the entire section. Because the NYZG section is located close to the sandy deserts in NE China (Fig. 2a), and has been demonstrated to be sourced from these areas (Xie et al., 2012; Chen and Li, 2011), the loess samples are enriched in sand-sized particles associated with short-distance transport, which accords with their proximal provenance. Therefore, we infer that variations in the content of the sand-fraction (>63 μm) in the NYZG section should be sensitive to migration of the desert margin and to wet-dry climate oscillations within the dust source areas, as is the case for the loess deposits in the northern CLP.
The new grain-size record from the NYZG section plotted on the refined time scale is illustrated in Fig. 8. The grain-size variability is characterized by a generally long-term coarsening trend up-section. It is noteworthy that the content of the sand fraction (>63 μm) exhibits two abrupt coarsening events, at ~0.65 Ma and ~0.3 Ma. These events mark boundaries between intervals with different grain-size characteristics. Prior to ~0.65 Ma, the grain-size record is characterized by a pattern of low-amplitude, high-frequency fluctuations and the content of the sand fraction (>63 μm) varies from 2.7%–17.4% with an average of 8.5%. During the interval from ~0.65–~0.3 Ma, the amplitude of grain-size fluctuations increases significantly and the average content of the sand fraction reaches ~13%. After 0.3 Ma, the average content of the sand fraction increases sharply to 19.7%, reaching its maximum at ~0.2 Ma. Therefore, based on the pattern of stepwise increase in the sand content of the NYZG section, we conclude that the semi-arid region of NE China experienced a long-term drying trend after 1.0 Ma, punctuated by two significant drying events at ~0.65 Ma and ~0.3 Ma.

Northern China and central Asia contain the largest areas with an arid climate in the mid-latitudes of the northern hemisphere, composed mainly of shifting sandy desert in the northwest and semi-stabilized and stabilized sandy deserts in the east (Lu et al., 2013). These deserts are one of the most important sources of dust for the global aerosol system (Fig. 1b), and thus they play a significant role in modulating global climate on various time scales (Uno et al., 2009). In addition, their formation and development during the Cenozoic provide the key to the improved understanding of changes in Asian monsoon circulation and the climatic implications of the uplift of the Himalayan-Tibetan plateau (Guo et al., 2002b). Most of the previous research has focused on the investigation of the intercalated eolian dune sands/loess preserved within the Cenozoic stratigraphy in northwest China (Sun et al., 2009; Zheng et al., 2015), and the wind-blown dust deposits (the Red-clay and loess-

![Fig. 7. Depth variations of various grain-size fractions in the NYZG section (a) and LC section (central Chinese Loess Plateau) (b). The mean content and standard deviation for each size fraction are shown as bar charts. The grain-size data for the LC section span the entire Quaternary loess-paleosol sequence (Lu et al., 2004); the two peaks with the highest proportion of very coarse silt and very fine sand are the L9 and L15 marker beds.](image-url)
4.2. Possible forcing mechanisms of the long-term aridification of NE China

A hypothesis has been proposed that cooling and ice volume expansion in high latitudes during the late Cenozoic was the major driver for the long-term stepwise aridification of the Asian continental interior (Ding et al., 2005; Lu et al., 2010; Lu and Guo, 2014). The nature of this forcing mechanism can be summarized as follows: (1) Numerical modeling results have demonstrated that cooling in the North Atlantic and ice volume expansion in northern high latitudes caused an increased meridional temperature gradient, southward migration of the polar front, and intensification of the Siberian High. As a result, the northward movement of moisture-laden EASM airflows was suppressed, leading to aridification and stronger, colder winds in central Asia which entrained more and coarse dust particles which were deposited in downwind locations (Lu et al., 2013). (2) Ice volume expansion would cause global sea-level lowering and expose vast areas of continental shelf in the marginal seas of the Pacific (Wang, 1999), resulting in enhanced continentality, weakening of the EASM circulation, and eventually to expansion of the deserts in northern China (Ding et al., 2005; Lu et al., 2010).

The key proxies for reconstructing past ice sheet dynamics include records of the $\delta^{18}O$ of benthic foraminifera and ice-rafted debris (IRD) in marine sediments. The $\delta^{18}O$ record indicates that global ice volume dynamics underwent a fundamental change between 1.25 and 0.7 Ma, namely the mid-Pleistocene transition (MPT). At this time, the dominant periodicity of the climatic cycles changed from relatively low amplitude 41-kyr cyclicity to high-amplitude 100-kyr cyclicity (Ruddiman et al., 1986). With the increased amplitude of $\delta^{18}O$ fluctuations since the beginning of the MPT at about 1.25 Ma, global ice volume during glaciations exhibited a long-term increasing trend superimposed on the cycles of glacial and interglacial expansion and retreat. Particularly after the termination of the MPT at ~0.7 Ma (Fig. 9), the maximum volume of glaciations was established at the same time as the onset of the dominant 100-kyr cycles (Clark et al., 2006). As illustrated in Fig. 9, the increased abundance of IRD in North Atlantic deep-sea sediment cores from MIS 16 (~0.64 Ma) onwards also supports an increase in ice sheet thickness after the MPT (Hodell et al., 2008; Sosdian and Rosenthal, 2009). Thus, the long-term aridification trend in NE China, indicated by the results from the NYZG section, is in line with the increasing trend of global ice volume during the glaciations since the MPT; moreover, the drying event at ~0.65 Ma is consistent with an aridification response to the growth of larger/thicker ice sheets after the MPT.

As shown in Fig. 8, the two rapid increases in the >63 μm fraction in the NYZG section are generally coincident with the grain-size variations of the JB section, but differ from those of the LC section which is much closer to the humid Asian monsoon zone. The long-term drying trend of Asian dust source areas during the past 1.0 Ma has been discerned in other loess sections in northern China and central Asia. The loess records on the northern slopes of the Qilian Shan (Wu et al., 2005), West Kunlun Shan (Zan et al., 2013), Tian Shan (Fang et al., 2002) in northwestern China, as well as in Tajikistan in central Asia (Ding et al., 2002a), indicate a long-term drying trend since 1.0 Ma and suggest that a dramatic desert expansion occurred in the early Mid-Pleistocene.
(0.6–0.7 Ma). In addition, the mass accumulation rate of eolian dust in the North Pacific exhibits an increasing trend over the past 1 Ma, with rapid increases at 0.6–0.7 Ma, indicating the intensification of pulses of dust transport from the Asian interior during this interval (Rea et al., 1998). Thus, these results demonstrate that the entire arid zone of the Asian interior underwent a process of drying since 1.0 Ma, which was probably triggered by ice volume expansion in high latitudes.

Previous studies have suggested that the loess-paleosol sequences on the eastern margin of the Tibetan Plateau record a drying event at ~0.3 Ma (Qiao et al., 2014; Wu et al., 2002). This drying event seems also to be preserved in the loess deposits in northern China, such as in the NYZG section, as well as in the FS and JB sections on the CLP which are located on the margin of the EASM. In addition, the mass accumulation rate of eolian dust in core V21–146 (Hovan et al., 1991) from the North Pacific also exhibits a spike indicating an abrupt drying event at ~0.3 Ma (Fig. 8). The deep-sea $\delta^{18}O$ record, with deep-water temperature calibration, provides new evidence in support of the hypothesis that this drying event was driven by ice volume expansion. Although the benthic $\delta^{18}O$ record is commonly considered to be a record of global ice volume, it may be overprinted by deep-water temperature variability relating to local hydrographic conditions (Elderfield et al., 2012). As illustrated in Fig. 8, the seawater $\delta^{18}O$ record calibrated using the Mg/Ca paleothermometer method (Sosdian and Rosenthal, 2009), from DSDP Site 607 in the North Atlantic, clearly indicates a global ice volume increase at ~0.3 Ma, which is consistent with an ice volume driver for changes in the loess records adjacent to deserts in northern China.

4.3. Possible mechanism responsible for spatial differences in MS

As shown in Fig. 6, after 0.6 Ma the MS record of the LC section increased to much higher maximum values during the last five interglaciations. MS has been widely used as a summer monsoon climate proxy on the CLP (An et al., 1991; Liu and Ding, 1998) and the MS record from the LC section and other sites on the central CLP indicates an enhanced monsoon precipitation in northern China. The deep-sea $\delta^{18}O$ record shows that the interval after the MPT was characterized by warmer interglacials associated with substantial melting of ice sheets (Sosdian and Rosenthal, 2009); in addition, the deuterium paleothermometer from the Antarctica Dome C ice core (Jouzel et al., 2007) also indicates that the interglacial periods were characterized by warmer temperatures in Antarctica after the Mid-Brunhes Event (about 0.43 Ma). The change in the pattern of the MS record in the LC section is in good agreement with the occurrence of decreased global ice volumes during interglacials, as well as with the prolonged duration of these intervals after the MPT. Both of these conditions favor the enhancement of MS values via intensified pedogenic processes within the regions influenced by the summer monsoon (Han et al., 1998). We therefore propose that the grain size of loess deposits immediately adjacent to the Asian dust source areas, such as at the NYZG, JB and FS sections, could respond more sensitively to the intensification of drying in the Asian interior that resulted from the increased global ice volumes during glaciations after the MPT. At the same time, the MS record of loess deposits closer to the core of the summer monsoon zone, such as the LC section, was better able to record the enhanced monsoon precipitation that resulted from lower global ice volumes and the prolonged duration of interglacials after the MPT.

However, in contrast to the LC section, the MS record of the NYZG section exhibits maximum MS values after 0.6 Ma (e.g. in S4, S2 and S1) which are lower than those in the paleosols predating the MPT (Fig. 6). This divergence between the NYZG and LC sections may suggest that the climatic sensitivity of the MS of loess deposits varies between regions (Ding et al., 2005). The MS signals in Chinese loess deposits may be driven both by the formation of fine-grained pedogenic ferrimagnetic oxides and by the detrital input of coarser-grained magnetic minerals blown in from the source regions (Sun and Liu, 2000). Since the extent of these source regions varies, changes in the detrital input...
of magnetic minerals may distort the pedogenic MS signal associated with climatic changes (Maher, 1998; Orgeira et al., 1998). The grain size of the NYZG section exhibits a coarsening in the upper part of the sequence (Fig. 8), which as discussed above probably indicates drying since the MPT and expansion of the desert environment in NE China. Thus, even though there was increased summer monsoon precipitation during interglacial maxima after the MPT, at least on the CLP and probably also in NE China, the texture of the paleosols in NE China became coarser due to the reduced distance of dust transport from source regions. We propose that this increased flux of sand-sized quartz grains (with a diamagnetic susceptibility) probably led to the dilution of the MS signal derived from the pedogenic production of ferrimagnets at the NYZG site during these interglacial phases. In addition, we note that the S1, S2, S3 and S4 in the JB and FS section also exhibit relatively low MS peaks, similar in magnitude to those of S6–S9. This is in contrast to the prominent peaks for S1–S5 at LC section which is distinctly greater than those for S6 and earlier (Fig. 6). The explanation for this odd phenomenon in MS peaks could be similar to that for NYZG, since JB and FS are also closer to the sandy deserts than Luochuan and show upward coarsening as in NYZG, though not as pronounced (Fig. 8). However, this interpretation needs to be tested by future more detailed rock magnetic studies.

5. Conclusions

The grain-size record (≥63 μm fraction) of the NYZG loess section in NE China reveals a long-term drying trend after ~1.0 Ma, punctuated by two abrupt drying events at ~0.65 Ma and ~0.3 Ma. This finding constitutes new evidence for the stepwise intensification of aridification in the dust source regions of NE China. We propose that increasing global ice volume since the Mid-Pleistocene Transition was the major driver for this process of stepwise aridification. Ice volume expansion in northern high latitudes would have caused the increased frequency of strong, cold winds in the arid zone of inland Asia, weakening the EASM circulation and eventually causing the large-scale expansion of deserts in northern China. Many of the loess records in northern China and central Asia, together with the eolian dust record from the North Pacific, exhibit a similar drying trend, suggesting that the entire arid zone of the Asian interior underwent a process of aridification after 1.0 Ma.

In addition to the foregoing, the loess deposits of the central CLP reveal a coeval trend of enhanced precipitation during interglacials in the core region of the summer monsoon, which we suggest resulted from lower global ice volumes and the prolonged duration of interglacial phases after the Mid-Pleistocene Transition. However, the MS record from the NYZG section does not exhibit this trend, and we propose that this was probably caused by regional differences in the climatic sensitivity of the MS of Chinese loess deposits. The MS signal of Chinese loess deposits reflects variations in the content of both pedogenically-produced ferrimagnets, which are related to increased humidity, and detrital magnetic minerals blown in from the source regions. However, significant changes in the supply of detrital ferrimagnets, such as may have occurred at the NYZG section, would be likely to distort the pedogenic component of the MS signal, which reflects precipitation changes. In addition, the increased flux of sand-sized quartz grains (with a diamagnetic susceptibility) would potentially dilute the pedogenic component.

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Appendix A. Supplementary data

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