Netherlands Journal of Geosciences — Geologie en Mijnbouw | **91 – 1/2** | **189 - 198** | **2012**

Palaeoclimatic changes in northeastern Qinghai-Tibetan Plateau revealed by magnetostratigraphy and magnetic susceptibility analysis of thick loess deposits

H.Y. Lu[1,*], Xianyan Wang[1], Xiaoyong Wang[1], X.F. Sun[1], S.W. Yi[1], Y.L. Zhou[1,2], Q.Y. Liu[1,3], J. Swinehart[1,4] & J. Vandenberghe[1,5]

1 School of Geographic and Oceanographic Sciences, Institute for Climate and Global Change Research, Nanjing University, Nanjing 210093, China.
2 College of Tourism and Environment, Shaanxi Normal University, Xi'an 710062, China.
3 Department of Chemistry and Life Sciences, Ankang College, Ankang 725000, China.
4 School of Natural Resources, IANR, University of Nebraska-Lincoln, Lincoln, NE 68588, USA.
5 Faculty of Earth and Life Sciences, Vrije Universiteit, De Boelelaan 1085, 1081 HV, Amsterdam, the Netherlands.
* Corresponding author. Email: huayulu@nju.edu.cn.

Manuscript received: September 2011, accepted: August 2012

Abstract

Reconstruction of a complete Quaternary record of climatic changes in the northeastern Qinghai-Tibetan Plateau is not well obtained, because of high relief and extensive surface erosion. In this study, two long cores obtained from thick loess deposits in the region, both contain clear alternations of loess and paleosols, indicating distinct climate changes during the Quaternary. The palaeomagnetic stratigraphy and optically stimulated luminescence dating indicate that the loess deposition began approximately 2.0 Ma ago, with continuous accumulation until the Holocene. Dust accumulation rates in this region are much higher than those in the central Chinese Loess Plateau, suggesting an extended dust source and/or robust transport agent. Variations of magnetic susceptibility of the loess are a good proxy index of warm/wet and cold/dry alternations and are correlated with the intensity of pedogensis. The magnetic susceptibility record reveals that a relatively cold/dry climate dominated the northeastern Qinghai-Tibetan Plateau in the Quaternary, punctuated by warm/wet phases. A stepwise strengthening of the plateau summer monsoon, with a significant strengthening at around 1200-1000 ka and at least 7 phases of strengthening of the plateau summer monsoon in the past 800 ka are interpreted from the core data. The cores provide evidence that strengthened warm/wet climates occurred at around 80-130, 190-250, 290-340, 385-420, 500-625, 690-720 and 755-780 ka, which may correlate to warm/wet phases in the Qinghai-Tibetan Plateau. The palaeoclimate changes probably were regulated by the glacial-interglacial alternations.

Keywords: Northeastern Qinghai-Tibetan Plateau, loess deposit, magnetostratigraphy, palaeoclimatic changes, Quaternary

Introduction

Climatic changes occurring on the high and cold northeastern Qinghai-Tibetan Plateau (NETP) are not well understood, because of high relief and extensive erosion. Unconsolidated sediments are generally not well preserved, and long depositional archives are scare, except in a few basins where fluvio-lacustrine sediments have been accumulated (Wang et al., 1986; Chen et al., 1995a; Shen et al., 2004; Hough, 2011). In addition, age models for fluvio-lacustrine sedimentation are not well constrained due to a lack of good dating techniques, no uniform sedimentation rates and hiatuses in the records. The proposed Quaternary climatic changes in this region reviewed by Colman et al. (2007) are controversial and need further investigation.

Deposits of aeolian silt (loess) occur sporadically in basins, river terraces and piedmonts in the NETP, these aeolian sequences should provide a good record of Quaternary palaeoclimatic changes, because the dating methods are robust and palaeoclimatic implications of the proxy indexes are well understood (see the reviews of Liu and Ding, 1998; An, 2000; Porter, 2001; Stevens et al., 2007). Compared with the loess deposits of Chinese Loess Plateau (Liu, 1985; Kukla, 1987; Ding et al., 1994; Liu and Ding, 1998; Guo et al., 1998, 2009; Lu et al., 2004a; 2006; 2010), knowledge of loess deposits in the NETP is quite poor, mainly because these loess deposits are difficult to access and are often covered by thick colluvium, making sampling difficult.

A few pioneering geologists mentioned the loess deposits in the NETP (Chen, 1947) (Fig. 1), but scientific investigations were not implemented until the 1980s, with work on age determinations and palaeoclimatic interpretations of the loess deposits at Lanzhou and Ganzi (Burbank & Li, 1985; Rolph et al., 1989; Chen et al., 1990; Fang, 1994; Fang et al., 1996). However, investigations of the loess deposit in the Xining Basin (Fig. 1) by Li et al., (1991, 1999), Zhu et al. (1994), Zeng et al. (1995), and Chen et al. (1995b) considered only the distribution, soil stratigraphy, magnetism and sedimentology of the upper part of the loess deposits. In particular, the early research was based on incomplete demagnetisation for constructing the magnetostratigraphy of the Dadunling loess deposit (Zeng et al., 1995). In recent years, detailed sampling of loess over the last glacial-interglacial cycle and the Holocene have enabled reconstruction of high-resolution climatic changes (Chen et al., 1995b; Kemp et al., 1996, 2001; Lehmkuhl, 1997; Lu et al., 2001, 2004c, 2006; Lehmkuhl et al., 2003; Küster et al., 2006; Vriend et al., 2011). A comprehensive study of the thick Quaternary loess deposits of this region, which record long-term climatic and environmental changes, along with independent dating has yet to be published.

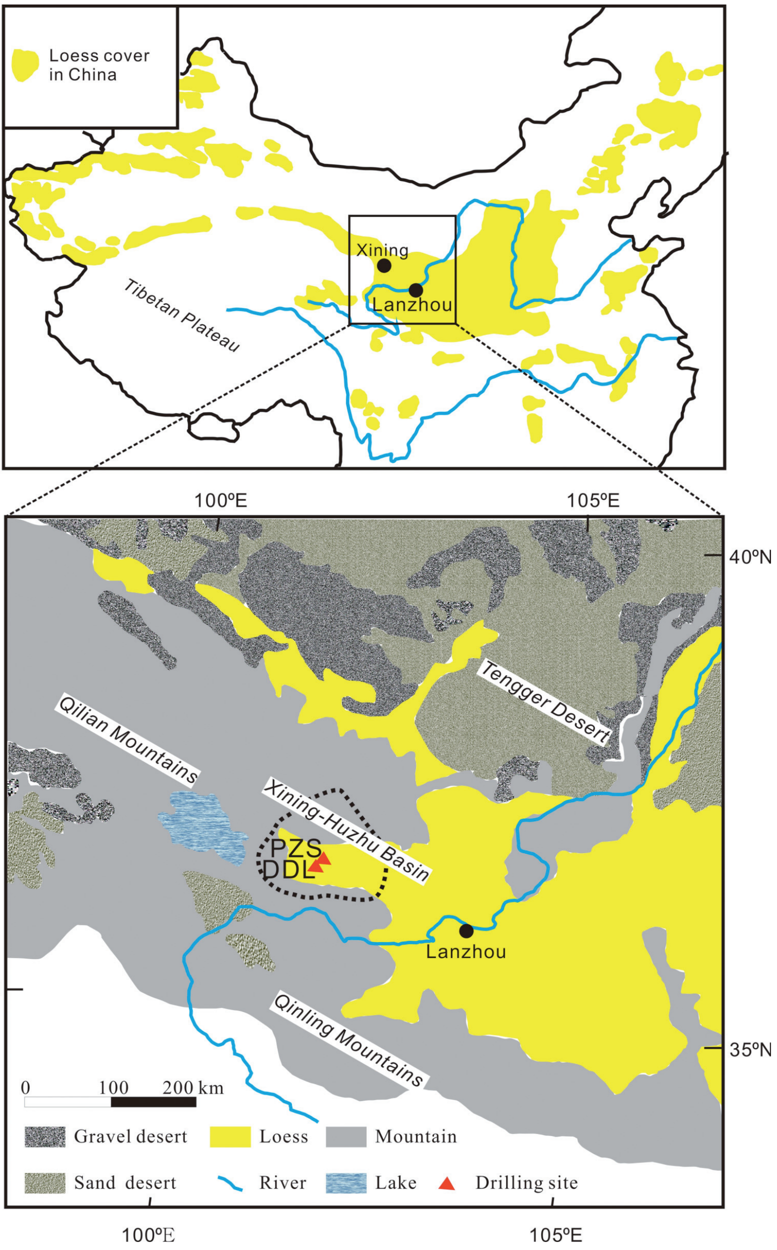


Fig. 1. Location of drilling sites and loess distribution in the northeastern Qinghai-Tibetan Plateau.

In the autumn of 2004, two cores, one 181.6 metres and the other 232.15 metres long, were obtained from the thickest loess deposit in the Xining Basin in order to reconstruct long-time climatic changes in this region. The preliminary pedostratigraphy has been reported by Lu et al. (2007). Here, we present the detailed magnetostratigraphy analysis and palaeoclimate interpretation based on magnetic susceptibility (MS). This study is the first to present a lengthy aeolian record of palaeoclimatic changes in the NETP with independent age constraints.

Background and characteristics of the loess deposits

The Xining-Huzu basin is located in the NETP (Fig. 1) where it is interpreted to be a young part of the Plateau that was growing during the late Cenozoic (Tapponnier et al., 2001). The bedrock includes lower Proterozoic gneiss and schist, limestone of Cambrian age and clastics of Triassic to Cretaceous age (Bureau of Geology and Mineral Resources of Qinghai Province, 1991). Basin and range type faulting produced accommodation space for thick fluvio-lacustrine deposits during the Cenozoic era. These sediments are intercalated with thick gypsum and salt layers, indicating distinct wet and dry changes during the Palaeogene and Neogene. During the middle Miocene, aeolian silt began to accumulate in this basin (Lu et al., 2004b; Wang et al., 2006, 2012) as a synchronous deposit of the fluvio-lacustrine sediments, indicating that a more arid environment had developed (Lu et al., 2004b, 2010). From the early to late Pleistocene, loess was deposited on bedrock units, Tertiary fluvio-lacustrine deposits and river terraces. Loess thickness varies from several metres to about 240 metres, with basal ages varying from the early Pleistocene to late Pleistocene (Lu et al., 2004 b).

Loess of the NETP is distinguished from the loess deposits in the central Chinese Loess Plateau by its coarser grain size, more rapid accumulation rate and more weakly-developed and thinner palaeosol units (Lu et al., 2004b, 2004c, 2007; Vriend et al., 2007). Mean grain size of the loess of the central Loess Plateau is approximately 15 µm (300 samples), whereas the loess of the NETP is around 20 µm (500 samples). The NETP loess-palaeosol sequences also contain sand layers that suggest episodic desertification of surrounding area and strong winds. Sources of these loess deposits probably include the Tibetan Plateau (TP), where there is considerable surface accumulation of glacially grinded silt particles (Li et al., 1991, 1999; Fang, 1994); in addition, some of the silt particles may come from arid and semiarid regions of northwest China (Li et al., 1999).

Atmospheric circulation patterns that appear to be the major force of climatic changes in the NETP include the plateau monsoon circulations, which may be associated with the Asian monsoon and the Westerlies (Tang, 1993; Lu et al., 2001, 2004c; Vandenberghe et al., 2006).

Methods

Two cores were drilled about 10 km apart in the Xining-Huzhu basin (Panzishan (PZS) and Dadunling (DDL), Fig. 1, 2). Both sites appear to be located on loess depocentres containing the thickest loess-paleosol deposits and the most complete stratigraphic sequences in the NETP.

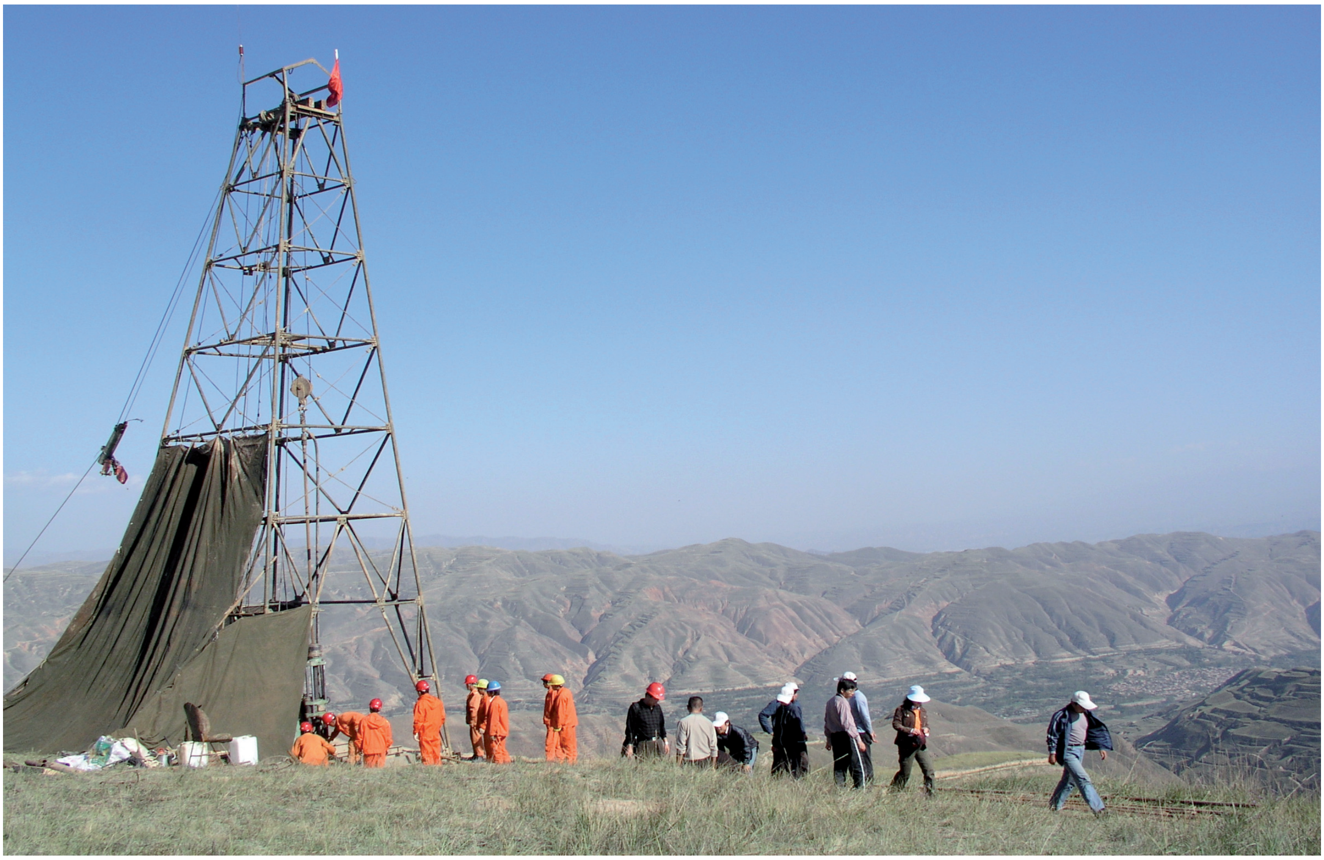
At the Panzishan site (36.649° N, 101.844° E, 2728 m a.s.l), the 186-metre loess-palaeosol sequence (measured from outcrop) was completely cored and reached fluvial gravel at the base of the loess. The core may be divided into three parts: 1) the uppermost samples (0-4.45 m) were obtained by digging a well; 2) samples from 4.43 to 25.53 m were collected by gravity drilling; 3) samples from 19.6 to 181.6 m were collected by hydraulic drilling. Core recovery was better than 96% and a complete loess-paleosol sequence was obtained.

At the Dadunling site (36.657° N, 101.787° E, 2740 m a.s.l) cores were obtained by hydraulic drilling at two closely spaced locations: 1) 0-20.65 m thick; and 2) 20-232.15 m thick. The change in drilling sites was necessitated by an equipment problem. Core recovery was better than 95% and the cores contain alternating coarse loess and weak paleosols.

The fresh cores were cut and sampled in the field and in situ magnetic susceptibility (MS) of selected samples was measured immediately. Systemic sampling was done at 5 cm intervals producing a total of 8314 bulk samples. The samples were cut into $2 \times 2 \times 2$ cm^3 blocks at 10 cm intervals and three parallel samples were prepared, for a total of more than 4000 oriented samples. The mass-specific low-field MS(c) of all bulk samples was measured in laboratory, using a Bartington MS2 meter at a frequency of 470 Hz, after drying below 40° C and measured three times with a stable error background. The oriented samples were measured at a resolution of 0.5 m and all the samples were systematically demagnetised in an alternating magnetic field or through stepwise heating. All samples were measured by a 2G superconductive magnetic metre in zero magnetic fields (<300 nT). Stepwise thermal and alternative demagnetisation of natural remanent magnetisation (NRM) was performed on selected samples (Fig. 3). Alternative demagnetisation was undertaken in a magnetic field from 0 to 100 mT with 5 mT interval; typical samples were heated to 680° C, with 12-18 steps of demagnetisation and 10-50° C temperature increments. Progressive demagnetisation successfully isolated the characteristic remanent magnetisation (ChRM) components for most of the samples after removing a viscous component of magnetisation after the 150-300° C treatment (Fig. 3). The principal components direction was computed by a 'least-squares fitting' technique (Kirschvink, 1980).

Age of the thick loess deposit

Loess deposits in the Xining-Huzu basin have long been considered to be of Quaternary age (Li et al., 1991; Zeng et al., 1995;



a.

b.

Fig. 2. a. The drilling site at PZS; b. The recovered aeolian loess core from the PZS site at depth of around 9 meter.

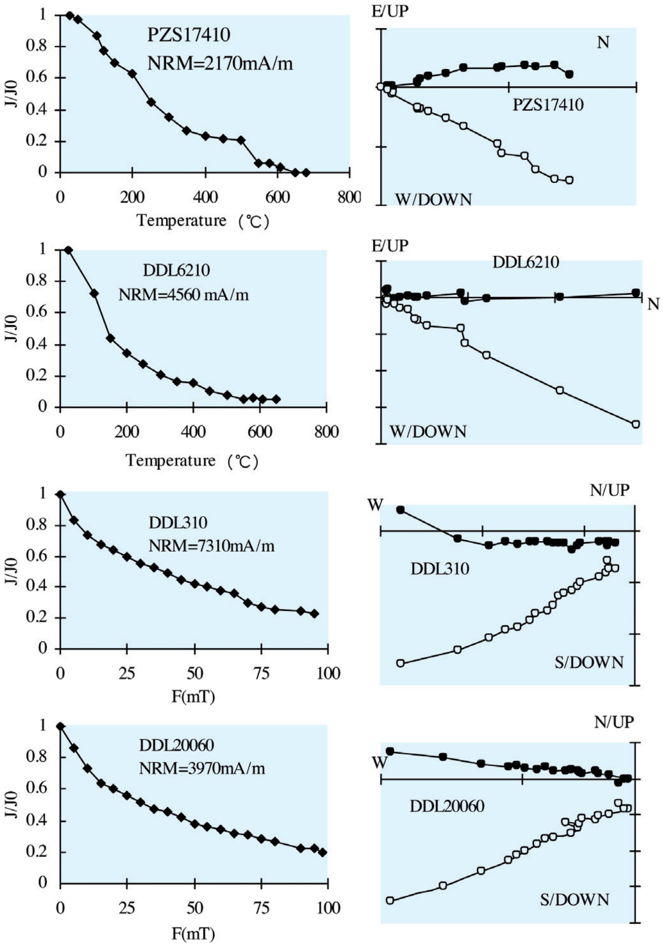


Fig. 3. Typical demagnetisation curves of samples of Xining loess and paleosol samples. J/J0 is ratio of normalised magnetic polarisation and the initial magnetic polarisation; F(mt) is intensity of alternating magnetic field with unit mT (thousandth Tesla).

Lu et al., 2001, 2004b). Optically stimulated luminescence dating (OSL) has confirmed that the upper part of the loess was formed during the late Quaternary (Chen et al., 1995b; Lu et al., 2001, 2004c; Buylaert et al., 2008; Vriend et al., 2011); Excavated fossils and pedostratigraphy analysis also indicate this loess was deposited in Pleistocene times (Bureau of Geology and Mineral Resources of Qinghai Province, 1991). The upper positive magnetic chron of the PZS sequences correlates with the Brunhes positive chron, and the Brunhes/Matuyama boundary (B/M) is placed at a depth of 87.0 m (Fig. 4a) (Cande & Kent, 1995). The two positive subchrons in the Matuyama negative chron must be correlated with the Jaramillo and Olduvai subchrons, respectively. This correlation provides direct age constraints to the thick loess deposit. With this magnetostratigraphic correlation strategy, a dust sedimentation rate of 11.2 cm/ka after the Olduvai subchron was determined and this rate is extrapolated to the lowest part of the PZS loess-palaeosol sequence, yielding a basal age of the loess deposit of approximately 2.0 Ma.

For the DDL loess sequence, there is a thick positive magnetostratigraphic zone in the upper part that can be conclusively correlated with the Brunhes positive chron, and therefore the Brunhes/Matuyama boundary is placed at a depth of 128.0 m (Fig. 4a) (Cande & Kent, 1995). However, there is a clear hiatus at a depth of about 138 m where the positive part above the hiatus may be correlated with the Jaramillo subchron, and there are multiple alternations of normal and reverse magnetic polarity below this hiatus. These cannot be interpreted as Quaternary deposits, as there are not so many magnetic polarity changes in the Pleistocene, therefore, interpretation of these sediments is not clear in this study. Our field and laboratory investigations show the lower part is brown-reddish silt, with a homogeneous structure and no laminations. It is a typical loess-like deposit, similar to the wide-spread Red Clay deposit of the Miocene time in this region (Lu et al., 2004b; Wang Xianyan et al., 2006, 2012). Therefore, we speculate the lower 94.15 m may represent an aeolian silt that can be correlated with the Red Clay deposit at several kilometres distance (Lu et al., 2004b; Wang Xianyan et al., 2006, 2012).

Dust sedimentation rates of the central Loess Plateau average between 5 to 7 cm/kyr, but on the NETP, the rate is considerably greater, averaging between 9 and 13 cm/kyr (Table 1). This suggests that the NETP is close to dust sources and/or the dust transport agent is very robust. This high dust accumulation rate

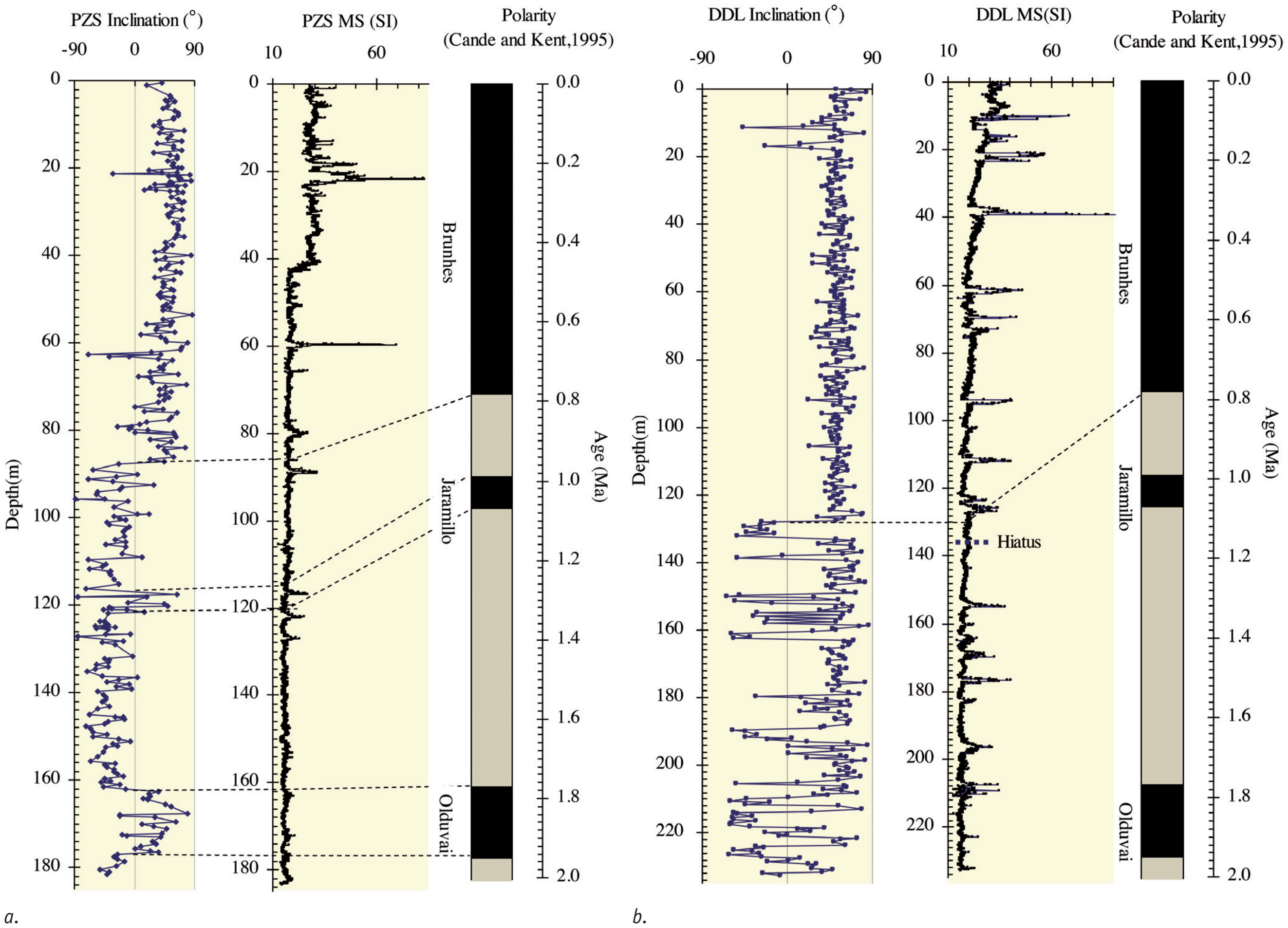


Fig. 4. a. Magnetostratigraphy and magnetic susceptibility variations of loess-paleosol sequences from Panzishan (PZS) core; b. Magnetostratigraphy and magnetic susceptibility variations of loess-paleosol sequences from Dadunling (DDL) core.

Table 1. Average loess sedimentation rate (S.R.) in the Northeastern Qinghai-Tibetan Plateau (NETP) and Chinese Loess Plateau (CLP) during the Quaternary.

Site	Thickness (cm)	Duration (kyr)	S.R. (cm/kyr)
DDL	13,800	1070	12.9
PZS	18,200	2000	9.1
XF	17,400	2580	6.74
LC	13,600	2580	5.27

may provide a unique opportunity for the study of higher resolution climatic events in this region. Onset of a wide-spread mantle of loess deposition on the central Chinese Loess Plateau is dated at about 2.4-2.6 Ma, corresponding to the expansion of ice cover in the northern hemisphere (Liu and Ding, 1998; Lu et al., 2010). However, the NETP loess deposits are approximately 0.4-0.6 Ma younger than those of the Loess Plateau. This time difference may be caused by an unstable tectonic framework resulting in erosion of older loess. This interpretation is supported by evidence that the NETP dust source was formed considerably earlier than 2.0 Ma, indicating that a relatively constant dust input to this region should have occurred since the late Cenozoic (Lu et al., 2004b; Wang Xianyan et al., 2006, 2012). The absence of loess deposits during 2.6-2.0 Ma (and also the absence of the aeolian Red Clay deposit during 7.5-2.6 Ma) in the Xining basin is probably caused by unsuitable depositional conditions, rather than a cessation of dust deposition.

Abundant silt particle generation and robust dust transport indicates that the regional atmospheric circulation favoured dust transportation and deposition at elast beginning about 2.0 Ma in the NETP. Thus, this study indicates that a favourable environment for dust deposition, similar to that of the modern environment, existed much earlier than previously suggested (Zeng et al., 1995).

Interpretation of the magnetic susceptibility changes

Loess deposits are a mixture of aeolian silts from distal and near sources in arid to semiarid climates, so that physical and chemical characteristics of different loess deposits are in many ways identical (Liu, 1985; Jahn et al., 2001; Chen and Li, 2011; Zhang et al., 2012). Major oxide and rare earth element analyses, as well as our field investigations, show that the loess deposits in the Xining-Huzu Basin are well mixed with a homogenous distribution of chemical elements. They are similar to typical loess deposits on the Chinese Loess Plateau which are well mixed and sorted before deposition and are interpreted to have multiple sources and long transport distances. The character of the loess deposits is significantly influenced by local climate changes which can modify the intensity of pedogenesis by controlling surface weathering and bioturbation. It is generally accepted that MS of loess in northern China is highly influenced by climate changes (Kukla, 1987; Zhou et al., 1990; An et al., 1991; Maher and Thompson, 1992; Liu et al., 2007). Higher MS values correspond to a more humid and warmer palaeoclimate, whereas lower MS values are linked to a drier and colder palaeoclimate.

The MS of the samples from the DDL and PZS records are shown in Figs 4a and 4b. All the paleosol horizons show high susceptibility values ranging between $21\cdot10^{-8}\,m^3/kg$ and $94.3\cdot10^{-8}\,m^3/kg$, with the highest values of $94.3\cdot10^{-8}\,m^3/kg$ at 39.2 m in the DDL core and $82.3\cdot10^{-8}\,m^3/kg$ at 21.8 m in the PZS core. The loess units are characterised by uniform low susceptibility values ranging between $13\cdot10^{-8}\,m^3/kg$ and $33.2\cdot10^{-8}\,m^3/kg$, with the lowest value occurring at 121.7 m ($15\cdot10^{-8}\,m^3/kg$) for the DDL core and 103.65 m ($13\cdot10^{-8}\,m^3/kg$) for the PZS core. Loess units accumulated during relatively cold/dry periods when the plateau winter monsoon was strong, producing frequent dust storms and high dust sedimentation rates. The paleosol units accumulated under a warm and wet climate, when the plateau summer monsoon was stronger. Therefore, similar to the loess-paleosol sequences on the Chinese Loess Plateau, MS in the NETP loess can also be used as a proxy index of past climatic changes at orbital timescales. This conclusion is further supported by detailed rock magnetic investigations on loess deposits during the late Pleistocene at the NETP (Wang Xiaoyong et al., 2003, 2006).

MS from loess sections may be modified by oxidation during long-term exposure, and therefore the MS values may be somewhat misleading in terms of climatic interpretation (Balsam, 2001, personal communication). Our drilling offers an excellent opportunity to test this proposal; we carried out both immediate in situ field measurement and laboratory measurement six months later for the core samples MS (Fig. 4a and 4b), and compared these measures (Fig. 5). The two measurements correlate well, suggesting that exposure to air does not have a significant influence on the MS of the loess sequences.

Implications for wet-dry variations in the high and cold region

Climate change over the Qinghai-Tibetan Plateau is driven primarily by the plateau monsoon circulation, although there are some controversies related to the monsoon forcing mechanism (Tang et al., 1993; Lu et al., 2004c; 2006; Vandenberghe et al., 2006; Colman et al., 2007). There is a consensus that the plateau monsoon circulation plays a vital role on the wet/warm and dry/cold variations in the NETP at orbital timescales. In this plateau monsoon dominated region, the climate was warm and wet in the interglacial periods and cold and dry in the glacial periods. For the first time, the two cores described here should yield a record to aid in understanding past plateau monsoon changes during the Quaternary.

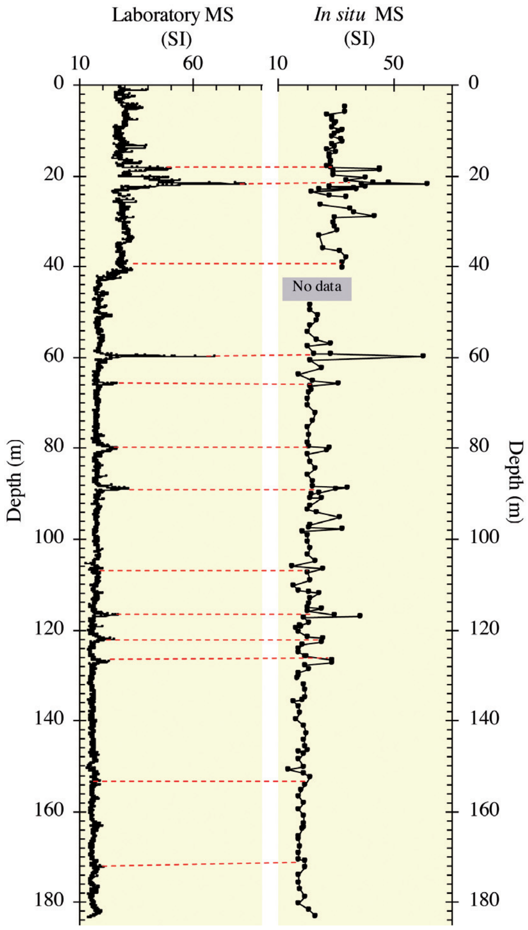


Fig. 5. Comparison of in situ field MS and laboratory MS of the PZS core. The similarity of the two curves demonstrates that oxidation of the samples by exposure to air does not substantially influence magnetism of the loess and paleosol samples.

The mean MS value of these cores, 23.5·10^{-8} m^3/kg (n = 2757) for DDL and 20.3·10^{-8} m^3/kg (n = 3622) for PZS, are lower than those of the Luochuan sequences (89.7·10^{-8} m^3/kg, n = 3444), suggesting that a dry and cold climate dominated the NETP throughout the Quaternary (Fig. 6). The relatively low and consistent MS values observed for loess deposited in glacial periods indicate consistent availability of dust and an active transport agent correlated to cold periods in the Northern Hemisphere. Moreover, the MS values show a gradual increase through time, while the amplitude is enhanced from the lower to the upper part (Fig. 6). This may indicate a long-time strengthening of the plateau summer monsoon over successive interglacial periods in the past around 1.0 Ma.

Using independent OSL ages (Lu et al., 2004c) and the palaeomagnetic stratigraphical boundary constraints, the MS curves of the loess-paleosol alternations at the NETP were compared with the typical loess time series of the central Loess Plateau (Lu et al., 1999) to obtain age controls of each rapid MS shift (Fig. 6). A time scale for the loess deposits in the Xining Basin was obtained by linear interpolation between the age control points of the magnetostratigraphy and loess/paleosol boundaries (Fig. 6). This new MS time series reveals several interesting features of the plateau monsoon. First, there are distinct changes in MS around 1.0 Ma. Before 1.0 Ma, the MS curve is relatively smooth, but after 1.0 Ma there are several MS peaks covering several tens of thousands of years. These intervals probably reflect significant fluctuations of the plateau monsoon climate at glacial-interglacial timescales (Fig. 6). The paleosol units are bracketed by thick loess units, indicating winter monsoon circulation prevailed most of the

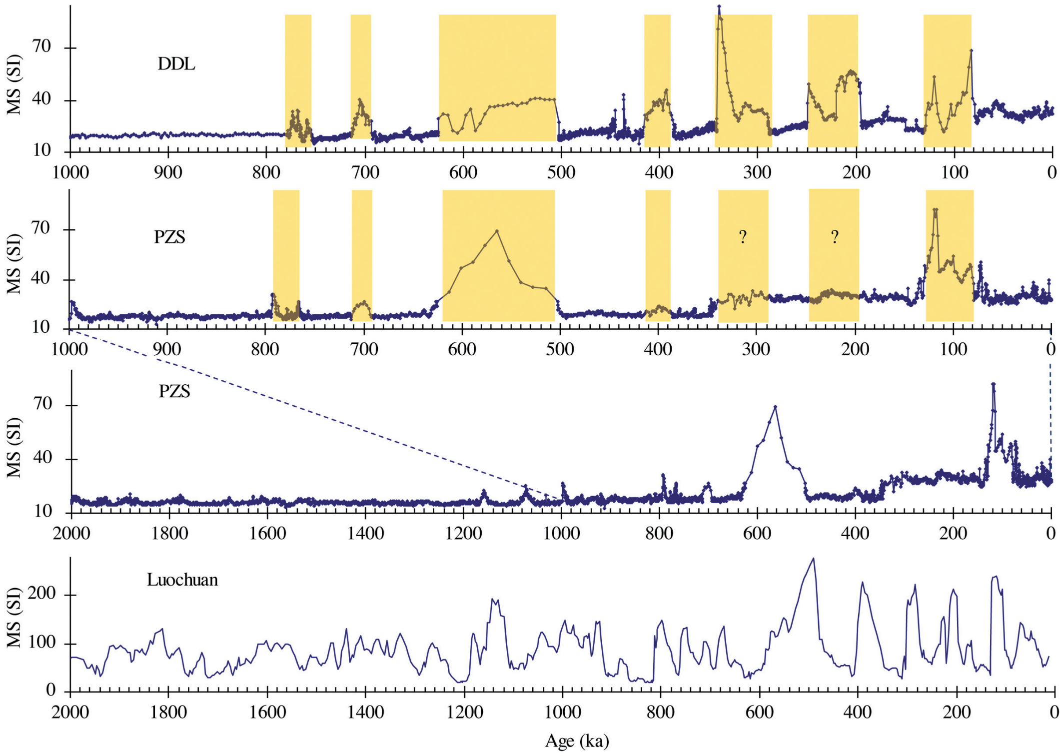


Fig. 6. An approximate time scale of the MS variations in the past 2.0 million years. The shaded intervals indicate high MS at both cores that correlate with phases of the strengthened plateau monsoon.

time, especially in the early part of the two records. There are also stepwise increases in the maximum MS values at 1200-1000 ka, which may imply strengthening of the plateau summer monsoon circulation and a climate dominated by wet and warm conditions. After this MS value shift, the relatively smooth magnetic changes are replaced by changes with greater amplitude. Finally, there is evidence for rapid climatic changes from a warm/wet to a cold/dry climate and vice versa at 625, 342, 248, 220 and 129 ka in the DDL MS time series. This suggests a rapid shift of the summer monsoon intensity from phase to phase. These indications of sudden changes of the plateau monsoon strength in the past 1000 ka have not been interpreted previously for the NETP.

Using this preliminary time scale, the plateau summer monsoon appears significantly strengthened at around 80-130, 190-250, 290-340, 385-420, 500-625, 690-720 and 755-780 ka as indicated by the highest MS values (Fig. 6) (there are not obviously high MS values during 190-250 and 290-340 ka in the PZS record, the reason is not clear). This may be a nonlinear local response to regional climate changes. This unique climatic feature has not been detected in either Chinese loess records (Lu et al., 2004a) or global ice volume changes (Zachos et al., 2001), and may indicate that in addition to global climatic change forcing regional climatic changes, local conditions may be important in modifying the climatic changes (Ravelo et al., 2004; Lu et al., 2010).

Conclusions

The thick loess deposits of the northeastern Qinghai-Tibetan Plateau provide a good record of palaeoclimatic and palaeoenvironmental changes over a wide region where past climatic and environmental changes have yet to be reconstructed in detail. Onset of dust deposition in the Xining-Huzu basin indicates that a favourable environment for loess accumulation began at approximately 2.0 Ma. The loess record reveals multiple cold/dry and warm/wet variations, suggesting periodic climatic changes in this region. The magnetic susceptibility changes are associated with alternations of thick loess and thin soil sequences. The plateau monsoon shifted to greater amplitude at around 1200-1000 ka. This increase may indicate that the palaeoclimate went through a phased evolution. The plateau summer monsoon was strengthened at around 80-130, 190-250, 290-340, 385-420, 500-625, 690-720 and 755-780 ka, and mountain glaciers were probably significantly reduced during these times. These climatic events may represent a local nonlinear response to global climate changes. The ongoing analysis of these two long cores will offer more detailed information on long-term changes in climate in this high and cold region.

Acknowledgements

We thank Prof. William Balsam and Dr Thomas Stevens for improving the English of this paper, and the drill group for carefully drilling cores during the three months fieldwork. Thanks also go to Profs Zhisheng An, Zhengtang Guo, Rixiang Zhu, Tungsheng Liu and Sumin Wang for their encouragements and helps and Weidong Huang, Chuanbin Yang and Lingjuan Wen for field and laboratory assistance. This research is funded by the National Natural Science Foundation of China (40930103, 41021002, and 40325007), the National Global Change Programme of China (2010CB950203) and the Royal Netherlands Academy of Arts and Sciences (grant number 04-PSA-E-02).

References

An, Z.S., 2000. The history and variability of the East Asian paleomonsoon climate. Quaternary Science Reviews 19: 171-187.

An, Z.S., Kukla, G.J., Porter, S.C. & Xiao, J.L., 1991. Evidence of monsoon variation on the Loess Plateau of central China during the last 130,000 years, Quaternary Research 36: 29-36.

Burbank, D.W. & Li, J.J., 1985. Age and palaeoclimatic significance of the loess of Lanzhou, north China. Nature 316: 429-431.

Bureau of Geology and Mineral Resources of Qinghai Province, 1991. Regional Geology of Qinghai Province, Geological Publishing Hourse, Beijing, 662 pp. (In Chinese)

Buylaert, J.P., Murray, A.S., Vandenberghe, D., Vriend, M., De Corte, F. & Van den haute, P., 2008. Optical dating of Chinese loess using sand-sized quartz: Establishing a time frame for Late Pleistocene climate changes in the western part of the Chinese Loess Plateau. Quaternary Geochronology 3: 99-113.

Cande, S.C. & Kent, D.V., 1995. Revised calibration of the geomagnetic polarity time scales for the late Cretaceous and Cenozoic. Journal of Geophysics Research 100, 6093-6095.

Chen, F.B., Gao, S.H., Chen, J.L., Ge, T.M., Liang, C.Y., Pan, L.M. & Xu, H., 1990. A preliminary study on Ganzi loess magnetostratigraphy. Chinese Science Bulletin, 35 (20): 1600. (In Chinese)

Chen, M.X., 1947. Landform in central Gansu province. Geological Reviews 12, 545-556. (In Chinese)

Chen, F.H., Wang, S.M., Li, J.J., Shi, Y.F., Li, S.J., Cao, J.X., Zhang, Y.T., Wang, Y.F. & Kelts, K., 1995a. Palaeomagnetic record from RH lacustrine core in Zoige basin of Tibetian Plateau. Science in China (B) 38(12), 1513-1521.

Chen, F.H., Wu, R.J., Pompei, D. & Oldfield, F., 1995b. Magnetic property and particle size variations in the late Pleistocene and Holocene parts of the Dadongling loess section near Xinning, China. Quaternary Proceedings 4: 27-40.

Chen, J. & Li, G.J., 2011. Geochemical studies on the source region of Asian dust. Science in China Earth Science 54: 1279-1301.

Colman, S.M., Yu S.Y., An, Z.S., Shen J. & Henderson, A.C.G., 2007. Late Cenozoic climate changes in China's western interior: a review of research on Lake Qinghai and comparison with other records. Quaternary Science Reviews 26: 2281-2300.

Ding, Z.L., Yu, Z.W., Rutter, N.W. & Liu, T.S., 1994. Towards an orbital time scale for Chinese loess deposits. Quaternary Science Review, 13(1): 39-70.

Fang, X.M., 1994. A preliminary investigation of formation and source of Malan loess deposit in the eastern Qinghai-Tibetan Plateau and its adjacent region. Sciences in China (series B) 24(5): 539-546. (In Chinese)

Fang, X.M., Chen, F.B., Shi, Y.F. & Li, J.J., 1996. Ganzi loess and maximum glaciation on the Qinghai-Xizang (Tibetan) Plateau. Chinese Science Bulletin 41 (20): 1865-1867.

Guo, Z.T., Liu, T.S.Fedoroff, N., Wei, L.Y., Ding, Z.L., Wu, N.Q., Lu, H.Y., Jiang, W.Y. & An, Z.S., 1998. Climate Extremes in Loess of China Coupled with the Strength of Deep-Water Formation in the North Atlantic. Global and Planetary Change 18: 113-128.

Guo, Z.T., Berger, A., Yin, Q.Z. & Qin, L., 2009. Strong asymmetry of hemispheric climates during MIS-13 inferred from correlating China loess and Antarctica ice records. Climate of the Past 5: 21-31.

Hough, B.G., 2011. The evolution of the northeastern margin of the Tibetan Plateau: Stratigraphy, Paleoclimate, and Tectonics. Ph.D. dissertation, University of Rochester, 2011, AAT 3442799, 224 pp.

Jahn, B., Gallet, S. & Han, J., 2001. Geochemistry of the Xining, Xifeng and Jixian sections, Loess Plateau of China: eolian dust provenance and paleosol evolution during the last 140 ka. Chemical Geology 178: 71-94.

Kemp, R.A., Derbyshire, E., Chen, F.H. & Ma, H.Z., 1996. Pedosedimentary development and palaeoenvironmental significance of the S1 palaeosol on the northeastern margin of Qinghai-Xizang (Tibetan) Plateau. Journal of Quaternary Science 11: 95-106.

Kemp, R.A., Derbyshire & E., Meng, X.M., 2001. A high-resolution micromorphological record of changing landscapes and climate on the western Loess Plateau of China during oxygen isotope stage 5. Palaeogeography, Palaeoclimatology, Palaeoecology 170: 157-169.

Kirschvink, J.L., 1980. The least-squares line and plane and the analysis of palaeomagnetic data. Geophysical Journal ofthe Royal Astronomical Society 62: 699-718.

Kukla, G., 1987. Loess stratigraphy in central China. Quaternary Science Reviews 6, 191-207.

Küster, Y., Hetzel, R., Krbetschek M. & Tao, M.X., 2006. Holocene loess sedimentation along the Qilian Shan (China): significance for understanding the processes and timing of loess deposition. Earth and Planetary Science Letters 25: 114-125.

Lehmkuhl, F., 1997. The spatial distribution of loess and loess-like sediments in the mountain areas of Central and High Asia, Zeitschrift für Geomorphologie, Supplementband 111: 97-116.

Lehmkuhl, F., Klinge, M., Rees-Jones, J. & Rhodes, E.J., 2003. Late Quaternary eolian sedimentation in central and south-eastern Tibet. Quaternary International 68/71: 117-132.

Li, Z.Zeng, Y.N. & Shan, W.D., 1991. Distribution and features of loess deposit in northeastern Qinghai province. Journal of Qinghai Normal University (natural science) 4: 51-56. (In Chinese)

Li, Z.and Nie, S.R., 1999. Loess deposit at Xining and its provenance. Journal of Earth Sciences 24(6): 1-3. (In Chinese)

Liu, Q.S., Deng, C.L., Torrent, J., & Zhu, R.X., 2007. Review of recent developments in mineral magnetism of the Chinese loess. Quaternary Science Reviews 26: 368-383.

Liu, T.S., 1985. Loess and environment, China Ocean Press (Beijing): 31-67.

Liu, T. & Ding Z., 1998. Chinese loess and the palaeomonsoon. Annual Review of Earth and Planetary Science 26: 111-145.

Lu, H.Y., Liu, X.D., Zhang, F.Q., An, Z.S. & Dodson, J., 1999. Astronomical calibration of loess-paleosol deposits at Luochuan, central Chinese Loess Plateau. Palaeogeography, Palaeoclimatology, Palaeoecology 154: 237-246.

Lu, H.Y., Ma, H.Z., Tan, H.B., Li, Z., Miao, X.D., An, Z.S., Wang, X.Y., Cao, G.C. & Vandenberghe, J., 2001. The Plateau Monsoon changes during the past 130 kyr revealed by loess deposit at Xining. Quaternary Sciences 21(5): 416-426. (In Chinese)

Lu, H.Y., Zhang, F.Q., Liu, X.D. & Duce, R., 2004a. Periodicities of palaeoclimatic variations recorded by loess-paleosol sequence in China. Quaternary Science Reviews 23: 1891-1900.

Lu, H.Y., Wang X.Y., An Z.S., Miao X.D., Zhu R.X., Ma H.Z., Li Z., Tan, H.B. & Wang, X.Y., 2004b. Geomorphologic evidence of phased uplift of the northeastern Qinghai-Tibet Plateau since 14 million years ago. Science in China (Series D) 47(9): 822-833.

Lu, H.Y., Wang, X.Y., Ma, H.Z., Tan, H.B., Vandenberghe, J., Miao, X.D., Li, Z., Sun, Y.B., An, Z.S. & Cao, G.C., 2004c. The Plateau Monsoon Variation during the Past 130 kyr Revealed by Loess Deposit at Northeast Qinghai-Tibet (China). Global and Planetary Change 41: 207-214.

Lu, H.Y., Vandenberghe, J., Miao, X.D., Tan, H.B. & Ma, H.Z., 2006. Evidence for an abrupt climatic reversal during the Last Interglacial on the northeast Qinghai-Tibetan Plateau. Quaternary International 154-155: 136-140.

Lu, H.Y., Wang Xianyan, Sun X.F., Wang Xiaoyong, Yi, S.W., Zhou, Y.L. & Liu, Q.Y., 2007. Loess stratigraphy and palaeoclimate changes during Quaternary in northeastern Tibetan Plateau. Quaternary Sciences 27(2): 230-241. (In Chinese)

Lu, H.Y., Wang, X.Y. & Li, L.P., 2010. Aeolian sediment evidence that global cooling has driven late Cenozoic stepwise aridification in central Asia. *In:* Clift, P.D., Tada, R. & Zheng, H. (eds): Monsoon Evolution and Tectonics – Climate Linkage in Asia. Geological Society, London, Special Publications 342: 29-44.

Madsen, D.B., Ma H.Z., Rhode, D, Brantingham, P.J. & Forman S.L., 2008. Age constraints on the late Quaternary evolution of Qinghai Lake, Tibetan Plateau. Quaternary Research 69: 316-325.

Maher, B.A. & Thompson, R., 1992, Paleoclimatic significance of the mineral magnetic record of the Chinese loess and paleosols. Earth and Planetary Science Letters 121: 71-80.

Porter, S.C., 2001. Chinese loess record of monsoon climate during the Last Glacial-interglacial cycle. Earth-Science Reviews 54: 115-128.

Ravelo, A.C., Andreasen, D.H., Lyle, M., Lyle, A.O. & Wara, M.W., 2004. Regional climate shifts caused by gradual global cooling in the Pliocene epoch. Nature 429: 263-267.

Rolph, T.C., Shaw, J., Derbyshire, E. & Wang, J., 1989. A detailed geomagnetic record from Chinese loess. Physics of Earth and Planetary Interiors 56: 151-164.

Stevens, T., Thomas, D.S.G., Armitage, S.J., Lunn, H.R. & Lu, H.Y., 2007. Reinterpreting climate proxy records from late Quaternary Chinese loess: A detailed OSL investigation. Earth-Science Reviews 80: 111-136, doi: 10.1016/j.earscirev.2006.09.001.

Shen, J., Lu, H.Y., Wang, S.M., Chen, S.Y., Yang, X.D., Wu, Y.H. & Zhu, Z.Y., 2004. A 2.8 Ma record of environmental evolution and tectonic events inferred from the Cuoe core in the middle of Tibetan Plateau. Science in China, series D, 47 (11): 1025-1034.

Tang, M.C., 1993. Progress of the study on the Plateau Monsoon. Plateau Meteorology 12: 95-101. (In Chinese)

Tapponnier, P., Xu, Z.Q., Roger, F., Meyer, B., Arnaud, N., Wittlinger, G. & Yang, J., 2001. Oblique stepwise rise and growth of the Tibet Plateau. Science 294: 1671-1677.

Vandenberghe, J., Renssen, H., Van Huissteden, K., Nugteren, G., Konert, M., Lu, H., Dodonov, A. & Buylaert, J.-P., 2006. Penetration of Atlantic westerly winds into Central and East Asia. Quaternary Science Reviews 25: 2380-2389.

Vriend, M., Prins, M.A., Buylaert, J.P., Vandenberghe, J. & Lu, H.Y., 2011. Contrasting dust supply patterns across the north-western Chinese Loess Plateau during the last glacial-interglacial cycle. Quaternary International 240: 167-180.

Wang, J., Derbyshire, E. & Shaw, J., 1986. Preliminary magnetostratigraphy of Dabuxun Lake, Qaidam Basin, central Asia. Phys. Earth Planet. Inter. 44: 41-46.

Wang, Xianyan, Lu, H.Y., Ji, J.F., Wang, X.Y., Zhao, J.B., Huang, B.C. & Li, Z., 2006. Origin of the Red Earth sequence on the northeastern Tibetan Plateau and its implications for regional aridity since the middle Miocene. Science in China Series D-Earth Sciences 49(5): 505-517.

Wang, Xianyan, Lu, H.Y., Vandenberghe, J., Zheng, S.H., Van Balen, R., 2012. Late Miocene uplift of the NE Tibetan Plateau inferred from basin filling, planation and fluvial terraces in the Huang Shui catchment. Global and Planetary Change 88-89: 10-19.

Wang, Xiaoyong, Lu H.Y., Li Z., Deng C.L., Tan H.B. & Song Y.G., 2003. Palaeoclimatic implication of the magnetic minerals of loess deposits in the northeastern Qinghai-Tibet Plateau. Chinese Science Bulletin 48: 2126-2133.

Wang, Xiaoyong, Lu, H.Y., Xu, H.F., Deng, C.L., Chen, T.H. & Wang, X.Y., 2006. Magnetic properties of Late Pleistocene loess deposits at northeastern Qinghai-Tibetan Plateau: palaeoclimatic implications. Geophysical Journal International 167: 1138-1147.

Zachos, J.C., Pagani, M., Sloan, L.Thomas, E. & Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 292: 686-693.

Zeng, Y.N., Ma, H.Z.Li, Z., Li, L.Q., 1995. Formation and development of Huangshui River terraces in the Xining region. Scientia Geographica Sinica 15: 253-258. (In Chinese)

Zhang, H.Y., Lu, H.Y., Jiang, S.Y., Vandenberghe, J., Wang, S.J. & Cosgrove, R., 2012. Provenance of loess deposits in the Eastern Qinling Mountains (central China) and their implications for the paleoenvironment. Quaternary Science Reviews 43: 94-102.

Zhou, L.P., Oldfield, F., Wintle, A.G., Robinson, S.G. & Wang, J.T., 1990. Partly pedogenic origin of magnetic variations in Chinese loess. Nature 346: 737-739.

Zhu, R.X., Zhou, L.P., Laj, C., Mazaud, A. & Ding, Z.L., 1994. The Blake geomagnetic polarity episode recorded in Chinese loess. Geophysical Research Letters 21: 697-700.