EXPERIMENTAL INVESTIGATIONS OF MAGNETIZATION PROCESSES IN CHINESE LOESS

PhD dissertation

Ronghua Wang

Department of Earth Science
Faculty of Mathematics and Natural Sciences
University of Bergen

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List of two publications and one manuscript under review

1. Introduction

Loess is a widespread 'loose' deposit, which has been a subject of numerous scientific researches since the 1800's century. A general consensus about its origin and pathways of formation has been reached after discourse for about a century (Pye, 1995; Wright, 2001). As a unique terrestrial paleoclimatic and paleomagnetic archive, loess has been actively investigated during the last three decades (Heller &Evans, 1995; Smalley et al., 2001; Evans & Heller, 2001; Tang et al., 2003; Liu et al., 2007).

Loess and intercalated paleosols on the Chinese loess plateau (CLP) have provided numerous records of long-term variations of the East Asian Monsoon (EAM), which is connected to the global glacial-interglacial cycles during the last 2.6Ma (Liu & Ding, 1993, 1998; An et al., 2000; Ding et al., 2002). The time frame of loess/paleosol sequences is mainly established by paleomagnetic polarity stratigraphy (Heller & Liu, 1982, 1984; Heller & Evans, 1995), relying on the ability of loess/paleosol to apparently faithfully record and retain geomagnetic field directions imposed during their formation.

A number of features of the geomagnetic field, however, are inconsistently or imperfectly recorded across CLP, such as:

- The Matuyama/Brunhes boundary (MBB) sometimes occurs in loess layer L8 formed during a glacial period, contradictory to its true occurrence within marine isotope stage (MIS) 19.1 (Evans & Heller, 2001; Tang et al., 2003; Jin & Liu, 2010, 2011a and references therein). It was later relocated in paleosol S8 at Lingtai and Zhaojiachuan by redefining the climatic boundary between loess layer L8 and paleosol S8 (Liu et al., 2008), but confirmations from more sites are decisive.

- Inferred transitional fields associated with MBB show a number of high-frequency 'swings' of polarity with no preferred virtual polarity pole (VGP) paths (Spassov et al., 2001; Yang et al., 2010; Jin & Liu, 2010)

- Geomagnetic excursions in Brunhes and paleo-secular variation are only observed at a few localities on the CLP (Fang et al., 1997; Zhu et al, 1998, 1999, 2006, 2007; Pan et al., 2002; Heslop et al., 1999).
- Anomalous intervals of normal polarity in loess layer L9 in many areas have been attributed to remagnetization (Wang et al., 2005; Jin & Liu, 2011b).

Unconformities in deposition and post-depositional processes may suppress loess from recording high-frequency geomagnetic field variations (Stevens et al., 2006, 2007; Zhu et al., 2007; Sun et al., 2010a). Moreover, the acquisition/retention of remanent magnetization in loess is poorly, and is likely to be complex and site-specific.

One major limitation for decoding the paleomagnetic signal in loess/paleosol is the lack of a realistic model for the acquisition of both the primary and secondary remanent magnetizations. A detrital remanent magnetization (DRM) acquired and retained in subaerially deposited grains is *a priori* likely to be fundamentally different from the experimentally established model of DRM in water-laid sediments (Barton et al., 1980; Tauxe & Kent, 1984). Nevertheless, the model of post-depositional remanent magnetization (pDRM) (Irving & Major, 1964; Kent, 1973; Løvlie, 1974) for water-laid sediments was uncritically adopted to account for the misfit of the MBB between Chinese loess and marine sediments (Zhou & Shackleton 1999; Spassov et al., 2003a).

Experimental investigations of how loess acquires a depositional remanent magnetization have thus ‘waited’ decades to be done (Zhao & Roberts, 2010; Wang & Løvlie, 2010).

2. Summary

In an attempt to address factors that may influence/control the acquisition of remanent magnetization in Chinese loess, laboratory and *in-situ* experiments have been carried out and described in this thesis. Three papers (two published and one under review in G-cubed) are included:

Paper #1 reports on the finding that the production of superparamagnetic (SP) grains during thermal demagnetization commences at exceptional low temperatures around 200°C. It also indicates that the main magnetic carriers of Chinese loess/paleosol are single domain (SD) and pseudo single domain (PSD) magnetite and maghemite grains.

Paper #2 reports on DRM obtained by controlled subaerial deposition of loess material in the laboratory, with a comparison to subaqueous deposition. The main result is that DRM with a significant inclination error is locked after the first wetting of dry deposited loess material.

Paper #3 describes *in-situ* experiments that simulate a geomagnetic field 'reversal' by turning loess blocks upside down *in situ* for about one year. Partial remagnetization occurs in part of the loess blocks apparently independent of percolating water (precipitation), and its spatial distribution is heterogeneous on sample-volume scale. Differential Thermal Expansion (DTE) is proposed to account for the remagnetization.

Following the view expressed by Richard P. Feynman in his Nobel Lecture (December 11, 1965);

> *We have a habit in writing articles published in scientific journals to make the work as finished as possible, to cover all the tracks, to not worry about the blind alleys or to describe how you had the wrong idea first, and so on . . . .*

- I have also included descriptions of two time-consuming experiments that address some crucial questions about loess magnetism, but that for different reasons did not reach a level permitting publication:

a) Assess if freezing-thawing of pristine loess with varying water content is a potential remagnetization process.
b) To test if magnetic grains cemented by precipitated calcium carbonate, can be released and realigned in a new magnetic field direction.

3. A brief outline about loess

3.1. Characteristics

The word ‘loess’ was first proposed by Karl Caeser von Leonhard in 1821 to name the Rhine River valley loam. It is derived from a German word meaning ‘loose’, and was proposed to have an aeolian origin by von Richthofen in 1882.
Typical/classical loess has the following characteristics (Liu et al., 1989; Pécsi, 1991; Smalley et al., 2006, 2011):

1. Similar appearance: homogeneous, porous, fragile, unstratified and yellowish.
2. Uniform grain size: well sorted grains with predominant silt size (10-50μm).
3. Uniform mineral composition: mainly quartz (40-80%) and lesser amounts of feldspars, calcite and dolomite, in addition to some heavy minerals (2-5%).
4. Meta-stable structure: formed by partly calcium-cemented and aggregated loess grains, and responsible for the collapsibility and vertical or sub-vertical outcrops recognized in the field.
5. Intercalated fossil soils (paleosols): formed during warm and wet interglacials, in contrast to the parental loess formed during cold and arid glacials.
6. Confined fauna: different species of snails (steppe or forest) are found ubiquitously in loess and paleosols.
7. Subaerial transportation and deposition: excluded secondary loess, which has been exposed to, for example, fluvial reworking.

3.2. Distribution

Loess covers some 10% of the land surface of the world, mostly in the temperate and marginal semiarid zones of deserts (Heller & Evans, 1995, Fig.1). One of the most massive and extensive loess accumulation areas is the Chinese Loess Plateau (Fig.2), where loess deposits up to 200 metres thick cover some 440.000 km^2 around the region of the Yellow River (Liu, 1989).

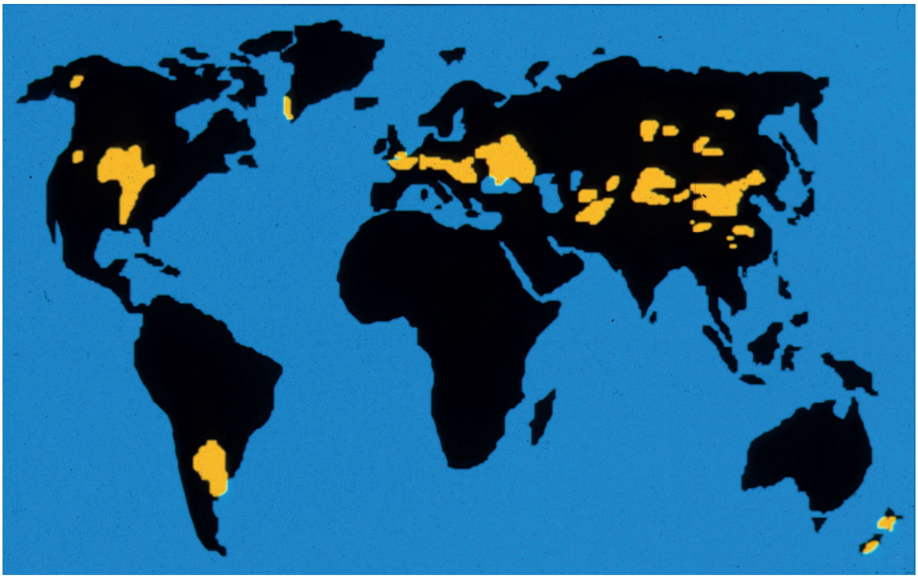

Figure 1.Global distribution of loess deposits indicated by the yellow areas (From Pye, 1995). http://serc.carleton.edu/details/images/12517.html

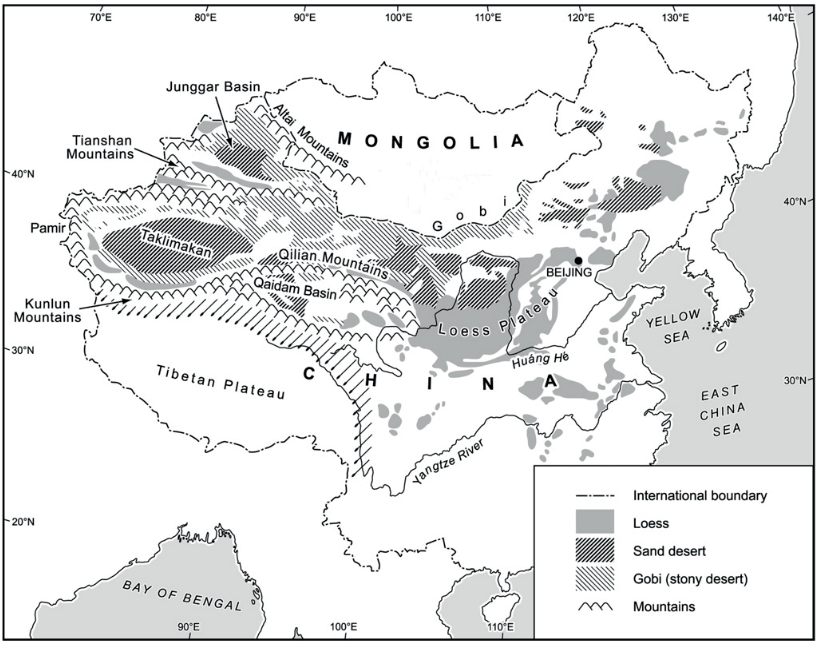

Figure 2. Location of the Chinese Loess Plateau and its potential desert source regions. From Maher, 2011.

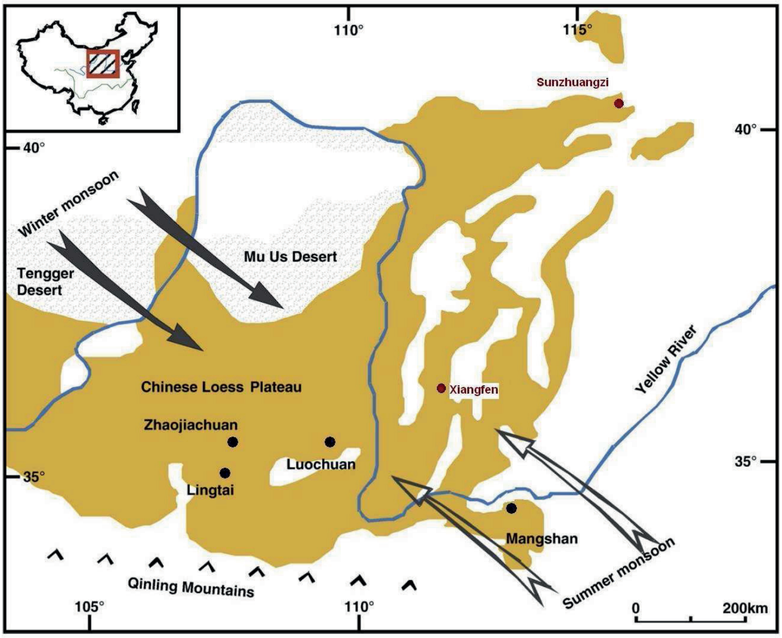

Figure 3. Schematic map showing the loess distribution on the CLP. Locations of the experimental sites (red dots) and studies sites cited (black dots) are marked as well. Modified after Jin & Liu 2011a.

3.3. Formation

Formation of loess consists of four main stages: production of silt-sized mineral particles, transportation and deposition of these particles, and post-depositional modification (Pye, 1995; Liu, 1989; Nemecz et al., 2000).

3.3.1 Silt production and source area

Glacial grinding, sub-glacial weathering, frost action and fluvial abrasion (Heller and Evans, 1995; Wright, 2001) are the main processes that generate abundant silt grains in deserts in Asia or marginal zones of the Pleistocene ice sheets in Europe and North America (Sun, 2002; Porter, 2007). Remote sensing recognises many global/regional sources of modern dust such as dry/drying lakes, alluvial fans and flood plains (Okin et al., 2011), which may also have been supplementary origins of aeolian silt grains in the past.

3.3.2 Transportation and deposition

Silt grains from source areas become suspended and transported by strong and turbulent winds. Silt will deposit when the wind gets weaker, or fall out with rain. Fluvial transportation and local recycling are also important processes for re-distribution of loess material (Kohfeld & Harrison, 2003; Smalley et al., 2009).

3.3.3 Post-depositional modifications

After the grains are deposited, rainwater/snow/ice, vegetation and secondary calcification will turn the dust deposits into loess (Liu, 1989; Heller & Liu, 1995). Complex soil formation processes (pedogenesis) will convert the parent material (loess) into paleosol. Depletion of calcium carbonates, neoformation of clay minerals and magnetic minerals are common features in paleosol (Liu, 1989; Singer, et al., 1996; Kemp, 2001; Muhs, 2007).

4. Key points in Chinese loess studies

4.1.Stratigraphy, chronology and dating

Chinese loess was originally divided into three stratigraphic units: the Malan, Lishi and Wucheng loess (Liu, 1989). Malan loess is the youngest, deposited in Late Pleistocene, while the Lishi and Wucheng loess deposited in Middle and Early Pleistocene. The loess/paleosol layers are named from the top to the bottom: S0, L1, S1, L2, S2…L32, S32, L33.

Loess often overlies fluvial/lacustrine sediments, conglomerates or Red Clay. The chemical composition and grain size distribution of Red Clay suggest that it also has an aeolian origin, but that it has been exposed to very intensive weathering during Pliocene and Miocene (Ding et al., 1998).

Paleomagnetic polarity stratigraphy of the classical Luochuan section gave the first reliable time frame for loess/paleosol on CLP, showing that loess deposition started around 2.6Ma (Heller & Liu, 1984; Heller & Evans, 1995). See Fig. 4. Polarity stratigraphy of the Red Clay later suggests its accumulation to start at least around 7Ma (Guo et al., 2002).

The time frame established by paleomagnetic polarity uncovered an exceptional good correlation between variations of magnetic susceptibility (MS) of loess on CLP and the marine $\delta^{18}O$ records (Heller & Liu, 1986). See Fig. 5. High-resolution chronologies of loess/paleosol sequences have consequently been obtained by correlation of loess proxies (grain size, MS) to the astronomically tuned marine $\delta^{18}O$ records (Tauxe et al., 1996; Sun et al., 2006).

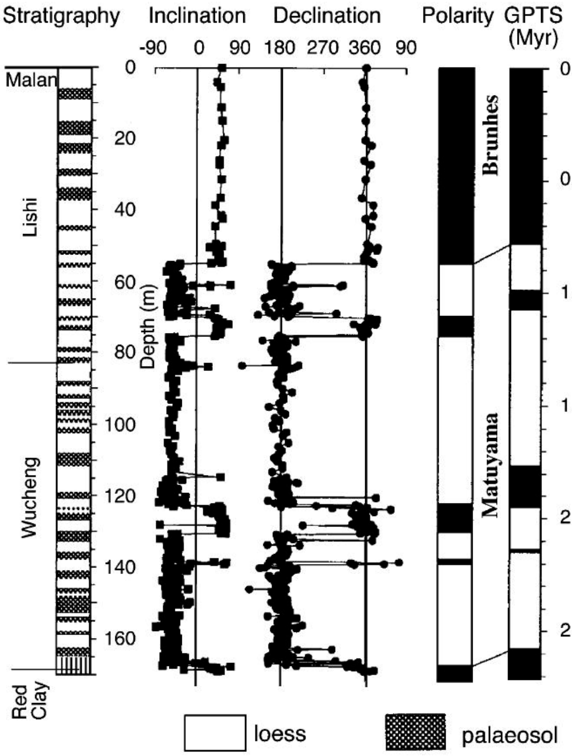

Figure 4. Paleomagnetic polarity stratigraphy of loess/paleosol sequence over 2.6 Ma. Adopted from Heller & Evans, 2001.

Different luminescence dating techniques on quartz and feldspars give absolute ages of loess back to 100kyrs (Buylaert et al., 2008; Singhvi et al., 2001; Stevens et al., 2006, 2007). Close-spaced age controls make it possible to retrieve millennial-scale paleoclimatic variations, and to directly assess the sedimentation rate of loess deposition during Holocene and late Pleistocene. Loess sedimentation rates are found to be highly variable (3-100cm/kyr), and it is suggested that loess accumulation is short episodes of flux with extended periods of quiescence (Singhvi et al., 2001; Stevens et al., 2006, 2007; Zhu et al., 2007).

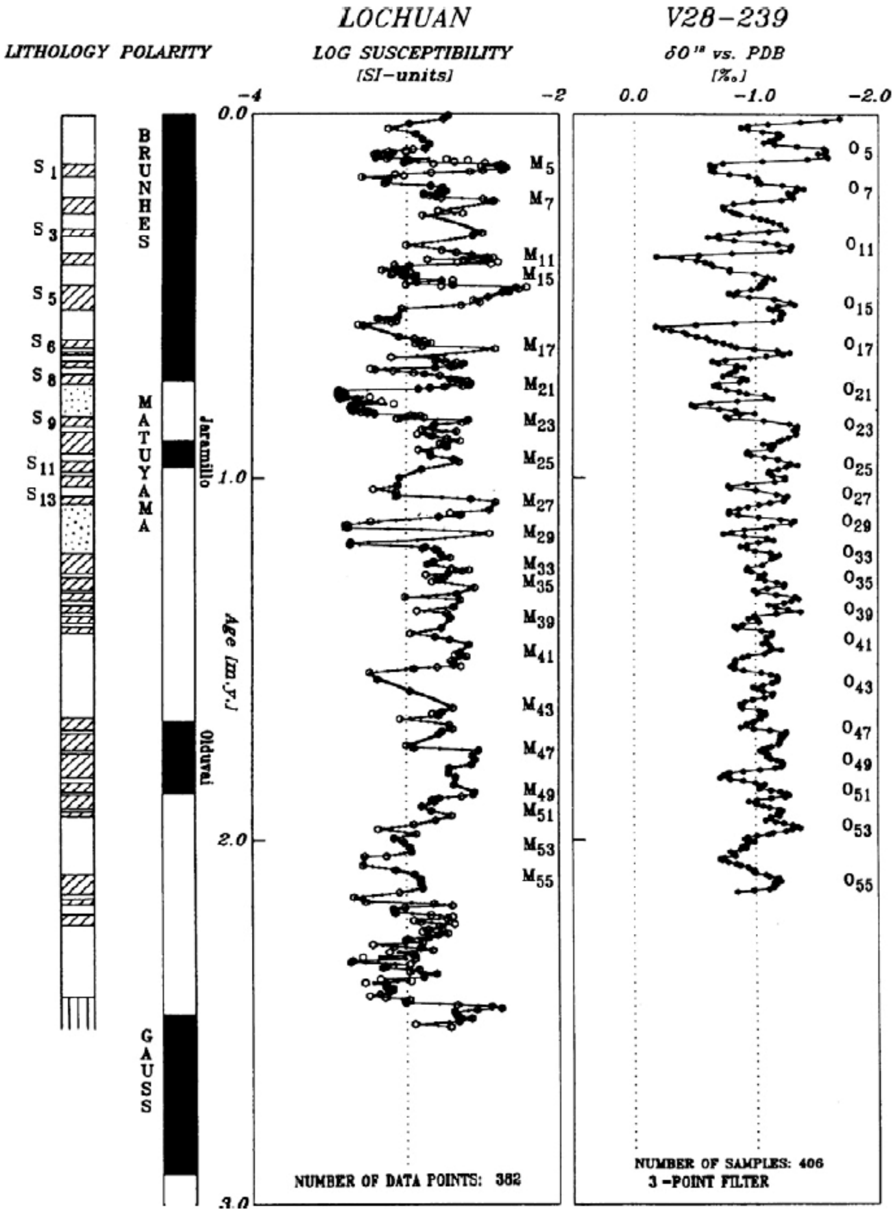

Figure 5. Magnetostratigraphy for the loess/palaeosol sequences and correlation of the MS of Luochuan loess with the marine oxygen isotope stages. After Heller & Liu, 1982.

4.2. Climatic imprints on magnetic properties

Reconstructions of paleo-precipitation, paleo-temperature, wind vigour and direction are based on various proxies (Maher & Thompson, 1995; Liu et al., 1995; Bloemendal & Liu 2005; Sartori et al., 2005; Sun et al., 2010b; Maher 2011), including grain size, magnetic properties, elemental isotopes, chemical compositions etc. In return, reconstructed paleo-environments may help us understand how magnetic properties of loess respond to climatic changes.

The accumulation of Chinese loess is tightly linked to the EAM and glaciations (Liu & Ding, 1993, 1998; Ding et al., 1995). Strengthening of the winter monsoon coincides with influx of aeolian sand/silt, while strengthening of summer monsoon coincides with increased precipitation and soil formation. Through pedogenesis, very fine particles of magnetite and maghemite (SP to SD) are produced either as result of chemical processes or assisted by biological organism (Maher & Taylor, 1988; Banerjee, 2006).

Climate will influence not only the sources of dust (silt), but also transport pathways and post-depositional alteration. The concentration of magnetic grains, their grain size and mineralogy will all vary in accord to paleoclimatic fluctuations, producing long-term records of magnetic proxies.

The exceptional good correlation between MS variations in terrestrial loess and $\delta^{18}O$ records in oceanic cores (Fig.5) suggests that MS is a reliable proxy for climatic variations (Heller & Liu, 1986; Kukla et al., 1988). A crucial point in this respect is that while MS variations of loess are controlled by continental precipitation patterns, $\delta^{18}O$ values in marine sediments are controlled by the global ice volume.

In addition to MS, saturated isothermal remanent magnetization (SIRM), anhysteretic remanent magnetization (ARM) and frequency dependent susceptibility (fd%) are magnetic parameters that also correlates well with paleoclimatic proxies (Sun et al., 1995; Tang et al., 2003; Liu et al., 2007).

4.3. Natural remanent magnetization and its carriers

The Natural remanent magnetization (NRM) of loess may consist of detrital remanent magnetization (DRM), post-depositional remanent magnetization (pDRM), chemical remanent magnetization (CRM) and viscous remanent magnetization (VRM).
DRM is generally assumed to be the primary remanent magnetization, which is ubiquitously overprinted by a VRM acquired during Brunhes Chron. This VRM usually amount to some 80% of NRM and is erased by thermal demagnetization above 300°C (Heller & Evans, 1995; Liu et al., 2003).
VRM is the most significant overprint in loess, while the importance of pDRM and CRM are still uncertain.

Loess contains mainly magnetite with minor contributions of maghemite and hematite. Grain sizes of these magnetic particles vary between tens of nanometers to tens of micrometers, with domain states extending from SP - SD - PSD and multi-domain (Evans & Heller, 2001; Liu et al., 2007). Multi-domain (MD) magnetite and most hematite are considered to have an aeolian origin, while ultra-fine magnetite/maghemite grains (SP and SD) are results of pedogenesis (Liu et al., 1993; Sun & Liu, 2000; Spassov et al., 2003b).

However, only a fraction of the total magnetic grains actually contributes to the NRM.

The ubiquitous VRM in loess is mainly carried by grains close to the SP-SD boundary and MD magnetite grains (Yu & Tauxe, 2006; Liu et al., 2007; Jin & Liu, 2011b).

Pedogenic CRM (carried by PSD maghemite) is proposed to gradually overprint the primary DRM (carried by PSD/MD magnetite) by using low temperature demagnetization of NRM and characteristic remanent magnetization (ChRM) separated by partial thermal demagnetization (Liu et al., 2003).

4.4. Inconsistent paleomagnetic records

4.4.1 The Matuyama-Brunhes Boundary

The position of MBB on the CLP is usually encountered in the lower part of L8 (Fig.6), which formed during a glacial, and is thus at variance with marine cores where MBB occurs during the interglacial period MIS stage 19.1 (Evans & Heller, 2001). Moreover, microtektites found at Luochuan above the MBB were assumed to have same origin as the Australasian microtectites, which occur below the MBB in ODP 769A (Zhou & Shackleton, 1999).

The MBB-discrepancy has been a matter of dispute for some time and has been accounted for by a 20-30kyr delayed magnetization composed of pDRM and CRM (Zhou & Shackleton, 1999). The lock-in model necessary to explain this lag, as suggested by Spassov et al. (2003a), apparently fits well with both the lowering of the MBB position and the directional behaviour during the polarity transition. However, this model requires lock-in depths of up to 2-3m, which is significantly larger than ca 20cm proposed for marine sediments (deMenocal et al., 1990; Rorberts & Winklhofer, 2004).

Liu et al., (2008) put an end to this hypothesis of delayed magnetization that demands such unrealistic large lock-in depths. Variations in quartz grain size (insensitive to pedogenesis) are used to pinpoint the L8-S8 boundary at Lingtai and Zhaojiachuan (Fig.7). The MBB observed in lower part of L8 is thus relocated in the upper part of S8, which instead of S7, correlating to MIS19. It is also pointed out that the microtektites found in loess do not have the same geochemical composition as the Australasian microtektites, implying different origins and ages.

Therefore, MBB is recorded on the CLP without significant delay as in marine cores (Wang, et al., 2006; Liu et al, 2008; Jin & Liu, 2011a).

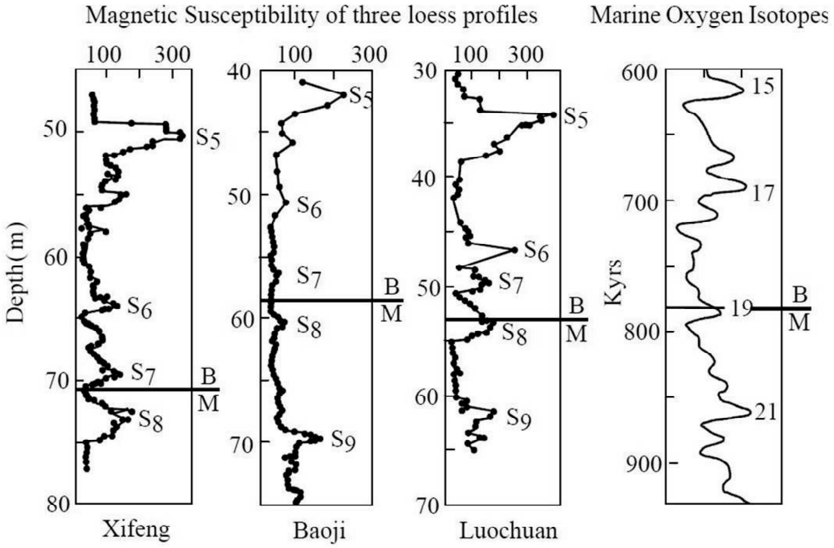

Figure 6. MBB position at three loess profiles compared with records in marine sediments. MBB was observed in L8 or the upper part of S8, while occur in MIS19. After Tang et al., 2003.

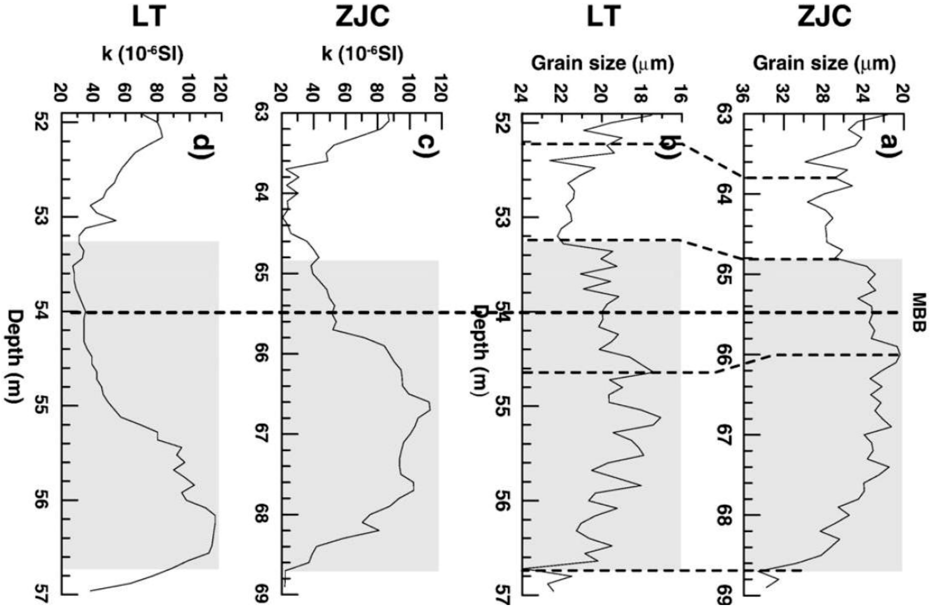

Figure 7. Redefined boundary of L8/S8 using quartz grain size at Zhaojiachuan (ZJC) and Lingtai (LT) section. The MBB will be relocated to be at the top of S8, which is marked in the grey area. After Liu et al., 2008.

4.4.2. The MBB transition

The MBB-transition in high-deposition rate marine sediments is characterized by a gradual and continuous change in paleomagnetic directions and intensity. However, on CLP the MBB transition often show multiple polarity ‘swings’, which may occur 3 to 8 times (Spassov et al., 2001; Yang et al., 2010), and their directional features differ even within one site (Jin & Liu, 2010). Virtual geomagnetic polarity (VGP) paths associated with MBB recorded in loess are neither longitudinally confined as found in both marine sediments and basaltic rocks (Sun et al., 1993). The MBB transitional records have therefore been suggested to be the result of complicated magnetization processes rather than true geomagnetic behaviour (Spassov et al., 2001).

4.4.3.Geomagnetic excursions and paleo-secular variation (PSV)

Short-time geomagnetic excursions (i.e., Mono Lake, Laschamp and Blake) are rarely and imperfectly recorded (Fang et al., 1997; Pan et al., 2002; Zhu et al., 1998, 1999, 2006, 2007). There is so far just one report of paleo-secular variation in loess showing a good correlation with PSV records obtained from marine cores in Japan and lake sediments in France (Heslop et al., 1999).

4.4.4. Extensive remagnetization in L9

Distinct anomalies of normal polarity have been encountered within L9 at many areas on the CLP, such as in Lanzhou, Xi’an, Baoji, Sanmenxia, Luochuo, Xifeng, Mangshan and Weinan (Yang et al., 2004; Wang et al., 2005; Wang et al., 2010; Jin & Liu, 2011b). They were ascribed to be excursions (Yang et al., 2004) or a precursor to the MB reversal (Zheng et al., 2007), but are now attributed to remagnetization. Wang et al. (2005) suggest they represent normal polarity pDRM-overprints assisted by percolating water. However, Jin & Liu (2011b) propose low efficiency of grain alignment during intervals with low geomagnetic field intensity, enabling complete normal polarity overprint by VRM.

These observations raise the crucial question of how to discriminate anomalous paleomagnetic directions representing genuine geomagnetic field behaviour from features imposed by magnetization processes (or both).

5. Experimental assessment to magnetization processes

5.1 Thermal alteration of loess

Paper #1 (Wang & Løvlie, 2008) demonstrates that the creation of SP magnetite in loess (L1 from Nanzhai, Xiangfen, Fig.3.) may commence at low temperatures during progressive thermal demagnetization.

Progressive thermal demagnetization is the common technique to isolate and indentify magnetic components of NRM. Magneto-mineralogical changes during thermal demagnetization are commonly monitored by measuring MS between each demagnetization step, since the creation and destruction of magnetic phases is likely to be expressed by changes in relative MS. The dominant magnetic minerals in loess are magnetite (Fe_3O_4) and maghemite (γFe_2O_3). During thermal demagnetization, magnetite may oxidize to hematite (partly depending on grain-size) or a mixture of maghemite and hematite, while maghemite (a cation-deficient spinel with Fe^{3+} only) may structurally invert to hematite upon heating to 300-400℃. The magnitude of magnetic susceptibility depends on the composition, concentration and grain size of magnetic minerals.
We measured MS at 293K (MS_{293K}) and 77K (MS_{77K}) after each heating-step in order to assess changes in magnetic phases (*eg.* magnetic domain state). The temperature dependent susceptibility ($\kappa_{TD} = MS_{293K} - MS_{77K}$) of paramagnetic minerals increases with decreasing temperature according to the Curie law ($\kappa \sim 1/T$). Magnetic grains that are in a SP state at room temperature may pass the SP-SD threshold by cooling towards 77K (boiling temperature of liquid nitrogen), causing a decrease in MS due to the blocking of SP grains. MS may also decrease if magnetite passes through the Verwey-transition.

A positive linear relationship was observed between frequency dependent susceptibility (κ_{FD}) and temperature dependent susceptibility (κ_{TD}). It indicates that variations in κ_{TD} is dominated by the blocking/unblocking of SP/SD grains during cooling/heating, and can thus be used as a proxy for the production of SP-grains. Our results show an almost continuous production of SP grains, commencing at an unexpectedly low temperature around 200°C.

5.2 Laboratory-simulated subaerial deposition

Paper #2 (Wang & Løvlie, 2010) reports on the remanent magnetization imposed in re-deposited natural loess (L1, Xiangfen, Fig.3.) under controlled ambient magnetic field. See Fig. 8. Disintegrated loess (<63µm) was deposited into still (fresh) water and onto a dry surface that was wetted after each event of deposition (‘dust storm’). The ambient magnetic field was controlled a set of circular (2.4m in diameter) dynamically compensated Helmholtz-coils, generating a field of 50µT. The first 1/3 of deposition was in a normal polarity field (inclination +57°), followed a reversed polarity field (inclination -57°), and the last 1/3 in a normal polarity field.

DRM imposed by subaerial redeposition may resemble that in pristine loess for same magnitude of intensity. However, anisotropy factor around 2.5% is comparable to that for reworked loess (Liu et al., 1988; Hus, 2003), while a significant inclination error (~20°) is generally absent in pristine loess (Jin & Liu, 2010). No traceable normal polarity pDRM during the field reversal indicates that most of the magnetization is locked after initial wetting.

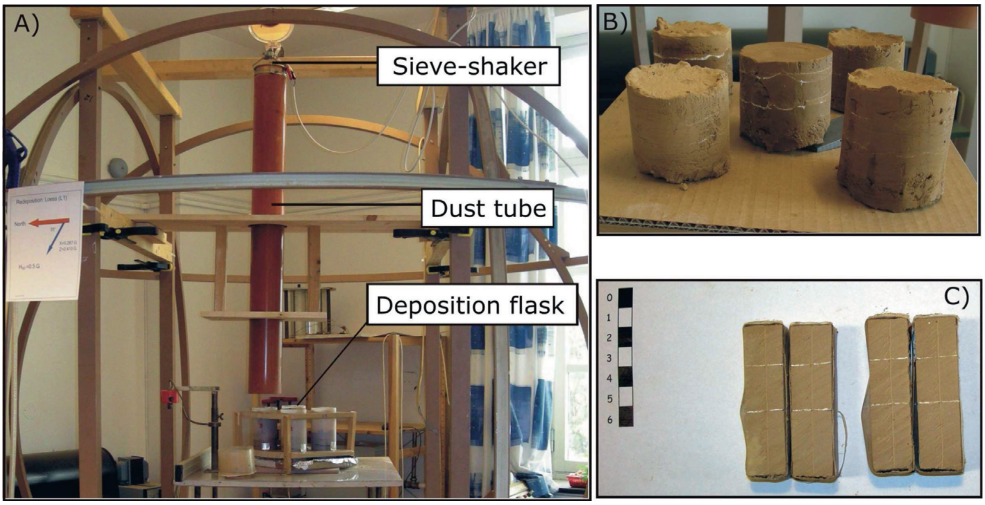

Figure 8. Subaerial deposition of loess-‘dust’. A) Set-up inside the Helmholtz-coils. B) Samples after drying in air. C) Rectangular slabs showing the two $CaCO_3$-layers deposited at the time of magnetic field reversal.

DRM of loess deposited in water shows about 5 times higher Q-ratios (4π×NRM/MS) than the wetted loess, as well as a slightly more anisotropic oblate susceptibility ellipsoid (P_2 around 3%). These observations are in general accord with results of re-deposited sediments in fresh water (Barton et al., 1980; Zhao & Roberts, 2010). Remanent magnetization in water loess appears to be locked gradually by compaction/dewatering.

[At our presentation of these results at EGU/2010, results from a set of parallel experiments performed by Zhao & Roberts (2010) was presented in the following talk! These two papers are the only papers that so far have investigated the characteristics of DRM of loess produced under controlled conditions in the laboratory mimicking aeolian deposition and precipitation.]

Laboratory re-deposition experiments cannot mimic conditions occurring in nature. Unrealistic high sedimentation- and precipitation-rates in laboratory experiments may produce results that never could occur in nature. Moreover, high fidelity records of paleomagnetic directions (no inclination errors) on the CLP may thus be controlled by additional factors.

5.3 *In-situ* experiments

Post-depositional processes in loess/paleosol such as percolating water, freezing-thawing and root growth may cause changes in structure and mixing of grains (Kemp, 1995; Sun et al., 2010a). These physical disturbances may assist realignment of magnetic mineral grains resulting in partial or complete remagnetization.
Variations of natural conditions are impossible to simulate in the laboratory, and we have therefore performed *in-situ* experiments on the CLP to examine if any pDRM can be imposed during 8-17 months exposures to a ‘virtual’ geomagnetic field reversal. We believe that CRM-acquisition during such a short period will be insignificant and this is therefore not considered in the following paper.
Paper #3 (Løvlie, Wang & Wang, submitted G-cubed August 2011) describes in-situ experiments carried out on two sites separated by some 600 km but within the same annual precipitation regime (Xiangfen, and Sunzhuangzi, China, Fig.3.).
Loess blocks (30×30×25cm) were carved out, turned 180º along an East-West axis, put back into the loess-bed and left there for 8 and 17 months, see Fig.9.

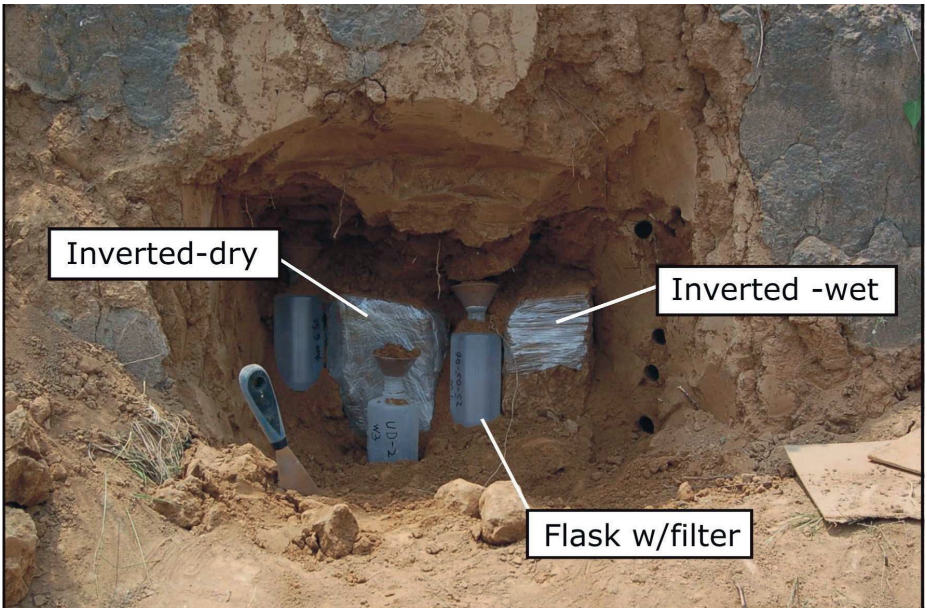

Figure 9. In-situ experiment at Xiangfen before covering up the site. The inverted ‘wet’ block has been strengthened at the top with cling-film because it might break in two pieces.

Partial remagnetization was found in both dry blocks (wrapped with cling-film) and wet blocks (open to percolating water). Remagnetization is most pronounced in the dry block at Xiangfen and in the wet blocks at Sunzhuangzi, we therefore conclude that percolating water is not a necessary condition for grain realignment to occur. This finding contradicts what we initially had thought; that water would be a key remagnetizing agent.

In order to explain partial remagnetization without water, we propose that unlocking magnetic grains in loess may be facilitated by differential thermal expansion (DTE) of the different minerals in loess. Volume expansion coefficients for quartz, phyllosilicates, plagioclase, calcite, K-feldspars, dolomite, amphiboles and magnetite, maghemite, hematite vary from between 5×10^{-6} to 25×10^{-6}. Temperature fluctuations will thus induce different volume changes in different minerals, creating volume changes of the internal voids. Increasing void volumes may unlock some magnetic grains. Remagnetization is therefore hypothesized to be the result of realignment of unlocked magnetic grains.

A major finding is the heterogeneous spatial distribution of partially remagnetized samples within a block. This heterogeneous magnetization may be a nature of loess magnetization, and may attribute to explain reports of anomalous and inconsistent paleomagnetic records.

Grain re-alignment assisted by DTE is likely to be active only in the youngest loess with negligible overburden (compaction) and weak bonds of calcium cement. However, in the case of turning loess-blocks upside down, gravity may assist in realigning magnetic grains.

5.4. Incomplete experiments

5.4.1. Stepwise calcium carbonate dissolution experiment

During soil formation in arid/semi-arid climate, calcium carbonate is continuously dissolved and precipitated (Muhs, 2007). Precipitated calcium carbonate may form thin layers of cement that may 'lock' magnetic grains prohibiting re-alignment. By dissolving this secondary $CaCO_3$ cement, it is conceivable that magnetic grains may be 'unlocked' and thus able to be aligned along new geomagnetic field directions.

Stepwise dissolution of calcium carbonate cement was performed in a specially constructed device that may let controlled amounts of liquid pass through cylindrical samples (~10cc) of loess from Xiangfen (L1, L4, L5) and Sanmenxia (L9). Experiments were done inside a set of self-compensating Helmholtz-coils (2.4m in diameter) in a horizontal field of 50µT. Air and controlled amounts of tap water and weak hydrochloride acid (0.05M/L) were forced through the samples by gravity and a pressure-gradient set up by the low pressure (0.5mBar) inside the low-pressure box. See Fig. 10.

The magnitude of NRM and shape/orientation of magnetic fabric (derived from AMS) did not show any clear and systematic changes after successive runs with hydrochloride solutions.

Subsequent thermal demagnetization revealed a steep directional component dipping steeper than the ambient magnetic field. The magnitude of this component shows no relationship to the amount of acid that had passed through the samples, indicating that the inferred realignment of magnetic grains was not directly related to the amount of any removed calcium cement.

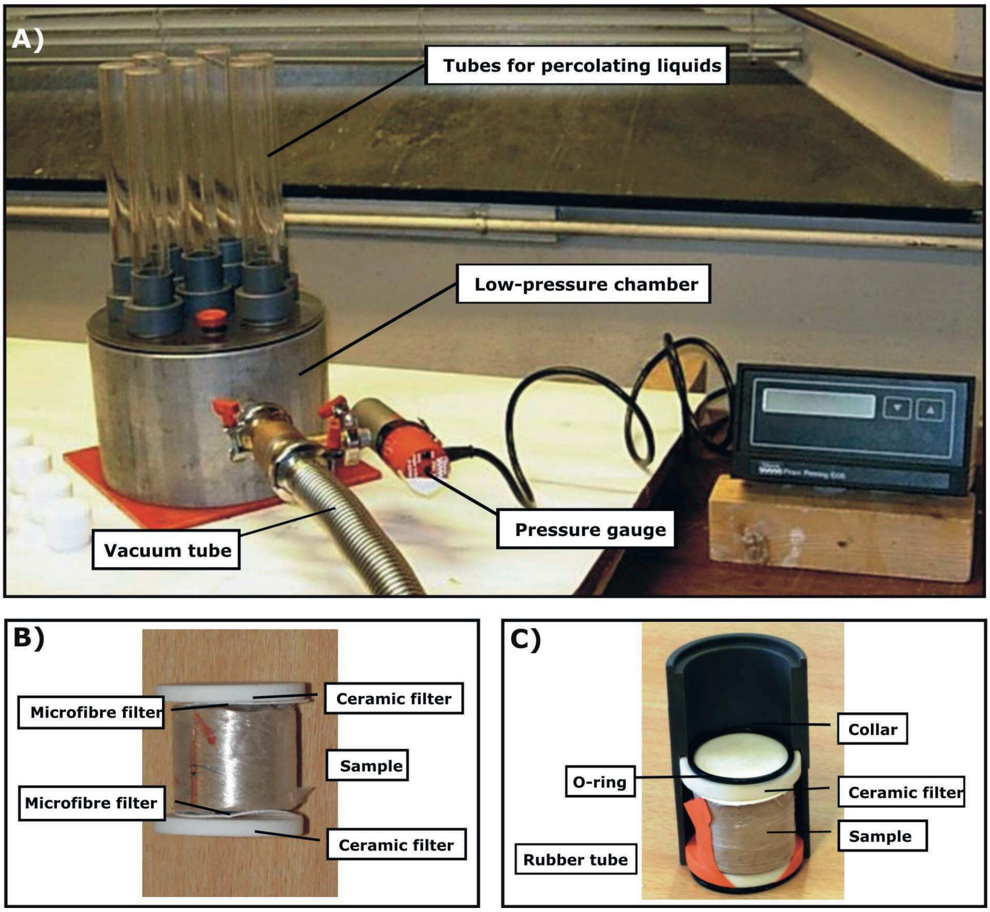

Figure 10. A) Apparatus for stepwise dissolution of calcium carbonate. B) Loess-sample wrapped in cling-film with glass microfibre and ceramic filters at the top and bottom. C) Exploded view of sample inside the ‘collar’.

After time-consuming testing of the apparatus and experimental runs, slight deformation of the samples became apparent. The pressure exerted by the rubber tubes and handling between each measurement eventually caused slight deformation of the wet samples, which probably imposed a magnetic component along the cylinder-axis of the samples.

Even if further ‘slight’ mechanical modifications of the apparatus might have solved the deformation-problem, the experiments were decided discontinued because time was running out.

5.4.2. Freezing-thawing experiment

The structure of soils and water-laden sediments may be disturbed by freezing and thawing due to volumetric expansion/reduction of interstitial water/ice. Løvlie & Putkonen (1996) showed experimentally that freezing-thawing of poorly sorted sediments from within frost polygons (Svalbard) acquired a freezing-thawing remanent magnetization (FRM).
Frost-action on CLP is rarely observed, though temperature inside loess on CLP pass through 0℃ several times during autumn/winter/spri ng. A banded fabric observed in S1 near Lanzhou is claimed to be due to freezing-thawing (Kemp et al., 1995), indicating loess may potentially acquire FRM.

We have performed freezing-thawing experiments on pristine L1 from Xiangfen (Fig.3.) loess according to the protocol outlined in Løvlie & Putkonen (1995).

Two sets of freezing-thawing experiments were done; one with samples containing pristine humidity (6% water by weight) and a second set with the same samples after adding water to increase the humidity to ca 14%. Both experiments implied 12 freezing-thawing cycles between –18°C to room temperature (21°C) lasting 6 to 12 hours in the geomagnetic field in the lab (D=0°, I=74°).

Only minor and scattered directional changes were observed, attributed to slight variations in temperature of samples when they were measured. The lack of FRM may be due to the well-sorted grain size distribution of loess compared to the polygon-sediments where FRM was acquired.

The low water content (6-15%) in natural loess may evidently reduce the effect of volumetric expansions of freezing pore water. It is therefore concluded that freezing-thawing is not likely to be a significant remagnetization process in loess.

5.5. Conclusions and perspectives

1. Subaerial re-deposition of loess material may monitor DRM acquisition process in pristine loess. However, additional factors producing high fidelity records of paleomagnetic directions in pristine loess need to be investigated.
2. Differential thermal expansion may be a fundamental process, which can impose remagnetization in Chinese loess without assistance of percolating water.
3. Freezing-thawing during short time period may not be an active remagnetization process in Chinese loess.
4. Calcium cement may play a role in locking magnetic grains in loess, but the importance of this mechanism to retain remanence needs more investigation.

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