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Magnetic signature of environmental change reflected by Pleistocene lacustrine sediments from the Nihewan Basin, North China

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Abstract

A mineral magnetic study has been conducted on Pleistocene lacustrine sediments from the Xujiayao Paleolithic site within the Nihewan Basin, North China. The magnetic signal is characterized by a dominance of high-coercivity (hematite) minerals that is modulated by low-coercivity magnetite–maghemite assemblages during interglacials. A high-amplitude record of the composition dependent magnetic $S_{-0.3\ T}$-parameter varies in accord with composite marine oxygen isotope records, suggesting climate modulation of magnetic composition. The Xujiayao site is situated at the northern outskirts of the Chinese Loess Plateau (CLP) and has neither received significant eolian input nor been exposed to pedogenic processes comparable to those acting on CLP. Mineral magnetic analyses suggest that variations in both magnetite and hematite are primarily controlled by detrital fluxes rather than by authigenic production of magnetic minerals. Here we propose that the fluctuations of magnetic signals at Xujiayao are not derived from varying compositions of eolian flux with glacial/interglacial periods or minute eolian influx during interglacials, but is likely dominated by runoff-related processes, by which some weathered/pedogenized loess and soils with stronger magnetic signals have been eroded and transported to the catchment during interglacials resulting in magnetic enhancement. The inferred continuous deposition from the Brunhes/Matuyama boundary to the paleosol S_1 (ca. 129 ka) gives the age of ca. 500 ka for the sediments carrying the Xujiayao Paleolithic site, suggesting an allogenic origin of the Paleolithic artifacts and mammalian bones dated by U–Th method to ca. 100 ka.

Keywords: Lacustrine; Eolian; Runoff; Mineral magnetism; Chinese Loess Plateau; Nihewan; Pleistocene

1. Introduction

Lacustrine sediments may retain high-resolution archives of past continental environmental and climatic changes (Oldfield, 1977; O'Sullivan, 1983; Haworth and Lund, 1984; Creer and Thouveny, 1996). The sedimentation in lakes is mainly controlled either by processes related directly to climate or by climatically modified catchment processes controlled by lithology, vegetation, hydrology and human activities (Zolitschka and Negendank, 1999). Although these processes can be in principle used to reconstruct paleoclimatic and/or paleoenvironmental conditions, the contributions from each component need to be disentangled. By detecting variations in the composition, concentration and grain size of magnetic minerals, mineral magnetism can provide detailed insights into the entire depositional history of magnetic particles in lacustrine sediments, and it has become an attractive way to untangle the abovementioned processes (Thompson and Oldfield, 1986; Thouveny et al., 1994; Verosub and Roberts, 1995; Stockhausen and Zolitschka, 1999; Evans and Heller, 2003; Demory et al., 2005).

The Nihewan Basin is situated at the northeastern edge of the Chinese Loess Plateau (CLP) and is one of the East Asian Cenozoic basins filled with Pliocene to Pleistocene fluvio-lacustrine sediments (Barbour, 1924, 1925; Yuan et al., 1996; Zhu et al., 2001, 2003, 2004; Wang et al., 2004, 2005; Deng et al., 2006a). In the celebrated CLP, mineral magnetic approaches have played a crucial role in deciphering continuous

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paleoclimatic records and have also been successfully applied to reconstruct the variability of the East Asian monsoon throughout the entire Quaternary (Kukla et al., 1988; Maher and Thompson, 1992; Evans and Heller, 1994, 2001; Heller and Evans, 1995; Florindo et al., 1999; Deng et al., 2005; Bloemendal and Liu, 2005). The present consensus is that the less changed loess mainly derives from dust deposits transported by the northwesterly winter monsoon, and the intervening paleosols formed under warm, moist summer monsoon conditions during interglacials are always magnetically enhanced due to soil production (pedogenesis) (Zhou et al., 1990; Thompson and Maher, 1995; Hunt et al., 1995; Liu et al., 2004a). In contrast to the loess/paleosol sequences in north-central China, the contemporaneous Nihewan sediments formed in subaqueous environments are general not affected by pedological weathering processes after deposition. In addition, the Nihewan Basin is located at fringe of the main monsoon trajectories that transport wind-blown dust from the arid Gobi and associated deserts of northwestern China to the CLP. Therefore the Nihewan deposits are excellent targets for applying mineral magnetic properties to discriminate contributions from runoff and eolian source material, both of which are likely to be affected by regional paleoclimatic variations. Specifically, it is critical to evaluate whether the Nihewan Basin has received eolian input in tune with the dust blown from northwestern China and deposited on the CLP. It is also crucial to assess whether any dust accumulating in the paleolake has retained its primary composition or has been exposed to post-depositional processes. The latter situation is likely to produce different more altered products than those in subaerially accumulated dust on the CLP.

We have previously performed a magnetostratigraphic investigation of two sections of Pleistocene sediments from the Nihewan sediments at Xujiayao (Shanxi Province), in order to date the Paleolithic site located within these sediments (Løvlie et al., 2001). The longer west section retained high-amplitude cyclic variations in the natural remanent magnetization (NRM), and this observation initialized the present investigation. Here we present results of a mineral magnetic investigation along this mid-Pleistocene lacustrine sequence. The main purpose of this study is to evaluate the potential of the Nihewan lacustrine sediments for recording regional paleoenvironmental change. We also discuss the age of the Xujiayao Paleolithic site by comparing and constraining magnetic climate-inferred signals with the marine oxygen isotope record that may provide an independent age control for the sediments younger than the Brunhes/Matuyama reversal (780 ka).

2. The locality, chronology and sampling

The Xujiayao section is located in Yanggao County, Shanxi Province (40°06′N, 113°59′E), northwestern margin of the Nihewan Basin and some 250 km west of Beijing (Fig. 1). The Liyigou River has eroded a 200–500-m wide valley with 15–20-m high escarpments into lacustrine sediments, which consist of grey–green to yellow–grey–green beds of silty clays with thickness ranging from less than 1 cm to several meters.

At the top of the sections, the sediments are patchily overlain by a 0.5-m-thick last interglacial soil (not sampled). A consistent normal polarity interval extends down to the Brunhes/Matuyama (B/M) boundary at 15.35 m. The reversed polarity section extends down to the deepest level of the section (Løvlie et al., 2001). The present section is thus confined within a time window determined by the B/M boundary at 15.35 m, and the top of the sampled section underlying the last interglacial soil belonging to marine oxygen isotope stage 5 (ca. 129 ka) (Lu et al., 1999; Heslop et al., 2000; Ding et al., 2002).

A total of 535 samples were collected continuously along a ca. 21-m vertical section including a 6-m vertical shaft dug into the valley floor. Samples were retrieved by trimming rectangular pedestals of sediment, which were subsequently conveyed to cubic plastic boxes (6.2 cm^3) sealed with tight lids.

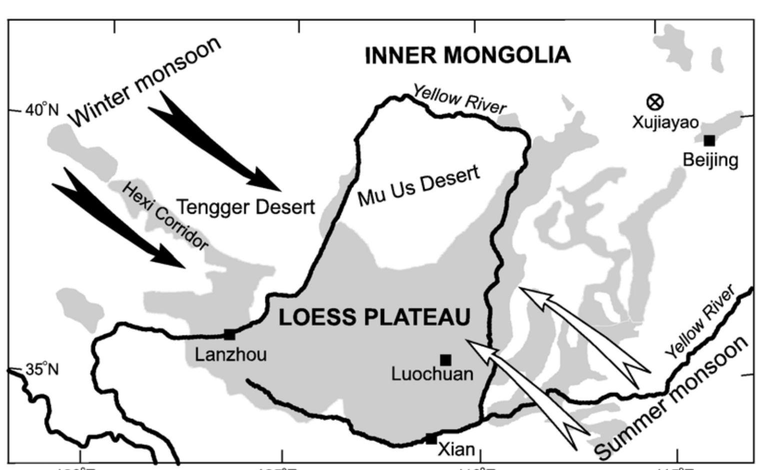

Fig. 1. Location map of the Xujiayao Paleolithic site and distribution of Chinese loess. The solid and open arrows denote the directions of winter and summer monsoons, respectively.

3. Mineral magnetic properties

3.1. Methods

Variations in the concentration and composition of magnetic minerals have been assessed by measuring low-field magnetic susceptibility, anhysteretic remanent magnetization (ARM) and saturation isothermal remanent magnetization (SIRM) of all samples. Volume specific magnetic susceptibility (k, in dimensionless SI units) was determined on a KLY-2 induction bridge. ARM was imparted in a 2G alternating field demagnetizer (160 Hz) in a DC field of 0.1 mT and an AC-field of 100 mT. SIRM was imparted in a DC field of 4 T by a Redcliffe pulse magnetizer. Back-field IRM was induced with a DC field of 0.3 T to get the ratio $S_{-0.3\ T}$ ($-IRM_{-0.3\ T}$/SIRM).

Remanent coercivity curves (B_{cr}) were determined on 10% of the samples by back-field application to the isothermal remanent magnetization (IRM) (maximum field 4 T). Thermomagnetic curves were run on 50–150 mg of dried sediment in fields varying between 200 and 600 mT and heated/cooled in air

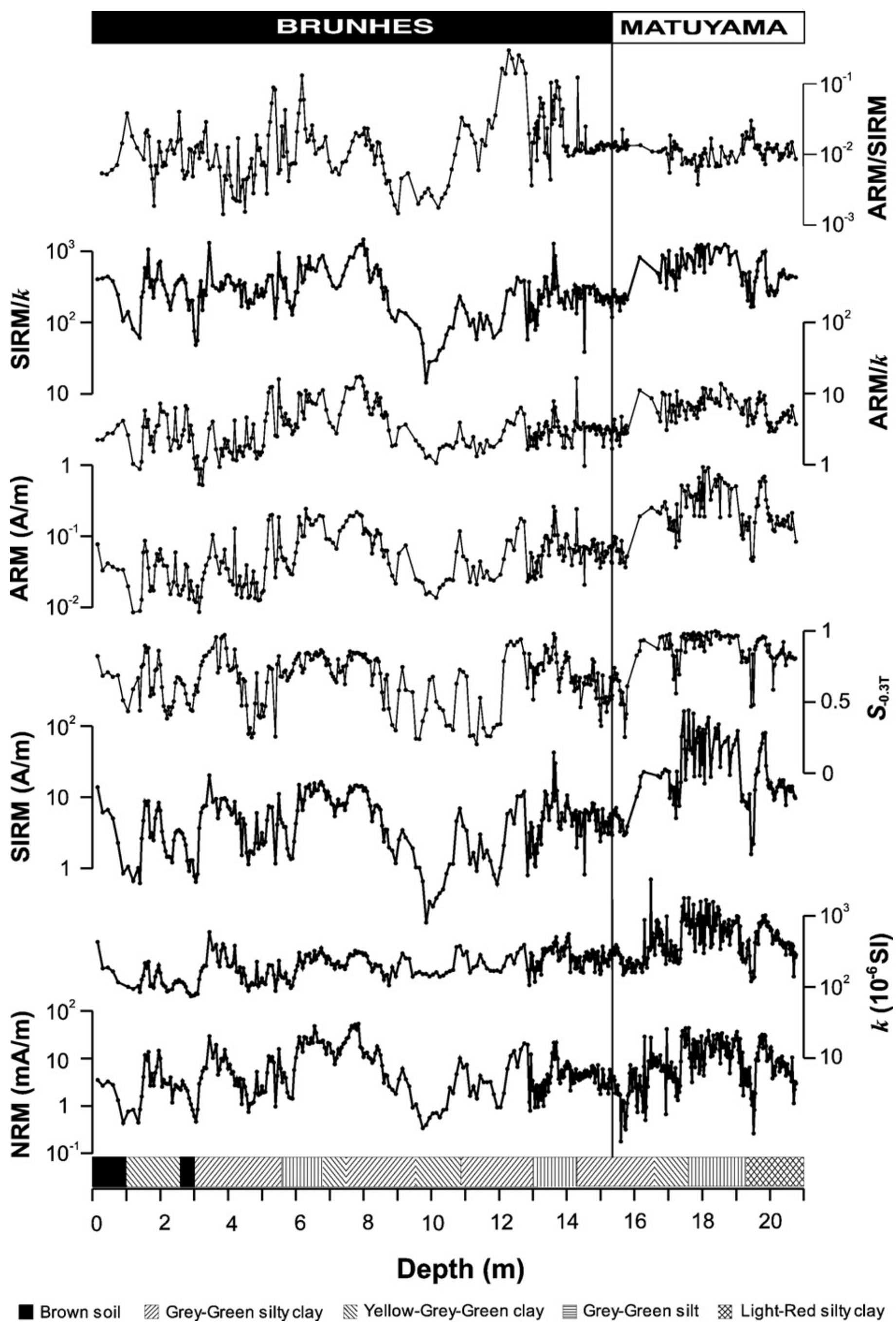

Fig. 2. Lithostratigraphy (legend at the bottom), stratigraphic variations of selected mineral magnetic parameters, NRM, k, SIRM, $S_{-0.3\ T}$, ARM, ARM/k, SIRM/k and ARM/SIRM, and geomagnetic polarity column to the top. Vertical line shows position of the Brunhes–Matuyama boundary.

to 700 °C (15–30 °C/min). Hysteresis curves were determined on 46 bulk samples using the alternating gradient force magnetometer (AGFM 2900) at Laboratoire des Sciences du Climat et de l'Environnement, Gif-sur-Yvette, France.

3.2. Stratigraphic variation of magnetic parameters

Stratigraphic variation of NRM (ranging between 0.18 and 53 mA m^{-1}) exhibits a number of pronounced high-amplitude cycles (Fig. 2). Parallel variations with comparable amplitudes are also defined by the concentration dependent parameters *k*, ARM and SIRM reflecting apparent concordant variations in the concentration of magnetic constituents (Fig. 2). *k* varies between 0.07 and 0.98 10^{-3} SI, which is a significantly smaller range compared to both ARM (8.5 to 932 mA m^{-1}) and SIRM (0.17 to 130.9 A m^{-1}).

$S_{-0.3\ T}$ is a measure of the proportion of low-coercivity ferrimagnetic grains to high-coercivity antiferromagnetic grains (Bloemendal et al., 1992). Values above 0.9 reflect dominance of magnetite (maghemite), while smaller ones represent increasing contributions from antiferromagnetic minerals (AFM) (hematite or goethite). $S_{-0.3\ T}$ ranges between 0.2 and 0.99 reflecting a two-component mineralogy consisting of varying concentrations of low- (magnetite–maghemite) and high-coercivity (hematite/goethite) minerals. Previous results of progressive thermal demagnetization of three-component IRM show unblocking temperature of maghemite (300–350 °C) and hematite (660–680 °C) only, with no indication of goethite (~120 °C) (Løvlie et al., 2001). ARM, SIRM and *k* are consequently controlled by variations both in concentration and composition. In such case, the ARM/*k*, SIRM/*k* and ARM/SIRM ratios will be less sensitive to characterize fine-scale variations in grain size of magnetite, although they also show less pronounced features compared with ARM and SIRM (Fig. 2).

3.3. Rock magnetic properties

Remanent coercivity curves reveal that none of the samples is saturated below 500 mT indicating the presence of AFM minerals all through the section (Fig. 3A). Features on the back-

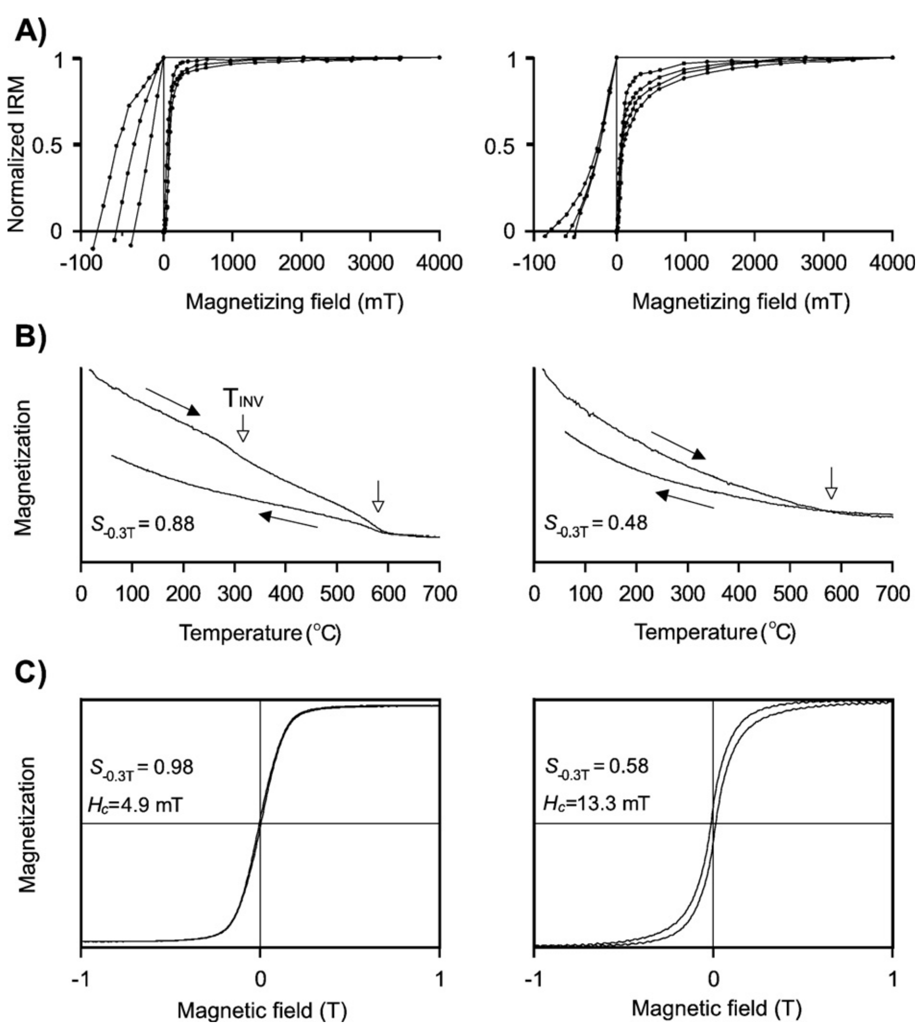

Fig. 3. Selected mineral magnetic curves for the two types of behavior defined by IRM acquisition curves. A) IRM acquisition and back-field curves; B) thermomagnetic curves, with solid arrows showing heating–cooling processes. Open vertical arrows indicate the inversion temperature of maghemite (T_{INV}) and Curie-temperature for magnetite (T_C), respectively; C) hysteresis curves after slope correction for paramagnetic contribution. The loops are measured in field up to ±1 T.

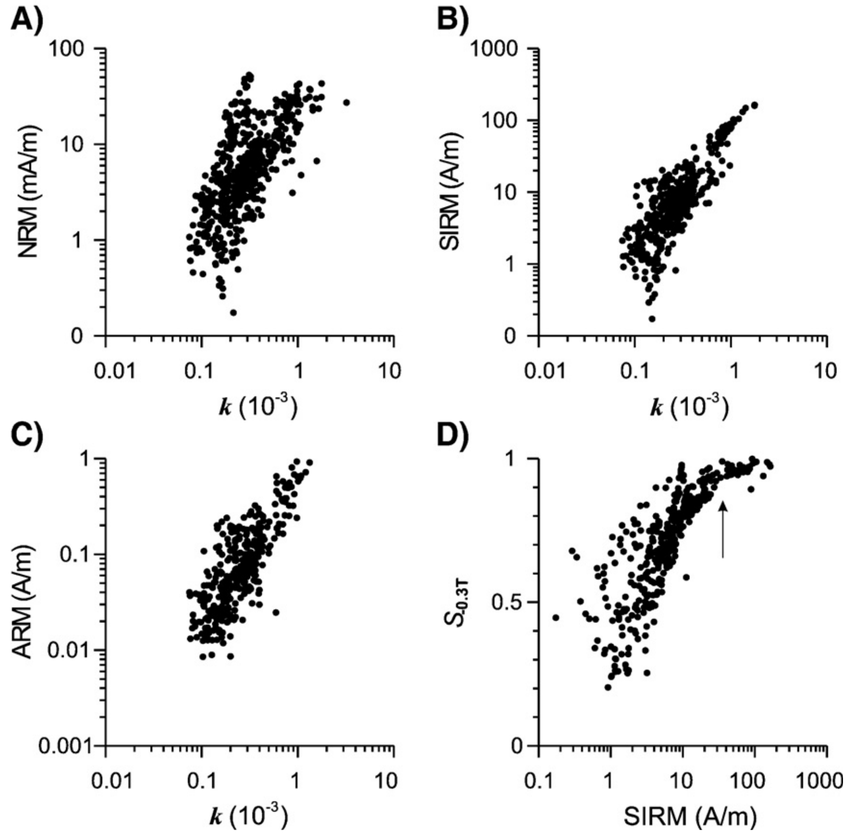

Fig. 4. Log–log scatter plots of selected magnetic parameters. A) k versus NRM. B) k versus SIRM. C) k versus ARM. D) SIRM versus $S_{-0.3\ T}$. Vertical line indicates change in slope at ca. 35 A m^{-1}.

field curves define two distinctly different types of behavior. Type 1 has shoulder-shaped to linear back-field curves (Fig. 3A, left) associated with remanent coercivities (B_{cr}) between 30 and 80 mT. Type 2 samples have concave back-field curves consisting of two more or less well defined linear segments (Fig. 3A, right) with B_{cr} ranging from 50 to above 100 mT. Both types reflect the presence of different coercivity distributions with varying degrees of overlap. Type 1 samples are dominated by low-coercivity minerals (magnetite), while type 2 is dominated by AFM minerals (hematite). Some of type 2 samples are evidently not saturated in 4 T, and consequently, the SIRM parameter (actually an $IRM_{4\ T}$) may be too low in some samples.

All thermomagnetic curves are irreversible with more than 20% reduction in high-field induced magnetization after heating (Fig. 3B). The two types of samples distinguished by their remanent coercivity properties also show different thermomagnetic curves. Type 1 samples display concave-down behavior at ca. 300 °C, reflecting the breakdown of thermally unstable maghemite. This type of curve defines a reversible Curie-point of magnetite (580 °C), which is significantly attenuated after heating to 700 °C (Fig. 3B, left). The significant loss of saturation magnetization after heating probably indicates the full oxidation of maghemite/magnetite to hematite and even partly destruction of magnetite. A weakly defined magnetite Curie-point (580 °C) is also discernable on the heating curve for type 2 samples. After heating, no Curie-point is present and the curves are completely dominated by paramagnetic contributions (Fig. 3B, right). The absence of a discernable Curie-point of hematite (680 °C) for both types of thermomagnetic curves may either be attributed to insufficient field to magnetically saturate hematite or its small contribution of magnetization compared to ferrimagnetic magnetite/maghemite.

Hysteresis curves were run on samples selected to cover the whole range of $S_{-0.3\ T}$ (0.2 to 0.99). The results define coercivities ranging from 4.5 to 46 mT (Fig. 3C). Samples with $S_{-0.3\ T}$ typical for magnetite ($S_{-0.3\ T}=0.98$) exhibit quite 'thin' loops, while quite a few samples with smaller $S_{-0.3\ T}$ values show wasp-shaped curves, suggesting a mixture of both hard and soft magnetic compounds (Tauxe et al., 1996a).

3.4. Intraparametric variations

Scatter plot of NRM versus k shows a weak linear relationship (Fig. 4A). The concentration dependent parameters (ARM, SIRM and k) all show comparable wedge-shaped log–log linear distributions (Fig. 4B, C and D) that are attributed to an interplay between magnetite with high specific ARM–SIRM and k, and AFM components characterized by low specific SIRM and k comparable to a paramagnetic matrix. At low concentrations of magnetite, k will effectively be controlled by paramagnetic and AFM minerals, while ARM and SIRM are controlled by AFM only. Increasing concentrations of magnetite will rapidly affect both k and SIRM, and consequently small variations in the ratio

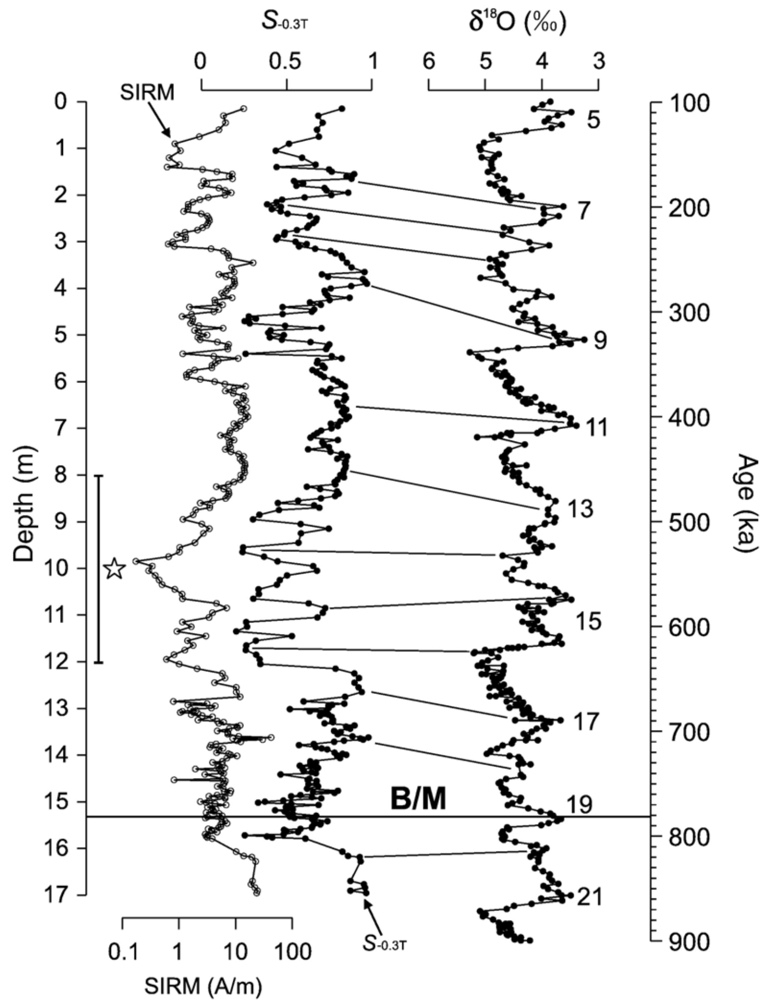

Fig. 5. Stratigraphic records of SIRM and $S_{-0.3\ T}$ with proposed correlation tie lines to the marine oxygen isotope record from ODP Site 677 (Shackleton et al., 1990) determined by subjective pattern analysis. Marine isotope stages are numbered in the graph to the right. Position of the Paleolithic site is indicated by a pentacle. B/M: Brunhes/Matuyama boundary.

$k_{magnetite}/(k_{hematite}+k_{paramagnetic})$ will produce a larger scatter in k compared to the SIRM-value ($SIRM_{magnetite}+SIRM_{hematite}$).

$S_{-0.3\ T}$ versus SIRM also exhibits a wedge-shaped distribution clearly showing that magnetic 'hard' samples have the lowest SIRM (Fig. 4D). The $S_{-0.3\ T}$ versus SIRM distribution shows a clear change in slope for SIRM values above 35 A m^{-1} (vertical arrow, Fig. 4D) that is associated with samples collected below 17.5 m inside a shaft dug into the valley floor (Løvlie et al., 2001). This change in slope may indicate genuine litho-magnetic properties of depositional origin, or reflect post-depositional alterations controlled by ground water. Data from below 17.5 m are consequently excluded in the following discussion.

4. Correlation with marine δ^{18}O record

Adopting a time window confined by the Brunhes/Matuyama boundary (B/M) (780 ka) at 15.35 m and a minimum age of the Xujiayao section determined by the last interglacial soil (ca. 129 ka) at the top (Lu et al., 1999; Heslop et al., 2000; Ding et al., 2002), the $S_{-0.3\ T}$ and SIRM curves can be visually correlated with the marine record of stable oxygen isotope variation from ODP Site 677 (Shackleton et al., 1990) (Fig. 5). Commencing with marine isotope stage (MIS) 19 at the B/M boundary (Tauxe et al., 1996b), troughs and peaks of the marine isotope and $S_{-0.3\ T}$ records can be identified, emphasizing the curve pattern more than amplitude. A number of tie lines were defined

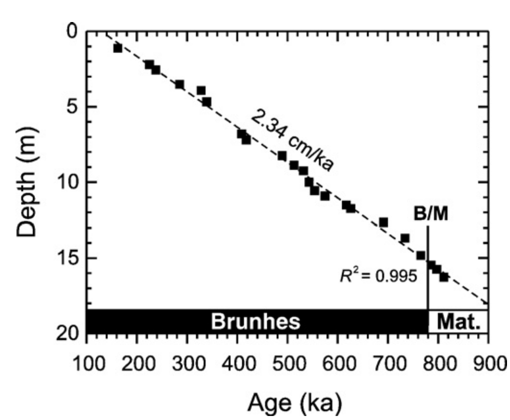

Fig. 6. Age–depth plot of the Xujiayao lacustrine sediments based on the chronostratigraphy in Fig. 5.

resulting in a detailed correlation between $S_{-0.3\ T}$ and the oxygen isotope signal. SIRM and $S_{-0.3\ T}$ data vary in reasonable concert with one major discrepancy at about 10 m. Here an interval with low SIRM is associated with a low $S_{-0.3\ T}$ interval showing high-amplitude variations, reflecting fine-scale variations in minute concentrations of magnetic mineral assemblage. The observation that within this interval $S_{-0.3\ T}$ exhibits a variational pattern comparable to the oxygen isotope curve, while the SIRM curve shows a distinct deviation adds confidence in the proposed correlation. We interpret that this correlation reflects climate variations in magnetic mineralogy, suggesting magnetite–maghemite dominance during interglacials. Based on the proposed correlation, the age–depth relationship was established, yielding an average accumulation rate of 2.34 cm/ka (Fig. 6).

5. Discussion

5.1. Composition and origin of magnetic minerals

The inferred magnetic climate signal in the Xujiayao sediments is characterized by a dominance of high-coercivity (hematite) minerals during glacial periods and increasing contributions of low-coercivity magnetite/maghemite assemblages during interglacial periods (Fig. 5). In these sediments with a significant amount of hematite in addition to magnetite/maghemite, k will be less reliable for monitoring the concentration of magnetic minerals since the specific k of magnetite is some 50 times larger than that of hematite (Thompson and Oldfield, 1986). The generally low value of k also questions the common assumption that k is controlled by ferrimagnetic minerals rather than by the paramagnetic matrix. Contrastingly, SIRM has a larger range but varies almost linearly (log–log) with k (Fig. 4B). Therefore it may be regarded as a better parameter for denoting variations in concentration of magnetic minerals. $S_{-0.3\ T}$ is a sensitive parameter assessing the relative proportion of magnetite to hematite and exhibits high-amplitude cyclic variations with much lower values (towards hematite) in the Xujiayao lacustrine samples compared to the Chinese loess. It has been shown that in hematite-dominated sediments, $S_{-0.3\ T}$ is very sensitive to even small contributions of low-coercivity minerals (magnetite/maghemite); only 2% of magnetite relative to hematite will yield $S_{-0.3\ T}$ values of larger than 0.8 (Hesse, 1997). The present results show that only 38% of the Xujiayao samples have $S_{-0.3\ T}>0.8$, implying that hematite is a dominating magnetic mineral. Thus it is likely that only minute amounts of magnetite–maghemite are sufficient to account for the inferred climate modulation of SIRM and $S_{-0.3\ T}$.

Climate controlled variations in magnetic mineralogy may be of both detrital and authigenic origin. As noted earlier, ARM/SIRM ratios between 0.15 and 0.25 are characteristics of intact magnetosomes (Moskovitz et al., 1993). Throughout the Xujiayao section ARM/SIRM values are consistently lower than 0.15 (Fig. 2), seemingly ruling out the presence of magnetosomes. However, for an assemblage of magnetite and hematite, ARM/SIRM is not likely to be diagnostic for magnetosomes since hematite is likely to attenuate the ARM/SIRM ratio by contributing more to SIRM than to ARM. Although the present ARM/SIRM values are below the diagnostic range for magnetosomes, we cannot rule out the presence of undetected, minute quantities of magnetosomes. We also emphasize that biogenic production of magnetite requires quite restricted redox-conditions at the water–sediment interface (Blakemore et al., 1985), and that there is presently no conclusive evidence of a positive correlation between the abundance of bacterial magnetite in lacustrine sediments and glacial–interglacial cycles (Oldfield and Wu, 2000; Snowball et al., 2002; Pan et al., 2004). We therefore propose that the magnetite in the Xujiayao sediments primarily represents detrital input rather than authigenic produced magnetite through biomineralization. The origin of hematite may either be detrital or result from post-depositional low-temperature oxidation of magnetite. Hematite dominates during glacials that might reflect selective oxidation of detrital magnetite. However, precipitation of hematite during glacial periods would imply the rather unrealistic situation of a climate dependent composition of the lake water in this semi-arid region. Specifically, previous microscope analysis of samples from the lower part of the investigated section reveals the presence of detrital hematite (Liu et al., 1992). Thermal demagnetization results clearly demonstrate that hematite is one of the dominant carriers of the primary remanence magnetization (Løvlie et al., 2001). Therefore it is proposed that the variations in both magnetite and hematite are primarily controlled by detrital fluxes and not by authigenic production of magnetic minerals associated with chemical or biological processes. Maghemite has been identified as a constituent of loess though its origin is still in dispute (Deng et al., 2000; Chen et al., 2005). The minor amounts of maghemite, as identified by thermomagnetic analysis, may originate either from the eolian source areas or the secondary maghemite grains associated with pedogenesis acting on the CLP. However, we do not exclude the possibility that maghemite may be the result of post-depositional low-temperature oxidation of magnetite at an early stage of sedimentation during interglacials.

5.2. Magnetic signal at Xujiayao: a linear response to eolian flux?

Considering the marginal location of Xujiayao with respect to the East Asian monsoon systems supplying the CLP with loess, both catchment runoff and wind-born dust may be conceivable sources of detrital fluxes providing the lacustrine sedimentation. On the CLP, the average loess accumulation rate is 7.1 cm/ka during the Brunhes Chron, and varies with climate being some 4 times higher during glacial periods than during interglacial periods (Heller and Evans, 1995). The average accumulation rate at Xujiayao is only about 2.34 cm/ka, which is significantly lower than the minimum deposition rates during interglacial periods on the CLP. The much lower accumulation rate and indistinctive change in sedimentation rates between glacials and interglacials (Fig. 6) probably suggest that eolian flux has not influenced the deposition in a significant way. By tentatively adopting SIRM as a proxy for the concentration of magnetite/hematite, order of magnitude calculations show that SIRM in the Xujiayao sediments carries only 1% of magnetic constituents compared to the Chinese loess (Florindo et al., 1999; Deng et al., 2005, 2006b; Wang et al., 2006). Comparable calculations for *k* also show that the Xujiayao sediments have only roughly 10% of the Chinese loess signal (Evans et al., 2002; Vidic et al., 2004; Liu et al., 2004b; Deng et al., 2005; Bloemendal and Liu, 2005). On the CLP, the enhancement of magnetic susceptibility in paleosols is widely attributed to pedogenic production of fine-grained ferrimagnetic minerals rather than climate dependent variations in eolian flux and sources (Zhou et al., 1990; Maher and Thompson, 1991; Banerjee and Hunt, 1993). It is therefore unlikely that the much weaker magnetic signal at Xujiayao compared to the Chinese loess reflects varying compositions of dust flux with glacial/interglacial periods. According to the behavior of the East Asian monsoon circulation, the eolian input into the paleolake during interglacials should be significantly lower than that during glacials because of the reduced winter monsoon (An, 2000). It is therefore unrealistic that a minute eolian influx during interglacials results in magnetic enhancement. Consequently, we conclude that the lacustrine sedimentation at Xujiayao is predominantly composed of river runoff material rather than eolian dust. The absence of a significant eolian flux component may either be attributed to major changes in the wind pattern or its very marginal location related to the dust-transporting wind systems supplying the CLP with dust.

Based on the above assumptions, it is more favorable to adopt a climate tuned runoff model than an eolian modulation model. Although the runoff history of the Xujiayao paleolake is presently poorly known, we may with reasonable certainty assume that the detrital flux into the lake has in some way been influenced by changes in environmental conditions controlled at least in part by climate variations. During cool and dry glacials, we infer that the sediments have a low concentration of detrital magnetic minerals. We attribute this to low erosion-rates and consequently relatively low detrital input to the lake. During warm and humid interglacials, however, detrital input by rain splash erosion and surface incision are likely to have been more intense because of increasing rainfall and surface-runoff. The higher energy of the runoff during interglacials is likely to have eroded neighboring loess/paleosol sections supplying the lake with material containing higher concentrations of partly weathered/pedogenized loess-derived magnetic minerals. Because of their higher magnetic susceptibility values, these pedogenized loess and soils may result in significant magnetic enhancement of interglacial lake sediments. This will have the magnetic characteristics we observed (stronger but softer) during interglacials and vice versa. However, the lack of independent paleoenvironmental indicators that might have confirmed the interpretation of the magnetic data (e.g., pollen, stable isotopes and bulk mineralogy), implies that we cannot exclude other possible sediment-source linkages that may obscure the proposed increase in

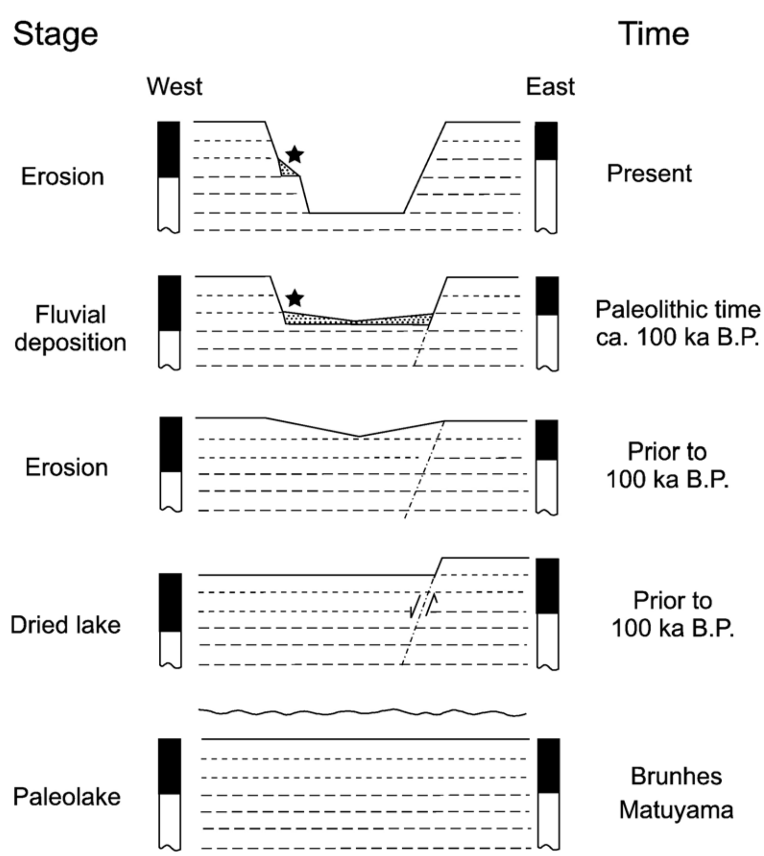

Fig. 7. A scenario depicting the evolution of the Liyigou river valley with the proposed fluvial deposits in which the Paleolithic site is situated (modified from Løvlie et al., 2000).

erosive input of magnetite-dominated assemblage during interglacials.

5.3. Age of the Xujiayao Paleolithic site

Detailed correlation of mineral magnetic parameters in the Xujiayao Pleistocene paleolake with a marine oxygen isotope record suggests that the lacustrine sedimentation at Xujiayao ended at the beginning of MIS 5 (Fig. 5), in general accord with recent high-resolution paleomagnetic results from several typical Nihewan group sections, e.g., Xiaochangliang and Donggou (Zhu et al., 2001; Zhu et al., 2003), Tai'ergou (Wang et al., 2004), Dongguttuo (Wang et al., 2005) and Xiantai (Deng et al., 2006a), some 50 km NE from Xujiayao. Thus the paleolake may have dried up in Middle/Late Brunhes Chron.

The Xujiayao Paleolithic site was discovered in 1976 and excavated in 1976 and 1977. Excavation of the locality in 1976 yielded nine piece of human remains, including one infantile upper jaw, one isolated upper molar, six fragments of parietal and one piece of occipital bone, and 13,650 pieces of stone-tool artifacts, including 2532 cores, 8302 flakes and blades, 1526 scrapers, 105 points, 106 burins, 11 borers, 1059 stone balls and bolas and 5 chopper-chopping tools (Jia and Wei, 1976; Jia et al., 1979). In addition, numerous mammal fossil fragments were also unearthed and at least 20 forms were identified, including *Struthio* sp., *Ochotona* sp., *Myospalax fontanieri*, *Microtus brandtioides*, *Canis lupus*, *Equus przewalskii*, *Coelodonta antiquitatis*, *Cervus elaphus*, *Megaloceros ordosianus*, *Bos primigenius*, *Panthera* cf. *tigris*, *Palaeoloxodon* cf. *naumanni*, *Equus hemionus*, *Cervus nippon grayi*, *Spirocerus hsuchiayaocus* (sp. Nov.), *Spirocerus peii*, *Procapra picticaudata przewalskii*, *Gazella subgutturosa*, *Gazella* sp. and *Sus* sp. The majority of these forms represent the typical cold-adapted large mammal associations that were abundant in the Late Pleistocene (Jia and Wei, 1976; Jia et al., 1979). A preliminary palynological analysis of samples collected at the depth of 10 and 12 m of the Paleolithic site reveals the presence of fossil pollen characterized by the dominance of herbaceous and shrubby taxa (55.1–77.9%) and appearance of many cold-resistant members of arboreous taxa (e.g., *Pinus*, *Picea*, *Abies* and *Betula*), indicative of a typical forest-steppe ecosystem (Yan et al., 1979). Six fossil teeth of *E. przewalskii* and *C. antiquitatis* excavated from a depth of 12 m of the Paleolithic site have subsequently been dated by uranium-series method (Chen et al., 1982), yielding a concordant ^{230}Th/^{234}U age of ca. 100 ka. However, ^{231}Pa/^{235}U ratios indicate that these samples have not remained as a closed system, and that the age consequently may not be reliable (Chen et al., 1982). Further uranium-series dating of fossil teeth of *C. antiquitatis* from a depth of 8 m yields comparable ^{230}Th/^{234}U and ^{231}Pa/^{230}Th ages of 104 ka and 90 ka, respectively (Chen et al., 1984), suggesting an age for the mammalian bones within the last interglacial (MIS 5).

The retrieved U-series ages for the mammal bones encountered some 5 m above the B/M boundary are not in accord with our magnetic climate-inferred age of ca. 500 ka for the sediments carrying the artifacts (Fig. 5). This age discrepancy may be accounted for by assuming that there are still unsolved methodical problems in geochronology, either in U-series dating to fossil bones or our less mature magnetic climate interpretations. However, we propose a more likely explanation implying that the mammal bones and tool artifacts were incorporated within fluvial sediments presently locally overlying the lacustrine sediments at the Paleolithic site (Løvlie et al., 2000). This suggestion implies that when the Paleolithic site was inhabited, it was located at the western shore of the ancient Liyigou River, consequently the valley floor was ca. 4.5 m higher than today. According to this scenario as illustrated in Fig. 7, the bones were probably never incorporated into the lake sediments, but rather within fluvial sediments located just above a major unconformity to the underlying lacustrine sediments. The bones have consequently either been transformed from some other localities, in which case the bones and artifacts must be younger, or the hominids occupied the shore of a river higher than today. We believe that these stone artifacts were found *in situ*, but since the age of these tools is inferred from the U–Th-dated bones, the bones and artifacts are hence younger than the sediments, and the Paleolithic Site does not represent a reliable chronostratigraphic marker horizon for the lacustrine sediments at Xujiayao (Løvlie et al., 2001).

6. Conclusions

The concentration and mineralogy-dependent magnetic parameters SIRM and $S_{-0.3\ T}$ in the Xujiayao lacustrine sediments define high-amplitude records interpreted to reflect high-resolution climatic variations between MIS 19 and MIS 5. The magnetic signal at Xujiayao cannot be attributed to either a linear response to eolian flux or post-depositional authigenic production of magnetic minerals, but is probably associated with climatically controlled runoff processes. It is tentatively concluded that the surface-runoff during interglacials eroded and carried weathered/pedogenized loess and soils from the neighbouring loess areas into the lake in addition to probably climate independent background flux dominated by AFM minerals (i.e. hematite). These eroded materials containing part of magnetically soft minerals (magnetite/maghemite) supplied the paleolake resulting in significant magnetic enhancement.

The magnetic susceptibility signal at Xujiayao shows a less pronounced climate modulation than SIRM, suggesting that SIRM may be a more sensitive proxy for climate variations than susceptibility in sediments with low concentrations of magnetite. Our results demonstrate that the Nihewan lacustrine sediments may retain high-resolution archives of environmental variations comparable to those of the loess deposits in China, and therefore may be applied to reconstruct regional paleoenvironmental conditions.

Finally, the inferred sedimentation rate constrains the age of ca. 500 ka for the sediments carrying the Xujiayao Paleolithic site, located some 5 m above the B/M boundary. This inferred Early Brunhes age of the lacustrine sediments does not call for revision of the U–Th-derived age of the Paleolithic site (ca. 100 ka), which is probably not directly related to the age of the sediments.

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