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High resolution magnetostratigraphy and deposition cycles in the Nihewan Basin (North China) and their significance for stone artifact dating

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Abstract

Three lacustrine sections in the Nihewan Basin, Xiaodukou, Donggutuo and Xiaochangliang (40.1–40.4°N; 114.6–114.7°E), were closely sampled for magnetostratigraphic and deposition cycle analysis. Rock magnetic investigations show that the characteristic remanent magnetization of the sediments is mainly carried by magnetite and hematite. The Xiaodukou sequence is one of the most complete sections in the basin and has recorded substantial parts of the Brunhes and Matuyama chrons back to the termination of the Olduvai subchron. Several subchrons within the Matuyama period have been documented such as the Jaramillo, the Cobb Mt. and others. The Matuyama/Brunhes boundary, the Jaramillo, as well as the Cobb Mountain events were observed also at Donggutuo. On the basis of grain size and susceptibility data and of field investigations, the sections are divided into two longer lasting lacustrine episodes with a fluvio-lacustrine deposit in between. They are structured by 15 high-frequency deposition sub-cycles. In each cycle, the grain size fines upwards, while magnetic susceptibility decreases. This behavior is due to cyclic water level change of the ancient lake Nihewan. At Xiaodukou, the variations of the 0.2 to 7.5 μm grain size fraction can be correlated with the marine oxygen isotope stages OIS 64–OIS 11. The grey-green clayey to silty Paleolithic stone artifact layers at Xiaochangliang and Donggutuo are located at depths of 55.4 m and 43–38.7 m, respectively. They were buried when the lake-level was rising. The artifact layers have been deposited around the Cobb Mountain event during the sedimentary sub-cycle 6 of the older lacustrine phase corresponding to OIS 35, 36. Thus in contrast to the results of other studies, the estimated age of the Xiaochangliang stone artifact layer does not exceed 1.26 Ma, while the Donggutuo stone artifact layers date back to 1.21–1.15 Ma. This age determination brings the Nihewan hominids in close relation to the findings of Homo Erectus at Lantian on the Chinese Loess Plateau.

Keywords: Magnetostratigraphy; Deposition cycle; Stone artifacts; Nihewan Basin

Introduction

Nihewan Basin is located between Yangyuan County and Weixian County of Hebei Province, China, between 40.1–40.4°N and 114.6–114.7°E. In the 1920s, Barbour, Teilhard de Chardin and others found and studied mammalian fossils, contained in late Cenozoic fluvio-lacustrine strata near Nihewan village, which eventually corresponded to the Villafranchian fauna in Europe (Barbour et al., 1926; Teilhard de Chardin and Piveteau, 1930). The lacustrine sediments in the ancient lake basin were called the "Nihewan Formation" (Barbour, 1924). A large amount of stone artifacts and mammalian fossils was found in the formation in the 1970s and 1980s (Gai and Wei, 1974; You et al., 1979; Tang et al., 1981; Wei, 1985). Numerous advanced stone artifacts, the shapes of which were clearly predetermined by the makers and partly consisted of prepared core, were found in Xiaochangliang, Donggutuo and other sections. These cultures might be placed in the artifact categories known in African Plio-Pleistocene stone tool assemblages. The core named "Donggutuo-shaped core" indicated the capability of the Donggutuo people in coping with the natural environment, and provided more information about the complexity of early human behavioral evolution, the genesis and spreading of hominids (Hou et al., 1999). At the end of the 1970s, a preliminary magnetostratigraphic study of the

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Nihewan lacustrine sequence was performed by Cheng et al. (1978). In the early 1980s, detailed magnetostratigraphic research was carried out in several sections of the basin, and some important results were obtained, such as the age of the "Nihewan Formation" being extended into the Middle Pleistocene, a magnetic polarity time series being established, and the age of the Donggutuo artifact layer being estimated at about 1.0 Ma (Li and Wang, 1982). Since the 1990s, comprehensive detailed magnetostratigraphic polarity, susceptibility and rock magnetic investigations of the Nihewan formation have been promoted using highly sensitive superconducting magnetometers and modern high field equipment (Yuan et al., 1996; Zhu et al., 2001, 2003, 2004; Wang et al., 2004, 2005, 2006; Deng et al., 2006) and new insights into the age of the Paleolithic sites have been achieved.

It remains difficult to reach firm conclusions regarding the comparison of magnetic polarity zones and magnetic susceptibility variations among different sites within the basin, the sediment thickness distribution and most important, the age of the stone artifact layers. Also, the sedimentation environment needs to be characterized more clearly. In this paper, we try to achieve improved understanding by developing a high resolution magnetostratigraphy and analysing the deposition cycles of the three fluvio-lacustrine successions at Xiaodukou, Donggutuo and Xiaochangliang in the Nihewan basin. This approach provides paleoenvironmental and stratigraphic information, and refines the age of the stone artifact layers.

Geological sections, sampling and measurements

The Xiaodukou section (XDK), northeast of Xiaodukou Village (40.22°N, 114.65°E) is located near the center of the ancient lake Nihewan. It is one of the important sections for studying the evolution of the Nihewan basin. The section is well exposed. Its deposition cycles have been formed continuously and can be clearly recognized. The sections at Xiaochangliang (XCL) and Donggutuo (DGT) are located near the margin of the basin towards the Fenghuang Mountains (Fig. 1). The stone artifacts are buried in the lower parts of these two sections. The sections have been important sites for studying Nihewan stone artifacts since the 1970s (Zhu et al., 2001, 2004). Our magnetostratigraphic research concentrates mainly on the sections at Xiaodukou and Donggutuo.

The Xiaodukou section with a thickness of 122.3 m is mainly composed of fine lacustrine sediments which are covered by 10.5-m-thick Late Pleistocene Malan loess. The lower part of the lacustrine sediments with a thickness of ~60 m mainly consists of gray or gray-green clay, silty clay and clayey silt interbedded with thin calcareous clay and calcareous layers. The ~10-m-thick middle part is composed of fine-grained yellow clayey silt, silt and fine or coarse-grained sand with cross-bedding structures and small gravel in the lower sand layers. The upper part of the ~42-m-thick lacustrine sequence is made up of yellow-green clayey silt and silty clay layers.

The Donggutuo section, with a reduced thickness of about 43.7 m, is located at the eastern margin of the basin, to the northeast of the Xiaodukou section. Stone artifacts have been found at the bottom of the section (43–38.7 m). The Xiaochangliang section, lying between the Xiaodukou and Donggutuo sections has a kind of intermediate thickness of about 63.2 m. Stone artifacts have been found in the lower part of this section at a depth of 55.4 m.

More than 1700 samples have been taken at intervals of 5–15 cm from the three sections for grain size analysis and magnetic susceptibility measurements. More than 720 orientated hand samples were taken from the Xiaodukou and Donggutuo sections at 20–25 cm intervals for paleomagnetic studies. Each hand sample was cut into 2–4 cubic specimens with a volume of 8 cm^3. The experiments and measurements were carried out in the paleomagnetic laboratory of the Institute

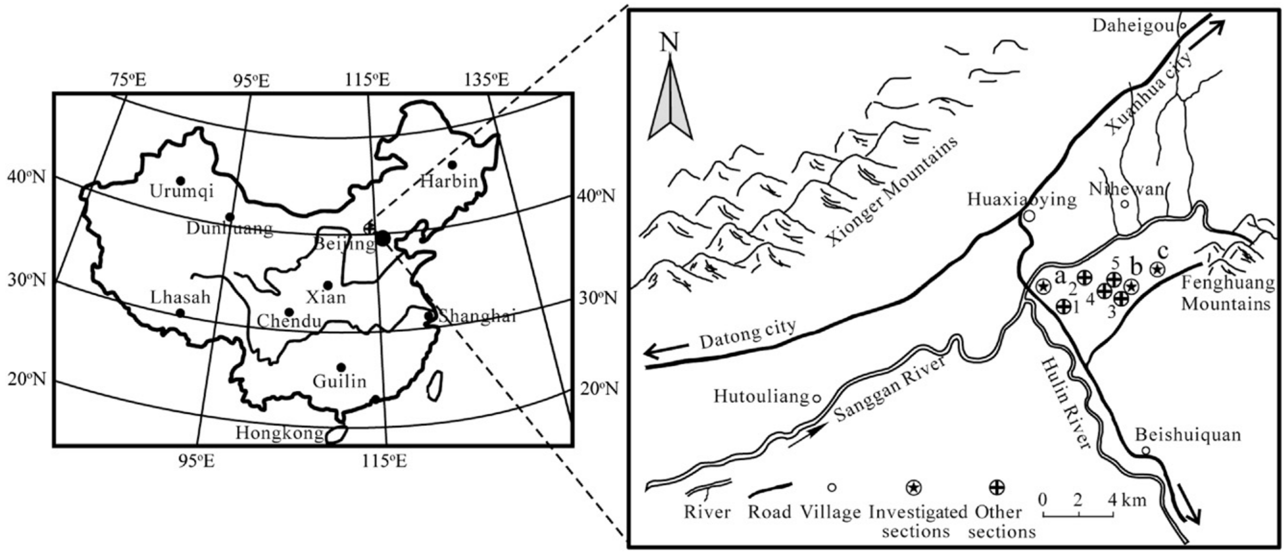

Figure 1. The sampling locations at Xiaodukou (a), Xiaochangliang (b), Donggutuo (c) and other sections of the Nihewan Formation at Taiergou (1), Haojiatai (2), Xiaoshuigou (3), Donggou (4) and Majuangou (5).

of Geology and Geophysics, Chinese Academy of Sciences in Beijing. A 2G three-axis cryogenic magnetometer, a MMTD60 thermal demagnetizer, a 2G660 pulse magnetizer and KLY-3S Kappabridge with built-in furnace were used for magnetostratigraphic, rock magnetic and anisotropy of magnetic susceptibility (AMS) investigations. The grain size analysis was done using a SALD-3001 laser analyzer. Bulk low field susceptibility was measured using a Bartington MS2 magnetometer in the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences.

Rock magnetism

IRM (isothermal remanent magnetization) acquisition, thermal demagnetization and IRM back field (H_{cr}) curves of some samples from Xiaodukou and Donggutuo are shown in Figure 2a. The IRM of most samples is saturated or reaches 85%–90% of SIRM (saturation isothermal remanent magnetization) at fields of 300–500 mT. H_{cr} of the SIRM is about 60–100 mT. There are several inflexions during thermal demagnetization at temperatures of 100°C, 200–300°C and 500–600°C. We attribute this behaviour to the presence of magnetite and maghemite, respectively, with variable medium coercivity and low unblocking temperatures. The IRM of some samples is saturated only at high fields of 1500–2000 mT; their H_{cr} values are about 120–160 mT (sample H40) or even higher up to 240 mT (such as sample D28). This behaviour indicates the presence of hematite with high coercivity and high unblocking temperatures (Dunlop and Ozdemir, 1997). The contribution of hematite to low field susceptibility is rather negligible.

Thermomagnetic analysis of samples from Xiaodukou and Donggutuo using a KLY-3 Kappabridge with a CS-3 high temperature furnace was performed in an argon gas atmosphere (Fig. 2b). The susceptibility usually stays rather stable during heating up to 500°C where it starts to drop and to decrease monotonously to zero at 580°C, the Curie point of magnetite. The gradual decrease of susceptibility on some heating curves from about 280°C to 380°C is interpreted to show the existence of maghemite, and the humps at 250°C may arise from the presence of iron sulfide (Roberts, 1995; Hu et al., 2000). All thermal susceptibility curves are irreversible. Upon cooling, the susceptibility increases rapidly and can be at room temperature up to 10 times higher than before heating . This may be due to mineral changes of iron sulfide and/or paramagnetic minerals to strongly magnetic magnetite during the heating process (Dunlop and Ozdemir, 1997).

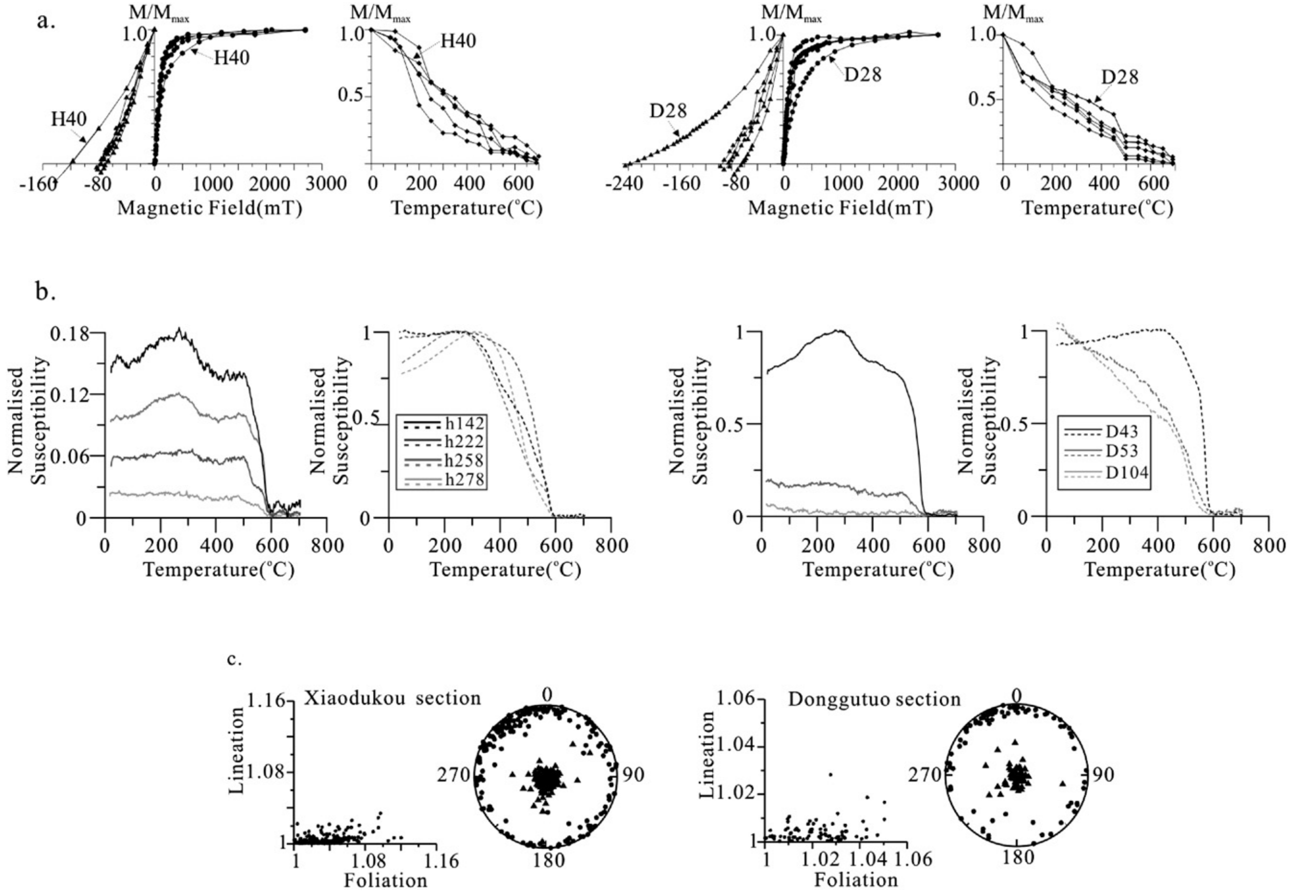

Figure 2. Rock magnetic properties of some samples from Xiaodukou and Donggutuo sections. (a) IRM acquisition, back field and thermal demagnetization curves of some samples. Left two columns: Xiaodukou section; Right two columns: Donggutuo section. (b) Thermal behaviour of low field susceptibility of samples. Left two columns: Xiaodukou section; Right two columns: Donggutuo section. Solid (dotted) lines represent the heating (cooling) curves. (c) Anisotropy of magnetic susceptibility (AMS). Left: Lineation(L)–Foliation(F) plots; right: stereographic projection of K_{max} (dots) and K_{min} (triangles) axes.

We conclude that the natural remanence of the sediments is carried mainly by low coercivity magnetite and sometimes by higher coercivity maghemite and hematite. The presence of minor amounts of iron sulfides implies a low oxidation potential environment.

Magnetic susceptibility anisotropy (AMS)

In order to check the reliability of the palaeomagnetic signal, the anisotropy of magnetic susceptibility (AMS) was measured before any demagnetization of the natural remanent magnetization. The magnetic lineation is found to be smaller than the magnetic foliation, indicating that the AMS ellipsoid is oblate (Fig. 2c). The inclinations of the minimum susceptibility axes ($K_{\min}$) are close to vertical and grouped tightly, whereas those of the maximum axes ($K_{\max}$) tend to be horizontal without recognizable preferred azimuthal alignment. Thus the original sedimentary environment is considered to have been undisturbed since deposition.

Natural remanent magnetization (NRM)

All samples were treated using thermal (8–13 steps) or AF (8–15 steps) demagnetization methods. The data were analyzed using principal component analysis (Kirschvink, 1980a,b) or Fisher (1953) means if stable intensity plateaus were reached during AF demagnetization of high coercivity minerals.

The results of thermal and alternating field demagnetization of some samples from Xiaodukou are represented in Figure 3a. Often remanence directions of normal polarity are relatively stable during demagnetization (e.g. samples H390, H391). The characteristic remanent magnetization (ChRM) can be evaluated above 200–250°C or 12–16 mT, respectively. The ChRM is either trending to the origin of the orthogonal vector projections or is defined as the mean of vectors which are stable in intensity upon AF demagnetization at higher fields. Its direction is usually parallel or antiparallel to the present day field direction. Many samples have two clearly separated NRM components (right two columns in Fig. 3a). The initial direction is very close to the present field direction at the sampling site at temperatures below 200–300°C or in alternating fields below 30–35 mT. This component is considered to be of secondary origin. The ChRM directions obtained at higher temperatures or alternating fields persist up to 600–700°C or 80–100 mT. Clearly reversed ChRM polarity is often observed (e.g. samples H46, H284, H365).

Both demagnetization methods are similarly efficient in getting the ChRM direction although high and low coercivity and high and low unblocking mineral phases are present in the Nihewan samples. Because AF demagnetization is able to remove secondary NRM components it seems that these secondary components often reside in low coercivity magnetite, possibly of multidomain grainsize. High coercivity hematite is little affected by AF treatment (e.g. samples H101). These high coercivity samples have maximum unblocking temperatures around 700°C. However, if both minerals are present (e.g. in sample H46), the ChRM polarity in both minerals has the same sign. Hence magnetite and hematite have been magnetized at the same time during sediment deposition.

At Donggutuo, thermal demagnetization yields usually better defined ChRM directions than AF cleaning (Fig. 3b). Often three components (secondary, transitional and primary) are clearly displayed during thermal demagnetization. Two inflexions of the curves are observed at 250–300°C and at 500–600°C. The remanence in some samples is not demagnetized until up to 680°C or 700°C, indicating that natural remanent magnetization of the sediments is carried also by hematite of high unblocking temperatures. This agrees with the AF cleaning results where NRM intensities often reach a stable plateau at higher fields.

NRM polarity

The ChRM inclinations and declinations of the two sections are plotted versus profile depth in Figures 4 and 5, respectively. Four main magnetozones are recognized in the Xiaodukou section: two with normal polarity, N1 (0–29.0 m) and N2 (53.9–62.9 m) and two with reverse polarity, R1 (29.0–53.9 m) and R2 (62.9–122.0 m) (Fig. 4). The magnetozones can be correlated with the geomagnetic polarity timescale (e.g. Singer et al., 1999; Channell et al., 2002). XDK magnetozones N1 and subdivided N2 correspond to the Brunhes chron and the Jaramillo subchron, respectively. Amongst the several very short normal polarity zones within the Matuyama interval, the double peak of normal polarity samples (e2) at a depth of 74–76 m, though not fully reversed back to normal, may be interpreted to have recorded the Cobb Mountain excursion (Channell et al., 2002).

The Cobb Mountain short polarity event with an age of 1.10–1.20 Ma was found and named during the late 1970s (Mankinen et al., 1978). Studies from the late 1980s to the early 1990s assigned the Cobb Mountain event as a global polarity event because it had been recorded not only in deep-sea sediments, but also in volcanic rocks worldwide (Mankinen and Grommé, 1982; Clement and Kent, 1987; Clement, 1992). Evidence for the Cobb Mountain event was also reported from Chinese loess (Zheng et al., 1992; Guo et al., 1998). The age of the event was determined by Shackleton et al. (1990) with 1.19 Ma when he improved the Late Pleistocene time scale using astronomical methods. Later, Cande and Kent (1995) and Channell et al. (2002) proved an age at about 1.201–1.211 Ma, and 1.190–1.215 Ma, respectively.

Two normal polarity samples exist at the bottom of the Xiaodukou section (122 m). Extrapolation of the age-depth relation between the onset of the Jaramillo subchron and the Cobb Mt. event arrives at an age of 1730 ka for the bottom sediments at 122 m. Therefore these samples may represent the termination of the Olduvai subchron which has been observed also in other central Nihewan Basin sites (Wang et al., 2004).

The average accumulation rate of sediments can be calculated utilizing the age of magnetic polarity boundaries on the condition that deposition has been basically continuous. The thickness of the lacustrine sediments between the Matuyama/Brunhes boundary (779 ka) and the end of the Jaramillo

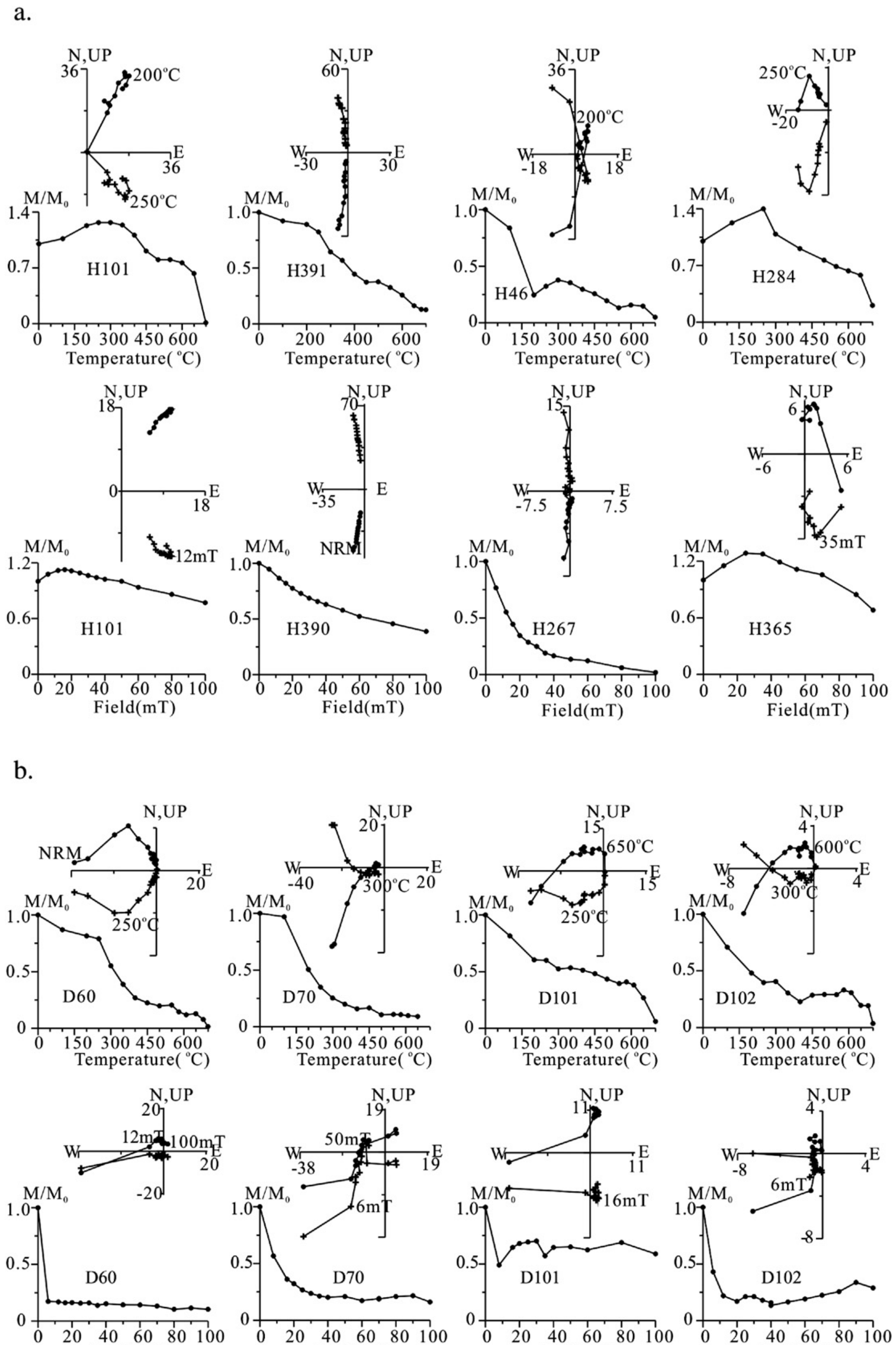

Figure 3. NRM thermal and AF demagnetization curves of some sister samples from Xiaodukou (a) and Donggutuo (b) sections. Orthogonal vector plots (+ horizontal plane, ● vertical plane, scale units in 10^{-3} A/m) and normalized intensity curves are shown.

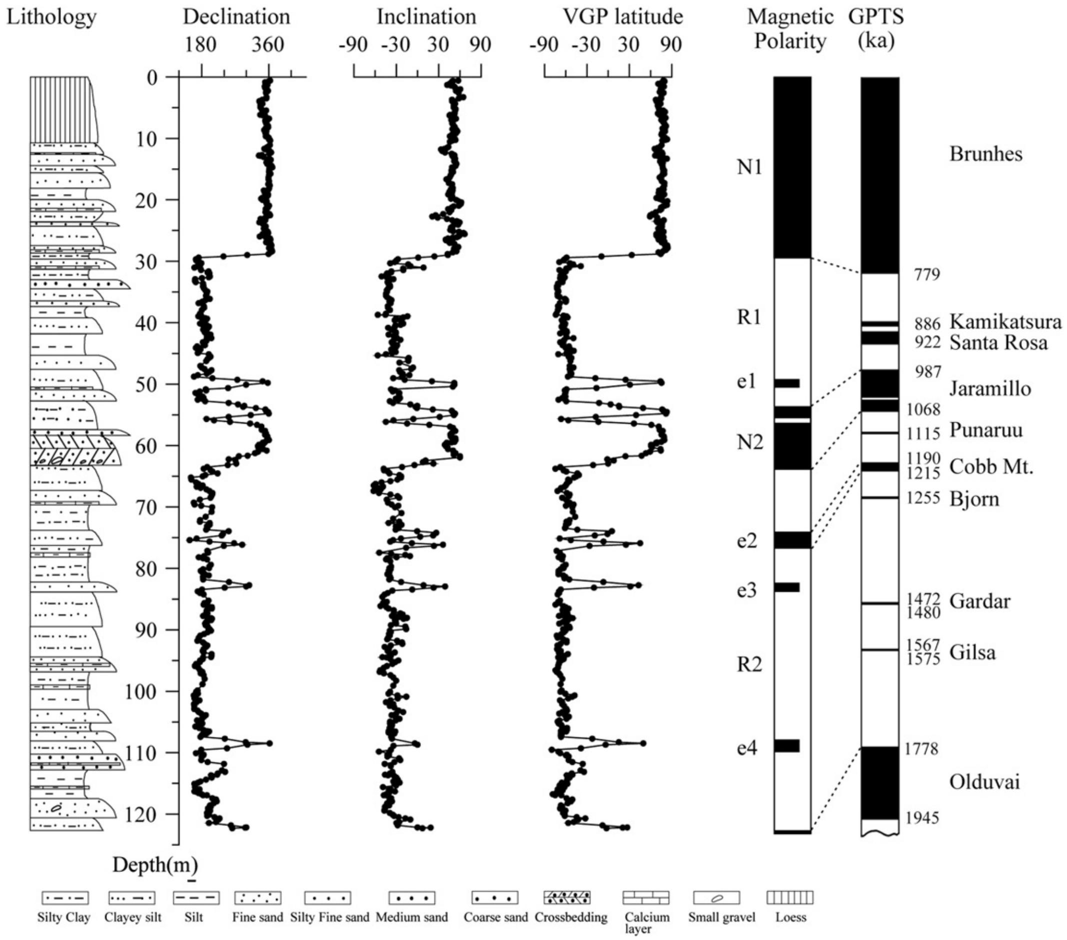

Figure 4. ChRM inclination and declination vs. depth for the Xiaodukou section in Nihewan Basin. Magnetic polarity pattern compared to geomagnetic polarity time scale (GPTS) as presented by Singer et al. (1999) and Channell et al. (2002).

(987 ka) is ~25 m, thus the average rate is 12.02 cm/ka. Given that the two normal polarity samples at 122 m represent the end of the Olduvai subchron, the thickness of sediments is ~59 m and the average rate is 8.32 cm/ka from the onset of the Jaramillo subchron (1068 ka) to 122 m (1778 ka) at Xiaodukou. The deposition rate of the upper lacustrine sediments is higher

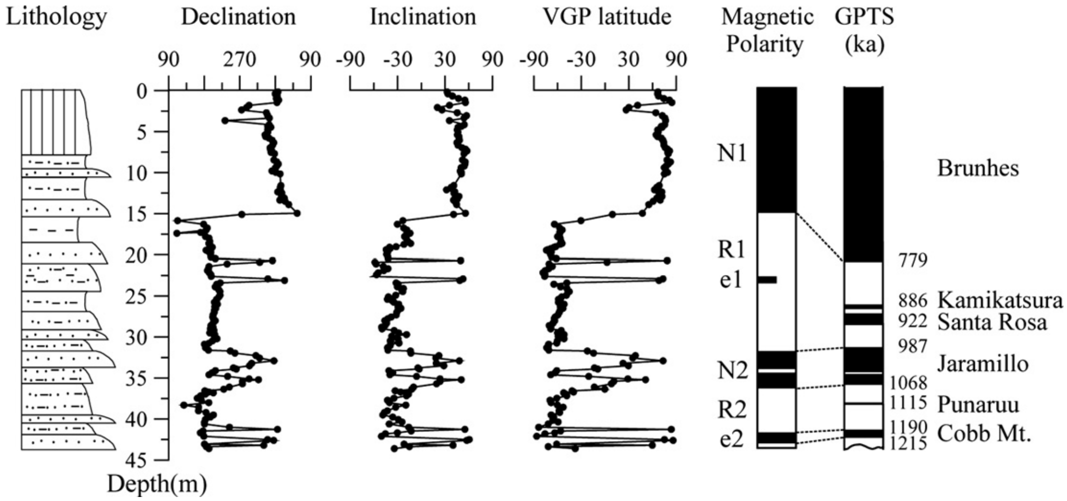

Figure 5. ChRM declination, inclination and resulting VGP latitude vs. depth for the Donggutuo section in the Nihewan Basin. Magnetic polarity pattern compared to geomagnetic polarity time scale (GPTS) as presented by Singer et al. (1999) and Channell et al. (2002). Lithological symbols as in Figure 4.

than that of the lower sediments, and the ratio is about 1.44. The higher deposition rate could arise from coarser grain size of the upper lacustrine sediments as compared to the lower lacustrine sediments.

The Tai'ergou section located 1.5 km southeast of Xiaodukou section was investigated by Wang et al. (2004). The depositional characteristics of this section are very similar to those of the Xiaodukou section, and both show good correlation in the susceptibility curve. Paleomagnetic results indicate that the bottom sediments of the Tai'ergou section recorded the Olduvai subchron (Wang et al., 2004). The average accumulation rate is about 8.17 cm/ka from the Matuyama/Brunhes boundary to the top of the Jaramillo subchron. The deposition rate between the onset of the Jaramillo subchron and the termination of the Olduvai subchron is about 5.72 cm/ka. The ratio of the deposition rates of the upper lacustrine sediments to that of the lower lacustrine sediments is 1.43. This is very close to that of Xiaodukou.

The afore-mentioned considerations lend strong support to the interpretation that the two normally magnetized samples at the bottom of the Xiaodukou section have recorded the termination of the Olduvai subchron.

Four main magnetozones have also been recognized in the Donggutuo section: two with normal polarity, N1 (0–15.0 m) and N2 (32.0–36.1 m) and two with reverse polarity, R1 (15.0–32.0 m) and R2 (36.1–43.7 m) (Fig. 5). DGT magnetozones N1 and N2 correspond to the Brunhes chron and the Jaramillo subchron, respectively. In addition, two short normal polarity zones (e1, e2) are observed. The younger e1 at a depth of about 23 m might correspond to either the Kamikatsura or the Santa Rosa excursion where as e2 at a depth of 42.5–43.2 m could be interpreted according to the deposition cycles analysis to have recorded the Cobb Mountain event (Channell et al., 2002).

Low field susceptibility and grain size

Figures 6–8 show negative correlation between magnetic susceptibility and clay fraction (0.2–7.5 μm) in the sediments, but susceptibility and sand fraction (100–250 μm) correlate positively over wide profile ranges (Yang and Li, 2002). On the other hand, slightly increased magnetic lineation values (up to 2%), highly sensitive to hydrodynamic changes, parallel the peaks of the grain size fraction 100–250 μm at Xiaodukou. Hence susceptibility variations may be dominated by hydrodynamic conditions and closely related to the characteristics of sediment deposition. Furthermore, the hydrodynamic conditions in the lake should have been controlled by the change of the lakeshore line and the advance or retreat of the rivers, that is, the rise or fall of the lake level. Therefore, susceptibility, grain size variation and magnetic lineation seem to reflect the change of hydrodynamic conditions and fluctuations of the lake level. The variations of these parameters represent a deposition cycle

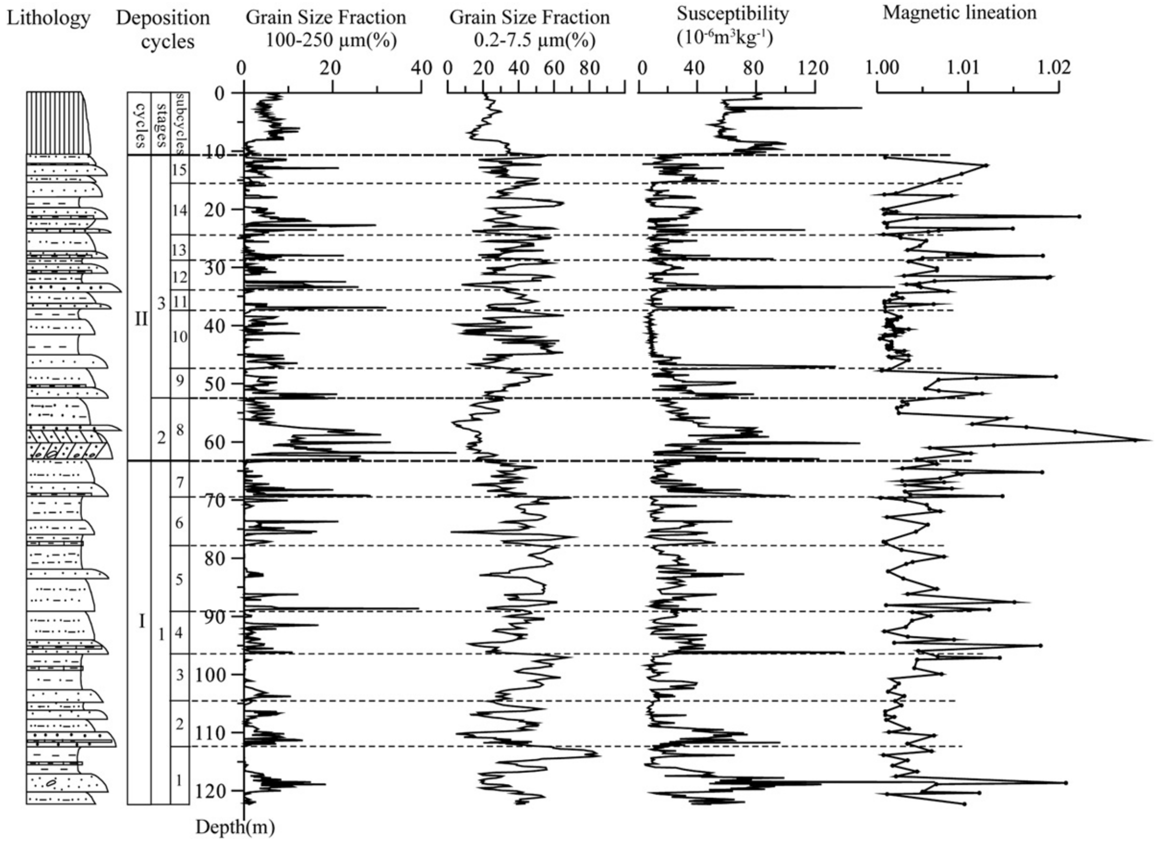

Figure 6. Lithology, interpreted deposition cycles, magnetic low field susceptibility, two grain size fractions (clay, sand) and magnetic lineation versus depth at Xiaodukou. Lithological symbols as in Figure 4.

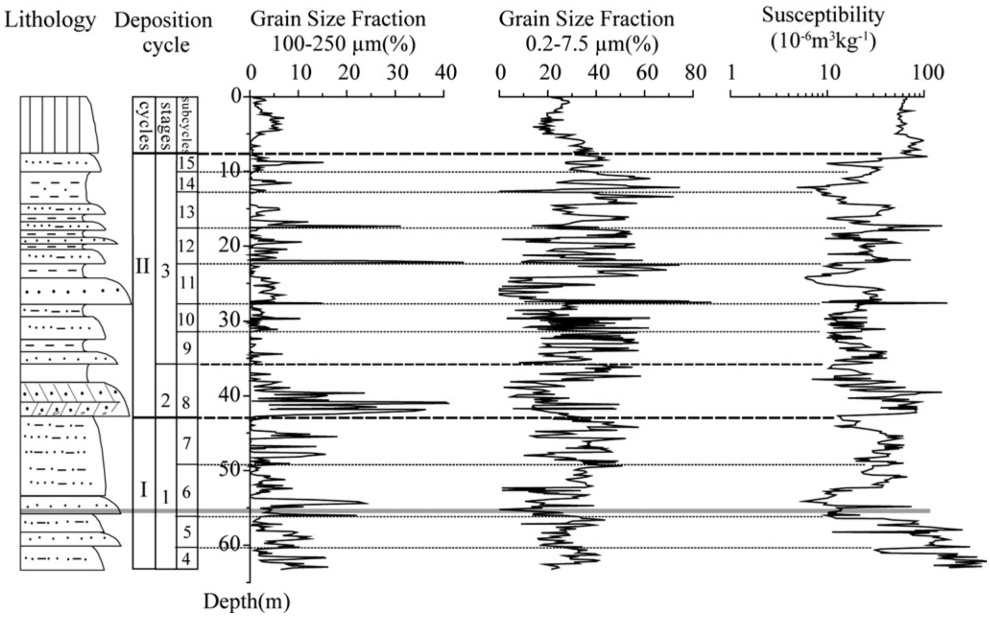

Figure 7. Lithology, interpreted deposition cycles, magnetic low field susceptibility and two grain size fractions (clay, sand) versus depth at Xiaochangling. Human artifact layer gray horizon. Lithological symbols as in Figure 4.

in which the grain size changes from coarse to fine and the lake level from low to high.

Deposition cycles and environment

Three sedimentary main stages can be recognized in the fluvio-lacustrine sequence at Xiaodukou according to the analysis of susceptibility, grain size as well as field observations: stage 1 (122.3–63.2 m), is characterized by a mean sediment grain size of 6.12 φ, the average fraction of clay and fine silt being high (39.6%) with a minor contribution from coarse silt and fine sand, whereas middle- and coarse-grained sand can hardly be found (Fig. 6). Hence a relative deep water lake environment with well defined deposition subcycles occurring at low frequency is indicated. Some fine sand aggregates or coarse silt embedded in the silty clay at the bottom suggest a delta environment. In stage 2 (63.2–52.6 m) the mean sediment grain size is 4.6 φ, the clay and fine silt fraction is low (15.2%) but the coarse silt and fine-grained sand are increasing (grain size fraction 100–250 μm up to 30%), whereas crossbedded middle- and coarse-grained sand with some gravels is found at the bottom of this cycle. Hence the environment was mainly river-dominated. Magnetic susceptibility is highest here. In stage 3 (52.6–10.5 m) the mean sediment grain size is getting coarser (5.9 φ) again, the content of fine material (35.5%) is slightly less than that of the stage 1. We interpret this as evidence for a relatively shallow water lake deposition with relative high frequency of deposition subcycles and narrow grain size fluctuation range. Thus we conclude that the sedimentary environment includes two

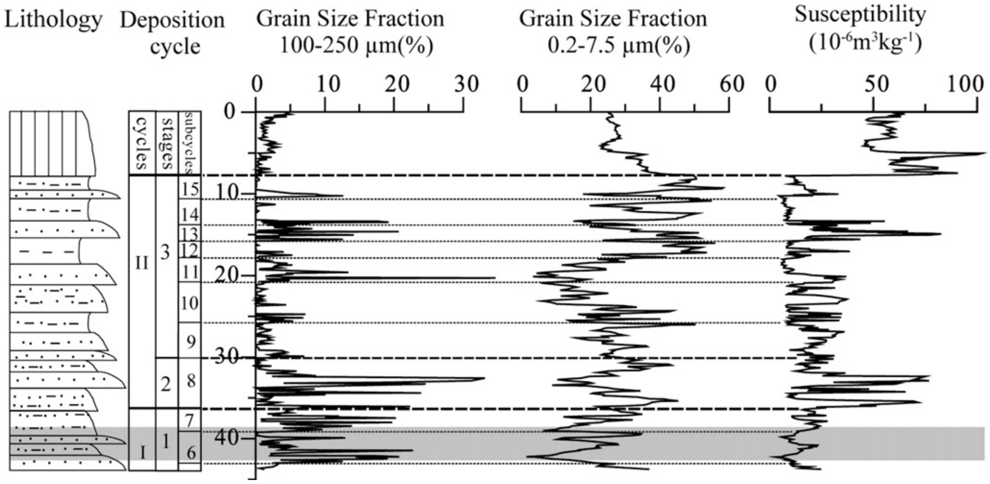

Figure 8. Lithology, interpreted deposition cycles, magnetic low field susceptibility and two grain size fractions (clay, sand) versus depth at Donggutuo. Human artifact layer gray horizon. Lithological symbols as in Figure 4.

long deposition cycles, Cycle I (122.3m–63.2 m) and Cycle II (63.2–10.5 m), which reflected the basin changed from lake to river then back to lake deposition. High frequency sub-cycles (numbered from 1 to 15 in Fig. 6) could be clearly identified in each cycle by the descending variations of magnetic susceptibility and grain size.

Similar sedimentary stages and cycles could also be recognized in the sections at Xiaochangling and Donggutuo (XCL: cycle I 63.2–43.0 m, cycle II 43.0–9.0 m; DGT: cycle I 43.7–36.2 m, cycle II 36.2–7.9 m) as shown in Figures 7 and 8.

The three sections, XDK, XCL and DGT, have different positions in the basin. XDK lies in centre of the lake basin, whereas XCL and DGT are located towards the eastern margin of paleolake Nihewan. The sedimentary facies vary largely in horizontal direction for the same deposition period. Because of the changing lake water depth, overall sediment and stratigraphic horizon thicknesses differ strongly in our sections. However, the boundaries of the sedimentary subcycles which are controlled by the rise or fall of the lake-level, should be isochronous. Moreover, the Jaramillo subchron was recorded in the fluviatile stage, the lower part of cycle II (with variable thickness between 3 and 8 m) in the middle of the three sections. This marker layer forming the boundary between cycle I and cycle II documents a prominent environmental shift. It corresponds to distinct tectonic movement in the basin and should exist within the whole range of the lake.

Assuming that the boundaries of each sedimentation cycle and of the high-frequency subcycles are isochronous and selecting the fluvial facies which contains the Jaramillo subchron at Xiaodukou and at Donggutuo, as a marker horizon, the three investigated sections can be correlated stratigraphically. We conclude that deposition at Xiaochangling began with sub-cycle 4, and at Donggutuo with sub-cycle 5.

Comparison with the oxygen isotope stages (OIS)

Vittori and Ventura (1995) pointed out that the clay fraction curve in Late Quaternary Po River valley sediments has a good similarity with the marine oxygen isotope stages. The high clay content peaks correspond to odd oxygen isotope stages, and the lows to even stages. The sediments were enriched in clay and silt in warm periods, whereas coarse-grained fractions predominate in cold periods. Vittori and Ventura suggested, that climate control on the grain size of sediments might be more obvious in lacustrine environments. The deposition environment at Xiaodukou is mainly controlled by lake level change, as reflected by the grain size distribution. Meanwhile, rising or falling lake level should correspond to climatic change if tectogenesis is absent. The lake level will be rising and result in sediment fining when the climate is warm and moist, and vice versa. The fine-grained sediments (0.2–7.5 μm fraction) transported in suspension are sensitive to changing hydrodynamic conditions. The depth-dependent curves of this fraction reflect the fluctuation of the lake level controlled by climate. With the magnetic polarity reversals set as age control points, the 0.2–7.5 μm fraction curves correlate well with the marine oxygen isotope index corrected by Berger et al. (1994), applying Milankovitch theory (Fig. 9). The concentration peaks of this fraction correspond to odd oxygen isotope stages, and the lows to even ones.

Malan loess caps the three sections of the Nihewan formation. Susceptibility and grain size of the Nihewan Malan Loess suggest the presence of paleosol layer S1 at the bottom of the loess at Xiaodukou (11 m depth). Since paleosol S1 formed at the time of OIS 5 about 130 kyr ago (Yang et al., 2003) , there is a deposition gap of about 250 kyr between the beginning loess deposition and the end of Nihewan lake sedimentation some 400 kyr ago.

Age determination of the stone artifact layer

In the lower parts of the Donggutuo and Xiaochangling sections, located near the margin of the ancient Nihewan lake, a stone artifact layer has been found (Wei, 1985; Tang et al., 1995; Hou et al., 1999). The Donggutuo cultural site was found and excavated by Wei and others in 1981. A magnetostratigraphic investigation of Donggutuo section was completed by Li and Wang in 1982 using an astatic magnetometer and AF demagnetization equipment. The result indicated that the Jaramillo subchron onset was located about 5 m above the bottom of the Donggutuo section. The stone artifact was buried in the layer about 2 m above the bottom of the section. Using the geomagnetic polarity time scale of Mankinen and Dalrymple (1989), the age of the stone artifact layer was estimated to be 1.00 Ma (Li and Wang, 1982). According to the joint Sino-American excavation of the stone artifact site at Donggutuo in 1991 and 1992 and the excavation in 1997 (Schick et al., 1991; Hou et al., 1999), the cultural site can be divided into five layers A, B, C, D and E at depths of 43–38.7 m. Stone artifacts have been found not only in layer E directly contacting to basement, but also in the higher layers D, C and at the base of layers B, A. The thickness of the sediment bearing the stone artifacts is 4.3 m (Hou et al., 1999).

In this paper, the Matuyama/Brunhes boundary located at a profile depth of 15.0 m and the Jaramillo subchron between 32.0 and 36.1 m (Fig. 5). We interpret the normal polarity zone near the bottom of the section to represent the Cobb Mt. event and have observed that the artifact layers occur around this event. Using the age data of these subchrons given by Channell et al. (2002), we have calculated the age of the artifact layers to range from 1204 ka to 1119 ka. Since the artifact layers lie in OIS stages 36 and 35 by correlating to sub-cycles at Xiaodukou, we can deduce an age of ~1.21 to ~1.15 Ma there. These results confirm the earlier contention that the Donggutuo Paleolithic site has an age of about 1.1 to 1.2 Ma (Li and Wang, 1982; Wang et al., 2005). They further show that the ancient culture experienced a period when the climate changed from cold to warm.

A cultural site was discovered by You et al. in the lower part of the Xiaochangling section in 1978 (about 55.4 m from the top, see Fig. 7). Tang et al. (1995) estimated the stone artifact age at 1.78 to 1.67 Ma based on the investigation of vertebrate fossils and preliminary paleomagnetic results. Recently, Zhu et al. (2001) published a paper in which the age of the Xiaochangliang artifact layer was 1.36 Ma as derived from a comparison of paleomagnetic results obtained from the sections at Xiaochangliang and Donggou.

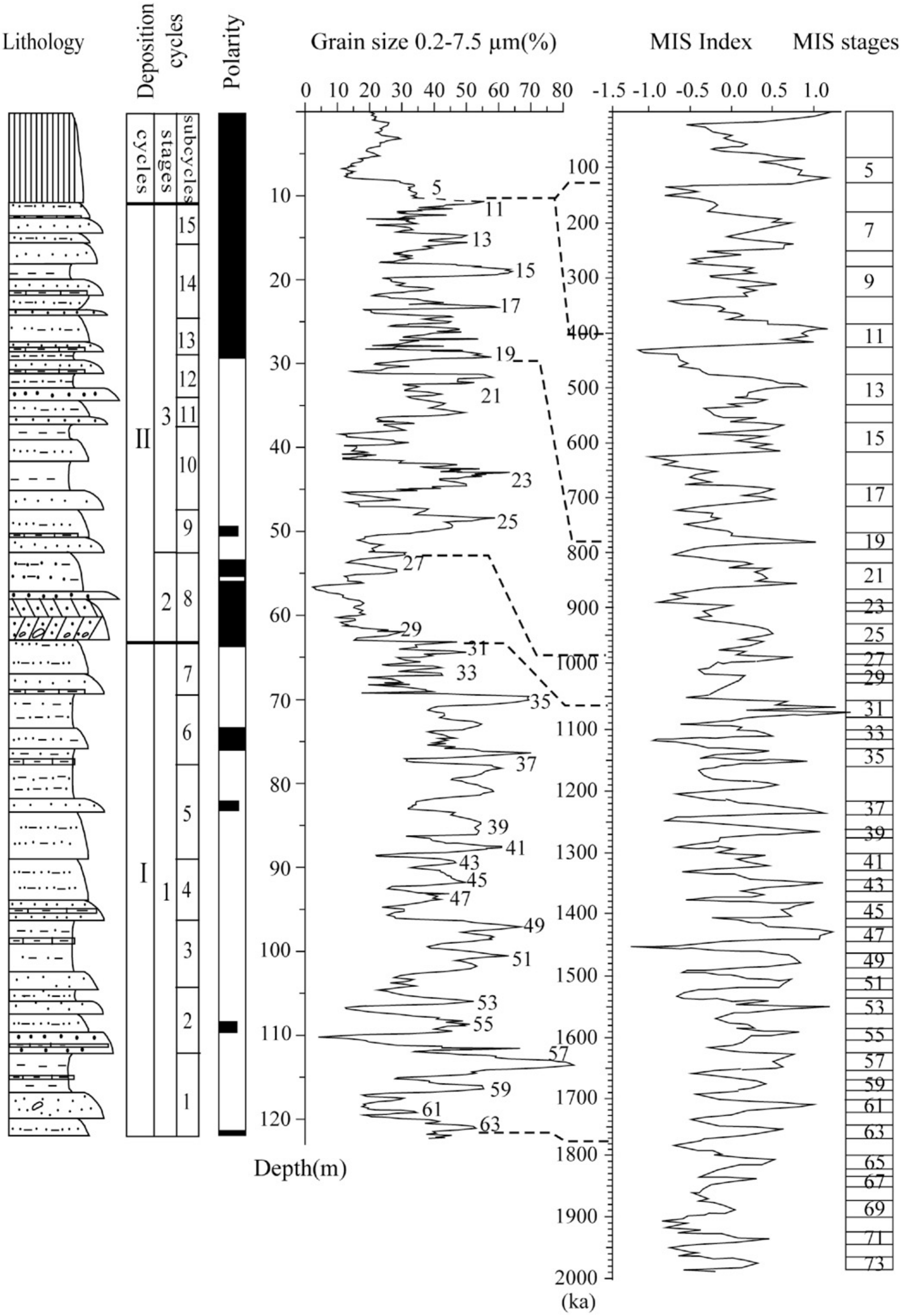

Figure 9. Lithology, deposition cycles, magnetic polarity pattern and 0.2–7.5 mm grain size fraction at Xiaodukou compared with the marine isotope stage template of Berger et al. (1994). Magnetic polarity interpretation and ages see Figure 4.

The sediment thickness between the M/B boundary and the termination of the Jaramillo subchron is 26.5 m in the Donggou section (Table 1), resulting in an average accumulation rate of 12.74 cm/ka; the sediment thickness from the onset of the Jaramillo subchron to the termination of the Olduvai is 32.3 m, with an average accumulation rate of 4.55 cm/ka (Zhu et al., 2001). The deposition rate from the M/B boundary to the termination of Jaramillo subchron is 2.8 times that from the onset of the Jaramillo to the termination of Olduvai subchrons. The big change – about double our values – in deposition rate is rather questionable when considering the basically continuous deposition of fine-grained material unless some major deposition

Table 1
Location of some polarity events and deposition rates (R1 upper, R2 lower part of Nihewan Formation)

Section	Thickness (m)	M/B (m)	Jaramillo (m)	Olduvai (m)	R1 (cm/ka)	R2 (cm/ka)	R1/R2	Reference
Xiaodukou	122.3	29	53.9–62.9	122	12.02	8.32	1.44	This paper
Tai’ergou	129.3	33.6	50.6–74	114.6–128.8	8.17	5.72	1.43	Wang et al. (2004)
Xiaoshuigou	140	30	49–52	104–140	9.14	7.32	1.25	Cheng (1999)
Donggou	90	18.7	45.2–48.8	81.1	12.74	4.55	2.8	Zhu et al. (2001)
Majuangou	95.6		17.2–22.0	85.0	–	8.87	–	Zhu et al. (2004)
Xiaochangliang	73	21	46.6–49.4	–	12.31	ca. 9.19	–	Zhu et al. (2001)
Xiaochangliang	76	23	48–53	–	12.02	ca. 8.97	–	Cheng (1999)
Dongguto	43.7	17	32–36.1	–	7.21	–	–	This paper

breaks are invoked or magnetostratigraphic results have been misinterpreted. Moreover, the average deposition rate of another section at Majuangou, which lies 1 km to the northwest of the Donggou section, is 8.87 cm/ka between the onset of the Jaramillo and the termination of the Olduvai subchrons (Zhu et al., 2004). Therefore, the 1.36 Ma age of the Xiaochangliang artifact layer, which was assigned by Zhu et al. (2001) to the sediments 13.4 m below the Jaramillo subchron onset at Xiaochangliang and calculated using the average deposition rate of 4.6 cm/ka of the Donggou section because of apparently similar lithological development in both sections, could well be overestimated.

We try to estimate the age of the Xiaochangliang artifact layer in three ways: (1) the deposition cycle analysis and comparison of the sections Xiaodukou, Dongguto and Xiaochangliang (Figs. 6–9) show that the artifact layers occur at the bottom of the high frequency sub-cycle 6, which is equivalent to OIS 36 at about 1.22 Ma. (2) The Cobb Mountain normal polarity event with an age of 1.215–1.19 Ma is recorded at Xiaodukou in deposition sub-cycle 6. (3) The age of the stone artifact layer at Xiaochangliang can also be estimated by means of the average deposition rate. The Olduvai subchron was recorded in the lower parts of the Tai’ergou (Wang et al., 2004) and Xiaoshuigou sections (Cheng, 1999) which are near our sections. The deposition rates at Tai’ergou and Xiaoshuigou are 8.17 cm/ka and 9.14 cm/ka, respectively from the M/B boundary to the termination of the Jaramillo subchron, and the rates from the onset of the Jaramillo to the termination of the Olduvai subchron are 5.72 cm/ka and 7.32 cm/ka, respectively. The average deposition rate of the upper lacustrine sediments (termination of Jaramillo subchron to M/B boundary, stage 3) is bigger than that of the lower lacustrine sediments (termination of Olduvai subchron to onset of Jaramillo subchron, stage 1) in both sections, and their ratios are 1.43 and 1.25, respectively (average = 1.34). Although thickness and deposition rate at Xiaodukou near the centre of the Nihewan basin are bigger than those at Tai’ergou and Xiaoshuigou, the deposition rate ratio of the upper lacustrine sediments to that of the lower ones is consistent (stage 3/stage 1 = 1.44). We emphasize that this ratio at Xiaochangliang should be similar to that at Tai’ergou and Xiaoshuigou. The deposition rate from the M/B boundary to the termination of the Jaramillo subchron is 12.31 cm/ka (Zhu et al., 2001) or 12.02 cm/ka (Cheng, 1999) at Xiaochangliang. Using the average deposition ratio of 1.34 from Tai’ergou and Xiaoshuigou, a synthetic deposition rate from the onset of the Jaramillo subchron to the bottom of the Xiaochangliang section has been calculated as 9.19 or 8.97 cm/ka, respectively. Hence, the corresponding age of the Xiaochangliang stone artifact layers which occur 17.6 m (Zhu et al., 2001) or 11 m (Cheng, 1999) below the onset of the Jaramillo subchron, has been estimated at about 1.27 Ma or 1.20 Ma, respectively.

The artifact layers at Xiaochangliang and Dongguto have accumulated at nearly the same time (the relative position of artifact layer in sub-cycle 6 at Xiaochangliang is below that at Dongguto). Based on the ages of magnetic polarity events, the correlation of sediment cycles and the average deposition rates we have assigned their ages at ~1.26 Ma and ~1.21 Ma, respectively (see also Li and Yang, 2003). The artifact layers at Dongguto appear to span a slightly longer time interval than those at Xiaochangliang. They could have lasted until about 1.15 Ma.

The newly discovered cultural sites at Cenjiawan and Feiliang in the Nihewan basin have been assigned ages of ~1.1 Ma and ~1.2 Ma, respectively (Wang et al., 2006; Deng et al., 2007). These sites show that “Nihewan hominids” flourished during the period 1.26–1.1 Ma in the basin. Magnetostratigraphic results from the Gongwangling loess section near Lantian, Shanxi Province (An and Ho, 1989) showed that the Lantian man fossils occurred in the lower silty loess layer (L15) with an age of ~1.22 Ma on the time scale of Heslop et al. (2000). Zheng et al. (1992) identified the Cobb Mountain polarity event in the lower silty loess layer (L15) of the section Duanjiapo. Since the Lantian hominid fossils have been found in the middle of the layer L15, they can be ascribed an age of 1.22 Ma. The age of the cultural site Xihoudu in the Sanmenxia basin is about 1.27 Ma according to magnetostratigraphic investigations by Zhu et al. (2003).

The cultural sites which were discovered at Dongguto, Xiaochangliang, Xihoudu and Gongwangling, existed over a stratigraphical thickness of several meters to more than ten m below the onset of the Jaramillo subchron at 1.068 Ma. Variations in depositional facies and sedimentation rates should not be neglected completely at these localities, small measurement errors of sediment thickness cannot be excluded and even magnetic polarity zonation differs slightly from place to place. We are, however, in a position to conclude, that the four detected cultural sites were active between 1.27 Ma and 1.15 Ma.

Conclusions

The ferromagnetic minerals of the sediments of the three sections Xiaodukou, Xiaochangliang Dongguto in the

Nihewan Basin are mainly dominated by magnetite, with minor contributions from maghemite, hematite and iron sulphides in some samples. Low field susceptibility correlates with the sand fraction of the sediments and suggests major sedimentation control by lake-level rise and fall.

The sediments at Xiaodukou offer one of the most complete magnetostratigraphies in the Nihewan Basin beginning with the termination of the Olduvai subchron. The Matuyama/Brunhes boundary has been observed in the upper lacustrine sediments (29 m from the top, sedimentation stage 3), the Jaramillo subchron in the fluvial deposits of the middle section (53.9–62.9 m from the top, stage 2), the Cobb Mt. event together with other short excursions also are documented during the Matuyama chron. Sedimentation stopped some 400 ka ago. The Donggutuo section has been deposited since the Cobb Mt. event. The M/B boundary is found in the upper lacustrine sediments (15.0 m from the top, stage 3), and the Jaramillo subchron again in the fluvial deposits of the middle section (32.0–36.1 m from the top, stage 2).

Based on susceptibility and grain size analysis, up to 15 deposition sub-cycles have been identified in the sections. Each sub-cycle is made up of a lacustrine transgression and regression system, which implies fluctuating lake levels. The sub-cycles 1–3 are absent in the Xiaochangliang section and sub-cycles 1–4 are missing in the Donggutuo section documenting paleolake expansion to these sites at a later stage. The fluvial sediments separating the lower and upper lacustrine sediments in the three sections (sedimentation stage 2) serve as a marker layer and indicate that lacustrine basin evolution consisted of two major cycles.

The sedimentary sub-cycles of the clay fraction (grain size 0.2–7.5 μm) of the lacustrine sediments are controlled by climate changes and can be correlated with OIS 64 to 11. The human artifact layers of the Xiaochangliang and Donggutuo sections have been uncovered in the sedimentary sub-cycle 6 dated around the Cobb Mt. event, and are related to OIS 36–35, with ages of ~1.22 Ma and ~1.21–1.15 Ma, respectively. The age estimates of the stone artifact layers based on the deposition rate, give evidence of an age of ≤ 1.26 Ma at Xiaochangliang and from 1.204 to 1.119 Ma at Donggutuo, respectively. The stone artifact layers seem to represent a restricted time period, whereby the age of stone artifact layer at Xiaochangliang seems to be slightly older than that at Donggutuo, but the former are not exceeding 1.26 Ma. The Palaeolithic cultural sites which have been found in different geographical locations at Donggutuo (~1.21–1.15 Ma), Xiaochangliang (≤1.26 Ma), Cenjiawan (~1.1 Ma), Feiliang (~1.2 Ma) in the Nihewan basin and Xihoudu (~1.27 Ma), and Lantian (~1.22 Ma), were active between 1.27 Ma and 1.1 Ma ago and emphasize a significant and vivid occupation of Northern China by early man.

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