Quaternary International 400 (2016) 202–211

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Magnetostratigraphic dating of the Shanshenmiaozui mammalian fauna in the Nihewan Basin, North China

Ping Liu [a, b, *], Zhijun Wu [c], Chenglong Deng [d, *], Haowen Tong [e], Huafeng Qin [d], Shihu Li [d], Baoyin Yuan [d], Rixiang Zhu [d]

[a] Key Laboratory of Computational Geodynamics, Chinese Academy of Sciences, Beijing, 100049, China
[b] University of Chinese Academy of Sciences, Beijing, 100049, China
[c] Nihewan National Reserve, Zhangjiakou, 075000, Hebei Province, China
[d] State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, 100029, China
[e] Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing, 100044, China

A R T I C L E I N F O

Article history:
Available online 6 November 2014

Keywords:
Nihewan Basin
Nihewan formation
Nihewan faunas
Magnetostratigraphy
Shanshenmiaozui mammalian fauna

A B S T R A C T

Timing of the mammalian faunas in the Nihewan Basin, North China has provided insights into our understanding of Quaternary biochronology and biostratigraphy in East Asia. Here we contribute to this topic with detailed magnetostratigraphic investigation, coupled with mineral magnetic measurements on a fluvio-lacustrine sequence in this basin, which contains the Shanshenmiaozui mammalian fauna. Magnetite and hematite were identified as the main carriers for the characteristic remanent magnetizations. Magnetostratigraphic results show that the Shanshenmiaozui sedimentary sequence recorded the Brunhes chron, the Jaramillo subchron, and the late Matuyama chron. Stratigraphic correlation in terms of lithology, magnetic susceptibility and magnetic polarity sequences between the Shanshenmiaozui, Xiaochangliang and Dachangliang sections indicates that the Shanshenmiaozui mammalian fossil layer is younger than the Xiaochangliang and Dachangliang artefact layers, which have been previously estimated to be about 1.36 Ma. The age of the Shanshenmiaozui mammalian fossil layer at the bottom of the section is estimated to be about 1.2 Ma. The new magnetostratigraphy of the Shanshenmiaozui section provides useful constraints on lithostratigraphic and biostratigraphic correlations in the Nihewan Basin.

1. Introduction

The Nihewan Basin lies approximately 150 km west to Beijing, and is located in the transition zone between the North China Plain and the Inner Mongolian Plateau (Fig. 1). The basin is a downfaulted basin filled with Pliocene to Holocene lacustrine, fluvial and wind-blown deposits (Wei, 1985; Chen, 1988; Zhou et al., 1991; Zhu et al., 2007; Deng et al., 2008). The fluvio-lacustrine sedimentary sequences have been named the Nihewan Beds (Barbour, 1924). Numerous Paleolithic sites and mammalian faunas have been found in the sequences (Zhou et al., 1991; Wei, 1997; Chen, 1988; Zhu et al., 2003, 2007; Xie, 2006; Xie et al., 2006; Deng et al., 2008). Especially, the mammalian fossils preserved in the Nihewan sedimentary sequence, known as the Nihewan faunas (sensu lato). In particular, the mammalian fossils collected near the Nihewan village and reported by Teilhard de Chardin and Piveteau in 1930s comprise the typical early Pleistocene mammalian fauna in North China, known as the Xiashagou Fauna or the Nihewan Fauna (sensu stricto) and traditionally corresponding to the Villafranchian Fauna in Europe (Barbour, 1925; Teilhard de Chardin and Piveteau, 1930; Qiu, 2000). Many efforts have been made to date and correlate the sedimentary sequences in the Nihewan Basin through magnetostratigraphical, paleontological, sedimentological, rock magnetic, geochemical, and palynological investigations, which have contributed significantly to our understanding of chronological framework of the complex stratigraphy and depositional systems in the basin (Barbour, 1924; Teilhard de Chardin and Piveteau, 1930; Li and Wang, 1982; Yuan et al., 1996; Wei, 1997; Qiu, 2000; Lovlie et al., 2001; Zhu et al., 2001, 2003, 2004, 2007; Wang et al., 2004, 2005, 2008; Deng et al., 2006a, 2007, 2008; Li et al., 2008; Liu

* Corresponding authors. Key Laboratory of Computational Geodynamics, Chinese Academy of Sciences, Beijing, 100049, China.
E-mail addresses: liuping@mail.iggcas.ac.cn (P. Liu), cldeng@mail.iggcas.ac.cn (C. Deng).

http://dx.doi.org/10.1016/j.quaint.2014.09.024
1040-6182/

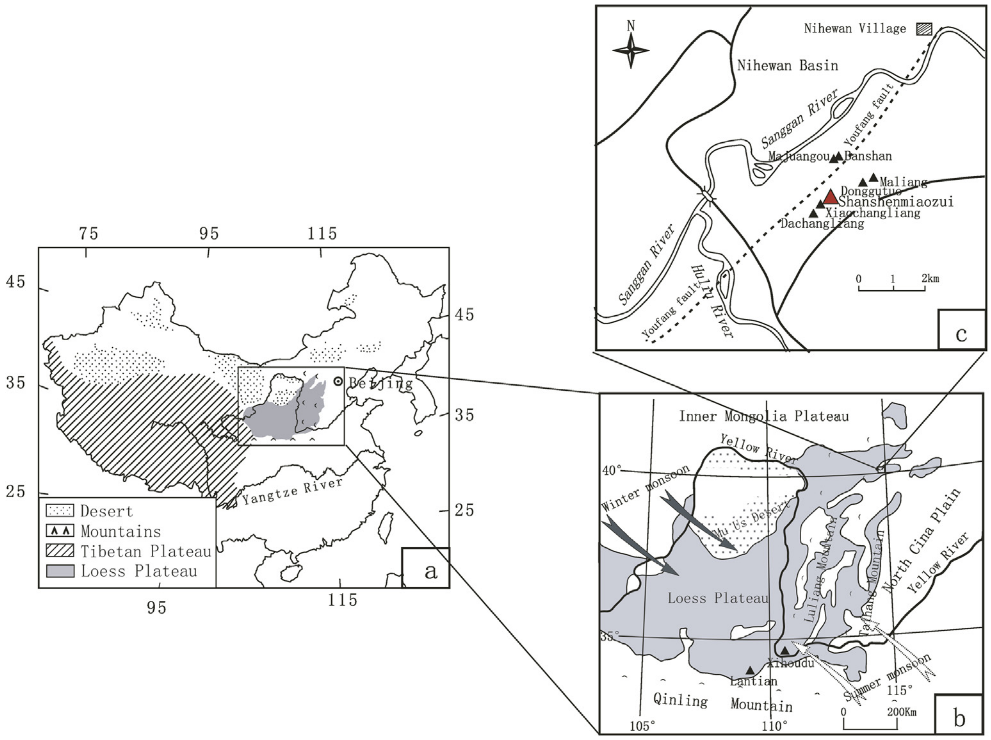

Fig. 1. Schematic map showing the Loess Plateau, the Nihewan Basin, the Shanshenmiaozui mammalian fossil site (red triangle) and other mammalian fossil sites (black triangles) mentioned in this paper (modified from Guo et al.(2002), Deng et al. (2006a), Liu et al. (2010)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2010, 2012; Ao et al., 2013a,b). However, detailed magnetostratigraphic investigations on some newly found and excavated mammalian fossil sites remain requisite.

The Shanshenmiaozui mammalian fossil site bears the richest and best preserved fauna recovered in the Nihewan Basin during the past decades (Tong et al., 2011, 2012). It is very useful to understand the chronology of the Nihewan faunas (sensu lato) and the evolution of some important taxa. In this study, we carried out a detailed magnetostratigraphic investigation coupled with rock magnetic data on the Shanshenmiaozui section. The results of our study contribute to a better understanding of stratigraphic correlation and chronologic sequence of the mammalian faunas in the Nihewan Basin.

2. Geological setting and sampling

The Shanshenmiaozui mammalian fossil site (40°13′3.1″N, 114°39′51.5″E) in the eastern margin of the Nihewan Basin lies about 200 m southeast of the well-known Xiaochangliang Paleolithic site. Here, the sediments have a thickness of 62.8 m, capped by late Quaternary loess sediments and underlain by Jurassic volcanic breccia. The fluvio-lacustrine sequence in the Shanshenmiaozui section contains mainly grayish-yellow and grayish-green silty clays, silts, and sandy silts. The Shanshenmiaozui mammalian fossils are found near the bottom of the section.

The Shanshenmiaozui mammalian fossil site was discovered by Geoffrey Pope and Susan Keates and excavated in 1994 by Qi Wei (Wei et al., 2011), who discovered some mammalian fossils and stone artifacts and offered some important clues of big mammalian fossils. Haowen Tong (Tong et al., 2011) formally excavated the site during the years 2006–2008, resulting in the discovery of abundant mammalian fossils. A list of the mammalian faunas are presented in Table 1.

Table 1
Comparison of the fossil list of the Shanshenmiaozui and Xiaochangliang faunas in the Nihewan Basin. SSMZ, Shanshenmiaozui; XCL, Xiaochangliang.

SSMZ (Tong et al., 2011; Wei et al., 2011)	XCL (You et al., 1980; Tang et al., 1995)
Leporidae gen. et sp. indet.	*Allophaiomys* cf. *A. pliocaenicus*
Ochotona sp.	*Mimomys chinensis*
Canis chihliensis sp.	*Pachycrocuta licenti*
Ursus sp.	*Martes* sp.
Pachycrocuta sp.	*Palaeoloxodon* sp.
Felidae gen. et sp. indet.	*Hipparion* sp.
Mammuthus trogontherii	*Proboscidipparion sinensis*
Proboscidipparion sp.	*Equus sanmeniensis*
Equus sanmeniensis	*Coelodonta antiquitatis*
Coelodonta nihowanensis	*Cervus* sp.
Elasmotherium sp.	*Gazella* sp.
Sus sp.	Bovinae indet.
Cervus sp.	
Eucladoceros sp.	
Spirocerus sp.	
Gazella sinensis	
Bovinae gen. et sp. indet.	

Total 290 block samples oriented by magnetic compass in the field were collected at 20-cm intervals. Cubic specimens of 20 mm × 20 mm × 20 mm were obtained from those block samples in the laboratory for rock-magnetic and magnetostratigraphic studies.

3. Methods

To check the reliability of the sediments, anisotropy of magnetic susceptibility (AMS) measurements were performed using a KLY-4s Kappabridge (Agico Ltd., Brno) before any thermal demagnetization was conducted. In order to monitor changes in magnetic mineral

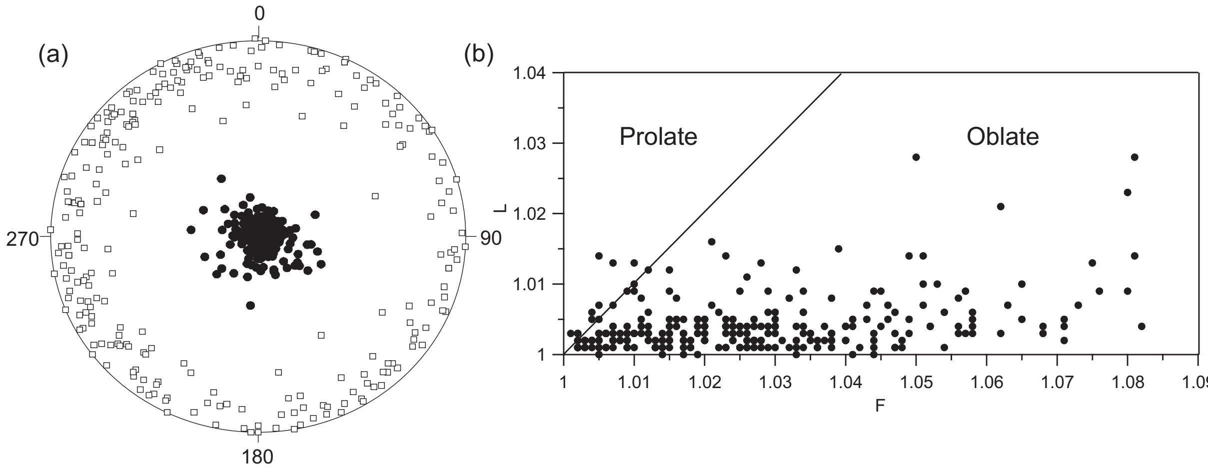

Fig. 2. Anisotropy of magnetic susceptibility (AMS) characteristics of specimens from the Shanshenmiaozui section. (a) Projection of axes of K_{max} (open squares) and K_{min} (solid circles). (b) Magnetic lineation (*L*) versus magnetic foliation (*F*).

composition during heating treatment (Roberts et al., 1995; Deng et al., 2001), high-temperature magnetic susceptibilities ($\chi-T$ curves) were measured on selected samples using MFK1-FA at a frequency of 976 Hz with CS-3 high-temperature furnace (Agico Ltd., Brno). Hysteresis loops and isothermal remanent magnetization (IRM) acquisition and its back-field demagnetization characteristics were measured at room temperature using MicroMag 3900 Vibrating Sample Magnetometer (Princeton Measurements Corp., USA).

Remanence measurements were made using 2G Enterprises Model 760-R cryogenic magnetometer installed in a magnetically shielded space (<300 nT). To confirm the paleomagnetic results, two sets of parallel specimens were measured on the Shanshenmiaozui samples. Firstly, all the 290 specimens were subjected to progressive thermal demagnetization of 13–21 steps up to a maximum temperature of 680 °C with 25–50 °C interval below 585 °C and 10–15 °C above 585 °C using a magnetic measurements thermal demagnetizer (PGL100) with a residual magnetic field less than 10 nT. Then, the second set of 87 parallel specimens, which did not give reliable characteristic remanent magnetization (ChRM) directions by thermal demagnetization in the first set specimens, were subjected to 80 °C and 150 °C thermal demagnetization

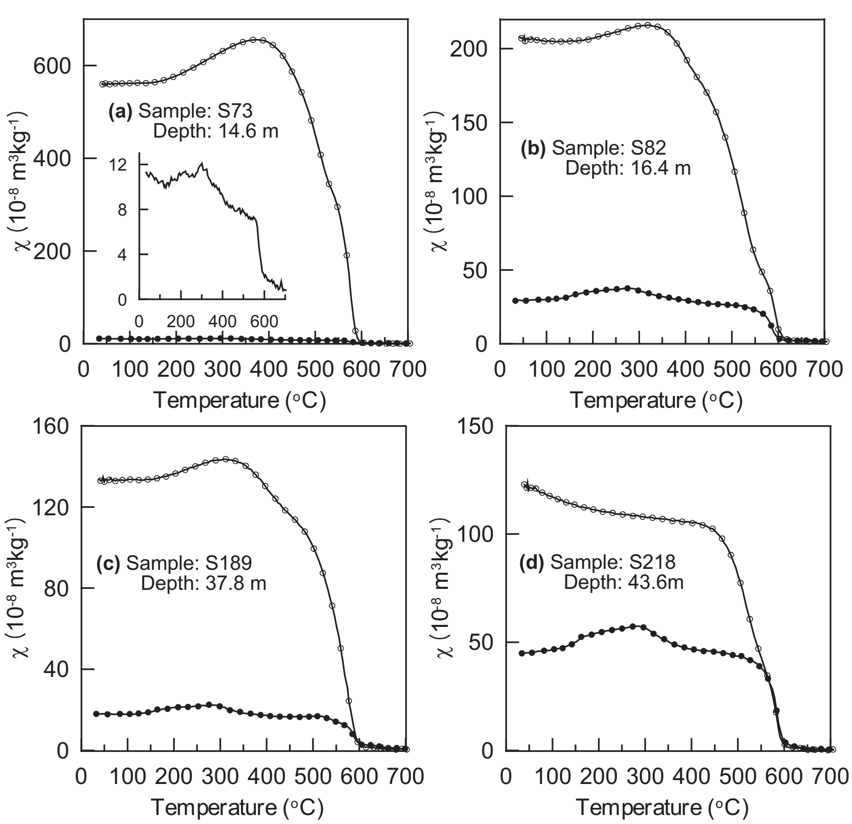

Fig. 3. High-temperature magnetic susceptibility (χ-*T*) of selected specimens of the Shanshenmiaozui section. The solid/open circles represent heating/cooling curves.

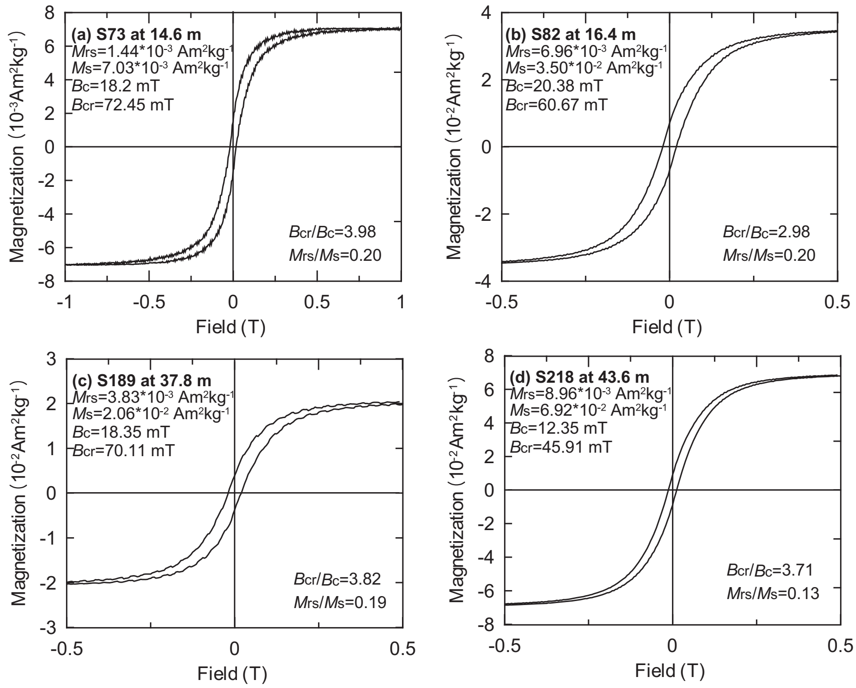

Fig. 4. Hysteresis loops of representative specimens of the Shanshenmiaozui section after slope correction for paramagnetic contribution. The hysteresis loops were measured in fields up to ±1.0 T. Mrs, Ms, Bc and Bcr indicate saturation remanent magnetization, saturation magnetization, coercivity and remanent coercivity, respectively.

followed by alternating field (AF) demagnetization at peak fields up to 60 mT and then settling with the same thermal demagnetization steps above. Both methods were capable of isolating the ChRMs after removal of soft secondary component of magnetization.

The demagnetization results of the selected specimens were evaluated by orthogonal diagrams (Zijderveld, 1967) and magnetic components isolated using principal component analysis (PCA) (Kirschvink, 1980) with the PaleoMag software (v.3.1.0 d40) developed by Craig H. Jones and Joya Tetreault (Jones, 2002). The ChRM directions were determined with linear least squares fitting through the origin by using at least four continuous steps of demagnetization and with a maximum angular deviation (MAD) usually smaller than 15°.

4. Results

4.1. AMS

The susceptibility tensor for each specimens was calculated from measurements in 15 positions, by a described method (Jelinek, 1978). In the 290 specimens studied, most of the magnetic foliation (*F*) was found to be larger than the magnetic

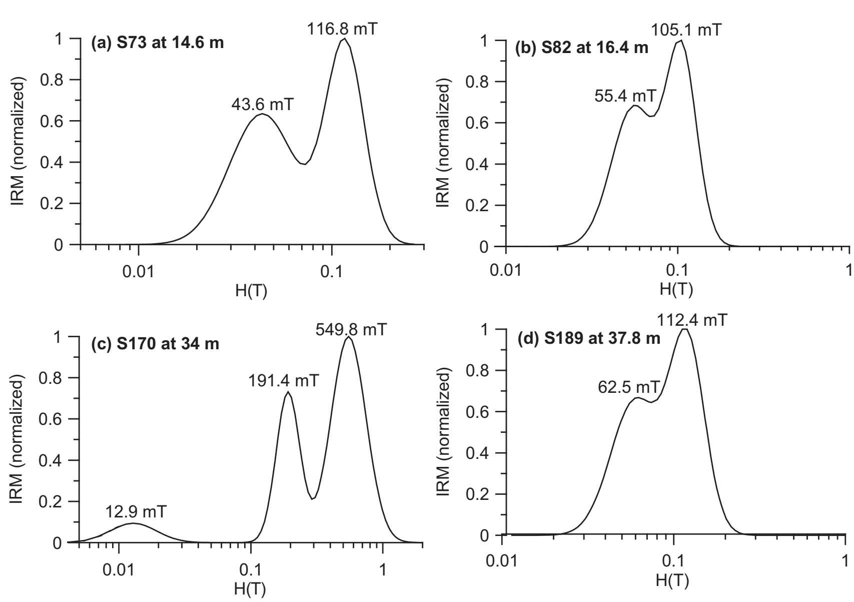

Fig. 5. Coercivity distribution for the selected specimens of the Shanshenmiaozui section, which is calculated using the MAG-MIX package of Egli (2003).

lineation (L) (Fig. 2), which indicates that the AMS ellipsoid is oblate. The minimum susceptibility axes (K_{min}) of the AMS ellipsoid are close to the vertical, perpendicular to the bedding plane, whereas most maximum axes (K_{max}) are close to the horizontal, parallel to the bedding plane. The AMS results are typical for an original sedimentary magnetic fabric, indicating that the Shanshenmiaozui sedimentary sequence we have sampled has not been disturbed since deposition and preserved the original sedimentary status, which imply that the Shanshenmiaozui section is suitable for magnetostratigraphic study (Vlag et al., 1996; Zhu et al., 1998).

4.2. Mineral magnetic measurements

To avoid oxidization during heating, the specimens were heated in an argon atmosphere. A run with an empty furnace tube was performed before measuring the sediment specimens to decrease the background of the empty furnace. All the $\chi-T$ curves of selected specimens show a major decrease in magnetic susceptibility at about 585 °C (Fig. 3), the Curie point of magnetite, suggesting that magnetite is the major contributor to the susceptibility. Some specimens show heating curves with a susceptibility hump near 250–300 °C, which may be ascribed to gradual unblocking of fine-grained (near the superparamagnetic/single-domain boundary) ferrimagnetic particles (Deng et al., 2005). Some specimens show heating curves with a drop of magnetic susceptibility between ~300 °C and ~450 °C, which is interpreted as the conversion of metastable maghemite to weakly magnetic hematite (Stacey and Banerjee, 1974; Deng et al., 2005).

The cooling curves of all samples show a significant increase in magnetic susceptibility after thermal treatment, which is mainly attributed to the neoformation of magnetite grains from the transformation of iron-containing silicates/clays (Deng et al., 2001; Ao et al., 2009) or to the neoformation of magnetite by reduction due to the burning of organic matter (Deng et al., 2005). Hematite, which is another important carrier of the natural remanence in the Nihewan fluvio-lacustrine sediments suggested by the progressive thermal demagnetization analyses (Wang et al., 2004, 2005; Deng

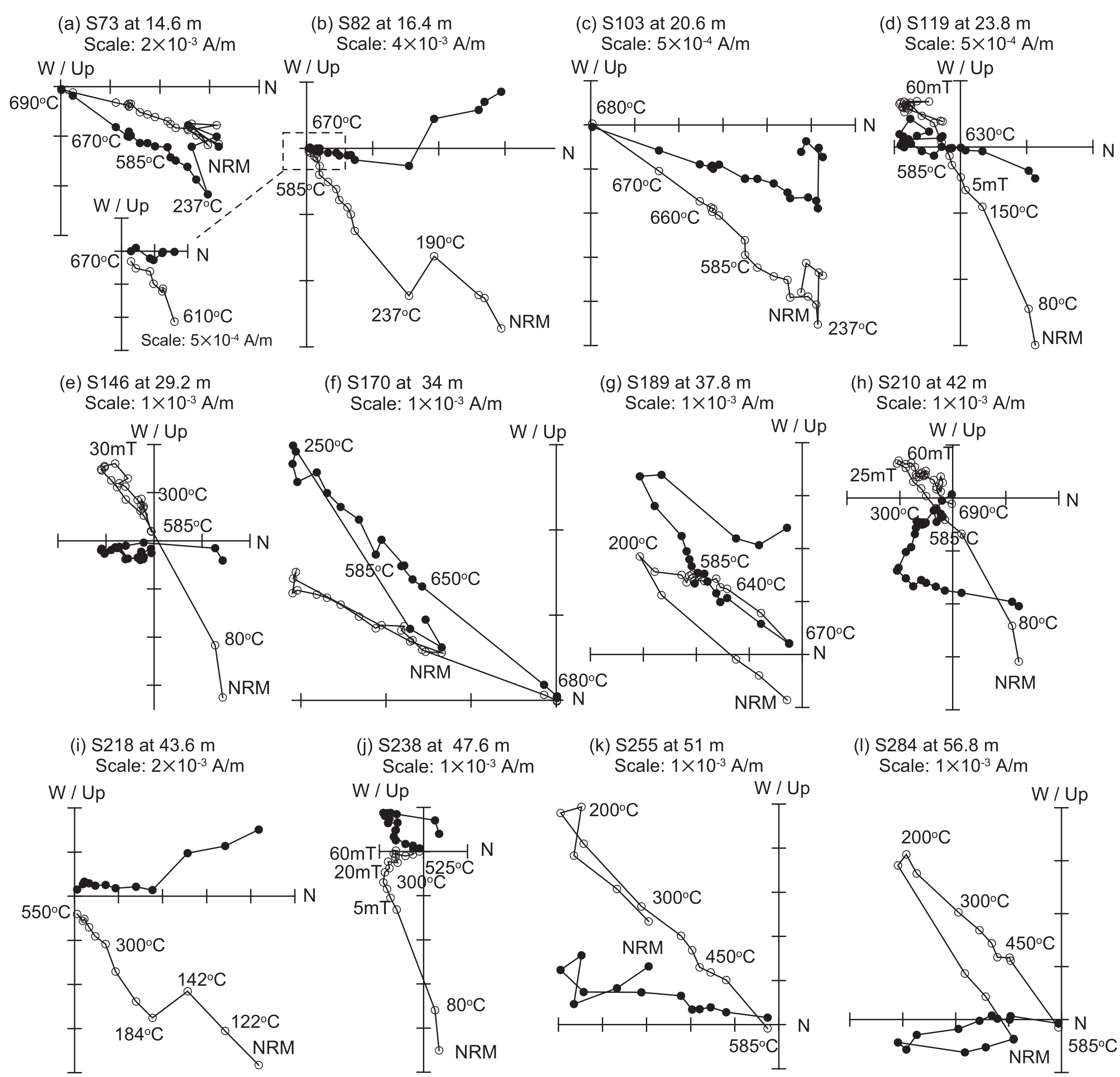

Fig. 6. Orthogonal vector projections of representative progressive thermal demagnetization of the selected specimens from the Shanshenmiaozui section. Solid (open) circles represent the horizontal (vertical) planes. The numbers refer to temperatures in °C or alternating fields in mT. NRM is the natural remanent magnetization.

et al., 2006a, 2008; Liu et al., 2010, 2012; and this study), is not well expressed in the $\chi-T$ curves because its weaker susceptibility is masked by the much stronger contributions of magnetite and maghemite (Deng et al., 2001, 2006b).

The magnetic field was induced the highest 1.0 T for each specimens. Saturation magnetization (M_s), saturation remanent magnetization (M_{rs}), and coercivity (B_c) were determined after the correction for the paramagnetic contribution identified from the slope at high fields. As for the selected specimens, two of them show the hysteresis loops closed about 300 mT (Fig. 4 b, d), which is consistent with the presence of a dominant ferrimagnetic phase; and two show the hysteresis loops closed above 500 mT (Fig. 4 a, c), indicating the presence of high-coercivity components. The hysteresis ratios (M_{rs}/M_s vs. B_{cr}/B_c) (Day et al., 1977) indicate that the average magnetic grain size falls in the pseudo-single domain range.

The methods of unmixing (Robertson and France, 1994; Kruiver et al., 2001; Egli, 2003) were further used to analyze the magnetic compositions. IRM acquisition curves of selected specimens were analyzed using MAG-MIX package of Egli (2003). The derivative curves were plotted to illustrate the coercivity distribution (Fig. 5). The specimens give a two-humped distribution except for specimen S170. The first component has coercivities at 10–60 mT, while coercivities of the second component vary from 100 to 200 mT except for S170 with the highest coercivity of 550 mT. The fist and second components of lower coercivity with the evidence coming from the $\chi-T$ curves are assigned to magnetite (Fig. 5 a, b, d), and the component of specimen S170 with higher coercivity indicates the presence of hematite (Fig. 5 c), as demonstrated by the stepwise thermal demagnetization (Fig. 6).

Those behaviors detailed above suggest that both magnetite and hematite dominate the remanence carriers in the Shanshenmiaozui fluvio-lacustrine sediments, which is well consistent with those of other sections in the Nihewan Basin (Zhu et al., 2001, 2003, 2007; Wang et al., 2004, 2005, 2008; Deng et al., 2006a, 2007, 2008; Li et al., 2008; Liu et al., 2010, 2012; Ao et al., 2013a,b).

4.3. Paleomagnetic measurements

The intensity of the natural remanent magnetization (NRM) of the samples was usually of the orders of 10^{-3}–10^{-6} A/m. Representative demagnetization diagrams are shown in Fig. 6. Generally, a secondary magnetic component, probably of viscous origin, was present and was removed by thermal demagnetization at 200–300 °C or by AF demagnetization at 15–20 mT. For some specimens, the high-stability ChRM component was separated up to 550 °C or 585 °C (Fig. 6 i, k, l). However for some specimens the high-stability ChRM component persists up to 680 °C (Fig. 6 a, b, c, f, g) or up to 60 mT and then up to 525 °C–690 °C (Fig. 6 d, e, h, j). The behaviors document that magnetite and hematite dominate the remanence carriers in the Shanshenmiaozui sediments. As a result, 212 (73%) specimens gave reliable ChRM directions. The virtual geomagnetic pole (VGP) latitudes were calculated from the ChRM vector directions (Fig. 7 e). Those VGP latitudes were subsequently used to define the magnetostratigraphic polarity in the Shanshenmiaozui section (Fig. 7 f).

Four magnetozones are recognized in the Shanshenmiaozui section (Fig. 7): two with normal polarity, N1 (0–22 m) and N2 (42–47 m); and two with reverse polarity, R1 (22–42 m) and R2 (47–62.4 m). The sedimentary layer bearing the Shanshenmiaozui

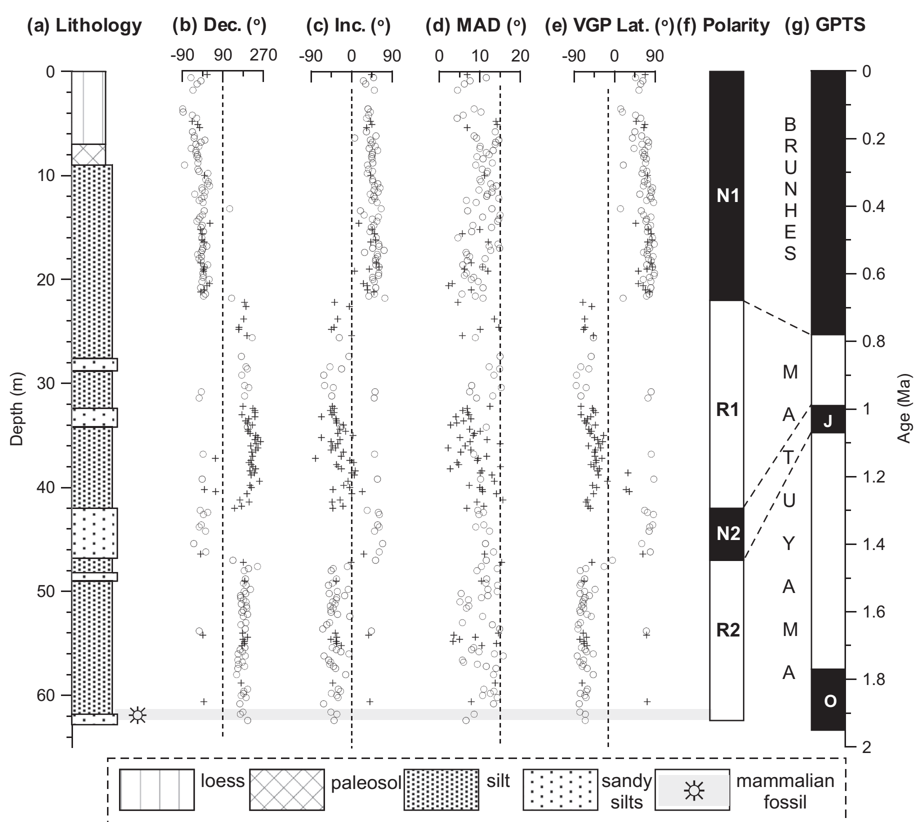

Fig. 7. Lithostratigraphy and magnetostratigraphy of the Shanshenmiaozui section. (a) Lithology. (b) Declination (Dec.). (c) Inclination (Inc.). (d) Maximum angular deviation (MAD). (e) Virtual geomagnetic pole (VGP) latitude. (f) Magnetic polarity zonation. (g) Geomagnetic polarity timescale (GPTS) (Cande and Kent, 1995). Circles and crosses in (b–e) represent the ChRM of magnetite and hematite, respectively; J, Jaramillo; O, Olduvai. N, normal polarity; R, reverse polarity.

mammalian fauna occurs within magnetozone R2 and at the bottom of the section.

5. Discussion

5.1. Biostratigraphy

The Shanshenmiaozui mammalian fossil site was excavated in 1994 by Qi Wei. The new systematic excavation by Haowen Tong during the past few years resulted in the discovery of abundant mammalian fossils. The fauna consists of the following taxa: Leporidae gen. et sp. indet., *Ochotona* sp., *Canis chihliensis* sp., *Ursus* sp., *Pachycrocuta* sp., Felidad gen. et sp. indet., *Mammuthus trogontherii*, *Proboscidipparion* sp., *Equus sanmeniensis*, *Coelodonta antiquitatis nihowanensis*, *Elasmotherium* sp., *Sus* sp., *Cervus* sp., *Eucladoceros* sp., *Spirocerus* sp., *Gazella sinensis* and Bovinae gen. et sp. indet (Tong et al., 2011; Wei et al., 2011; Tong, 2012). Almost all the aforementioned taxa (12 out of 17) are in the typical elements of the classical Xiashagou Fauna, that is, the Nihewan Fauna (sensu stricto) (Table 1) (Liu et al., 2012), which suggests an early Pleistocene for the Shanshenmiaozui mammalian fauna. These materials are helpful in understanding the evolution of some important taxa. The materials of *M. trogontherii*, *C. antiquitatis nihowanensis*, *Sus* sp. and *Eucladoceros* sp. are better represented and preserved than those ever reported (Tong et al., 2011). Especially, the species of *M. trogontherii* found in the Shanshenmiaozui locality is the richest material in China. The discovered abundant juvenile mandibles and their teeth are important as for the only complete juvenile mandible of an early *Mammuthus* in the world, which will provide some important information for the study of the evolution of *Mammuthus* (Tong, 2012). There are eight taxa found in both Shanshenmiaozui (17 taxa) and Xiaochangliang (12 taxa) faunas (Table 1), suggesting a similar age for the two mammalian faunas.

There is occurrence of landslide mentioned by Haowen Tong (Tong et al., 2011). However, the section we sampled is located at the east cliffy of the Shanshenmiaozui ridge. There is no landslide in our section. Based on the lateral stratigraphic correlation in the field, the fossil-bearing layer at the new locality is slightly younger than that of the famous cultural layers at Xiaochangliang and Dachangliang Paleolithic sites, which have been paleomagnetically dated to be about 1.36 Ma (Zhu et al., 2001; Deng et al., 2006a).

5.2. Stratigraphic correlation in terms of lithology and magnetic susceptibility

The Shanshenmiaozui site is only ~200 m southeast of the Xiaochangliang site (Fig. 1) and ~400 m southeast of the Dachangliang site, which have been well investigated bio-, litho-, and magneto-stratigraphically (Zhou et al., 1991; Tang et al., 1995; Zhu et al., 2001, 2004; Deng et al., 2006a). These three sections can be well correlated based on lithostratigraphic and magnetostratigraphic grounds.

Stratigraphic correlation between the sections at Shanshenmiaozui, Xiaochangliang and Dachangliang has been well

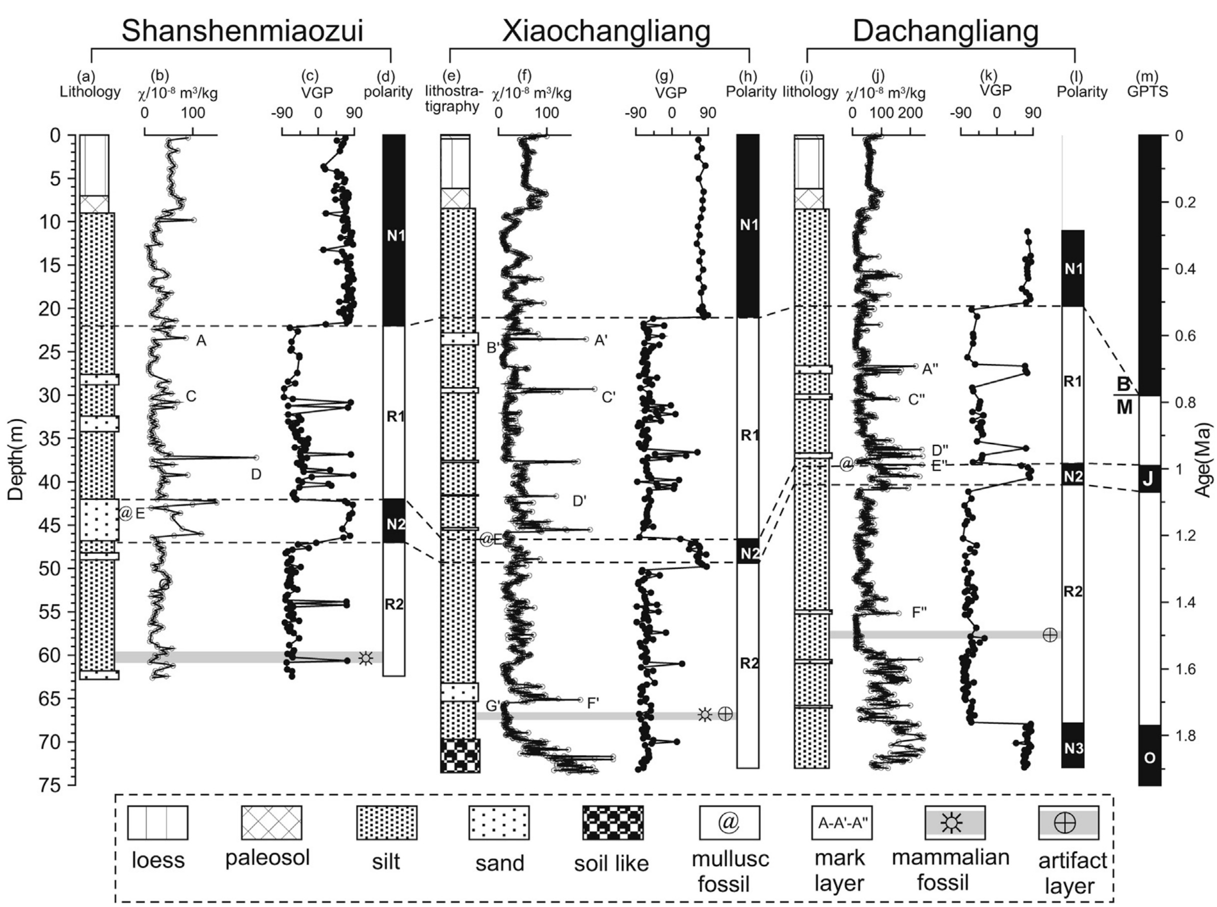

Fig. 8. Lithostratigraphy, magnetic susceptibility profiles, virtual geomagnetic pole (VGP) latitudes, and magnetostratigraphy of the Shanshanmiaozui (a–d), Xiaochangliang (e–h) and Dachangliang (Xiantai) (i–l) sections. Geomagnetic polarity timescale (GPTS) (Cande and Kent, 1995) is showed in panel (m). B, Brunhes; M, Matuyama; J, Jaramillo; O, Olduvai. N, normal polarity; R, reverse polarity. Data of the Xiaochangliang (e–h) and Dachangliang (i–l) sections are after Zhu et al. (2001) and Deng et al. (2006a), respectively.

constrained by field-work, magnetic susceptibility, lithology, and stratigraphic marker layers. The three sections could be found to have almost the same sequence bearing pronounced sedimentological marker layers. As for the magnetic susceptibility, several fine-grained sand layers with high values of magnetic susceptibility (layers A–A′–A″, C–C′–C″, D–D′–D″ in Fig. 8) are found at the same position within the polarity framework of each section. Also the layer containing mollusk fossils (layer E–E′–E″) can be found in the same magnetozone (N2) in the three sections.

5.3. Correlation of the recognized magnetozones to the geomagnetic polarity timescale (GPTS)

Based on the biochronology and stratigraphic correlation constrained by field-work, magnetic susceptibility, lithology, and stratigraphic marker layers among the Shanshenmiaozui, Xiaochangliang and Dachangliang sections, the magnetic polarity sequences of the three sections can be well correlated. The magnetozones obtained with the Shanshenmiaozui section can readily be correlated to the GPTS (Cande and Kent, 1995; Hilgen et al., 2012). The two normal magnetozones N1 and N2 in the Shanshenmiaozui magnetozones respectively correspond to the Brunhes normal chron and the Jaramillo normal subchron (Fig. 7); and the two reverse magnetozones R1 and R2, to successive reverse polarity portions of the late Matuyama reverse chron.

Extrapolating or interpolating in terms of sediment accumulation rates (SARs) is a conventional method during magnetostratigraphic dating when precise absolute ages are unavailable. When using the SAR of during the Jaramillo subchron, the age of the Shanshenmiaozui mammalian fauna can be estimated to be about 1.38 Ma. As for the sediments are sandy silts in the Jaramillo subchron with relatively higher SAR, the estimated age of ~1.38 Ma may be incorrect. However, if we use the SAR between the Matuyama/Brunhes boundary and the lower boundary of the Jaramillo subchron for extrapolation, the age of the fauna can be estimated to be ~1.20 Ma. Continental fluvio-lacustrine sequences, e.g., those in the Nihewan Basin usually have high variability in SARs (Deng et al., 2007, 2008). In order to precisely determine the age of the Shanshenmiaozui mammalian fauna, we further convert magnetic susceptibility vs depth to magnetic susceptibility vs age (Fig. 9 a, b), and then fit the termination of the Jaramillo subchron (1.072 Ma) in the Xiaochangliang and Shanshenmiaozui sections, and finally adjust the bottom age of the mammalian fossil layer from 1.1 Ma to 1.36 Ma. The correlation coefficient of magnetic susceptibility variations obtained from the two sections is the highest when the bottom age of this section is given at 1.19 Ma (Fig. 9 d). If the same age of the Xiaochangliang and Shanshenmiaozui sections is selected, the peak and valley of the magnetic susceptibility with age between the two sections match well (Fig. 9 c). Considering all the above-mentioned evidences together, the age of the Shanshenmiaozui mammalian fauna at the bottom of the section is estimated to be about 1.2 Ma. Thus, the Shanshenmiaozui fauna is slightly younger than the Xiaochangliang and Dachangliang Paleolthic site, which have been paleomagnetically dated to be about 1.36 Ma (Zhu et al., 2001; Deng et al., 2006a).

Most of the well-dated mammalian fossil sites in the eastern Nihewan Basin are younger than the Gauss-Matuyama geomagnetic reversal (2.581 Ma in ATNTS2012). The newly dated Shanshenmiaozui mammalian site lies to the south of the Sangganhe River while the classical Nihewan Fauna sensu stricto (Xiashagou Fauna) (Liu et al., 2012) site is in the north of the Sangganhe River. The relationship of mammalian faunas between the two sides of the Sangganhe River is still unknown. Magnetostratigraphic dating

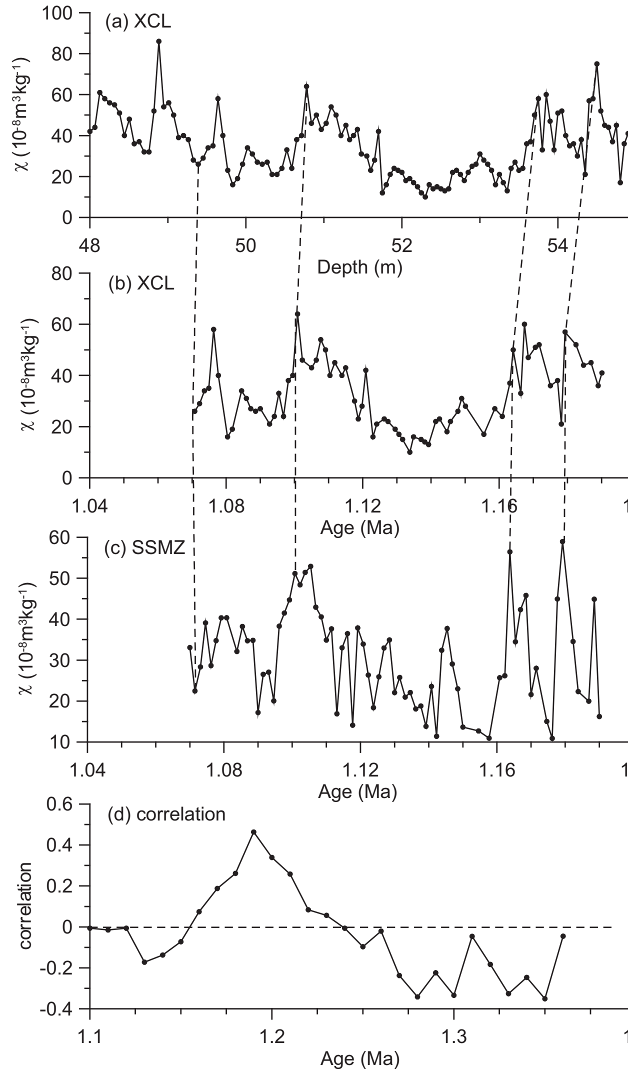

Fig. 9. (a) Magnetic susceptibility vs depth and (b) magnetic susceptibility vs age in the Xiaochangliang section. (c) Magnetic susceptibility vs age in the Shanshenmiaozui section. SSMZ, Shanshenmiaozui; XCL, Xiaochangliang. (d) Correlation coefficients of magnetic susceptibility between the Shanshenmiaozui and Xiaochangliang sections vs bottom age of the Shanshenmiaozui section.

of the Shanshenmiaozui section and associated mammalian fauna in this study provides important constraints on lithostratigraphic and biostratigraphic correlations between the two sides of the Sangganhe River as well as between the two blocks of the Youfang Fault.

6. Conclusions

Magnetite and hematite were identified as the main carriers for the characteristic remanent magnetizations in the Shanshenmiaozui fluvio-lacustrine sequence of the eastern Nihewan Basin. Stratigraphic correlation in terms of lithology, magnetic susceptibility and magnetic polarity sequences between the Shanshenmiaozui, Xiaochangliang and Dachangliang sections suggests that the Shanshenmiaozui sedimentary sequence recorded the Brunhes normal chron, the Jaramillo normal subchron and the reverse polarity portions of the intervening Matuyama reverse chron. The age of the Shanshenmiaozui mammalian fauna is estimated to be about 1.2 Ma.

Acknowledgements

Paleomagnetic and mineral magnetic measurements were made in the Paleomagnetism and Geochronology Laboratory, Institute of Geology and Geophysics, Chinese Academy of Sciences. Financial assistance was provided by the National Natural Science Foundation of China (Grant Nos. 41274007 and 40904016), the Ministry of the Land and Resources of China (Grant No. 201211005), and the Ministry of Science and Technology of China (Grant No. 2014FY110300). BY also acknowledges support from the National Natural Science Foundation of China (Grant No. 41240020). CD received support from the National Key Basic Research Program of China (Grant No. 2012CB821900) and the Chinese Academy of Sciences (Grant No. KZCX2-EW-117).

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quaint.2014.09.024.

References

Ao, H., Dekkers, M.J., Deng, C.L., Zhu, R.X., 2009. Palaeclimatic significance of the Xiantai fluvio-lacustrine sequence in the Nihewan Basin (North China), based on rock magnetic properties and clay mineralogy. Geophysics Journal International 177, 913–924.

Ao, H., Dekkers, M.J., An, Z.S., Xiao, G.Q., Li, Y.X., Zhao, H., Qiang, X.K., Chang, H., Chang, Q.F., Wu, D.C., 2013a. Magnetostratigraphic evidence of a mid-Pliocene onset of the Nihewan formation-implications for early fauna and hominid occupation in the Nihewan Basin, North China. Quaternary Science Reviews 59, 30–42.

Ao, H., An, Z.S., Dekkers, M.J., Li, Y.X., Xiao, G.Q., Zhao, R., Qiang, X.K., 2013b. Pleistocene magnetochronology of the fauna and Paleolithic sites in the Nihewan Basin: significance for environmental and hominin evolution in North China. Quaternary Geochronology 18, 78–92.

Barbour, G.B., 1924. Preliminary observation in Kalgan Area. Bulletin of the Geological Society of China 3, 167–168.

Barbour, G.B., 1925. The deposits of the Sankanho Valley. Bulletin of Geological Society of China 4, 53–55.

Chen, M.N., 1988. Study on the Nihewan Beds (in Chinese with English abstract). Ocean Press, Beijing, p. 143.

Cande, S.C., Kent, D.V., 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. Journal of Geophysical Research 100, 6093–6095.

Day, R., Fuller, M., Schmidt, V.A., 1977. Hysteresis properties of titanomagnetites: grain–size and compositional dependence. Physics of the Earth and Planetary Interiors 13, 260–267.

Deng, C.L., Zhu, R.X., Jackson, M.J., Verosub, K.L., Singer, M.J., 2001. Variability of the temperature-dependent susceptibility of the Holocene eolian deposits in the Chinese loess plateau: a pedogenesis indicator. Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy 26, 873–878.

Deng, C.L., Vidic, N.J., Verosub, K.L., Singer, M.J., Liu, Q.S., Shaw, J., Zhu, R.X., 2005. Mineral magnetic variation of the Jiaodao Chinese loess/paleosol sequence and its bearing on long-term climatic variability. Journal of Geophysical Research 110, B03103. http://dx.doi.org/10.1029/2004JB003451.

Deng, C.L., Wei, Q., Zhu, R.X., Wang, H.Q., Zhang, R., Ao, H., Chang, L., Pan, Y.X., 2006a. Magnetostratigraphic age of the Xiantai Paleolithic site in the Nihewan Basin and implications for early human colonization of Northeast Asia. Earth and Planetary Science Letters 244, 336–348.

Deng, C.L., Shaw, J., Liu, Q.S., Pan, Y.X., Zhu, R.X., 2006b. Mineral magnetic variation of the Jingbian loess/paleosol sequence in the northern Loess Plateau of China: implications for Quaternary development of Asian aridification and cooling. Earth and Planetary Science Letters 241, 248–259.

Deng, C.L., Xie, F., Liu, C.C., Ao, H., Pan, Y.X., Zhu, R.X., 2007. Magnetochronology of the Feiliang Paleolithic site in the Nihewan Basin and implications for early human adaptability to high northern latitudes in East Asia. Geophysical Research Letters 34, L14301. http://dx.doi.org/10.1029/2007GL030335.

Deng, C.L., Zhu, R.X., Zhang, R., Ao, H., Pan, Y.X., 2008. Timing of the Nihewan formation and faunas. Quaternary Research 69, 77–90.

Egli, R., 2003. Analysis of the field dependence of remanent magnetization curves. Journal of Geophysics Research 108 (B2), 2081. http://dx.doi.org/10.1029/2002JB002023.

Guo, Z.T., Ruddiman, W.F., Hao, Q.Z., Wu, H.B., Qiao, Y.S., Zhu, R.X., Peng, S.Z., Wei, J.J., Yuan, B.Y., Liu, T.S., 2002. On set of Asian desertification by 22 Myr ago inferred from loess deposits in China. Nature 416, 159–163.

Hilgen, F.J., Lourens, L.J., Van Dam, J.A., 2012. The Neogene Period. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M. (Eds.), The Geologic Time Scale. Elsevier.

Jelinek, V., 1978. Statistical processing of anisotropy of magnetic-susceptibility measured on groups of specimens. Studia Geophysica et Geodaetica 22, 50–62.

Jones, C.H., 2002. User-driven integrated software lives:" Paleomag" Paleomagnetics analysis on the Macintosh. Computers and Geosciences 28, 1145–1151.

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

Kruiver, P.P., Dekkers, M.J., Heslop, D., 2001. Quantification of magnetic coercivity components by the analysis of acquisition curves of isothermal remanent magnetisation. Earth Planetary Science Letter 189, 269–327.

Li, H.M., Wang, J.D., 1982. Magnetostratigraphic study of several typical geologic sections in North China. In: Liu, T.S. (Ed.), Quaternary Geology and Environment of China. Ocean Press, Beijing, pp. 33–38.

Li, H.M., Yang, X.Q., Friedrich, H., Li, H.T., 2008. High resolution magnetostratigraphy and deposition cycles in the Nihewan Basin (North China) and their significance for stone artifact dating. Quaternary Research 69, 250–262.

Liu, P., Deng, C.L., Li, S.H., Zhu, R.X., 2010. Magnetostratigraphic dating of the Huojiadi Paleolithic Site in the Nihewan Basin, North China. Palaeogeography Palaeoclimatology Palaeoecology 298, 399–408.

Liu, P., Deng, C.L., Li, S.H., Cai, S.H., Cheng, H.J., Yuan, B.Y., Wei, Q., Zhu, R.X., 2012. Magnetostratigraphic dating of the Xiashagou Fauna and implication for sequencing the mammalian faunas in the Nihewan Basin, North China. Palaeogeography, Palaeoclimatology, Palaeoecology 315-316, 75–85.

Lovlie, R., Su, P., Fan, X.Z., Zhao, Z.J., Liu, C., 2001. A revised paleomagnetic age of the Nihewan Group at the Xujiayao Palaeolithic Site, China. Quaternary Science Reviews 20, 1341–1353.

Qiu, Z.X., 2000. Nihewan fauna and Q/N boundary in China (in Chinese with English abstract). Quaternary Sciences 20, 142–154.

Roberts, A.P., Cui, Y.L., Verosub, K.L., 1995. Wasp-waisted hysteresis loops - mineral magnetic characteristics and discrimination of components in mixed magnetic systems. Journal of Geophysical Research-Solid Earth 100, 17909–17924.

Robertson, D.J., France, D.E., 1994. Discrimination of remanence-carrying minerals in mixtures, using isothermal remanent magnetisation acquisition curves. Physics Earth Planetary International 82, 223–234. http://dx.doi.org/10.1016/0031-9201(94)90074-4.

Stacey, F.D., Banerjee, S.K., 1974. The Physical Principles of Rock Magnetism. Elsevier, Amsterdam, p. 195.

Tang, Y.J., Li, Y., Chen, W.Y., 1995. Mammalian fossils and the age of Xiaochangliang paleolithic site of Yangyuan, Hebei (in Chinese with English abstract). Vertebrata Palasiatica 33, 74–83.

Teilhard de Chardin, P., Piveteau, J., 1930. Les mammiferes fossiles de Nihowan (China). Annales de Paleontologie 19, 1–134.

Tong, H.W., Hu, N., Han, F., 2011. A Preliminary report on the excavations at the early Pleistocene fossil site of Shanshenmiaozui in Nihewan Basin, Hebei, China. Quaternary Sciences 31 (4), 643–653.

Tong, H.W., 2012. New remains of *Mammuthus trogontherii* from the Early Pleistocene Nihewan beds at Shanshenmiaozui, Hebei. Quaternary International 255, 217–230.

Vlag, P., Thouveny, N., Williamson, D., Rochette, P., BenAtig, F., 1996. Evidence for a geomagnetic excursion recorded in the sediments of Lac St Front, France: a link with the Laschamp excursion? Journal of Geophysical Research-Solid Earth 101, 28211–28230.

Wang, H.Q., Deng, C.L., Zhu, R.X., Wei, Q., Hou, Y.M., Boeda, E., 2005. Magnetostratigraphic dating of the Donggutuo and Maliang Paleolithic sites in the Nihewan Basin, North China. Quaternary Research 64, 1–11.

Wang, X.S., Yang, Z.Y., Lovlie, R., Min, L.R., 2004. High-resolution magnetic stratigraphy of fluvio-lacustrine succession in the Nihewan Basin, China. Quaternary Science Reviews 23, 1187–1198.

Wang, X.S., Lovlie, R., Su, P., Fan, X.Z., 2008. Magnetic signature of environmental change reflected by Pleistocene lacustrine sediments from the Nihewan Basin, North China. Palaeogeography, Palaeoclimatology, Palaeoecology 260, 452–462.

Wei, Q., 1985. Paleoliths from the lower Pleistocene of the Nihewan beds in the Donggutuo site. Acta Anthropologica Sinaca IV (4), 289–300 (In Chinese with English abstract).

Wei, Q., 1997. The framework of archaeological geology of the Nihewan basin (in Chinese with English abstract). In: Tong, Y.S. (Ed.), Evidence of Evolution-Essays in Honor of Prof. Chungchien Young on the Hundredth Anniversary of His Birth. China Ocean Press, Beijing, pp. 193–207.

Wei, Q., Li, Y., Cheng, S.Q., 2011. Shanshenmiaozui Artifacts in the Nihewan Basin (in Chinese). In: Archaeology in Life–An Zhimin Anniversary Articles. Cultural Relics Publishing House, Beijing, pp. 179–194.

Xie, F., Li, J., Liu, L.Q., 2006. Paleolithic Archeology in the Nihewan Basin (in Chinese). Huashan Literature & Arts Press, Shijiazhuang, China, p. 278.

Xie, F., 2006. Nihewan (in Chinese). Cultural Relics Publishing House, Beijing, China, p. 330.

Yuan, B.Y., Zhu, R.X., Tian, W.L., Cui, J.X., Li, R.Q., Wang, Q., Yan, F.H., 1996. Magnetostratigraphy dating on the Nihewan formation (in Chinese). Science in China-Series D 26, 67–73.

You, Y.Z., Tang, Y.J., Li, Y., 1980. Paleolithic artifacts from Nihewan Formation (in Chinese with English abstract). Quaternaria Sinica 5, 1–13.

Zhou, T.R., Li, H.Z., Liu, Q.S., Li, R.Q., Sun, X.P., 1991. Cenozoic Paleogeography of the Nihewan Basin (in Chinese). Science Press, Beijing, p. 162.

Zhu, R.X., Coe, R.S., Zhao, X.X., 1998. Sedimentary record of two geomagnetic excursions within the last 15,000 years in Beijing, China. Journal of Geophysical Research-Solid Earth 103, 30323–30333.
Zhu, R.X., Hoffman, K.A., Potts, R., Deng, C.L., Pan, Y.X., Guo, B., Shi, C.D., Guo, Z.T., Yuan, B.Y., Hou, Y.M., Huang, W.W., 2001. Earliest presence of humans in northeast Asia. Nature 413, 413–417.
Zhu, R.X., An, Z.S., Potts, R., Hoffman, K.A., 2003. Magnetostratigraphic dating of early humans in China. Earth Science Reviews 61, 341–359.
Zhu, R.X., Potts, R., Xie, F., Hoffman, K.A., Deng, C.L., Shi, C.D., Pan, Y.X., Wang, H.Q., Shi, R.P., Wang, Y.C., Shi, G.H., Wu, N.Q., 2004. New evidence on the earliest human presence at high northern latitudes in northeast Asia. Nature 431, 559–562.
Zhu, R.X., Deng, C.L., Pan, Y.X., 2007. Magnetochronology of the fluvio-lacustrine sequences in the Nihewan Basin and implications for early human colonization of Northeast Asia (in Chinese with English abstract). Quaternary Sciences 27, 922–944.
Zijderveld, J.D.A., 1967. A.C. demagnetization in rocks: analysis of results. In: Collinson, D.W., Creer, K.M., Runcorn, S.K. (Eds.), Methods in Paleomagnetism. Elsevier, New York, pp. 254–286.