High-resolution record of geomagnetic excursions in the Matuyama chron constrains the ages of the Feiliang and Lanpo Paleolithic sites in the Nihewan Basin, North China

Hong Ao and Zhisheng An
State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075, China (aohong@ieecas.cn)

Mark J. Dekkers
Paleomagnetic Laboratory Fort Hoofddijk, Department of Earth Sciences, Faculty of Geosciences, Utrecht University, Budapestlaan 17, NE-3584 CD Utrecht, Netherlands

Qi Wei and Shuwen Pei
Laboratory of Human Evolution, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing 100044, China

Hui Zhao and Hongli Zhao
State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075, China

Guoqiao Xiao
State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Wuhan 430074, China

Xiaoke Qiang
State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075, China

Dacheng Wu
Research Institute of Exploration and Development, Tarim Oilfield Company, Korla 841000, China

Hong Chang
State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075, China

[1] The Nihewan Basin (40°C14N) in North China is a rich source of Early Pleistocene Paleolithic sites and thus a key area for studying early human evolution in high-latitude (from an early human perspective) East Asia. Here a high-resolution magnetostratigraphic investigation is carried out on a fluvio-lacustrine section in the north-eastern Nihewan Basin, which contains the Feiliang and Lanpo Paleolithic sites. Paleomagnetic results suggest that this section records the lower portion of the Brunhes polarity chron and the upper Matuyama polarity chron. Furthermore, the Jaramillo polarity subchron and seven of the nine validated geomagnetic excursions within the Matuyama polarity chron are identified, including the Kamikatsura, Santa Rosa, Intra-Jaramillo, Cobb Mountain, Bjorn, Gardar and Gilsa excursions. The Feiliang artifact layer is located just at the bottom...
of the Cobb Mountain excursion, thus its age is estimated to be ~1.2 Ma. The Lanpo artifact layer appears to be coeval with the Gilsa excursion, yielding an estimated age of ~1.6 Ma. This study provides new evidence for the presence of early humans in North China before 1.5 Ma and documents the powerful role of geomagnetic excursions: they provide valuable age control points for ongoing efforts to date the early Paleolithic sites.

Components: 9200 words, 10 figures.

Keywords: Early Pleistocene; East Asia; Nihewan Basin; human evolution; magnetostratigraphy.

Index Terms: 1105 Geochronology: Quaternary geochronology; 1513 Geomagnetism and Paleomagnetism: Geomagnetic excursions; 1520 Geomagnetism and Paleomagnetism: Magnetostratigraphy.

Received 9 February 2012; Revised 14 June 2012; Accepted 14 June 2012; Published 25 August 2012.


1. Introduction

[3] Timing of early human presence in regions over the globe with different paleoclimate conditions is an important and intriguing component for a comprehensive understanding of hominin evolution across the world [Dennell, 2009]. The Nihewan Basin is an intermountainous basin at the northeastern margin of the Chinese Loess Plateau, about 150 km west of Beijing (Figure 1). It spans a relatively small area of ~150–200 km$^2$ and is filled with thick and continuous fluvo-lacustrine sediments of Mid-Pliocene to Late Pleistocene age (known as the Nihewan Formation) [e.g., Zhou et al., 1991; Deng et al., 2008; H. Ao et al., Magnetostratigraphic evidence of a mid-Pliocene onset of the Nihewan Formation—implications for early fauna and hominin occupations in the Nihewan Basin, North China, submitted to Quaternary Science Reviews, 2012]. Despite its small size, the Nihewan Basin is one of the most important areas for studying early human occupation in East Asia after their initial migration out of Africa [Schick et al., 1991; Schick and Dong, 1993; Dennell and Roebroeks, 2005; Gao et al., 2005; Zhu et al., 2007; Dennell, 2009, 2012; Keates, 2010]. Up to now, most of the sparse Early Pleistocene Paleolithic sites in East Asia were found in the Nihewan Formation, such as the dated sites of Majuangou (MJG) at 1.66–1.55 Ma [Zhu et al., 2004b], Xiaoachangliang (XCL) at 1.48 Ma [Ao et al., 2010b], Xiantai (XT) at 1.48 Ma [Ao et al., 2010b], Banshan (BS) at 1.32 Ma [Zhu et al., 2004b], Feiliang (FL) at 1.2 Ma [Deng et al., 2007], Cenjiawan (CJW) at 1.1 Ma [Wang et al., 2006], Donggutuo (DGT) at 1.12–1.06 Ma [Ao et al., 2010b], Huojiadi (HJD) at ~1 Ma [Liu et al., 2010b]. Maliang (ML) at 0.79 Ma [Ao et al., 2010b] and Hougou (HG) at 0.4 Ma [Zuo et al., 2011], all in the northeastern part of the basin (Figure 1). Combining the electron spin resonance (ESR) dating of ~0.3 Ma for the Dongpo Paleolithic site (Figure 1b) in the eastern basin [Liu et al., 2010a], the currently established chronology of the Paleolithic sites in the Nihewan Basin spans an age range from ca 1.7 to 0.3 Ma. Even older and younger Paleolithic sites are anticipated to be documented in the next few years, because target sections with the appropriate age range have been identified [Dennell, 2009; Yuan et al., 2011; Ao et al., submitted manuscript, 2012]. The abundant Pleistocene Paleolithic sites and stone tools thus make the basin ideal to investigate early human evolution and behavior in 40°N East Asia.

[3] The Feiliang (FL) and Lanpo (LP) localities are two of the Early Pleistocene Paleolithic sites in the northeastern Nihewan Basin (Figure 1). A recent paleomagnetic study has indicated that the FL Paleolithic site is located below the Jaramillo polarity subchron [Deng et al., 2007]. Extrapolating the sedimentation rate during the Jaramillo polarity subchron on the one hand or that between the Brunhes-Matuyama boundary and the lower boundary of the Jaramillo on the other provides an estimated age of ca 1.3 and 1.2 Ma, respectively [Deng et al., 2007]. For the LP Paleolithic site, there is no stringent age control available up to now, although regional lithological and stratigraphic correlations in the field indicate that it is possibly older than the early XCL and XT Paleolithic sites. In this study, we present a high-resolution paleomagnetic study of the LP section that contains the FL and LP Paleolithic sites, aiming to refine the age of the FL site and to
provide an age estimate for the LP site via full consideration of the short-duration geomagnetic excursions in the Matuyama polarity chron recorded by the LP section. Finding these excursions, essentially point levels in the geological record with excellent age control, provides precise age constraints for the Paleolithic sites.

2. Geological and Archaeological Settings

[4] The LP section is located between the southern bank of the Sanggan River and eastern bank of the Huliu River, around which most of the early Paleolithic sites in the Nihewan Basin were found (Figure 1). The Nihewan Formation at the LP section, with a stratigraphic thickness of 57.5 m, is mainly composed of greyish-green silty clays and greyish-yellow clayey silts and intercalated by some silty sands. It is underlain by Jurassic breccia and is capped by aeolian Holocene soil (S₀), last glacial loess (L₁) and last interglacial soil (S₁). Note that the present LP section is a composite section from three exposures. The upper part (0–13.4 m) is located at about 100 m northeast of the DGT Paleolithic site. The middle part (13.4–47.8 m) is located at ca 20 m southwest of the FL Paleolithic site. The lower part (47.8–57.5 m) passes directly through the LP Paleolithic site. Two distinctive marker layers consisting of yellow silty sands were used for local stratigraphic correlations between the upper and middle parts on the one hand and between the middle and lower parts on the other. These two marker layers can be traced in the field from DGT to LP sites.

[5] The FL Paleolithic site lies in the lake-margin clayey silts, which correlates to the depth interval of 43–43.5 m in the composite LP section. The cooperative excavation of the FL Paleolithic site by the Institute of Archeology and Cultural Relics (Hebei Province, China) and Indiana University (USA) in
1990 (17 m², 0.5 m thick) yielded 108 stone artifacts in a clayey silt layer, including 8 cores, 34 whole flakes, 36 flake fragments, 2 scrapers and 28 chunks [Xie et al., 1998]. Among the 108 stone artifacts, 19 were conjoint to 9 refitting groups [Xie et al., 1998]. In addition, 1419 mammalian bone fragments were unearthed from this site, but the broken nature of the fragments hinders an unambiguous identification of the mammalian species [Xie et al., 1998]. This is typical of many Nihewan Paleolithic sites, which contain very little hard faunal evidence, especially the DGT and XCL sites are notorious in this issue (respectively 1525 fragments, 79% unidentifiable [Schick et al., 1991; Keates, 2010] and 3291 fragments, 90% unidentifiable [Tang et al., 1995; Peterson et al., 2003]). The LP Paleolithic site is located in a layer of silty sands and clayey silts at 54.1–55.3 m stratigraphic level of the lower LP composite section. A total of 28 stone artifacts were found at this site, including 6 scrapers, 12 cores, 7 flakes and 3 modified pieces [Yuan et al., 2011]. Ten stone artifacts from the FL and LP sites are shown in Figure 2.

Figure 2. Typical stone artifacts from the FL (Figures 2a–2f) and LP (Figures 2g–2j) Paleolithic sites. (a) Whole flake; (b, c) scrapers; (d, e) whole flakes; (f) flake fragment; (g) whole flake; (h, i) cores and (j) whole flake.
[6] The lithic raw materials exploited at FL and LP sites were locally available from nearby rock outcrops. Chert is the predominant raw material used for making stone artifacts. Direct hard hammer percussion is the main flaking technique. Most of the artifacts are small in size (e.g., Figure 2). A few scrapers were identified as retouched pieces, which were modified on flakes by direct hammer percussion. The artifacts are not regular in shape, associated with zigzag working edges. Overall, the stone toolkits from these two sites can be characterized by a lack of standard of shapes and an absence of formal tool categories, showing simple fracture typical of African Oldowan technology (i.e., mode 1 core and flake technologies).

3. Sampling and Methodology

[7] In order to obtain samples that are as fresh as possible, at least 40 cm of the outcrop was removed to eliminate potential weathering effects and disturbance due to vegetation. Subsequently, a total of 280 block samples were taken from the Nihewan Formation with a 20 cm stratigraphic interval, and oriented by magnetic compass in the field. The overlying (eolian) loess sediments were not sampled, because there is a sedimentation hiatus between the top of the Nihewan Formation and the bottom of the overlying loess. From each block sample, 2–3 cubic specimens of 2 cm × 2 cm × 2 cm for thermal demagnetization were cut in the laboratory. Some left-overs of these block samples were further used for measurements of magnetic mineralogy. The measurements of paleomagnetism and magnetic mineralogy were all performed at the Institute of Earth Environment, Chinese Academy of Sciences (IEECAS, Xi’an, China).

[8] In order to reveal the morphology of the magnetic particles and in turn shed light on whether or not in situ overgrowing has occurred, scanning electron microscope (SEM) analyses were performed on magnetic extracts from four levels selected from the Brunhes (1 m) and Matuyama (44.6 m) polarity chrons and Gardar (51 m) and Gilsa (55 m) excursions in the LP section. Magnetic particles were extracted using a continuous flux setup and a rare earth magnet. This procedure is successful in extracting the dominant ferrimagnetic minerals, such as magnetite, greigite and pyrrhotite, if present. To prevent charging of the particles during SEM observation, the magnetic extracts were coated with platinum before SEM observation. A Zeiss EVO Ma 10 SEM instrument was used at 20.0 kV under low vacuum conditions. This instrument has a large motorized 5 axis stage and variable standard pressure capability, complemented with a SmartSEM software. It is therefore well suited for our purpose.

[9] Before thermal demagnetization, the anisotropy of magnetic susceptibility (AMS) was measured for all 280 levels (i.e., 1 sample for each level) using a MFK1-FA Kappabridge (Agico Ltd., Brno). Furthermore, on selected 12 samples from different magnetozones of the section, both temperature-dependent susceptibility ($\chi-T$) and isothermal remanent magnetization (IRM) acquisition measurements were conducted. The $\chi-T$ curves were measured in an argon atmosphere at a frequency of 976 Hz from room temperature up to 700°C and back to room temperature using a MFK1-FA Kappabridge instrument equipped with a CS-3 high-temperature furnace. The magnetic field during measurement was 300 A/m (peak-to-peak). In order to determine the temperature-dependent background susceptibility, a run with an empty furnace tube was performed before measuring the sediment samples. The susceptibility of each sediment sample was obtained by correcting the measured background susceptibility (furnace tube correction) using the CUREVAL 5.0 program (AGICO, Czech Republic). IRM acquisition curves were determined using an ASC IM-10-30 pulse magnetizer (generates fields up to a maximum field of 2.7 T) and an AGICO JR-6A spinner magnetometer for remanence measurements. A total of 34 IRM steps were performed.

[10] Stepwise thermal demagnetization of the natural remanent magnetization (NRM) was conducted using a TD-48 thermal demagnetizer. As a rule, samples were stepwise heated of 10–50°C temperature increments to a maximum temperature of 680°C. When more than 90% of the starting NRM remanence was demagnetized at 580°C and the measured NRM directions were unstably oscillating, thermal demagnetization was stopped after 580°C. After each demagnetization step, remaining NRM was measured using a 2-G Enterprises Model 755-R cryogenic magnetometer housed in a magnetically shielded space (<150 nT). The starting NRM intensity of the samples was usually of the order of $10^{-4}$–$10^{-6}$ A/m, while the instrumental background (or noise) magnetization level in the magnetometer was generally of the order of $10^{-8}$–$10^{-9}$ A/m. Demagnetization results were evaluated using orthogonal vector component diagrams [Zijderveld, 1967] and the principal component direction was computed for each sample using a least-squares fitting technique [Kirschvink, 1980]. The principal component analyses (PCA)
were conducted using the PaleoMag software developed by C.H. Jones and J. Tetreault.

4. Results

4.1. Magnetic Mineralogy

The SEM images indicate that the magnetic particles in the magnetic extracts are all dominated by irregularly shaped magnetite (Figure 3). The edges of most magnetite particles are fairly rounded, while the truly sharp rims are not common. Their sizes range from <10 μm to >100 μm (but are typical between 20 and 50 μm). These characteristics point to a detrital origin. Ferrimagnetic greigite and pyrrhotite are not found in the Nihewan Formation in line with previous studies [e.g., Deng et al., 2006b; Wang et al., 2008; Ao et al., 2010a].

For the 280 levels from the LP section, the magnetic fabric is generally oblate, with the magnetic foliation (F) larger than the magnetic lineation (L) (Figure 4a). The minimum susceptibility axes (K_{min}) of the AMS ellipsoid are mainly close to the vertical, perpendicular to the bedding plane; so the maximum axes (K_{max}) are close to the horizontal, parallel to the bedding plane (Figure 4b). This AMS behavior coincides with a primary sedimentary fabric [e.g., Rees and Wooddall, 1975; Wang et al., 2005; Liu et al., 2010b]. The evenly distributed K_{max} directions indicate that there was no influence of prevailing wind direction or riverine flux on the deposition [e.g., Zhu et al., 2004a; Zhang et al., 2010].

χ—T curves are useful for further revealing the magnetic mineralogy of the sediments. Consistent with the (magnetically) ubiquitous occurrence of magnetite in the Nihewan Formation [e.g., Løvlie et al., 2001; Deng et al., 2006b; Ao, 2010; Ao et al., 2010a; Liu et al., 2012], all selected samples from the LP section are characterized by a major χ drop when heated to around 580°C (Figure 5). Some heating curves show a slight χ increase from room temperature to ~300°C, which may result from the gradual unblocking of fine-grained ferrimagnetic particles or the release of stress upon heating [van Velzen and Zijderveld, 1995; Liu et al., 2005, 2010c; Deng et al., 2006a]. The following χ drop between ca 300 and 500°C is interpreted as being due to the conversion of ferrimagnetic maghemite to weakly magnetic hematite [Løvlie et al., 2001; Deng et al., 2006b, 2008] or to changes in crystallinity, grain size or morphology of the magnetic particles during heating [Dunlop and Özdemir, 1997; Ao, 2008; Ao et al., 2009]. The χ of hematite is about two orders of magnitude lower than that of magnetite. It is prone to be
masked magnetically by the much stronger contribution of magnetite, thus its behavior on the $\chi$--$T$ curves is generally poorly expressed when both minerals are present. Hematite also occurs in the Nihewan Formation as suggested by IRM acquisition curves (Figure 6), progressive thermal demagnetization analyses (Figure 7) and recent magnetic studies [e.g., Løvlie et al., 2001; Wang et al., 2004, 2005; Deng et al., 2006b; Ao et al., 2010a].

[14] IRM acquisition curves of samples from the magnetic excursions and ‘regular polarity’ are essentially the same in line with a similar magnetic mineralogy (Figure 6). Consistent with the dominant contribution of magnetite to the magnetic mineralogy, all IRM acquisition curves undergo a major increase below 300 mT. However, these curves are not saturated at 1 T and increase slightly between 300 and 2700 mT, implying the presence of high-coercivity hematite.

4.2. Paleomagnetism

[15] In most samples from the LP section, the NRM is composed of two components: (1) a secondary low-temperature component (LTC) isolated by progressive demagnetization to 200–300°C (occasionally up to 400°C) followed by (2) a characteristic remanent magnetization component (ChRM) isolated at higher temperatures (Figure 7). The ChRM shows a relatively straightforward unidirectional trajectory toward the origin in orthogonal plots, while the LTC does not decay toward the origin for most samples. Further the LTC is predominantly of normal polarity and clusters around the present-day geomagnetic field (Figure 8a). Therefore, the LTC is interpreted as a secondary (or viscous) magnetization component in line with other recent paleomagnetic studies on the Nihewan Formation [e.g., Løvlie et al., 2001; Zhu et al., 2001, 2004b; Deng et al., 2006b; Liu et al., 2012]. Consistent with a normal polarity LTC overprint, the NRM decreases significantly by demagnetization to 200–350°C, associated with an additional peak between 150 and 300°C for the reversed samples (Figure 7). After removal of this secondary overprint, the ChRM is unblocked during the demagnetization steps up to 580 or 680°C (Figure 7). This demagnetization behavior indicates that both magnetite and hematite are important ChRM carriers, which is in accord with the IRM acquisition and $\chi$--$T$ curves (Figures 5 and 6). When comparing the 400 to 580°C with the 600 to 680°C parts of the unblocking spectra, no significant difference in ChRM direction was observed between magnetite and hematite (Figure 7). This indicates that both magnetic carriers recorded the same paleomagnetic field when their remanences became fixed in the sediments [Charreau et al., 2005]. From the 280 demagnetized levels, 222 levels yield stable ChRM components based on at least 4 consecutive demagnetization steps on the one hand and a maximum angular deviation (MAD) of $\leq 15^\circ$ on the other [May and Butler, 1986; Zhu et al., 2008]. These ChRM directions result in an antipodal distribution of 91 normal and 131 reversed orientations on the equal area projection (Figure 8b), while the distribution of the LTC evidently is not antipodal (Figure 8a). The 91 normal ChRM directions yield an overall mean of declination $D = 354.2^\circ$ and inclination $I = 49.9^\circ$ ($\kappa = 9.3$, $\alpha_{95} = 5.1^\circ$; $\kappa$ is the precision parameter and $\alpha_{95}$ is the radius of 95% confidence cone around the mean direction). The 131 reversed ChRM directions yield an overall mean of $D = 179.3^\circ$ and $I = -47.9^\circ$ ($\kappa = 10.4$, $\alpha_{95} = 4^\circ$). Furthermore, the reversal test [McFadden
Figure 5. The $\chi$-$T$ curves for selected samples from the LP section. Solid (dashed) lines represent heating (cooling) curves.
and McElhinny, 1990; Tauxe, 1998] is positive (Figure 8c) with an angular difference of 3.9° between the overall mean directions of each polarity (Figure 8b). This is less than the 95% radius of confidence angle of 6.44° and yields a class B reversal test [McFadden and McElhinny, 1990]. Therefore, these lines of evidence indicate a primary origin of the ChRM. Finally, the virtual geomagnetic pole (VGP) latitudes calculated from all the 222 ChRM directions were used to establish the magnetostratigraphic column of the LP section (see Figure 9 and Table S1 in the auxiliary material).1

[16] Combining the recent magnetostratigraphic data of the Nihewan Formation from nearby sections, such as the DGT [Wang et al., 2005], XCL [Zhu et al., 2001], XT [Deng et al., 2006b], Xiaodukou (XDK) [Li et al., 2008], MJG [Zhu et al., 2004b] and Xiashagou (XSG) sections [Liu et al., 2012] (Figure 10), the magnetostratigraphic polarity sequence determined for the LP section (Figure 9) can be readily correlated to the Pleistocene Geomagnetic Polarity Time Scale (GPTS) [Channell et al., 2002; Lourens et al., 2004; Laj and Channell, 2007; Roberts, 2008] (Figure 9). The correlation suggests that the LP section records a continuous geomagnetic polarity pattern of the post-Olduvai Matuyama reversed polarity chron and the lower portion of the Brunhes normal polarity chron. The Brunhes-Matuyama boundary is located at a depth of 9.8 m. The Jaramillo polarity subchron was identified at 29.1–34.9 m. In addition to the Matuyama-Brunhes boundary and Jaramillo polarity subchron, seven geomagnetic excursions (labeled e1–7) are identified in the LP section, which are defined on at least two

---

1Auxiliary materials are available in the HTML. doi:10.1029/2012GC004095
Figure 7. The direction and intensity evolution of the NRM during progressive stepwise thermal demagnetization for selected samples from the LP section. Open and closed symbols in the orthogonal vector endpoint projections [Zijderveld, 1967] indicate projections on to the vertical and horizontal planes, respectively. Numbers on the plots indicate heating temperature (in °C).
consecutive levels (Figure 9). These excursions comply well with the validated ones in the post-Olduvai Matuyama polarity chron, i.e., e1 to Kamikatsura, e2 to Santa Rosa, e3 to Intra-Jaramillo, e4 to Cobb Mountain, e5 to Bjorn, e6 to Gardar and e7 to Gilsa [Channell et al., 2002; Laj and Channell, 2007; Roberts, 2008] (Figure 9).

5. Discussion

5.1. Magnetostratigraphy

[17] Consistent with recent studies [e.g., Løvlie et al., 2001; Zhu et al., 2001, 2004b; Deng et al., 2006b, 2007, 2008; Li et al., 2008; Liu et al., 2010b, 2012], our analyses of the paleomagnetism and magnetic mineralogy indicate that magnetite and hematite are the principal NRM carriers in the Nihewan Formation. The magnetite grains have variable sizes (Figure 3), but they generally show an average pseudo-single-domain (PSD) behavior as a whole with fairly rare true multidomain (MD) and single-domain (SD) behavior on Day plots [see Deng et al., 2006b; Ao et al., 2009, 2010a]. Although hematite is not found in our magnetic extracts, which is possibly due to a less efficient extraction of the antiferromagnetic hematite with weak magnetism, it truly occurs in the bulk samples as suggested by the IRM acquisition curves (Figure 6), progressive thermal demagnetization analyses (Figure 7) and recent magnetic studies [e.g., Løvlie et al., 2001; Wang et al., 2004, 2005; Deng et al., 2006b; Ao et al., 2010a]. Both magnetite and hematite are considered to be a detrital origin [Liu et al., 1992; Deng et al., 2006b; Wang et al., 2008; Ao et al., 2009; Ao, 2010]. Minor amounts of possible maghemite, as indicated by the $\chi$–$T$ curves (Figure 5), may originate from secondary maghemite grains formed due to pedogenesis in the regional catchments or on the Chinese Loess Plateau [Deng et al., 2006b; Wang et al., 2008]. In addition, the combination of SEM observation (Figure 3), $\chi$–$T$ curves (Figure 5), IRM acquisition curves (Figure 6) and thermal demagnetization (Figure 7) does not hint at a prominent occurrence of biogenic SD magnetite and greigite (or pyrrhotite) in the Nihewan Formation.

---

**Figure 8.** Equal area projections of (a) 198 directions of the low temperature NRM component and (b) 222 directions of the high-temperature ChRM component of the LP section samples. The red open circle shows the present-day Earth’s field geocentric axial dipole direction. The black open circles represent the (overall) mean directions of both polarities. (c) Reversal test diagram [Tauxe, 1998] of the ChRM.
Our new magnetostratigraphy of the LP section is comparable to the recently established magnetostratigraphic records of nearby DGT [Wang et al., 2005], XCL [Zhu et al., 2001], XT [Deng et al., 2006b], XDK [Li et al., 2008], MJG [Zhu et al., 2004b] and XSG [Liu et al., 2012] sections, which are all located on the northeastern Nihewan Basin (see Figure 1 for their locations), with similar variability of lithology (Figure 10). Like the XCL and DGT sections [Zhu et al., 2001; Wang, 2007; Li et al., 2008], the LP section does not record the Olduvai polarity subchron; the fluvio-lacustrine sedimentation started later at these locations (Figure 10). However, the upper part of the Olduvai polarity subchron was found in the very nearby XT section [Deng et al., 2006b] (Figure 10d). The bottom of the XT section is ~800 m southwest of the LP Paleolithic site and has a lower topographical altitude. This indicates that the (horizontally lying) Nihewan Formation has gradually younger onset ages from XT section in the southwest to DGT section in the northeast (see Figure 1 for their locations). The bottom of the LP section must be quite close to the top of the Olduvai polarity subchron (Figure 10).

In the young horizontal strata, the ancient normal direction is the same as the normal remagnetized direction, thus the normal excursions in a reversed chron have the possibility to be a normal remagnetization, not a paleomagnetic field of normal polarity [Scott et al., 2007]. As indicated by following evidence, however, this case is less likely for the LP section. (1) The thermal demagnetization

Figure 9. Lithostratigraphy and magnetostratigraphy of the LP section and correlation to the geomagnetic polarity timescale (GPTS). (a) Lithology, (b) declination, (c) inclination, (d) maximum angular deviation (MAD), (e) virtual geomagnetic pole (VGP) latitude and (f) paleomagnetic polarity sequence of the LP section. (g) GPTS [Channell et al., 2002; Lourens et al., 2004; Laj and Channell, 2007; Roberts, 2008].
Figure 10. Comparison of the magnetostratigraphy of the LP section with other nearby sections. The lithostratigraphy and magnetostratigraphy are depicted from the (a) Donggutuo (DGT) [Wang et al., 2005], (b) Lanpo (LP) (this study), (c) Xiaochangliang (XCL) [Zhu et al., 2001], (d) Xiantai (XT) [Deng et al., 2006b], (e) Xiaodukou (XDK) [Li et al., 2008], (f) Majuangou (MJG) [Zhu et al., 2004b] and (g) Xiashagou (XSG) [Liu et al., 2012] sections (see Figure 1 for the locations of these sections). (h) GPTS [Channell et al., 2002; Lourens et al., 2004; Laj and Channell, 2007]. K, Kamikatsura; SR, Santa Rosa; IJ, Intra-Jaramillo; Punaruu; CB, Cobb Mountain; Bj, Bjorn; Ga, Gardar; Gi, Gilsa; R, Réunion.
The results of the samples from these excursions have a high quality (Figure 7), and the ChRM directions have passed the reversal test [McFadden and McElhinney, 1990; Tauxe, 1998] (Figure 8c). This indicates a successful removal of the secondary overprint and subsequent isolation of the ChRM. (2) As indicated by similar SEM images (Figure 3), \( \chi - T \) (Figure 5) and IRM acquisition (Figure 6) curves, samples from these excursions have a similar magnetic mineralogy with the nearby ‘regular reversed polarity’ samples, in which magnetite and/or hematite dominate the NRM carriers (Figure 7), without ferrimagnetic greigite or pyrrhotite occurring in large amount. (3) Except for e1 (Kamikatsura) excursion that occurred in a silty sand layer, the other six excursions are all located in silty clay or clayey silt layers (Figure 9), which are less likely to be linked to remagnetization [Wang et al., 2004] and are also not confined to a lithology with weak NRM, high porosity or strong surface weathering. (4) The geomagnetic excursions recorded in the LP section appear to be reproducible in nearby sections. For example, the Kamikatsura, Santa Rosa and Punaruu excursions were also identified in the XT and DGT sections [Wang et al., 2005; Deng et al., 2006b; Ao et al., 2010b] (Figures 10a and 10d). The Cobb Mountain and Bjorn excursions were found in the MJG section [Zhu et al., 2004b] (Figure 10f). The Santa Rosa, Cobb Mountain, Bjorn and possibly Gilsa excursions were detected in the XDK section [Li et al., 2008] (Figure 10e). The Kamikatsura, Intra-Jaramillo Gilsa and Réunion excursions seem to exist in the XSG section [Zhu et al., 2004b] (Figure 10g). The Gardar excursion appears to occur in the Yangshuizhan (YSZ) section (Ao et al., submitted manuscript, 2012) (not shown here). Therefore, the combined evidence indicates the reliability of the geomagnetic excursions recorded in the LP section. (21) Generally, there are major changes in sedimentation rates during different magnetozones and in different sections (Figure 10). The interval between the Matuyama-Brunhes boundary and Jaramillo polarity subchron has a higher sedimentation rate than the Brunhes polarity chron and the interval between the Jaramillo and Olduvai polarity subchrons (Figure 10) [see also Ao et al., 2012]. This variability of sedimentation rates is not uncommon in the continental fluviolacustrine sediments in the eastern Nihewan Basin, which can be due to local faulting activity, or changes of sedimentary environments (e.g., growth or retreat of the paleolake). In addition, the local variations, e.g., minor differences in paleotopography, distance to the paleoshore, and/or riverine input, may result in small scale sedimentary hiatus that can differ among reasonably nearby sections [Deng et al., 2008; Ao et al., submitted manuscript, 2012].

[22] In the Chinese loess sequence, the excursions of Kamikatsura, Santa Rosa, Intra-Jaramillo Punaruu, Cobb Mountain and Gilsa were also identified [e.g., Zheng et al., 1992; Li et al., 1997; Guo et al.,]
1998, 2002; Pan et al., 2002; Yang et al., 2004, 2007]. For example, the Kamikatsura excursion was identified in the Baoji section [Yang et al., 2004]; The Santa Rosa and Punanru excavations were found in both the Weinan and Baoji sections [Pan et al., 2002; Yang et al., 2004, 2007]; The Intra-Jaramillo excursion was found in the Jingbian section [Guo et al., 2002]; The Cobb Mountain excursion was found in the Lantian and Dongshanding sections [Zheng et al., 1992; Li et al., 1997]; the Gilsa excursion was observed in the Dongshanding and Baoji sections [Li et al., 1997; Yang et al., 2007]. Generally, these excavations were not expressed as well as they are in the Nihewan Formation. For example, the Gilsa excursion was defined based on just one or two samples from the paleosol S22 of the loess sequences in the Dongshanding and Baoji sections [Li et al., 1997; Yang et al., 2007]. In addition, the Santa Rosa, Gardar and Gilsa excavations were also identified in lacustrine sediments from the Heqing Basin (South China) [An et al., 2011]. It seems that lacustrine sediments (and deep-sea sediments) are more prone to record the geomagnetic excavations than the continental eolian sediments. In the Chinese loess deposits, there remains a debate on how significant the ‘lock-in depth’ of post-depositional remanent magnetization can be, because the Matuyama-Brunhes boundary is often identified in the loess unit L9, which corresponds to marine oxygen isotope stage (MIS) 20 [Zhou and Shackleton, 1999; Liu et al., 2008; Zhao and Roberts, 2010]. Note that the Matuyama-Brunhes boundary should be located in MIS 19, as indicated by the deep-sea sediments [e.g., Tauxe et al., 1996; Lisiecki and Raymo, 2005]. Consistent with the marine sediments but unlike Chinese loess deposits, both the Nihewan and Heqing basins have a Matuyama-Brunhes boundary in MIS 19 [Ao et al., 2010b; An et al., 2011], without showing prominent lock-in depths within the Matuyama polarity chron.

5.2. Age Estimation of the Feiliang and Lanpo Paleolithic Sites

[23] Our high-resolution record of the geomagnetic excavations in the Matuyama polarity chron provides valuable extra chronological control points for the FL and LP Paleolithic sites. The FL artifact layer is located just at the bottom of the Cobb Mountain excursion. The estimated age of the Cobb Mountain excursion ranges from 1.181 to 1.215 Ma [Channell et al., 2002, 2008; Singer et al., 2004; Silva et al., 2012], thus the age of the FL Paleolithic site is estimated to be ~1.2 Ma (Figure 9). This age estimate is consistent with the extrapolated age of 1.2 Ma based on the average sedimentation rate between the Matuyama-Brunhes boundary and the lower boundary of the Jaramillo polarity subchron in the FL section [Deng et al., 2007]. It is inconsistent, however, with the extrapolated age of 1.3 Ma based on a average sedimentation rate within the Jaramillo polarity subchron [Deng et al., 2007]. In the study of Deng et al. [2007], the FL artifact layer is located at the bottom of a less well-defined normal excursion below the Jaramillo polarity subchron, which is characterized by only one sample in a 2-m thick sediment interval. Thus at that time it was difficult to interpret that sample as the Cobb Mountain excursion. In the present study, however, the Cobb Mountain excursion is characterized by five consecutive samples, with a stratigraphic thickness of 1.8 m. Therefore our magnetostratigraphy, with a higher resolution of excavations, further refines the age of the FL Paleolithic site. This age estimate is approximately contemporaneous with the nearby DGT (1.12–1.06 Ma) site [Ao et al., 2010b] and with the Xihoudou (1.27 Ma) [Zhu et al., 2003] Paleolithic site in central China.

[24] The LP artifact layer is coeval to the Gilsa excursion. The estimated age of the Gilsa excursion ranges from ca 1.567 to 1.62 Ma [Udagawa et al., 1999; Channell et al., 2002; Leonhardt et al., 2009], thus the age of the LP Paleolithic site is estimated to be ~1.6 Ma. This age estimate is contemporaneous with the Gongwangling (~1.6 Ma) Paleolithic site in central China (Z. Y. Zhu et al., New dating of the fossil hominin cranium from Lantian (Gongwangling), China, manuscript in preparation for Proceedings of the National Academy of Sciences of the United States of America, 2012), and slightly younger than the oldest MJG-III Paleolithic site (1.66 Ma) reported so far in North China [Zhu et al., 2004b], which is located about 200 m north of the LP site (Figure 1). It also falls within the age range of 1.85–1.5 Ma that is considered the age range for the earliest human dispersal from Africa to Asia [Larick et al., 2001; Zhu et al., 2008; Ferring et al., 2011]. Further this age estimate for the LP Paleolithic site provides new evidence of early human presence in the high-latitude Nihewan Basin (40°N, high latitude is seen from an early human perspective) before 1.5 Ma. Before this finding, evidence of early human occupation in China for ages older than 1.5 Ma was only found at the nearby MJG sites [Zhu et al., 2004b] and from the debatable hominin incisors and stone tools from the subtropical Yuanmou Basin (~1.7 Ma) in 15 of 19
southeastern China [Zhu et al., 2008]. Combining the earliest skeletal and archeological evidence at Dmanisi (1.85–1.78 Ma) in western Eurasia [Ferring et al., 2011] and Java (1.51 Ma) in southeast Asia [Larick et al., 2001], early humans seem to have occupied wide areas of Eurasia before 1.5 Ma, which extended from at least 40°N latitude (i.e., Dmanisi and Nihewan Basin) to 7°S latitude (i.e., Java), across a habitat range from temperate grasslands to tropical woodlands and possibly forests. This implies that early humans became less dependent on the grasslands fairly quickly after their initial migration out of Africa, showing high adaptability to various climate and environmental conditions before 1.5 Ma. For example, mammalian fauna and pollen records indicate that the Yuanmou hominins lived in a varied habitat of subtropical bushlands and forests associated with open grasslands on an alluvial fan close to a lake or swamp [Zhu et al., 2008].

6. Conclusions

Paleomagnetic analyses conducted on the LP fluvio-lacustrine section in the northeastern Nihewan Basin, which contains the FL and LP Paleolithic sites, reveal the Kamikatsuara, Santa Rosa, Intra-Jaramillo Cobb Mountain, Bjorn, Gardar and Gilsa excursions in the upper Matuyama reversed polarity chron, in addition to the Jaramillo polarity subchron and Matuyama-Brunhes reversal boundary. The FL artifact layer is located at the lowermost part of the Cobb Mountain excursion, yielding an estimated age of ~1.2 Ma. The LP artifact layer and Gilsa excursion largely coincide, yielding an estimated age of ~1.6 Ma for the former. The present study shows that the short-duration geomagnetic excursions add considerable resolution power to the magnetostratigraphic dating tool: the set of chronological tie points for the ongoing effort to date early Paleolithic or hominin sites in China is considerably enhanced. It is foreseeable that the application of geomagnetic excursions to date other early Paleolithic or hominin sites in China and elsewhere will contribute substantially to a robust chronological framework and thereby to a better understanding of human evolution and dispersal across the world.

Acknowledgments

We thank the two editors and three reviewers for their insightful suggestions, which significantly improved this paper. This study was financially supported by the National Natural Science Foundation of China (41174057), the Key Projects of National Basic Research Program of China (2010CB833400) and the West Light Foundation of Chinese Academy of Sciences.

References

Deng, C. L., Q. Wei, R. X. Zhu, H. Q. Wang, R. Zhang, H. Ao, L. Chang, and Y. X. Pan (2006b), Magnetostratigraphic age of the XiataiPaleolithic site in the Nihewan Basin and implications for early human colonization of...


