Magnetostratigraphic evidence of a mid-Pliocene onset of the Nihewan Formation – implications for early fauna and hominin occupation in the Nihewan Basin, North China

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Abstract

The fluvi-lacustrine sediments in the Nihewan Basin of North China, known as the Nihewan Formation, are well-known for an abundance of Early Pleistocene mammalian fossils (known as the Nihewan Fauna senso stricto) and Paleolithic sites. The age at which the sedimentation started is thus crucial for our understanding of early fauna and hominin occupation and infilling history of the basin, but it is poorly constrained to date. Here we report on a detailed paleomagnetic investigation of the Yangshuizhan section that crops out in the northeastern Nihewan Basin, supplemented by rock magnetic analyses into the carriers of the natural remanent magnetization. Magnetite and hematite are shown to be the main carriers of the characteristic remanent magnetization. Magnetostratigraphic correlation to the geomagnetic polarity timescale indicates that the onset of the Nihewan Formation in this section occurs at ~3.7 Ma, just below the Gilbert–Gauss boundary and ca 1-Myr earlier than previously established evidence. This pushes the lower limit of the Nihewan Formation back in time from very late Pliocene (<2.8 Ma) to (at least) the mid-Pliocene. Combining the previously established magnetostratigraphic data with the present study, we arrive at a better understanding of the chronological framework and spatio-temporal history of the deposition of the terrestrial Nihewan Formation. Furthermore, it provides new perspectives of early fauna and hominin occupation in the Nihewan Basin.

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1. Introduction

The Nihewan Basin is a down-faulted basin at the northeastern margin of the Chinese Loess Plateau, about 150 km west of Beijing (Fig. 1). It has a relatively small area of roughly 150–200 km² and is filled with late Cenozoic fluvo-lacustrine and windblown deposits (Zhou et al., 1991; Deng et al., 2008). The fluvo-lacustrine sequence was named the Nihewan Formation (or Beds) (Barbour, 1924), and represents the type section of the Early Pleistocene in North China (Young, 1950). The Nihewan Formation is rich in Early Pleistocene Paleolithic sites and mammalian faunas. It is also a good archive of paleoclimatic variability, and has thus become a major focus of geologists, paleontologists, geochronologists, paleoanthropologists and paleoclimatologists (Qiu, 2000; Lavlie et al., 2001; Wang et al., 2004, 2008; Xie, 2006; Xie et al., 2006; Zhu et al., 2007; Deng et al., 2008; Ao et al., 2009, 2010a,b,c, 2012a,b; Dennell, 2009; Ao, 2010; Keates, 2010). During recent years, considerable progress has been made in paleomagnetic dating of the strata, mammalian fauna localities and Paleolithic sites in this basin with far-reaching implications for our understanding of early human colonization of high northern latitudes (from an early human perspective) of East Asia (see reviews of Zhu et al. (2007), Deng et al. (2008) and Dennell (2009)).

Based on recent high-resolution paleomagnetic dating of outcropping sections, which range in thickness from tens of meters to somewhat over two hundred meters, the earliest deposition of the Nihewan Formation is estimated to occur at ca 2.8 Ma, just prior to the beginning of the Pleistocene (see review of Deng et al., 2008; Liu...
et al., 2012). Here we report on the magnetostratigraphy of the outcropping Yangshuizhan (YSZ) section (40°13.126′N, 114°29.623′E), where the Nihewan Formation occurs above Pliocene or late Miocene eolian red clay that is underlain by Jurassic breccia. It has the potential to contain older sediments of the Nihewan Formation than previously reported sections, based on regional lithological and stratigraphic correlations. Consistent with our line of thought, high-resolution magnetostratigraphic results indicate that this outcropping section preserves the oldest well-dated deposits of the Nihewan Formation so far. Here the onset of the Nihewan Formation sedimentation has occurred just prior to the Gilbert–Gauss boundary, at an estimated age of ca 3.7 Ma based on linear extrapolation. The combination of our new and recently established magnetostratigraphic data puts new insights into the chronology and depositional history of the terrestrial Nihewan Formation. Further it provides new implications for early fauna and hominid occupation in the Nihewan Basin.

2. General setting

At present, the Nihewan Basin is characterized by a moderate semi-arid climate, with a mean annual temperature of ~7.7 °C and a mean annual rainfall of ~364 mm. Winters are relatively cold and dry under the influence of the East Asian winter monsoon, while summers are relatively warm and humid under the influence of the East Asian summer monsoon. Extensive exposures of horizontal Nihewan Formation (without obvious tilting of the strata) are found along the SW–NE trending Sanggan River and SE–NW trending Huli River (Fig. 1).

The YSZ section is located in the northeastern Nihewan Basin, on the western bank of the Huli River (Fig. 1). The outcrop has a thickness of 155.1 m, with 131 m for the fluvio-lacustrine Nihewan Formation and 24.1 m for the underlying eolian red clay. An unconformable contact between the Nihewan Formation and underlying red clay is clearly observed. Like in the nearby Hongya (HY) and Huabaogou (HBG) sections (Deng et al., 2008), in the YSZ section the Nihewan Formation can also be divided into two parts: an upper part consisting of grayish-green and grayish-yellow silty clays and clayey silts intercalated with fine-grained sand and conglomerate (or conglomeratic sand) layers, and a lower part comprising red silt clay intercalated with conglomeratic silts. The stratigraphic boundary between the two parts of the Nihewan Formation is located at ~71 m in the YSZ section. Generally, the conglomerates in its upper part are reasonably well sorted, with few angular or sharp pebbles and cobbles. In addition, the upper part in the YSZ section has two sedimentary layers rich in mammalian fossils. The mammalian fossils in YSZ-I layer (ca 39–40 m) include a very complete skull of Equus huanghoensis (Fig. 2), a left mandible of Nyctereutes sp., a humerus of Acinonyx sp. and a large number of mammalian bone fragments. The mammalian fossils in YSZ-II layer (ca 49.5–50.5 m) include six lower deciduous teeth of Equus sanmeniensis (Fig. 3), horse and elephant bones and other mammalian bone fragments.
3. Sampling and analytical methods

In order to obtain samples that were as fresh as possible, at least 40 cm of the outcrop was removed to eliminate potential weathering effects and disturbance due to vegetation. Then a total of 680 block samples were oriented by magnetic compass in the field and were taken at 10–40 cm stratigraphic intervals. Two cubic specimens of 2 cm × 2 cm × 2 cm were subsequently cut from each block sample in the laboratory for thermal demagnetization treatment. Some left-overs of these block samples were further used for rock magnetic measurements. All the rock magnetic and paleomagnetic measurements were performed at the Institute of Earth Environment, Chinese Academy of Sciences (IEECAS, Xi’an, China).

Before thermal demagnetization, the anisotropy of magnetic susceptibility (AMS) was measured for all the 680 levels (i.e., 1 sample for each level) using a MFK1-FA Kappabridge (Agico Ltd., Brno). Furthermore, on selected samples distributed over different lithological parts and magnetozones of the Nihewan Formation, both temperature-dependent susceptibility (χ–T) and isothermal remanent magnetization (IRM) acquisition measurements were conducted. All χ–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 subtracting the measured background susceptibility (furnace tube correction) using the CUREVAL 5.0 program (AGICO, Czech Republic). The IRM acquisition curves were determined using an ASC IM-10-30 pulse magnetizer (generate fields up to a maximum field of 2.7 T) and an AGICO JR-6A spinner magnetometer for remanence measurements. 26–28 IRM steps were performed on two pilot samples (at 2 and 12.4 m) from the upper Nihewan Formation; IRM acquisition curves determined afterwards on the other selected samples consist of 36 IRM steps.

For the Nihewan Formation, a sampling interval of 30 cm is generally considered sufficient to establish a high-resolution magnetostratigraphy (Deng et al., 2008). In the laboratory, 520 of the 680 samples equally distributed over the section (with the aforementioned ~30 cm stratigraphic interval) were selected for stepwise thermal demagnetization using a TD-48 thermal demagnetizer. They were stepwise heated to 680 °C, with 18 steps of demagnetization and 10–50 °C temperature increments. After each step of demagnetization, remanence was measured using a 2-G Enterprises Model 755-R cryogenic magnetometer housed in a magnetic shielded space (<150 nT). Demagnetization results were evaluated by orthogonal diagrams (Zijderveld, 1967) and the principal component direction was computed using a least-squares fitting technique (Kirschvink, 1980). The principal component analysis (PCA) was done with the PaleoMag software developed by C. H. Jones and J. Tetreault. The intensity of the natural remanent magnetization (NRM) of the samples was usually of the order of
10^3–10^6 A/m, while the background (or noise) magnetization level in the magnetometer was generally of the order of 10^-8–10^-9 A/m.

4. Results

4.1. Rock magnetism

For the 680 levels from the YSZ section, the magnetic fabric is generally oblate with the magnetic foliation (F) larger than the magnetic lineation (L) (Fig. 4a). The minimum susceptibility axes (K_{min}) of the AMS ellipsoid are mainly close to the vertical, perpendicularly to the bedding plane; so the maximum axes (K_{max}) are close to the horizontal, parallel to the bedding plane (Fig. 4b). This AMS behavior coincides with a primary sedimentary fabric (e.g., Rees and Wooddall, 1975; Wang et al., 2005; Liu et al., 2010a, 2012). The directional distribution of K_{max} appears to have a somewhat higher density towards south and the mean direction of K_{min} shows a slight departure from the vertical directed towards the north (Fig. 4b), this is consistent with the presence of a small fault between the YSZ and HY sections (see Fig. 1c), which resulted in a ~20 m vertical fault displacement between them.

Six χ–T curves from the YSZ section are shown in Fig. 5. All heating curves show a marked drop near 580 °C, while the background (or noise) magnetization level in the magnetometer was generally of the order of 10^-8–10^-9 A/m.

(e.g., Fig. 5a, c, e and f), which may result from the gradual unblocking of fine-grained (i.e., the superparamagnetic (SP) and small single-domain (SD)) ferrimagnetic particles or the release of stress upon heating (van Velzen and Zijderveld, 1995; Liu et al., 2005, 2010b; Deng et al., 2006a). A subsequent χ drop between 300 and 500 °C can be caused by the conversion of ferrimagnetic maghemite to weakly magnetic hematite (Lavlie et al., 2001; Deng et al., 2006b, 2008) or changes in crystallinity, grain size and morphology of the magnetic particles (Dunlop and Özdemir, 1997; Ao, 2008; Ao et al., 2009) during heating. Consistent with conversion of ferrimagnetic maghemite to weakly magnetic hematite (Lavlie et al., 2001; Deng et al., 2006b, 2008), two samples from the 83.6 and 125.4 m levels have cooling curves after heating to 700 °C that are lower than their corresponding heating curves (Fig. 5e–f).

In contrast, most samples have an increased χ during cooling after heating to 700 °C (Fig. 5a–d), which may result from the neo-formation of fine-grained magnetite via annealing of a mix of hematite and iron-containing paramagnetic silicates/clays (e.g., chlorite) (Tanikawa et al., 2008; Ao et al., 2009; Zhang et al., 2010, 2012). The χ of hematite is about two orders in magnitude lower than that of magnetite. Therefore, hematite is prone to be masked magnetically by the much stronger contribution of magnetite, thus its behavior on χ–T curves is generally poorly expressed. Actually, hematite also occurs in the Nihewan Formation as suggested by the IRM acquisition (Fig. 6) and progressive thermal demagnetization analyses (Fig. 7).

Our inferences of the magnetic mineralogy are consistent with recent magnetic analyses across the Nihewan Basin (e.g., Lavlie et al., 2001; Wang et al., 2004, 2005; Deng et al., 2006b; Ao et al., 2010a).

Consistent with a dominant magnetic contribution of magnetite to the magnetic mineralogy, all IRM acquisition curves undergo a major rise below 300 mT (Fig. 6a–f). In addition, some of the samples (e.g., the samples at depths of 2 and 68.6 m) increase slightly between 300 and 2700 mT and are not even saturated at 2700 mT (Fig. 6a, d), which provides evidence for the presence of high-coercivity hematite. In agreement with the dominant magnetite and hematite in these samples, cumulative log-Gaussian decomposition analysis of IRM acquisition curves (Kruiver et al., 2001) indicates two main components: a low-coercivity component (primary magnetite) and a high-coercivity component (primary hematite) (Fig. 6g, j). In the other four selected samples a low-coercivity component is also dominant supplemented by a rather weak high-coercivity component (Fig. 6h, i, k and l), which is consistent with dominant magnetite and minor hematite in these samples (Fig. 6b, c, e and f).

Similar to the variability of lithology, changes in low-field magnetic susceptibility of the YSZ section can be divided into three units (Fig. 8a and b). The upper Nihewan Formation that mainly consists of grayish-green and grayish-yellow silty clays/clayey silts has relatively low susceptibilities (7 × 10^{-8} m^3/kg < χ < 600 × 10^{-8} m^3/kg), while the lower part that mainly comprises red silts intercalated with conglomeratic silts has a distinctly higher susceptibility (360 × 10^{-8} m^3/kg < χ < 1762 × 10^{-8} m^3/kg). The underlying eolian red clay is characterized by relatively consistent low susceptibilities (138 × 10^{-8} m^3/kg < χ < 312 × 10^{-8} m^3/kg). This behavior indicates that the magnetic susceptibility is a powerful tool for distinguishing different lithological units in the Nihewan Basin.

4.2. Paleomagnetism

Similar to the approach that was used to resolve the Oligocene and Neogene magnetostratigraphy in northwest China (e.g., Huang et al., 2006, 2010), two rounds of progressive thermal demagnetization were performed, with the second round of demagnetization performed on horizons that initially showed erratic or anomalous
trajectories. Progressive thermal demagnetization trajectories are relatively straightforward for most samples from the YSZ section and are comparable to component structures of the Nihewan Formation elsewhere in the basin (e.g., Levlie et al., 2001; Zhu et al., 2001, 2004; Deng et al., 2006b; Liu et al., 2012). 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) the characteristic remanent magnetization (ChRM) component isolated at higher temperatures (Fig. 7). There are also some samples that are not significantly affected by the viscous and/or low-temperature component; they show a single ChRM component. For these samples, it is difficult to isolate a meaningful LTC. In general, ChRM shows a relatively straightforward unidirectional trajectory toward the origin of orthogonal plots from 200–300 °C. In contrast, the LTC does not decay toward the origin for most samples. It is predominantly of normal polarity and clusters around the present-day geomagnetic field (Fig. 7a). Therefore, the LTC is interpreted as a secondary overprint in line with other recent paleomagnetic studies on the Nihewan Formation (e.g., Levlie et al., 2001; Zhu et al., 2001, 2004; Deng et al., 2006b; Liu et al., 2012). The steep inclinations of the LTC in geographic coordinates (Fig. 9a) are consistent with a slightly tilted surface towards the south as indicated by the AMS behavior (Fig. 4). After removal of this secondary overprint, the ChRM is unblocked during steps up to 580 or 680 °C (Fig. 7). Consistent with the IRM acquisition and χ−T curves (Figs. 5 and 6), this demagnetization behavior indicates that both magnetite and hematite are important ChRM carriers. When comparing the 400–580 °C with the 600–680 °C parts of the unblocking spectra, no significant difference in ChRM direction was observed between magnetite and hematite (Fig. 7). This indicates that both magnetic carries recorded the same paleomagnetic field when their remanences became fixed in the sediments (Charreau et al., 2005). From the 520 demagnetized levels, 317 yield stable ChRM components based on (1) at least 4 consecutive demagnetization steps, (2) a maximum angular deviation (MAD) of <15° and (3) a calculated virtual geomagnetic pole (VGP) latitude >45° or <-45° (May and Butler, 1986; Zhu et al., 2008). They come from 252 individual horizons of the Nihewan Formation and from 65 horizons of the underlying red clay. The remaining 203 samples were excluded, because they have unstable demagnetization trajectories, MAD values >15°, VGP latitudes between −45 and 45°, or declinations trending roughly north (or south) but with upward (or downward) inclinations inconsistent with the expected field. The 252 ChRM directions retrieved from the Nihewan Formation result in an antipodal distribution of 118 normal and 134 reversed orientations on the equal area projection (Fig. 9b), while the distribution of the LTC evidently is not antipodal (Fig. 9a). The 118 normal ChRM directions yield an overall mean with declination D = 355.7° and inclination I = 47.6° (k = 19.5, a95 = 3.0°; k is the precision parameter and a95 is the radius of 95% confidence cone around the mean direction). The 134 reversed ChRM directions yield an overall mean of D = 179.1° and I = −49.5° (k = 15.9, a95 = 3.2°). Furthermore, the reversal test (McFadden and McElhinny, 1990; Tauxe, 1998) is positive (Fig. 9c) with an angular difference of 2.9° between the overall mean directions of each polarity (Fig. 9b). This is less than the 95% radius of confidence level angle of 4.38° and yields a class A reversal test (McFadden and McElhinny, 1990). Therefore, these lines of evidence indicate a successful removal of the
secondary overprint and subsequent isolation of the ChRM. For the 65 ChRM directions retrieved from the underlying red clay, most inclinations are shallower than expected (Fig. 8) possibly as a result of compaction (e.g., Muttoni et al., 2011). Among the 65 samples with meaningful ChRM directions, only 9 are reversed (so 56 are normal). This large difference in number of the reversed and normal samples makes the reversal test less useful in this red clay collection (McFadden and McElhinny, 1990). However, the good quality of the
4.3. Magnetostratigraphy

The VGP latitudes calculated from all the 317 ChRM directions (i.e., the 252 individual horizons of the Nihewan Formation and 65 horizons of the underlying red clay) are used to establish the magnetostratigraphic column (see Fig. 8 and Supplementary Table 1). The mammalian fossils of *E. huanghoensis* and *E. sanmeiensis* found at the depths of ca 40 and 50 m suggest an Early Pleistocene age for these two sedimentary layers (Deng and Xue, 1999). Combining this biostratigraphy and recently established magnetostratigraphies of the Nihewan Formation (Deng et al., 2008), we can readily correlate the geomagnetic polarity sequence determined for the YSZ section to the Plio-Pleistocene Geomagnetic Polarity Time Scale (GPTS) (Lisiecki and Raymo, 2005). The correlation suggests that the Nihewan Formation in...
the YSZ section records a complete geomagnetic polarity pattern from the late Gilbert reversed polarity chron to the early Brunhes normal polarity chron (Fig. 8). The relative lengths of the recorded magnetozones generally comply with the GPTS (Lisiecki and Raymo, 2005). The Matuyama–Brunhes and Gilbert–Gauss boundaries are located at 6.6 and 126.6 m, respectively. The Gauss–Matuyama geomagnetic reversal boundary, which corresponds approximately to the Pliocene–Pleistocene boundary (Gibbard and Head, 2010), is located at a depth of 87.4 m. The Jaramillo (9.9–13.9 m) and Olduvai (48.7–65.5 m) normal polarity subchrons are identified in the Matuyama reversed polarity chron. The Kaena (98.6–102.8 m) and Mammoth (111–113.4 m) reversed polarity subchrons are identified in the Gauss normal polarity chron. Generally, the polarity column of the YSZ section shows no correlation with variations of $c$ (Fig. 8). The four normal magnetozones (i.e., Gauss, Olduvai, Jaramillo and early Brunhes) are not characterized by very low $c$. Further, the $\chi-T$ curves, IRM acquisition and thermal demagnetization (Figs. 5–7) do not hint at a prominent occurrence of greigite (or pyrrhotite) in the Nihewan Formation (see also Ao et al., 2012b). Also biogenic SD magnetite has not been detected. Magnetic properties concur with detrital magnetite, implying that remagnetized strata are less likely (Ao et al., 2012b). In addition, the upper Nihewan Formation also records a short-lived normal magnetozone between the lower boundary of Jaramillo and upper Olduvai boundary, which possibly corresponds to the Gardar geomagnetic excursion (Channell et al., 2002).

Because of short thickness of the underlying aeolian red clay and the existence of a sedimentation hiatus between it and the overlying Nihewan Formation, it is impossible to correlate the magnetozones of the red clay to the GPTS with certainty (Fig. 8). However, the presence of a prominent sedimentation gap between the Nihewan Formation and underlying eolian red clay is undeniable.

5. Discussion

5.1. Chronology and depositional history of the Nihewan Formation

Our new magnetostratigraphy of the YSZ section is comparable to the established magnetostratigraphic records from nearby sections (Løvlie et al., 2001; Zhu et al., 2001, 2004; Wang et al., 2004, 2005; Deng et al., 2006b, 2007, 2008; Li et al., 2008; Liu et al., 2012) (Fig. 10). These combined magnetostratigraphic data together further refine our insight into the chronology and sedimentary history of the Nihewan Formation (Fig. 10). For the
The Nihewan paleolake is a significant sedimentary environment as the small Nihewan Basin (150 km in diameter). It is not excluded that the sedimentation rates in different sections and periods may vary, which is supported by the evident sedimentation gap between the Nihewan paleolakes in different sections across the Nihewan Basin. For example, various thick conglomeratic layers in the HBG, YSZ and HY sections (Fig. 10) imply that sedimentary hiatuses may occur at different levels in different sections and magnetozones, although they are close to each other along the Huliu River (Fig. 1). For example, a local fault is observed at the bottom of the YSZ section (Fig. 1c), which resulted in a ~20 m vertical displacement in the lower Nihewan Formation between the YSZ and HY sections. This is also a reason why the YSZ section has older outcropping Nihewan Formation than the HY section and the sedimentation rates have so remarkable variations between these two sections. The high sedimentation rates during the Olduvai polarity subchron in the YSZ and HY sections imply that a strong riverine input or the depocenter of the Nihewan paleolake possibly occurred in this area during that period. The presence of a prolonged Olduvai polarity subchron in both sections actually provides additional evidence for the reliability of the proposed magnetostratigraphic correlations. In addition, these magnetostratigraphic correlations are supported by the biostratigraphy as well (Fig. 10).

In the XSG, HBG, Majuangou (MJG), Donggou (DG), TEG, XDK, HJT and Xujuyao (XJY) sections, the basal unconformity of the Nihewan Formation is not exposed. In absence of an exposed basal unconformity, the age of the oldest Nihewan Formation sediments remains unknown in these sections. Among the well-dated sections so far, the underlying red clay is only found in the YSZ and HY sections, while the Nihewan Formation in the Xiaohchangliang (XCL), Xianxi (XT), Feiliang (FL) and Donggutuo (DGT) sections is directly overlain by Jurassic red sediments. For the sections, which are dated so far, the starting age of the outcropping Nihewan Formation appears to be different (Fig. 10). Before the presently reported evidence from the YSZ section, the oldest Nihewan Formation is found in the HY and XSG sections, in which the onset of deposition was determined to occur at ~2.8 Ma, just prior to the Pliocene–Pleistocene boundary (Deng et al., 2008; Liu et al., 2012). This is about 900–ka later than the present evidence from the YSZ section, in which the deposition of the Nihewan Formation started at ~3.7 Ma just below the Gilbert–Gauss boundary based on linear extrapolation of the sedimentation rate during the Gauss polarity chron (Fig. 8). Combining the present and previous published magnetostratigraphic data, it emerges that the Nihewan Formation was deposited from (at least) the mid-Pliocene to late Pleistocene (Fig. 10). So, previous suggestions that the Nihewan Formation consists of Pleistocene (Barbour, 1925) or very late Pliocene–Pleistocene (<2.8 Ma) strata (Deng et al., 2008) should be reappraised.

The deposition of the Nihewan Formation (as a result of the formation of paleolake) is more likely to be linked to regional down-faulting tectonic activities (Zhou et al., 1991; Deng et al., 2008; Yuan et al., 2009) than to changes in climate that became colder and drier during the Pliocene (e.g., Zachos et al., 2001; Lisiecki and Raymo, 2005, 2007). Tectonism includes activities of the Xiong’ershan, Youfang, and northern and southern Yuxian faults (Fig. 1). This tectonic formation of the Nihewan paleolake is supported by the evident sedimentation gap between the Nihewan Formation and underlying aeolian red clay deposits in the YSZ and HY areas in the northeastern basin. Before the onset of deposition of the Nihewan Formation, eolian red clay was accumulated not only on the vast Chinese Loess Plateau (Ding et al., 1998) but also in the (later) Nihewan Basin. Without the tectonic activities that led to formation of the Nihewan paleolake, continuous Pliocene (or late Miocene) eolian red clay and Quaternary loess deposition presumably would have been the case in the Nihewan Basin, similar to that on the Chinese Loess Plateau. Because of the tectonic activities, however, eolian red clay was redeposited associated with some conglomerates in some areas of the northeastern Nihewan Basin, such as the YSZ, HY and Shixia areas. Thus a reworked red sedimentary sequence, which makes up the lower Nihewan Formation, is found to overlie the eolian red clay (Deng et al., 2008). The stratigraphic boundary between the two parts of the Nihewan Formation is found below the Olduvai polarity subchron in the YSZ section (Fig. 8), close to the middle...
Fig. 10. Synthesis of the well-dated Nihewan Formation sections with associated mammalian faunas and/or Paleolithic sites to the geomagnetic polarity timescale (GPTS). The lithostratigraphy and magnetostratigraphy from the (a) Xujiayao (XJY) (Løvlie et al., 2001), (b) Donggutuo (DGT) (Wang et al., 2005), (c) Feiliang (FL) (Deng et al., 2007), (d) Xiaochangliang (XCL) (Zhu et al., 2001), (e) Haqiaotai (HJT) (Zhu et al., 2004), (f) Xiaodukou (XDK) (Li et al., 2008), (g) Ta'erzou (TEG) (Wang et al., 2004), (h) Xiantai (XT) (Deng et al., 2006b), (i) Donggou (DG) (Zhu et al., 2001), (j) Majuangou (MJG) (Zhu et al., 2004), (k) Huabangou (HBG) (Deng et al., 2008), (l) Hongya (HY) (Deng et al., 2008), (m) Xiashagou (XSG) (Liu et al., 2012) and (n) Yangshuizhan (YSZ) (this study) (See Fig. 1 for the locations of these sections). (o) GPTS (Channell et al., 2003; Lisiecki and Raymo, 2005). J, Jaramillo; O, Olduvai; R, Réunion; K, Kaena; M, Mammoth.
Olduvai polarity subchron in the HY section and just below the Jaramillo polarity subchron in the HBG section (Deng et al., 2008) (Fig. 10). This indicates that the lithostratigraphic change is not synchronous across the basin, which is rather common in a continental fluvo-lacustrine depositional setting, possibly due to different paleotopography, local faulting activities, distance to the paleoshore, and riverine input. At the northeastern margin of the Nihewan Basin, such as in the XCL, FL and DGT sections, the whole outcropping Nihewan Formation is characterized by grayish-green and grayish-yellow silty clays and clayey silts with associated fine-grained sands or conglomerates. At present, neither reworked red clay nor primary eolian red clay sequences are found in these sections.

Recuperated optically stimulated luminescence (ReOSL) dating has suggested that the termination of the Nihewan Formation in the HY section occurred at about 266 ka (Zhao et al., 2010), which is consistent with the overlying late Quaternary eolian loess and a late Brunhes magnetozone for the top of the Nihewan Formation in this area (Fig. 8). However, the top of the Nihewan Formation in the YSZ section corresponds to the very early Brunhes polarity chron (Fig. 8), which indicates that the top of the Nihewan Formation in the YSZ section may have been significantly eroded. The termination of the Nihewan Formation (as a result of drying up of the Nihewan paleolake) may be linked to both tectonic activities and climate changes. Consistent with increased global cooling (e.g., Zachos et al., 2001; Lisiecki and Raymo, 2005, 2007) and aridification of Asia (e.g., Deng et al., 2005, 2006a; Sun and An, 2005), the precipitation in the Nihewan Basin also had a long-term decreasing trend during the Pleistocene (Ao et al., 2009, 2010b; Ao, 2010). This would result in a decreased amount of water feeding the Nihewan paleolake. More importantly, geological and sedimentological evidence indicates that the northeastern Nihewan paleolake was no longer closed during the late Quaternary because of the combined influences of fault activity and erosion (Zhou et al., 1991; Yuan et al., 2009). There is a more than 30-m vertical fault displacement in the Pleistocene fluvio-lacustrine sediments between the XCL and MJG sections, which points to an active Youfang Fault during the entire Pleistocene. This indicates that Equus has migrated from North America to the Nihewan Basin via the Bering Strait shortly after 2.6 Ma when the sustained major Northern Hemisphere glaciations made the sea level to retreat from the Bering Strait (Lindsay et al., 1980; Deng and Xue, 1999; Wang and Deng, 2011). In addition, it seems that some large mammals also dispersed from Africa to the Nihewan Basin before 2 Ma. For example, the Palaeoloxodon antiques (straight tusked elephant) that originated in Africa (Beden, 1980) was also found in the XSG Fauna (2.2–1.7 Ma) (Liu et al., 2012). Consistent with the dispersal of Proboscidea out of Africa at 2.5–1.5 Ma (Tchernov and Shoshani, 1996), Hippopotamus sp. was also found in the HY Fauna (2.4 Ma) (Deng et al., 2008). Except for the XJY Fauna in the western Nihewan Basin, which occurs in the Brunhes polarity chron, all the other mammalian fauna sites in the northeastern Nihewan Basin are located within the Matuyama polarity chron (Fig. 10). The earliest fauna site currently known is found in the lower part of the Nihewan Formation in the HY section. It has an estimated age of ca 2.4 Ma between the Gauss–Matuyama boundary and the lower Olduvai boundary (Deng et al., 2008) (Fig. 10). Another fauna older than 2 Ma is the XSG Fauna (1.7–2.2 Ma) (Liu et al., 2012) (Fig. 10).

5.3. Implication for hominid occupation in the Nihewan Basin

The Nihewan Basin is a key area for investigating early hominid occupation in East Asia after the initial hominid migration out of Africa. Most of the few hominid or Paleolithic sites of the Early Pleistocene in China were found in the Nihewan Basin, such as the MJG (1.66–1.55 Ma) (Zhao et al., 2004), Lanpo (LP, 1.16 Ma) (Ao et al., 2012b), XCL (1.36 Ma) (Zhu et al., 2001), XT (1.36 Ma) (Deng et al., 2006b), BS (1.32 Ma) (Zhu et al., 2004), FL (1.2 Ma) (Deng et al., 2007; Ao et al., 2012b), Cenjiawan (CJW) (1.1 Ma) (Wang et al., 2006), DGT (1.1 Ma) (Wang et al., 2005), Huojiadi (HJD) (1.0 Ma) (Liu et al., 2010a) and ML (0.78 Ma) (Wang et al., 2005) Paleolithic sites in the Matuyama polarity chron (Fig. 10). Combined with the XJY Paleolithic site at ca 0.5 Ma (Løvlie et al., 2001; Wang et al., 2008), Houguo (HG) Paleolithic site at ca 0.4 Ma (Zuo et al., 2011) and Dongpo Paleolithic site at ca 0.3 Ma (Liu et al., 2010c) in the Brunhes polarity chron, the Paleolithic sites have a time span of ca 1.7–0.3 Ma. During field sampling for the present study, we also found two tool-like stones in the YSZ-II mammalian fossil-bearing layer (1.8 Ma). However, the features of these stones are not typical for stone artefacts found at the northeastern margin of the basin (e.g., MJG, XCL and DGT Paleolithic sites). Since only two of these tool-like stones were found in the YSZ section, the presence of a Paleolithic site at this section is not (yet) unambiguously demonstrated. Alternatively, it is also possible that the older stone artefacts display made evidence less obviously which could point to evolution of the technical ability of early hominids in this region. Up to now, most of the early Paleolithic sites in the Nihewan Basin (Fig. 10) were found at the northeastern margin, i.e. between the southern bank of the Sanggan River and eastern bank of the Hului River (Fig. 1). The presently documented oldest Paleolithic site is located at MJG (1.66 Ma) (Fig. 1) (Zhu et al., 2004), which is ~140-ka younger than the tool-like stones at the YSZ-II Fauna location (1.8 Ma). The incidental finding of tool-like stones in the YSZ section implies that early Paleolithic sites may be expected to be documented in the near...
future by more extensive dedicated archeological investigations on the poorly sampled older Nihewan Formation in the basin (e.g., along the western bank of the Huliu River).

6. Conclusions

Magnetostatigraphy indicates that the Nihewan Formation in the YSZ section records a complete geomagnetic polarity pattern from the late Gilbert to early Brunhes polarity chron. Based on this magnetostatigraphy, the onset of deposition of the Nihewan Formation in the YSZ section is estimated to be as early as ca 3.7 Ma, almost 1-Myr earlier than the recently established evidence. This further extends the lower limit of the Nihewan Formation from the currently established very late Pliocene (~2.8 Ma) to the mid-Pliocene. The present magnetostatigraphy also provides age controls for the E. huanghoensis and E. sanmeniensis fossil mammals found in the upper Nihewan Formation of this section. The combination of present and recently published magnetostatigraphy records considerably refines the chronological framework and depositional history of the Nihewan Formation and provides new clues and implications for early fauna and hominid occupation in the Nihewan Basin.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2012.10.025.

References


