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Earth-Science Reviews 61 (2003) 341–359

EARTH-SCIENCE REVIEWS

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Magnetostratigraphic dating of early humans in China

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Received 2 May 2002; accepted 9 October 2002

Abstract

China is a key area for research into human occupation in the Old World after the initial expansion of early humans out of Africa. Reliable age determinations are pivotal for assessing the patterns of human evolution and dispersal in this region. This paper reviews magnetostratigraphic studies of some early Pleistocene strata bearing hominin remains and/or artifact stone tools from northern to southern China. The quality and reliability of the paleomagnetic dates are also evaluated. New magnetostratigraphic results for the Xihoudu Paleolithic site in north-central China are also presented.

Among the few hominin or Paleolithic sites in China from the early Pleistocene, five have been well investigated. Three of these are in northern China at Xiaochangliang, Donggutuo and Gongwangling; the remaining two in southern China at Longgupo and Yuanmou. Considerable progress has been made during the past three decades towards paleomagnetically dating these sites. Indeed, the age estimates at Xiaochangliang and Gongwangling have been widely accepted. Magnetostratigraphic consensus about the age of the Donggutuo site has also been reached. However, the age determination for the two sites in southern China is still contested.

The integration of rock-magnetic stratigraphy with magnetic polarity stratigraphy has resulted in a determined age of 1.36 Ma for a stone tool-containing layer of lacustrine sediments at the Xiaochangliang site in the Nihewan Basin. Lithostratigraphic constraints have significantly contributed to determining the age of Lantian *Homo erectus* at Gongwangling, which occurred in a loess–paleosol sequence of the southern Loess Plateau. Its age, paleomagnetically derived, is about 1.15 Ma. These two paleomagnetic ages suggest an expansion and flourishing of human groups from northern to north-central China during the early Pleistocene. This suggestion has been reinforced by our new magnetostratigraphic age estimate of about 1.27 Ma for the Xihoudu site as will be presented in this paper. However, more work is needed for the age determinations of the hominin-bearing strata at the Longgupo and Yuanmou sites in southern China. Finally, we stress that it is necessary to combine biostratigraphy, lithostratigraphy and rock-magnetic stratigraphy with the traditional magnetic polarity stratigraphy in order to obtain reliable age determinations for strata bearing hominin remains or stone artifacts.

Keywords: Magnetic stratigraphy; China; Human fossil remains; Stone artifacts; Early Pleistocene; Paleolithic

1. Introduction

During the late Pliocene or early Pleistocene, hominins began to spread out of Africa. A reliable

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d0i:10.1016/S0012-8252(02)00132-0

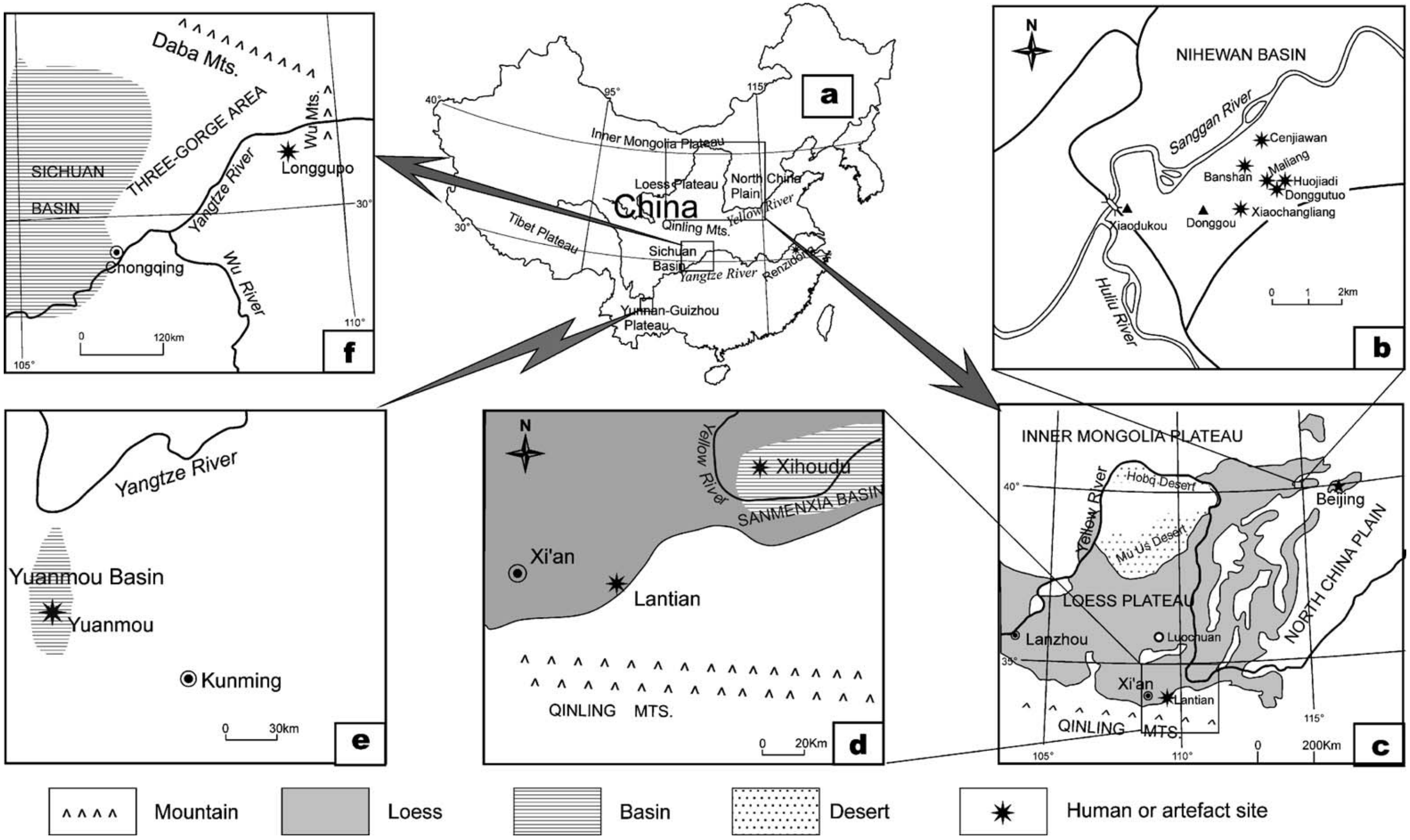


Fig. 1. Location of the Chinese Paleolithic and/or hominin sites mentioned in the text. The Yellow River and Yangtze River are respectively the major river systems in north and south China. The Qinling Mountains are the traditional dividing line between north and south China.

migration chronology is critical for assessing the patterns of human evolution and dispersal. Thus, the timing of human occupation and stone technologies in different regions of the world has been, and continues to be, a topic of common interest. Toward this end, dating by way of magnetic polarity chronostratigraphy has proved very useful in establishing temporal control of hominin-bearing strata over the world (Swisher et al., 1994; Abbate et al., 1998; Gabunia et al., 2000; Goren-Inbar et al., 2000; Oms et al., 2000; An and Ho, 1989; Huang et al., 1995; Zhu et al., 2001).

Asia was the first continent that early humans inhabited when they dispersed from Africa (Gibbons, 2001). China, in particular, has proven to be a laboratory for the study of human evolution in a temperate/subtropical setting. In the past two decades, geologists and geophysicists have carried out magnetic stratigraphic investigations on important Paleolithic sites in China, and the resulting age estimates for when early humans arrived in this area of Asia have been significantly revised. The purpose of this paper is to review developments provided by recent magnetostratigraphic investigations of early Pleistocene strata bearing hominin remains or Paleolithic stone artifacts. The principal sites involved follow along a northeast–southwest transect from the Nihewan Basin in northern China, through the Sanmenxia Basin and the southern Loess Plateau in north-central China, to the Three Gorge area in the middle Yangtze River and the Yuanmou Basin in southwestern China (Fig. 1a).

The Nihewan Basin (Fig. 1b), located in the transition zone between the North China Plain and the Inner Mongolian Plateau, has significantly contributed to our understanding of early human adaptability to northern climates. The Sanmenxia Basin (Fig. 1d) and Loess Plateau (Fig. 1c) in the middle Yellow River north of the Qinling Mountains, and the Three Gorge area in the middle Yangtze River south of the Qinling Mountains and east of the Sichuan Basin (Fig. 1f), were important habitats for hominin migration from south to north or from north to south. The east–west trending Qinling Mountains are the traditional dividing line between temperate northern China and subtropical southern China. The subtropical Yuanmou Basin (Fig. 1e), located along the upper Yangtze River, offers a possible route of human dispersal from western Asia to eastern and southern Asia. This review draws on published paleomagnetic studies of the Nihewan Basin, the Loess Plateau, the Three Gorge area and the Yuanmou Basin, as well as new results from the Xihoudu Paleolithic site in the Sanmenxia Basin.

2. Magnetostratigraphic results

2.1. Localities in the Nihewan Basin

The Nihewan Basin is filled with Pliocene to Pleistocene lacustrine and fluvial deposits, which have been named the Nihewan Beds (Barbour, 1924). The Nihewan Formation, which represents the type section of the early Pleistocene in North China (Young, 1950), was restricted to the lower portion of the Nihewan Beds. Today, the Pleistocene sediments, capped with the last glacial loess and the last interglacial paleosol, are dissected along a southwest–northeast track by the Sanggan River (Fig. 1b). Covering an area of roughly 150–200 km^2, the basin provides extensive sedimentary exposures consisting of well-developed late Cenozoic lacustrine deposits rich in mammalian fossils known as the Nihewan Fauna. These fossils correspond to the Villafranchian Fauna in Europe (Barbour, 1925; Teilhard de Chardin and Piveteau, 1930). A series of sedimentological, geochemical, paleontological and palynological studies (Chen, 1988; Tang et al., 1995; Yuan et al., 1996; Wei, 1997) have contributed significantly to our understanding of the complex stratigraphy and depositional systems in the Nihewan Basin. Specifically, the eastern margin of the basin, which is located approximately 150 km west of Beijing, has yielded a number of fossil-containing and archeological localities, including Xiaochangliang, Donggutuo, Maliang, Cenjiawan, Huojiadi and Banshan (Fig. 1b) (You et al., 1980; Schick et al., 1991; Wei, 1994; Feng and Hou, 1998; Hou, 2000). With the exception of Cenjiawan, these sites have been claimed to be early Pleistocene in age (Li and Wang, 1982; Schick et al., 1991; Schick and Dong, 1993; Wei, 1994; Feng and Hou, 1998; Zhu et al., 2001), and thus relevant to our understanding of early occupation in East Asia. The sites at Xiaochangliang and Donggutuo, recently magnetostratigraphically dated by Zhu et al. (2001) and Li et al. (submitted for publication), have turned out to be particularly important.

2.1.1. Xiaochangliang locality

The Xiaochangliang site (40.2°N, 114.65°E) is significant in that it is one of the few early Pleistocene localities in Asia where mammalian fossils occur in direct association with numerous stone artifacts (Pope and Keates, 1994). The artifacts include side scrapers, notches and, less frequently, examples of end scrapers, burins and disc cores (You et al., 1980; Huang, 1985; Chen et al., 1999; Keates, 2000). Since its discovery in 1978, this site has attracted the attention of geologists, paleontologists and paleoanthropologists. Given its importance, Xiaochangliang is one of the most intensively studied sites in the Nihewan Basin. However, its age had long been debated because of the unavailability of an accurate chronostratigraphic framework. Age determinations by way of electron spin resonance, thermoluminescence and radiometric isotopic methods could not be satisfactorily applied to these artifact-containing strata because of the absence of required materials.

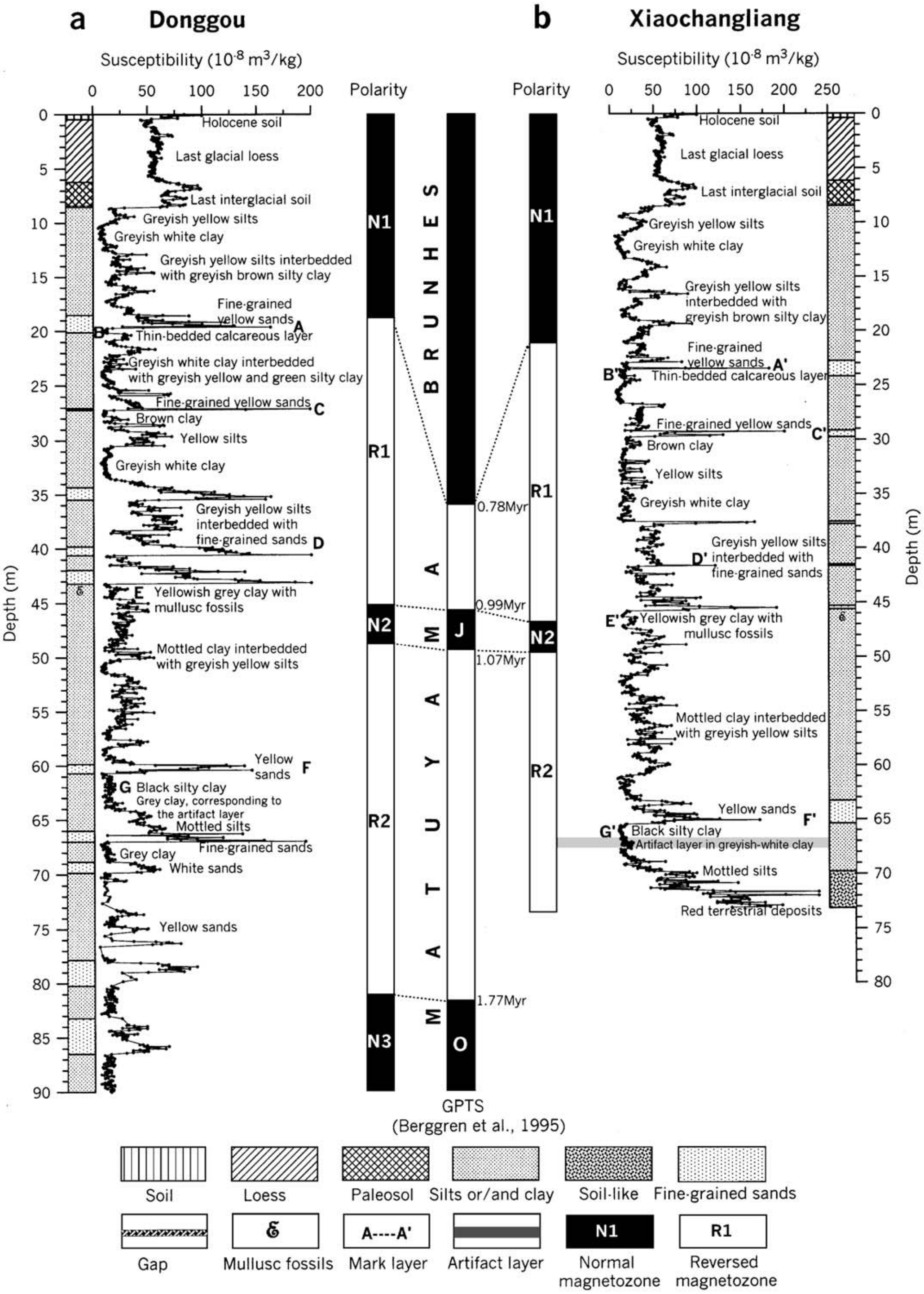
The first attempt to paleomagnetically estimate the age of the artifact layer at the Xiaochangliang site involved the magnetostratigraphic investigation at another site, the Xiaodukou section, some 3 km west from Xiaochangliang (Fig. 1b). Through this indirect and, hence, uncertain determination, Cheng et al. (1978b) proposed that the artifact layer had to be older than 1.5 Ma. However, just recently the first direct age determination of the artifact layer has been made available based on rock magnetic and paleomagnetic study carried out at Xiaochangliang (Zhu et al., 2001).

Through paleomagnetic polarity stratigraphy and rock magnetic susceptibility stratigraphy, Zhu et al. (2001) obtained an unambiguous chronology for this famous artifact-bearing strata at Xiaochangliang. They selected two adjacent sections, namely, Xiaochangliang (73-m thick) and Donggou (90-m thick), for detailed investigations. The two sections were found to have nearly identical sedimentary sequences containing pronounced sedimentological marker layers. Several fine-grained sand layers, associated with high values of magnetic susceptibility (layers A–A′, C–C′, D–D′ and F–F′ in Fig. 2), are found at the same position within the polarity framework of each section. A thinly bedded calcareous layer (layer B–B′ in Fig. 2) and a layer of yellowish-grey clay with mollusc fossils (layer E–E′ in Fig. 2) were also found in the two sections. Importantly, a distinctive 2-cm-thick black silty-clay layer, found immediately above the Xiaochangliang artifact layer (layer G′ in Fig. 2b), is also found in the Donggou section at a depth of 62.2 m (layer G in Fig. 2a). Therefore, the Xiaochangliang section can be safely correlated with the Donggou section on lithological, biostratigraphical and rock-magnetic grounds.

Paleomagnetic samples were collected at 25- and 35-cm intervals, yielding, respectively, 280 levels at Xiaochangliang and 257 levels at Donggou. Three parallel specimens were independently oriented and sampled from each level in the two sections. A total of 1611 samples were subjected to stepwise thermal or alternating field (AF) demagnetization. Some samples were subjected to combined thermal and AF demagnetization. A total of 223 (80%) and 207 (81%) sampling levels containing 669 and 621 samples gave reliable characteristic remanence directions at Xiaochangliang and Donggou, respectively. The averaged characteristic remanent magnetization (ChRM) vector direction for each set of three parallel specimens yielded virtual geomagnetic pole (VGP) latitudes that were used to define the succession of magnetostratigraphic polarity in the two sections.

Five magnetozones are recognized at the Donggou section (Fig. 2a): three normal, N1 (0–18.72 m), N2 (45.20–48.77 m) and N3 (81.12 m to the bottom); and two reversed, R1 (18.72–45.20 m) and R2 (48.77–81.12 m). At the Xiaochangliang section, there are four magnetozones (Fig. 2b): two normal, N1 (0–20.95 m) and N2 (46.55–49.35 m); and two reversed, R1 (20.95–46.55 m) and R2 (49.35 m to the bottom). Note that the stone tool layer at Xiaochangliang is found 17.6 m below the bottom of magnetozone N2. Closer to the center of the Nihewan paleolake, the Donggou section extends further back in time exposing the N3 normal mag-

Fig. 2. Lithology, magnetic susceptibility profiles and magnetostratigraphy of Donggou (a) and Xiaochangliang (b) sections in the Nihewan Basin and correlation with Berggren et al.’s (1995) geomagnetic polarity time scale (GPTS) (modified from Figs. 3 and 4 of Zhu et al., 2001). The two sections have an almost identical sequence of sedimentary facies containing pronounced sedimentological marker layers, A–G. J and O represent the Jaramillo and Olduvai subchrons, respectively.


a Donggou
b Xiaochangliang
Susceptibility (10^{-8} m^3/kg)
Polarity
Depth (m)
Holocene soil
Last glacial loess
Last interglacial soil
Greyish yellow silts
Greyish white clay
Greyish yellow silts interbedded with greyish brown silty clay
Fine-grained yellow sands
A
B
Thin-bedded calcareous layer
Greyish white clay interbedded with greyish yellow and green silty clay
Fine-grained yellow sands
C
Brown clay
Yellow silts
Greyish white clay
Greyish yellow silts interbedded with fine-grained sands
D
E
Yellowish grey clay with mullusc fossils
Mottled clay interbedded with greyish yellow silts
Yellow sands
F
G
Black silty clay
Grey clay, corresponding to the artifact layer
Mottled silts
Fine-grained sands
Grey clay
White sands
Yellow sands
A'
B'
C'
D'
E'
F'
G'
Artifact layer in greyish-white clay
Red terrestrial deposits
N1
R1
N2
R2
N3
BRUNHES
MATUYAMA
J
O
0.78Myr
0.99Myr
1.07Myr
1.77Myr
GPTS (Berggren et al., 1995)
Soil
Loess
Paleosol
Silts or/and clay
Soil-like
Fine-grained sands
Gap
Mullusc fossils
Mark layer
Artifact layer
Normal magnetozone
Reversed magnetozone

netozone. Magnetozones N1, N2 and N3 correspond to the Brunhes chron, the Jaramillo subchron and the Olduvai subchron, respectively. This correlation is further strengthened by the fact that the mammalian fauna preserved in the Xiaochangliang stone artifact layer indicates a late Pliocene to early Pleistocene age (Huang and Fang, 1991; Tang et al., 1995; Wei, 1997; Qiu, 2000). The layer preserves a rich vertebrate fauna, including *Allophaiomys* cf. *A. pliocaenicus*, *Mimomys chinensis*, *Hyaena* (*Pachycrocuta*) *licenti*, *Palaeoloxodon* sp., *Hipparion* sp., *Proboscidipparian sinensis*, *Equus sanmeniensis*, *Coelodonta antiquitatis*, *Martes* sp., *Cervus* sp., and *Gazella* sp. (You et al., 1980; Tang et al., 1995). Of these Nihewan faunal elements, the first six taxa are indicative of a late Pliocene to early Pleistocene age (You et al., 1980; Tang et al., 1995; Wei, 1997; Qiu, 2000). *E. sanmeniensis* ranges from early to middle Pleistocene (Tang et al., 1995; Wei, 1997; Deng and Xue, 1999).

At the Donggou section, magnetozone R2 with a thickness of 32.35 m is bounded by the termination of the Olduvai subchron (magnetozone N3) and the onset of the Jaramillo subchron (magnetozone N2). The time span between these two boundaries is known to be about 0.7 my (Berggren et al., 1995) yielding an average rate of sedimentation of about 4.6 cm/ky during this interval of reverse polarity. Note that the 2-cm-thick layer of black silty clay in the Donggou section—which correlates with the top of the artifact layer in the Xiaochangliang section—lies within magnetozone R2 13.4 m below the bottom of magnetozone N2 (that is, before the onset of the Jaramillo subchron) (Fig. 2). Assuming a constant rate of sedimentation during the deposition of magnetozone R2, the age of the black silty layer is calculated to be about 1.36 Ma.

This research into the Xiaochangliang site yields the oldest accepted date for human presence in northeast Asia (at latitudes around 40°N), and is an illustrative example of chronological correlation by means of rock-magnetic and paleomagnetic stratigraphy. It is thus reasonable to suspect that a combination of these magnetic stratigraphies may be applicable to the continued dating of other lacustrine successions, ultimately establishing a chronological sequence for Paleolithic sites in the Nihewan Basin.

2.1.2. Donggutuo locality

This site (40.2°N, 114.67°E) is one of the most extensively excavated and prolific sites yet studied in the Nihewan Basin (Schick et al., 1991; Wei, 1997; Hou, 2000). Here the Nihewan Beds have a thickness of about 36 m, capped by the last glacial loess (5 m) and the last interglacial soil (2.5 m) and underlain by Jurassic breccia (Fig. 3). The lake margin sediments mainly consist of clay, clayey silts, silts and fine-grained sands (Hou et al., 1999; Hou, 2000). The yellow fine-grained sands have the highest magnetic susceptibilities while the grey and greyish-yellow silts have the lowest.

The 5-m-thick artifact layer is located within the bottom interval of this section (Hou et al., 1999; Hou, 2000). The artifacts include cores/choppers, flake scrapers (Schick et al., 1991) and shaped-cores (Hou et al., 1999). There are five archeological horizons (A, B, C, D and E) (Schick et al., 1991; Hou et al., 1999; Hou, 2000). The top three horizons (A, B and C) are composed of silts and fine-grained sands. Horizon D is conglomeratic with some pebbles and cobbles in a silty sand and fine-grained sand matrix. The lowest horizon, level E, comprises sandy silts (Schick et al., 1991; Hou et al., 1999).

A preliminary paleomagnetic study of the Donggutuo sequence was conducted two decades ago by Li and Wang (1982), who claimed that the artifact layer is located about 5 m below the Jaramillo subchron. They then estimated the age of the Donggutuo site to be about 1.1 Ma, an age estimate that has been supported by the later paleomagnetic analysis of Schick and Dong (1993). However, this later work has proven difficult to evaluate as no paleomagnetic data appeared in the paper. Recently, Li et al. (submitted for publication) re-sampled the section at about 25-cm intervals, yielding 184 levels. Stepwise thermal or AF demagnetization was performed on all oriented samples. Remanences were measured using a 2G three-axis cryogenic superconducting magnetometer installed in a magnetic field-free space (< 300 nT). Four magnetozones are recognized: two normal, N1 and N2, and two reverse, R1 and R2. Magnetozone N2 is cut by a tiny reversed zone (Fig. 3). Magnetozones N1 and N2 correspond to the Brunhes chron and the Jaramillo subchron, respectively. The artifact layer lies just below the Jaramillo onset (~ 1.1 Ma). Therefore, Li et al. (submitted for publication)'s

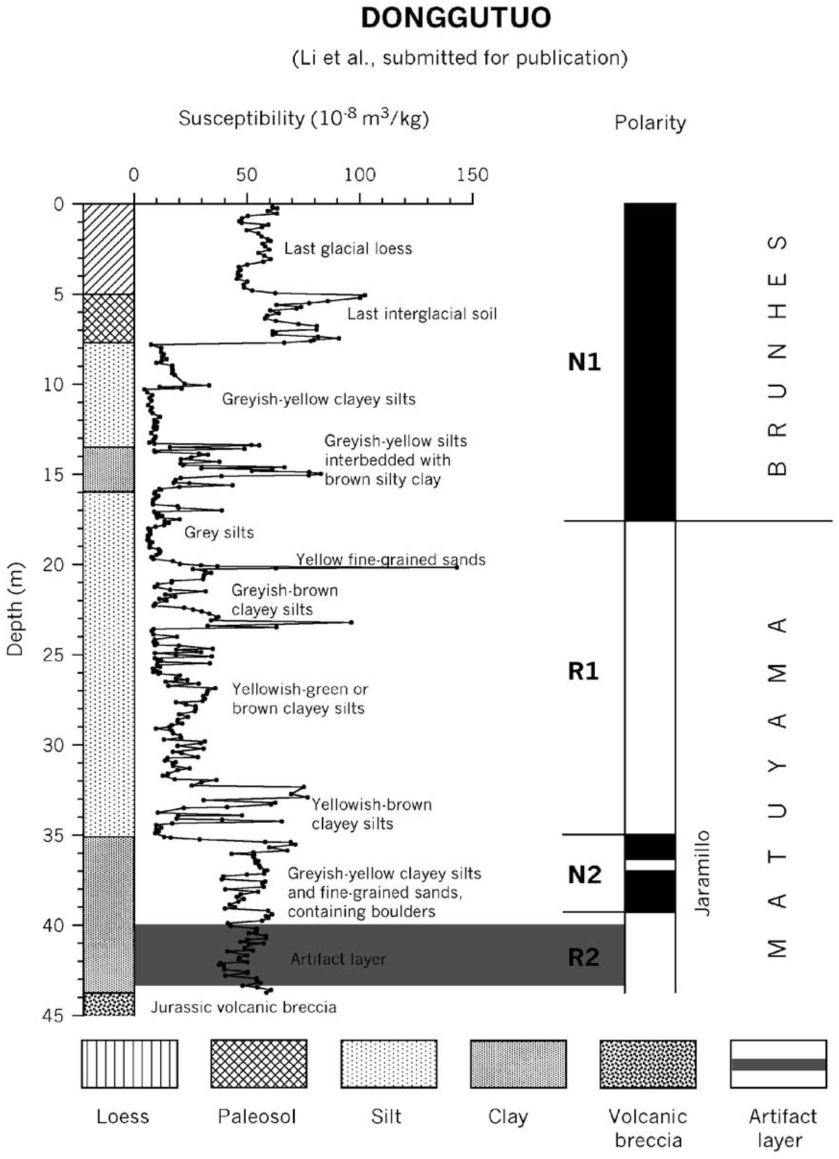


Fig. 3. Lithostratigraphy (Hou, 2000), magnetic susceptibility profile and magnetostratigraphy (after Li et al., submitted for publication) at Dongguto in the Nihewan Basin.

detailed paleomagnetic results support the previous conclusion (Li and Wang, 1982; Schick and Dong, 1993).

2.2. Gongwangling locality

Nearly four decades ago, the Lantian *Homo erectus* cranium was found at Gongwangling in the southern margin of the Chinese Loess Plateau. The loess–paleosol sequence at this locality has a thickness of about 35 m, and is underlain by weathered early Pleistocene sandy gravels (An and Ho, 1989) (Fig. 4). On the basis of morphological features and associated faunal assemblages, the age of the *H. erectus* fossil at this site was estimated to be older than that of Beijing Man from the Zhoukoudian site (Jia et al.,

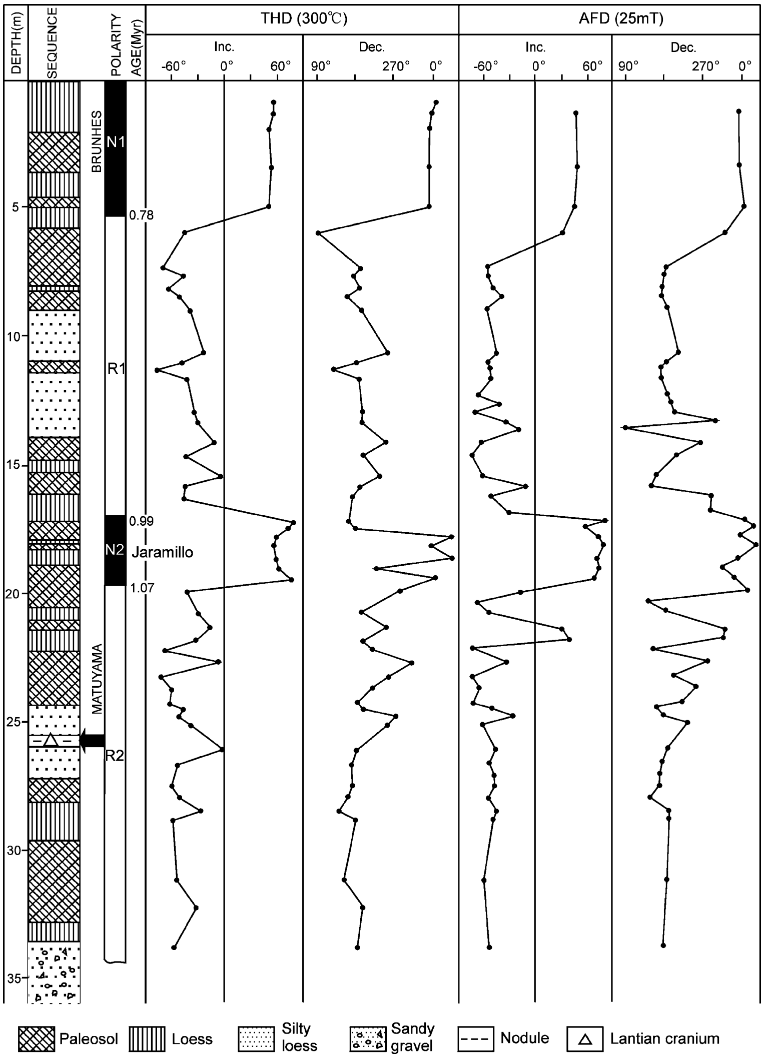


Fig. 4. Lithostratigraphy and magnetostratigraphy at Gongwangling in the southern Loess Plateau and correlation with the geomagnetic polarity time scale (modified from An and Ho, 1989). THD, thermal demagnetization; AFD, alternating field demagnetization; inclination; Dec., declination.

1966; Zhou, 1966). On biostratigraphical grounds the age was claimed to be about 0.7 Ma (Aigner and Laughlin, 1973). Subsequently, paleomagnetic analyses were conducted in order to quantitatively determine the age of the *H. erectus* fossil. Ma et al. (1978) and Cheng et al. (1978a) determined there to be two magnetozones in the Gongwangling sequence: the upper one being normal; and the lower one, reverse. The early human fossil is found in the lower magnetozone. Ma et al. (1978) correlated the upper magnetozone with the Brunhes chron, and the lower magnetozone with the late Matuyama chron. This attribution led them to estimate the age of *H. erectus* to be 0.75–0.80 Ma. However, Cheng et al. (1978a) correlated the upper magnetozone with the Jaramillo subchron and, therefore, suggested *H. erectus* to be older than its onset estimating the age to be 0.98 Ma. Liu and Ding (1984) claimed that one silty loess layer, in which the *H. erectus* fossil was found, was recognizable as the upper silty horizon (L9) of the Luochuan profile (Fig. 1c) in the Gongwangling loess–paleosol sequence. They concluded that *H. erectus* occurred just below the Matuyama/Brunhes boundary, estimating its age at 0.73–0.80 Ma.

The most detailed investigation of the Gongwangling site was conducted by An and Ho (1989) by means of magnetostratigraphy and lithostratigraphy. These researchers identified two sandy loess layers contained in the Gongwangling loess–paleosol sequence (Fig. 4), and claimed that they correspond to the upper (L9) and lower (L15) silty loess horizons in the classic Luochuan section, marker layers widely used in the Chinese Loess Plateau (Liu, 1985). The Lantian cranium was found midway within layer L15. Two sets of loess–paleosol samples from 60 levels at the Gongwangling locality were progressively demagnetized using thermal and AF methods. Four magnetozones (two normal, N1 and N2; and two reversed, R1 and R2) were established in this section (Fig. 4). On the basis of the lithological and paleomagnetic data, magnetozones N1 and N2 were proposed to correspond to the early Brunhes chron and the Jaramillo subchron; and magnetozones R1 and R2 to the late Matuyama chron separated by the Jaramillo subchron.

Based on the following considerations, this interpretation appears to be valid: the two silty loess layers give a reliable stratigraphic constraint on the Gongwangling section. The boundary between magnetozones N1 and R1 in the upper part of loess layer L8 can be safely correlated with the Matuyama/Brunhes boundary (Kukla and An, 1989; Liu et al., 1991a; Zheng et al., 1992). Magnetozone N2, which occurs between the middle part of paleosol S12 and the lower part of loess layer L10, can be correlated with the Jaramillo subchron (Rutter et al., 1991; Zheng et al., 1992; Heller and Evans, 1995; Pan et al., 2002). Based on the extrapolation of the mean deposition rate of the Gongwangling section, An and Ho (1989) estimated the age of Lantian *H. erectus* to be 1.15 Ma. Furthermore, the new astronomical time scale for the Chinese loess–paleosol sequences developed by Heslop et al. (2000) has well documented the age of each loess or paleosol unit and, in particular, gives an age of 1.22–1.19 Ma for loess layer L15. Hence, the age of Lantian *H. erectus* has been tightly constrained by magnetostratigraphic investigation and lithostratigraphic succession of loess–paleosols.

2.3. Xihoudu locality

Stone artifacts were uncovered in 1960 at the Xihoudu Paleolithic site (34.7°N, 110.7°E) in the Sanmenxia Basin (Fig. 1d). With a thickness of 87.5 m, the Xihoudu section can be divided into four lithologic portions (Fig. 5): the top portion (0–52.6 m) is composed of loess-like sediments. The second portion (52.6–62.5 m) is a 9.9-m-thick lakeshore sand layer with cross-bedding. The third portion (62.5–76.7 m) comprises lacustrine silts and sands. The bottom portion (76.7–87.5 m) consists of conglomeratic sands and silts. The layer bearing stone artifacts (53.4–53.9 m) comprises greyish-white and greyish-yellow sands. It preserves a rich vertebrate fauna, including *Proboscidipparion sinense*, *Elaphurus bifurcatus*, *Euctenoceros boulei*, *Bison palaeosinensis*, *E. sanmeniensis*, *C. antiquitatis* and *Elasmotherium inexpectatum* (Jia, 1989). The fauna can be correlated with the Nihewan mammalian fauna, which suggests an age interval from late Pliocene to early Pleistocene (Qiu, 2000; Tang et al., 1995; Wei, 1997; Deng and Xue, 1999). Based on the results of a broad-brush magnetostratigraphic study, the age of the artifact layer was initially claimed to be about 1.8 Ma (Jia, 1985). More detailed investigations are therefore needed in order to understand more accurately the chronology of the Xihoudu section and the age of the Paleolithic site. To this end, we now present a revised polarity stratigraphy.

We have paleomagnetically re-sampled the Xihoudu section at 5–30-cm intervals, and performed stepwise thermal and AF demagnetization techniques on 350 oriented samples. A total of 322 (92%) samples gave reliable characteristic remanence directions. Six magnetozones are recognized (Fig. 5): three normal N1 (0–20.2 m), N2 (34.9–43.2 m) and N3 (78.3–84 m) and three reversed R1 (20.2–34.9 m), R2 (43.2–78.3 m) and R3 (84–87.5 m).

On the basis of the biochronological and paleomagnetic data, the Xihoudu magnetozones have been correlated with the geomagnetic polarity time scale (Berggren et al., 1995) (Fig. 5). Magnetozones N1, N2 and N3 were identified as the Brunhes chron, the Jaramillo subchron and the Olduvai subchron, respectively, and magnetozones R1, R2 and R3 successive reverse polarity portions of the intervening Matuyama chron. This correlation relies on the following con-

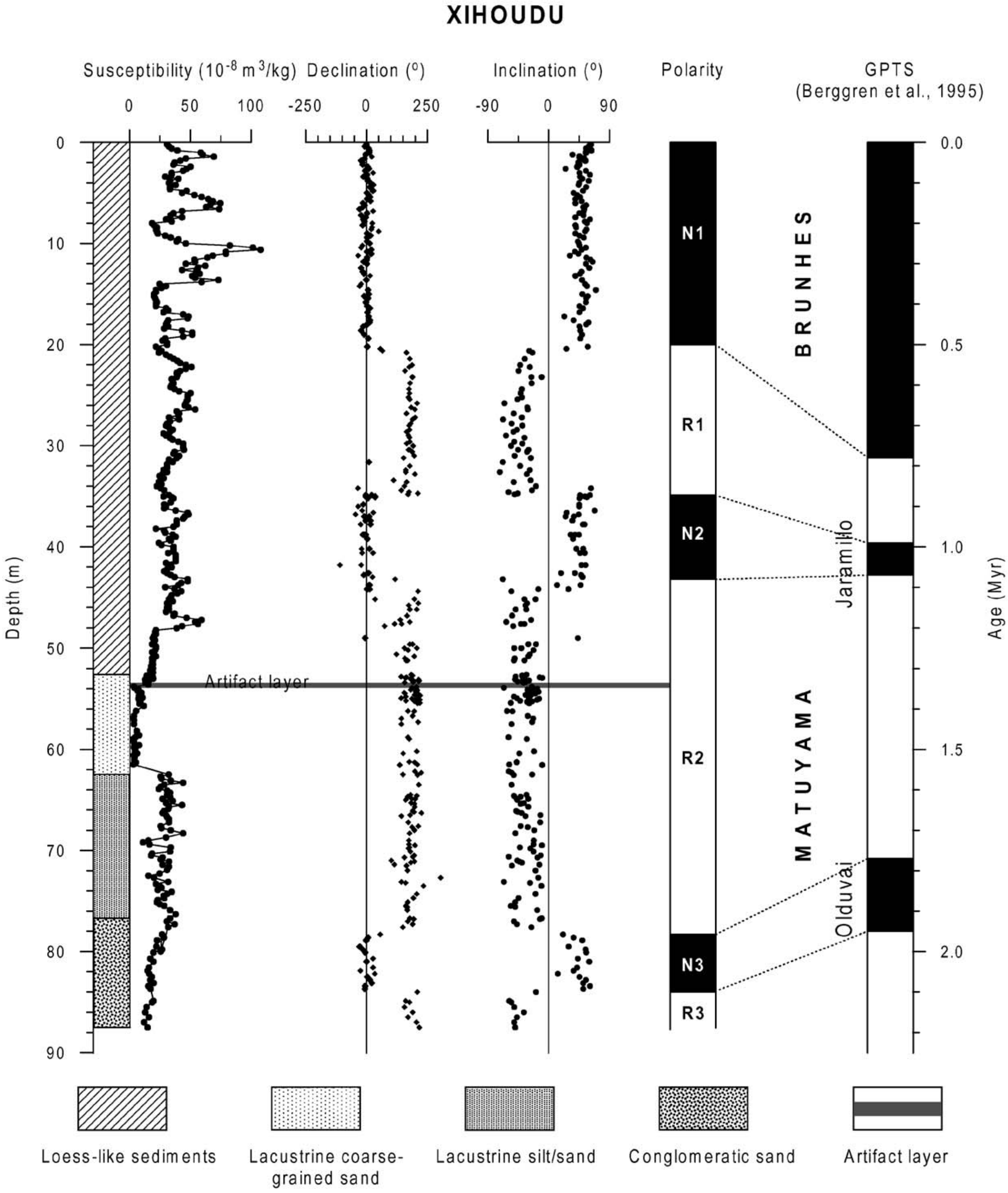


Fig. 5. Magnetostratigraphy at Xihoudu in the Sanmenxia Basin and correlation with Berggren et al.'s (1995) geomagnetic polarity time scale.

siderations: first, the mammalian fauna gives a comprehensive age interval from late Pliocene to early Pleistocene. Second, the Malan loess, which was deposited during the last glaciation period, is found to overlay the Xihoudu sequence. Third, the loess-like sequence in the upper portion of the Xihoudu succession displays no significant gaps and, therefore, appears to have recorded magnetozones N1, R1 and N2 in a substantially continuous fashion. Thus, magnetozones N1 and N2 can be correlated with the Brunhes chron and the Jaramillo subchron, respectively. Furthermore, there is no obvious gap between the loess-like sequence and the underlying lake sediments, indicating that magnetozone N3 corresponds to the Olduvai subchron. Magnetozone R2, bounded by the termination of the Olduvai subchron (N3) and the onset of the Jaramillo subchron (N2), spans roughly 0.7 my (Berggren et al., 1995). The thickness of magnetozone R2 is 35.1 m, while the artifact layer within it lies 10.2 m below the Jaramillo onset. Thus, if we assume a constant rate of accumulation for magnetozone R2, the age of the artifact layer can be estimated to be about 1.27 Ma.

2.4. Longgupo locality

Longgupo Cave (30.4°N, 109.1°E), also known as the Wushan Hominid Site, was discovered in 1984. It lies 20 km south of the Yangtze River near the eastern border of the Sichuan Basin (Fig. 1f). Dental fragments reported as early human, *Gigantopithecus* and crude stone artifacts were found in this cave (Huang and Fang, 1991). The cave infilling is mainly composed of two sedimentary units (Huang et al., 1995) (Fig. 6). The fossil-poor upper unit consists of a 12-m-thick cave breccia where clasts

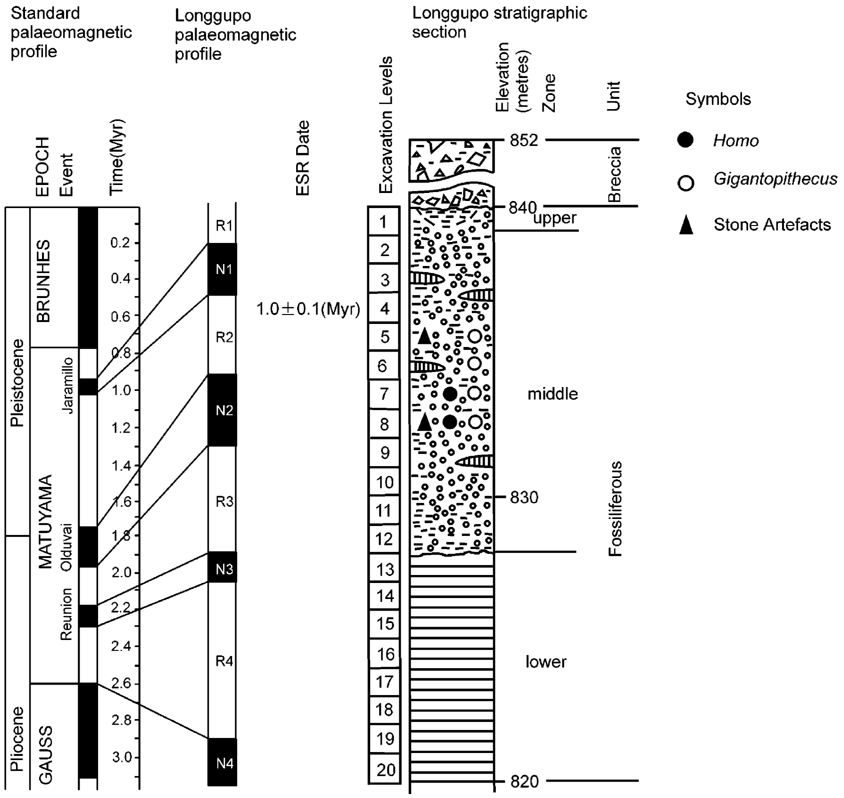


Fig. 6. Lithostratigraphy and magnetostratigraphy of the Longgupo Cave and correlation with the geomagnetic polarity time scale (after Huang et al., 1995).

are highly cemented in sandy clay. The fossiliferous lower unit (20 m thick) consists of three depositional zones excavated in 1-m levels. The upper zone (within level 1) consists of sandy clay lenses with some gravels and calcite concretions. The middle zone (levels 2–12), which mainly comprises a clay facies localized along the north and south cave walls in longitudinal channels 2–3-m wide, has yielded 68 mammalian genera including the primates *Procynocephalus*, *Macaca*, *Gigantopithecus* and *Homo* (Huang and Fang, 1991; Huang et al., 1995). The co-occurrence of *Sinomastodon*, *Nestoritherium*, *Equus yunnanensis*, *Ailuropoda microta* and *Mimomys peii* significantly constrains the middle zone clay facies to an age range from the late Pliocene to earliest Pleistocene. The rodent genus *Mimomys* was known to have lived between 1.6 and 2.0 Ma (cf. Balter and Gibbons, 2000). Levels 7–8 have yielded two hominin dental fragments—a fragmentary left mandible and a right upper lateral incisor—while levels 5 and 8 contain stone artifacts. The lower zone (levels 13–20) primarily consists of fluvial or lacustrine silts.

Paleomagnetic study of the fossiliferous lower unit of the Longgupo Cave sequence was first conducted by Liu et al. (1991b). One hundred oriented paleomagnetic samples were collected at 15–30-cm intervals. All of the samples were subjected to stepwise thermal demagnetization; remanences were measured using a Minispin magnetometer. These authors found that the hominin-bearing layers were within a normal magnetozone, and correlated them to the Reunion normal subchron recently dated at 2.13–2.15 Ma (Baksi and Hoffman, 2000). It should be noted, however, that the natural remanent magnetization (NRM) intensity values for these particular cave sediments were often quite weak, ranging from 7.06×10^{-9} to 0.1×10^{-9} A/m with a mean value of 3.58×10^{-9} A/m. Given such weak remanences, it is most doubtful that a Minispin magnetometer could have provided magnetic polarities with any accuracy.

Later, Huang et al. (1995) carried out a new paleomagnetic investigation on the Longgupo cave sequence. They recognized eight magnetozones: four normal N1, N2, N3 and N4, and four reversed R1, R2, R3 and R4 (Fig. 6). The hominin fossils were determined to be associated with a period of normal magnetic polarity within magnetozone N2. These authors correlated this magnetozone to the Olduvai subchron, which has been dated to extend from 1.95 to 1.77 Ma (Berggren et al., 1995). Huang et al.'s (1995) age estimate for the Longgupo hominin remains is 1.8–1.9 Ma, based on the following considerations: first, mammalian fauna provides an age constraint from late Pliocene to earliest Pleistocene. Second, electron spin resonance analysis of tooth enamel from level 4 yields an age of 1.0 ± 0.1 Ma based on the linear uptake model, which led the authors to assign the magnetically normal levels 2–3 to the Jaramillo subchron; and the magnetically normal hominin-bearing levels 7–8 to the Olduvai subchron.

Liu et al.'s (1991b) work was not widely known because it was published in a Chinese journal. When Huang et al. (1995) published their work, the Longgupo Cave attracted the attention of many paleoanthropologists for two reasons: first, the study may document the oldest archeological record in south China. Second, the work reinforced the age range of 1.6–1.8 Ma for hominin fossils from Java (Swisher et al., 1994), although this determination has come under attack (De Vos and Sondaar, 1994).

Yet, Huang et al.'s (1995) results have been strongly contested (Culotta, 1995; Schwartz and Tattersall, 1996; Balter and Gibbons, 2000; Langbroek and Roebroeks, 2000). There are no detailed paleomagnetic data made available in their publication; thus, it is difficult to evaluate these findings. Questions also arise from their age determined through electron spin resonance (cf. Culotta, 1995). Furthermore, the geology of cave deposits, such as at Longgupo, is very complex. Indeed, materials falling from above may mix with older cave deposits. In short, it is most challenging to attempt to magnetostratigraphically date cave sequences. However, more contentious than the dating at Longgupo is the notion that the travelers were pre-*erectus* (cf. Culotta, 1995). Some researchers even doubt that the teeth are, in fact, human (Gabunia et al., 2000). It has been argued that the morphology of fossils found at the Longgupo Cave site indicates the presence of hominoids whose specific taxonomic assignments remain unclear, even though the associated stone tools are certainly evidence of the presence of hominoids (Schwartz and Tattersall, 1996).

2.5. Yuanmou locality

The Yuanmou Basin (Fig. 1e), which is situated 110 km northwest of Kunming City, southwest China, is a north–south elongated basin in the southwestern part of the Yunnan–Guizhou Plateau with an altitude of 1050 to 1380 m (Qian and Zhou, 1991). The basin is mainly filled with late Cenozoic sediments that yield mammalian fossils. Incisors of *H. erectus* were discovered in the upper part of the Yuanmou sequence (Hu, 1973; Qian and Zhou, 1991).

The layer bearing the hominin remains preserves a rich vertebrate fauna, known as the Yuammou Fauna, containing *Homo erectus yuanmouensis*, *Nestoritherium* sp., *Megantereon nihowanensis*, *Cervocerus ultimus*, *Metacervulus capreolinus*, *Muntiacus lacustris*, *Paracervulus attenuatus*, *Eostyloceros longchuanensis*, *Procapreolus stenosis*, *H. licenti*, *E. yunnanensis*, *Canis yuanmouensis*, *Axis shansius*, *Axis* cf. *rugosus*, *Rusa yunnanensis*, *Gazella* sp., *Cervus* sp., *Ochotonoides complicidens*, *Rhizomys* sp., *Microtus* sp., *Arvicola* sp., *Hystrix subcristata*, *Vulpes* cf. *chikushanensis*, *Viverricula malaccensis fossilis*, *Hyaena* sp., *Panthera tigris*, *Panthera pardus*, *Cynailurus* sp., *Stegodon* sp., *Stegodon elephantoides*, *Rhinoceros sinensis*, *Rhinoceros* sp., *Sus* sp., *Sus scrofa*, *Rusa* sp., *Cervus stehlini*, *Bos* sp. and *Bibos* sp. (Qian and Zhou, 1991; Deng and Xue, 1999). The fossils, representing 38 species, exhibit the following characteristics: first, the mammalian fauna includes eight survivors from the Tertiary period, namely, *Nestoritherium* sp., *M. nihowanensis*, *C. ultimus*, *M. capreolinus*, *M. lacustris*, *P. attenuatus*, *E. longchuanensis* and *P. stenosis*. Second, 35 of the 38 taxa are extinct. Third, six taxa typical of the early Pleistocene are present, namely, *H. licenti*, *E. yunnanensis*, *C. yuanmouensis*, *A. shansius*, *A.* cf. *rugosus* and *R. yunnanensis*. Therefore, these Yuanmou faunal elements are indicative of an early Pleistocene age, and basically correspond to the Nihewan Fauna of the early Pleistocene in northern China (Qian and Zhou, 1991; Deng and Xue, 1999).

Paleomagnetic study of the Yuanmou sequence was pioneered by Li et al. (1976). Their result showed that Yuanmou *H. erectus* occurs within a tiny reverse polarity magnetozone bracketed by normal polarity magnetozones. These authors interpret these three magnetozones to the Gilsa normal event and those portions of the Matuyama reverse chron which border it. The Gilsa has an estimated age of 1.7 Ma (Worm, 1997) according to Valet and Meynadier's (1993) relative paleointensity record obtained from sediments from the equatorial Pacific. Li et al.'s (1976) paleomagnetic result is highly questionable, as it was based on only 76 samples collected at 10–15-m intervals, and of them only nine samples were subjected to stepwise AF demagnetization. All others were demagnetized only once in a peak AF of 30 mT. Also, the magnetic remanences were measured with an astatic magnetometer, a device considered rather insensitive by today's standards when sediment magnetism is involved.

Subsequently, several research groups have paleomagnetically documented the Yuanmou *H. erectus* to be within the Olduvai subchron (Cheng et al., 1977; Liang et al., 1988), a subchron considerably longer in duration than the Gilsa. Thereafter, 178 oriented samples were collected at 2–5-m intervals along the Yuanmou sequence and stepwise thermally demagnetized (Qian and Zhou, 1991). The remanences were measured using a cryogenic superconducting magnetometer at Peking University, a DIGICO flux-gate magnetometer and a Minispin magnetometer. Similar to Li et al's result, Qian and Zhou (1991) found the Yuanmou *H. erectus* to be within a thin reversed magnetozone, which is also bracketed by normal polarity magnetozones. This detailed work by Qian and Zhou (1991) confirmed the interpretation by both Cheng et al. (1977) and Liang et al. (1988) that the thin reversed magnetozone containing Yuanmou *H. erectus* is within the Olduvai subchron (Fig. 7). The paleomagnetic results are further supported by the Yuanmou fauna, which suggests an early Pleistocene age (Qian and Zhou, 1991; Deng and Xue, 1999), and by electron spin resonance age determinations, obtained from horse and rhinoceros fossil teeth, which yield an age of 1.1–1.6 Ma (Huang and Grün, 1998).

It should be noted, however, that the age of Yuanmou *H. erectus* presently remains open even though a number of studies mentioned above suggest there to be a consensus of its occurrence within or near the Olduvai subchron. Liu and Ding (1983) suggested that the age of Yuanmou *H. erectus* should be not earlier than the onset of the Brunhes chron on lithostratigraphic, biostratigraphic and magnetostratigraphic grounds. Recently, a joint Japanese–Chinese

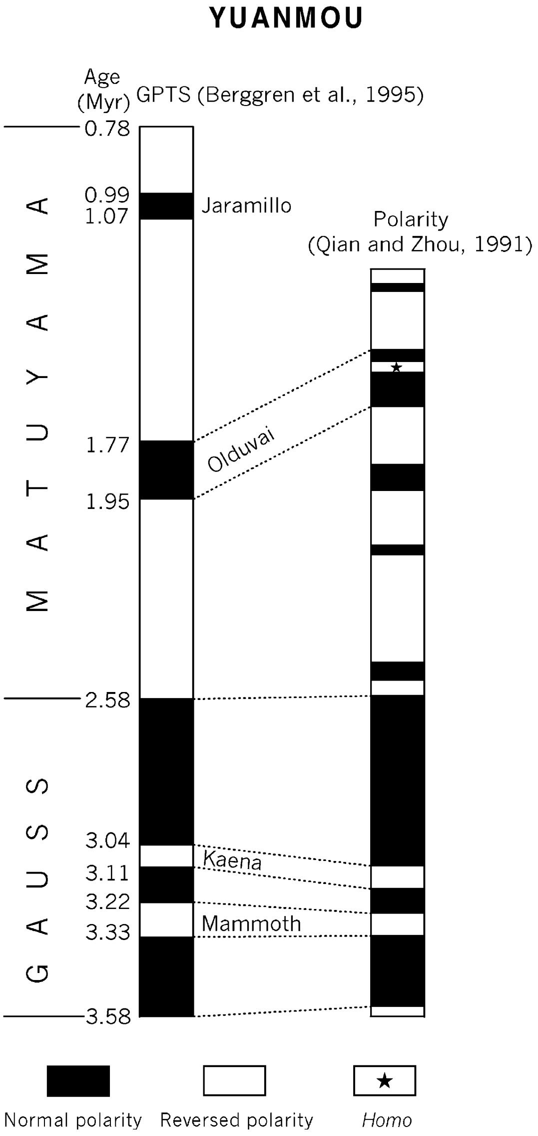


Fig. 7. Magnetostratigraphy of the late Cenozoic successions in the Yuanmou Basin and correlation with Berggren et al.'s (1995) geomagnetic polarity time scale (modified from Qian and Zhou, 1991).

team re-examined the lithostratigraphy, sedimentary facies and depositional systems of late Cenozoic successions including the excavated beds in the Yuanmou Basin that yielded the hominin remains (Urabe et al., 2001). Interestingly, the team's reconstructed magnetostratigraphy of the Yuanmou sequence placed the Yuanmou *H. erectus* above the Matuyama–Brunhes boundary (Hyodo et al., 2002), which has been most recently dated at 0.78–0.79 Ma (Singer et al., in press). These most recent results suggest that Yuanmou *H. erectus* should be assigned to the middle Pleistocene, rather than the early Pleistocene. In addition, we note that in the paleomagnetic results mentioned above the sediments bearing Yuanmou *H. erectus* possess reversed magnetic polarity. However, Hyodo et al. (2002) correlated this thin magnetozone to the 'Stage 17 event' at 0.69 Ma, a possible reversal during marine isotope stage 17 (Biswas et al., 1999). This finding is greatly at odds with previous results (Li et al., 1976; Qian and Zhou, 1991). Hence, there is currently no consensus on the age of the Yuanmou *H. erectus*, and additional detailed paleomagnetic investigations may be necessary to resolve the matter.

3. Implications of the magnetochronology

Although the timing of the first habitation and stone technology in different regions of the Old World remains a contentious topic in the study of human origin and migration (e.g. Huang et al., 1995; Behrensmeyer et al., 1997; Ambrose, 2001; Zhu et al., 2001), magnetostratigraphical investigations (summarized in Fig. 8) of early Pleistocene hominin-bearing strata along a northeast–southwest transect in China have significantly increased our understanding of this topic. There is a general consensus that Africa was the birthplace of humanity, and that Asia was not only the first continent early humans explored on their spread from Africa, but also was the departure point for later treks to the New World, Australia, and perhaps Europe (Gibbons, 2001). However, exactly when early humans first reached Asia has long puzzled paleoanthropologists (Balter and Gibbons, 2000; Gibbons, 2001).

During the past decade several new age determinations of the oldest out-of-Africa hominin sites have helped clarify the chronology. In this regard, the Dmanisi site in the Republic of Georgia, west Asia, is an excellent example. Paleontological, archeological, geochronological and paleomagnetic data from the Dmanisi site all suggest that the migration began in the early Pleistocene at about 1.7 Ma (Gabunia and Vekua, 1995; Gabunia et al., 2000), an age that is

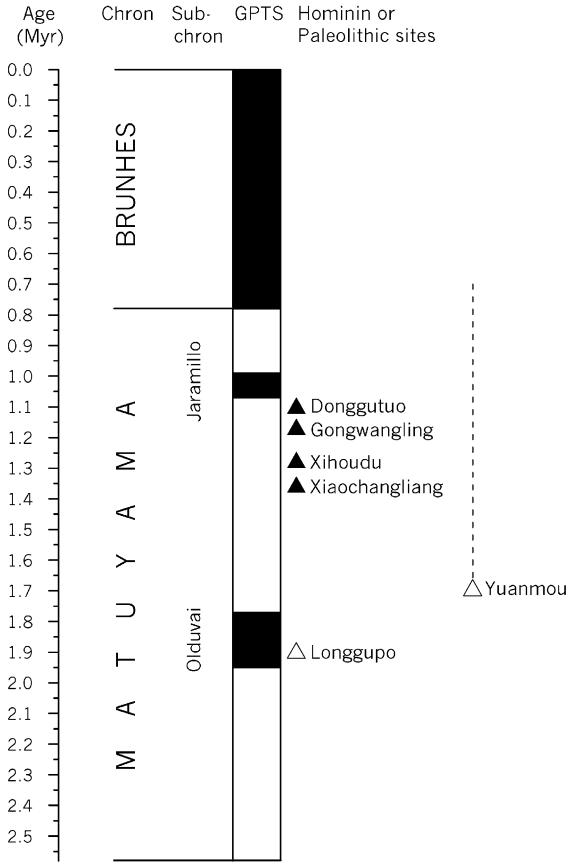


Fig. 8. A synthetic diagram related all hominin or Paleolithic sites reviewed in this paper to the geomagnetic polarity time scale (Berggren et al., 1995). The open triangles represent less certain paleomagnetic placement and ages than the shaded triangles.

considered to be reasonable by many geochronologists and paleoanthropologists (cf. Balter and Gibbons, 2000). Indeed, the Dmanisi humans are thus far the most ancient undisputed human fossils outside Africa (Balter and Gibbons, 2000).

As discussed in this paper, age determinations of early out-of-Africa hominin sites in south China and southeast Asia are now available: Yuanmou, 1.7 Ma (Li et al., 1976; Qian and Zhou, 1991); Longgupo, 1.9 Ma (Huang et al., 1995); Java, Indonesia, 1.8 Ma (Swisher et al., 1994), yet these dates remain controversial. In addition, the Renzidong Cave site (31.1 °N, 118.1 °E) along the lower Yangtze River in southern China (Fig. 1a)—at which some stone artifacts, bone artifacts and a great variety of vertebrate fossils, including *Procynocephalus*, were found—has been claimed to be earliest Pleistocene (Jin et al., 2000). However, a more precise age determination for this site remains unavailable. Obviously, then, evidence for the oldest hominin settlement in south China and southeast Asia remains unsolved.

Leaving the contested Yuanmou, Longgupo and Java sites aside, age analyses from certain hominin sites in North China appear to be widely accepted by researchers. In the Nihewan Basin, Xiaochangliang yields recognizable types of Paleolithic tools dated at 1.36 Ma (Zhu et al., 2001), while other unambiguous tool forms at Donggutuo have been dated at about 1.1 Ma (Li and Wang, 1982; Schick and Dong, 1993). In north-central China as well, Gongwangling yields a cranium of *H. erectus* dated at 1.15 Ma (An and Ho, 1989). Furthermore, our new paleomagnetic investigation presented in this paper suggests an age of ~ 1.27 Ma for the artifacts at the Xihoudu site, which is about 100 km northeast of the Gongwangling locality (Fig. 1d). Paleomagnetic dates, obtained on both lake sediments from the Xihoudu site in the Sanmenxia Basin and wind-blown deposits from the Gongwangling locality in the southern Loess Plateau, are highly compatible, lending support to An and Ho's (1989) contention that the middle region of the Yellow River has been occupied by early humans since around 1.2 Ma. Yet, there is still some question as to whether the stone tools excavated at Xihoudu are man-made or not (cf. Wei, 2000), a topic beyond the scope of this paper.

Paleomagnetic results from Xiaochangliang (Zhu et al., 2001), Donggutuo (Li and Wang, 1982), Gongwangling (An and Ho, 1989) and Xihoudu suggest an expansion and flourishing of human groups from northern to north-central China during the middle part of the early Pleistocene. In particular, the age of the Xiaochangliang site denotes up to now the oldest unambiguous presence of early humans in East Asia at a latitude of at least 40 °N, following the range extension to this same latitude in western Eurasia by ~ 1.7 Ma (Gabunia and Vekua, 1995; Gabunia et al., 2000; Vekua et al., 2002). The spread of toolmakers to such higher latitudes implies that early Pleistocene human populations in East Asia were able to adapt to diverse climatic settings. It also suggests that populations could have dispersed to and from East Asia over a broad latitudinal range, although highlands of the

Qinghai–Tibetan Plateau may have prohibited a northern migration route. Furthermore, the age of the Xiaochangliang Paleolithic site is ~ 0.2 my older than the Lantian *H. erectus* found at Gongwangling and ~ 0.1 my older than the Xihoudu site. These two sites are located on the middle Yellow River, about 900 and 800 km southwest of the Nihewan Basin, respectively. This chronology suggests that populations of early humans were able to occupy or shift their range over a considerable area—from the Nihewan Basin to the southern margin of the Loess Plateau—during a time of enhanced global and regional climatic variability that included intermittent aridification of north China (Liu and Ding, 1999; An et al., 2001).

In summary, magnetostratigraphy has proved to be useful in dating Pleistocene hominin-bearing strata in China. It should be noted that in the above cases biostratigraphy provides an important constraint for correlating the measured magnetic polarity intervals to the standard geomagnetic polarity time scale. Lithostratigraphy and rock-magnetic stratigraphy are also very useful for stratigraphic correlation. Therefore, traditional magnetic polarity stratigraphy coupled with lithostratigraphy, biostratigraphy and rock-magnetic stratigraphy can offer a powerful multiproxy approach (Opdyke and Channell, 1996) for the age determinations of early Pleistocene strata bearing early human remains or stone artifacts.

Acknowledgements

We thank Dr. Craig Feibel for helpful reviews on the manuscript. RZ is grateful to Dr. Femke Wallien for her suggestion to write this review, to Dr. Guo Bin for his help during field work and in the laboratory, and to Drs. Deng Chenglong and Pan Yongxin for useful discussion. This research was supported by the National Natural Science Foundation of China (Grant no. 40104001) and the Chinese Academy of Sciences (Grant no. KZCX1-07). KAH acknowledges support from the US National Science Foundation.

References

Abbate, E., Albianelli, A., Azzaroli, A., Benvenuti, M., Tesfamariam, B., Bruni, P., Cipriani, N., Clarke, R.J., Ficcarelli, G., Macchiarelli, R., Napoleone, G., Papini, M., Rook, L., Sagri, M., Tecle, T.M., Torre, D., Villa, I., 1998. A one-million-year-old *Homo* cranium from the Danakil (Afar) Depression of Eritrea. Nature 393, 458–460.

Aigner, J.S., Laughlin, W.S., 1973. The dating of Lantian man and his significance for analyzing trends in human evolution. Am. J. Phys. Anthropol. 39, 97–110.

Ambrose, S.H., 2001. Paleolithic technology and human evolution. Science 291, 1748–1753.

An, Z.S., Ho, C.K., 1989. New magnetostratigraphic dates of Lantian *Homo erectus*. Quat. Res. 32, 213–221.

An, Z.S., Kutzbach, J.E., Prell, W.L., Porter, S.C., 2001. Evolution of Asian monsoons and phased uplift of the Himalaya–Tibetan plateau since Late Miocene times. Nature 411, 62–66.

Baksi, A.K., Hoffman, K.A., 2000. On the age and morphology of the Reunion Event. Geophys. Res. Lett. 27, 2997–3000.

Balter, M., Gibbons, A., 2000. A glimpse of humans' first journey out of Africa. Science 288, 948–950.

Barbour, G.B., 1924. Preliminary observation in Kalgan Area. Bull. Geol. Soc. China 3, 167–168.

Barbour, G.B., 1925. The deposits of the Sankanho Valley. Bull. Geol. Soc. China 4, 53–55.

Behrensmeyer, A.K., Todd, N.E., Potts, R., McBrinn, G.E., 1997. Late Pliocene faunal turnover in the Turkana Basin, Kenya and Ethiopia. Science 278, 1589–1594.

Berggren, W.A., Kent, D.V., Swisher III, C.C., Aubry, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy in time scales and global stratigraphic correlations: a unified temporal framework for an historical geology. In: Berggren, W.A., Kent, D.V., Aubry, M.-P., Hardenbol, J. (Eds.), Geochronology, Timescales, and Stratigraphic Correlation, Spec. Publ. No. 54. Society of Economic Paleontologists and Mineralogists, Tulsa, OK, pp. 129–212.

Biswas, D.K., Hyodo, M., Taniguchi, Y., Kaneko, M., Katoh, S., Sato, H., Kinugasa, Y., Mizuno, K., 1999. Magnetostratigraphy of Plio-Pleistocene sediments in a 1700-m core from Osaka Bay, southwestern Japan and short geomagnetic events in the middle Matuyama and early Brunhes chrons. Palaeogeogr. Palaeoclimatol. Palaeoecol. 148, 233–248.

Chen, M.N., 1988. Study on the Nihewan Beds. Ocean Press, Beijing, pp. 1–145. In Chinese with English abstract.

Chen, C., Shen, C., Chen, W., Tang, Y., 1999. 1998 excavation of the Xiaochangliang site at Yangyuan, Hebei. Acta Anthropol. Sin. 18, 225–239 (in Chinese with English abstract).

Cheng, G.L., Li, S.L., Lin, J.L., 1977. Discussion on the age of *Homo erectus yuanmouensis* and the event of early Matuyama. Acta Geol. Sin. (1), 34–43.

Cheng, G.L., Li, S.L., Lin, J.L., 1978a. A research on the ages of the strata of "Lantian Man". Collected Papers of Paleoanthropology. Science Press, Beijing, pp. 151–157.

Cheng, G.L., Lin, J.L., Li, S.L., Liang, Q.Z., 1978b. A preliminary paleomagnetic survey of the Nihewan Bed. Sci. Geol. Sin. 7, 247–252.

Culotta, E., 1995. Asian hominids grow older. Science 270, 1116–1117.

Deng, T., Xue, X.X., 1999. Chinese Fossil Horses of *Equus* and Their Environment. Ocean Press, Beijing, pp. 1–158.

De Vos, J., Sondaar, P., 1994. Dating hominid sites in Indonesia. Science 266, 1726–1727.

Feng, X.W., Hou, Y.M., 1998. Huojiadi: a new Paleolithic site discovered in the Nihewan Basin. Acta Anthropol. Sin. 17 (4), 310–316 (in Chinese with English abstract).

Gabunia, L., Vekua, A., 1995. A Plio-Pleistocene hominid from Dmanisi, East Georgia, Caucasus. Science 373, 509–512.

Gabunia, L., Vekua, A., Lordkipanidze, D., Swisher III, C.C., Ferring, R., Justus, A., Nioradze, M., Tvalchrelidze, M., Antón, S.C., Bosinski, G., Jöris, O., de Lumley, M.A., Majsuradze, G., Mouskhelishvili, A., 2000. Earliest Pleistocene hominid cranial remains from Dmanisi, Republic of Georgia: taxonomy, geological setting, and age. Science 288, 1019–1025.

Gibbons, A., 2001. Tools show humans reached Asia early. Science 293, 2368–2369.

Goren-Inbar, N., Feibei, C.S., Verosub, K.L., Melamed, Y., Kislev, M.E., Tchernov, E., Saragusti, I., 2000. Pleistocene milestones on the out-of-Africa corridor at Gesher Benot Ya'aqov, Israel. Science 289, 944–947.

Heller, F., Evans, M.E., 1995. Loess magnetism. Rev. Geophys. 33, 211–240.

Heslop, D., Langereis, C.G., Dekkers, M.J., 2000. A new astronomical timescale for the loess deposits of Northern China. Earth Planet. Sci. Lett. 184, 125–139.

Hou, Y.M., 2000. Donggutuo Lithic Industry of the Nihewan Basin, North China. PhD dissertation, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, Beijing, China. 112 pp., in Chinese with English abstract.

Hou, Y.M., Wei, Q., Feng, X.W., Lin, S.L., 1999. Re-excavation at Donggutuo in the Nihewan Basin, north China. Quat. Sci. (2), 139–147 (in Chinese with English abstract).

Hu, C., 1973. Ape-man teeth from Yuanmou, Yunnan. Acta Geol. Sin. (1), 65–72.

Huang, W.W., 1985. On the stone industry of Xiaochangliang. Acta Anthropol. Sin. 4, 301–307 (in Chinese with English abstract).

Huang, W.P., Fang, Q.R., 1991. Wushan Hominid Site. Ocean Press, Beijing, pp. 1–230. In Chinese with English abstract.

Huang, P.H., Grün, R., 1998. Study on burying ages of fossil teeth from Yuanmou Man site, Yunnan province, China. Acta Anthropol. Sin. 17, 165–170 (in Chinese with English abstract).

Huang, W., Ciochon, R., Gu, Y., Larick, R., Fang, Q., Schwarcz, H., Yonge, C., de Vos, J., Rink, W., 1995. Early *Homo* and associated artifacts from Asia. Nature 378, 275–278.

Hyodo, M., Nakaya, H., Urabe, A., Saegusa, H., Xue, S., Yin, J., Ji, X., 2002. Paleomagnetic dates of hominid remains from Yuanmou, China, and other Asian sites. J. Hum. Evol. 43, 27–41.

Jia, L.P., 1985. China's earliest Paleolithic industries. In: Wu, R.K., Olsen, J.W. (Eds.), Palaeoanthropology and Paleolithic Archaeology in the People's Republic of China. Academic Press, New York, pp. 134–135.

Jia, L.P., 1989. Early Paleolithic industries in China. In: Wu, R.K., Wu, X.Z., Zhang, S.S. (Eds.), Paleoanthropology in China. Science Press, Beijing, pp. 81–96. In Chinese.

Jia, L.P., Zhang, Y.P., Huang, W.P., Tang, Y.J., Ji, H.X., You, Y.Z., Ding, S.Y., Huang, X.S., 1966. The Cenozoic in Lantian, Shaanxi Province. Proceedings of Field Symposium on Lantian Cenozoic in Shaanxi Province. Science Press, Beijing, pp. 1–31. In Chinese.

Jin, C., Zheng, L., Dong, W., Liu, J., Xu, Q., Han, L., Zheng, J., Wei, G., Wang, F., 2000. The early Pleistocene deposits and mammalian fauna from Renzidong, Fanchang, Anhui Province, China. Acta Anthropol. Sin. 19 (3), 184–198 (in Chinese with English abstract).

Keates, S.G., 2000. Early and Middle Pleistocene Hominid Behaviour in Northern China. BAR International Series 863. John and Hedges, Oxford, p. 107.

Kukla, G., An, Z.S., 1989. Loess stratigraphy in central China. Palaeogeogr. Palaeoclimatol. Palaeoecol. 72, 203–225.

Langbroek, M., Roebroeks, W., 2000. Extraterrestrial evidence on the age of the hominids from Java. J. Hum. Evol. 38, 595–600.

Li, H.M., Wang, J.D., 1982. Magnetostratigraphical study of several typical geologic sections in North China. Quaternary Geology and Environment of China. Ocean Press, Beijing, pp. 33–38.

Li, P., Qian, F., Ma, X., Pu, Q., Xing, L., Ju, S., 1976. Preliminary study on the age of the Yuanmou Man by paleomagnetic technique. Sci. China (6), 579–591 (in Chinese).

Li, H.M., Yang, X.Q., Li, H.T., 2002. High-resolution study on magnetostratigraphy and cyclic sedimentology of three sections in the Nihewan Basin, North China: significance on age determination of stone artifact layer. Sci. China (D) (submitted for publication).

Liang, Q., Jiang, N., Sun, R., 1988. The magnetic stratigraphy study on Late Cenozoic strata in Yuanmou Basin. Yunnan Geol. 7 (3), 245–256 (in Chinese with English abstract).

Liu, T.S., 1985. Loess and the Environment. Ocean Press, Beijing, pp. 1–251.

Liu, T.S., Ding, M.L., 1983. Discussion on the age of Yuanmou Man. Acta Anthropol. Sin. 2, 40–48.

Liu, T.S., Ding, M.L., 1984. A tentative chronological correlation of early human fossil horizons in China with the loess-deep sea records. Acta Anthropol. Sin. 3, 93–101 (in Chinese with English abstract).

Liu, T.S., Ding, Z.L., 1999. Comparison of Plio-Pleistocene climatic changes in different monsoonal regions and implications for human evolution. Quat. Sci. (4), 289–298 (in Chinese with English abstract).

Liu, X.M., Liu, T.S., Shaw, J., Heller, F., Xu, T.C., Yuan, B.Y., 1991a. Paleomagnetic and paleoclimatic studies of Chinese loess. In: Liu, T.S. (Ed.), Loess, Environment and Global Change. Science Press, Beijing, pp. 61–81.

Liu, C., Jin, Z.X., Zhu, R.X., Yang, H., 1991b. Chronological measurement of the earliest strata bearing *Homo* fossils in China: a magnetostratigraphic study on the lower Pleistocene in Wushan (in Chinese with English abstract).

Ma, X.H., Qian, F., Li, P., Ju, S.Q., 1978. Paleomagnetic dating of Lantian Man. Vertebr. PalAsiatica 16, 238–243 (in Chinese).

Oms, O., Parés, J.M., Martínez-Navarro, B., Agustí, J., Toro, I., Martínez-Fernández, G., Turq, A., 2000. Early human occupation of Western Europe: paleomagnetic dates for two Paleolithic sites in Spain. Proc. Natl. Acad. Sci. U. S. A. 97, 10666–10670.

Opdyke, N.D., Channell, J.E.T., 1996. Magnetic Stratigraphy. Academic Press, San Diego, pp. 1–346.

Pan, Y.X., Zhu, R.X., Liu, Q.S., Guo, B., Yue, L.P., Wu, H.N., 2002. Geomagnetic episodes of the last 1.2 Myr recorded in Chinese loess. Geophys. Res. Lett. 29 (8), 10.1029/2001GL014024.

Pope, G.G., Keates, S.G., 1994. The evolution of human cognition and cultural capacity: a view from the Far East. In: Curuccini, R.S., Ciochon, R.L. (Eds.), Integrative Paths to the Past: Paleoanthropological Advances in Honor of F. Clark Howell. Prentice-Hall, Englewood Cliffs, pp. 531–567.

Qian, F., Zhou, G.X., 1991. Quaternary Geology and Paleoanthropology of Yuanmou, Yunnan, China. Science Press, Beijing. 242 pp.

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

Rutter, N.W., Ding, Z.L., Evans, M.E., Wang, Y., 1991. Magnetostratigraphy of the Baoji loess–paleosol section in the north-central China loess plateau. Quat. Int. 7, 97–102.

Schick, K.D., Dong, Z., 1993. Early paleolithic of China and eastern Asia. Evol. Anthropol. 2, 22–35.

Schick, K.D., Toth, N., Wei, Q., Clark, J.D., Etler, D., 1991. Archaeological perspectives in the Nihewan Basin, China. J. Hum. Evol. 21, 13–26.

Schwartz, J.H., Tattersall, I., 1996. Whose teeth? Nature 381, 201–202.

Singer, B.S., Relle, M.K., Hoffman, K.A., Battle, A., Laj, C., Guillou, H., Carracedo, J.C., 2002. ^{40}Ar/^{39}Ar ages from transitionally magnetized lavas on La Palma, Canary Islands, and the geomagnetic instability timescale. J. Geophys. Res. (in press).

Swisher, C.C., Curtis, G.H., Jacob, T., Getty, A.G., Suprijo, A.,Widiasmoro, 1994. Age of the earliest known hominids in Java, Indonesia. Science 263, 1118–1121.

Tang, Y.J., Li, Y., Chen, W.Y., 1995. Mammalian fossil and the age of Xiaochangliang Paleolithic site of Yangyuan, Hebei. Vertebr. PalAsiatica 33, 74–83 (in Chinese with English abstract).

Teilhard de Chardin, P., Piveteau, J., 1930. Les mammifères fossiles de Nihowan (Chine). Ann. Paléontol. 19, 1–154.

Urabe, A., Nakaya, H., Muto, T., Katoh, S., Hyodo, M., Xue, S., 2001. Lithostratigraphy and depositional history of the Late Cenozoic hominid-bearing successions in the Yuanmou Basin, southwest China. Quat. Sci. Rev. 20, 1671–1681.

Valet, J.-P., Meynadier, L., 1993. Geomagnetic field intensity and reversals during the past four million years. Nature 366, 234–238.

Vekua, A., Lordkipanidze, D., Rightmire, G.P., Agusti, J., Ferring, R., Maisuradze, G., Mouskhelishvili, A., Nioradze, M., Ponce de Leon, M., Tappen, M., Tvalchrelidze, M., Zollikofer, C., 2002. A new skull of early *Homo* from Dmanisi, Georgia. Science 297, 85–89.

Wei, Q., 1994. Banshan Paleolithic site from the Lower Pleistocene in the Nihewan Basin in northern China. Acta Anthropol. Sin. 13 (3), 223–238 (in Chinese with English abstract).

Wei, Q., 1997. The framework of archaeological geology of the Nihewan Basin. In: Tong, Y., et al. (Eds.), Evidence for Evolution-Essays in Honor of Prof. Chungchien Yong on the Hundredth Anniversary of His Birth. Ocean Press, Beijing, pp. 193–207. In Chinese with English abstract.

Wei, Q., 2000. On the artifacts from Xihoudu site. Acta Anthropol. Sin. 19 (2), 85–96 (in Chinese with English abstract).

Worm, H.-U., 1997. A link between geomagnetic reversals and events and glaciations. Earth Planet. Sci. Lett. 147, 55–67.

You, Y.Z., Tang, Y.J., Li, Y., 1980. Discovery of the Palaeoliths from the Nihewan Formation. Quat. Sin. 5, 1–11 (in Chinese).

Young, C.C., 1950. The Plio-Pleistocene Boundary in China. Report 18th Intern. Geol. Congr., London, 115–125.

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

Zheng, H.B., An, Z.S., Shaw, J., 1992. New contributions to Chinese Plio-Pleistocene magnetostratigraphy. Phys. Earth Planet. Inter. 70, 146–153.

Zhou, M.C., 1966. Mammalian fossils in association with the Lantian Man. Proceedings of Field Symposium on Lantian Cenozoic in Shaanxi Province. Science Press, Beijing, pp. 286–287. In Chinese.

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.

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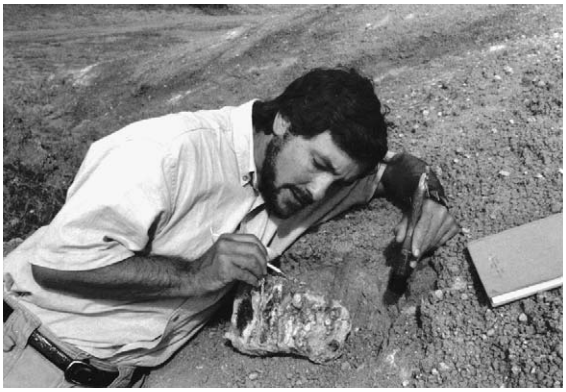

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