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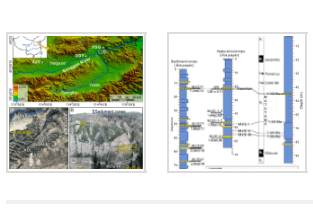

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Table 1

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^{26}Al/^{10}Be burial dating of Majuangou sites in Nihewan Basin, northern China

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Highlights

- The Majuangou sites in Nihewan Basin record one of the earliest human settlements in East Asia.
- The lowest cultural layer MJG-III was dated to 1.66 Ma by magnetostratigraphy.
- Samples from excavation pits and sediment cores were analyzed by simple burial dating.
- Ages of 1.28 ± 0.11, >1.49, and ~1.63 ± 0.09 Ma are assigned to cultural layers of Banshan, MJG-I and MJG-III.
- The new results provide the first radio-isotopic age control to the Early Pleistocene Paleolithic sites in Nihewan Basin.

Abstract

The Paleolithic site of Majuangou-III (MJG-III) in the Nihewan Basin, magnetostratigraphically dated to 1.66 million years ago (Ma), has been widely cited as documenting one of the earliest human settlements in China. Nevertheless, it remains important to cross-check the paleomagnetic dating with an independent and well-established radio-isotopic dating method. Here we report the application of ^{26}Al/^{10}Be burial dating to the Majuangou sites, assigning 1.28 ± 0.11 Ma (1σ), >1.49 Ma and close to 1.63 ± 0.09 Ma to Banshan, MJG-I and MJG-III, respectively. The proposed age sequence is supported by the general consistency between dates and stratigraphy as well as the consistency of dates between the samples from excavated cross-sections and those from deeply buried sediment cores. The age results agree with the previous magnetostratigraphy, providing the first radio-isotopic age for the earliest human occupation in high-latitude northern China.

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Keywords

^{26}Al/^{10}Be burial dating; Paleolithic sites; Majuangou; Nihewan basin; Early pleistocene; Early human dispersal

1. Introduction

The search for traces of our remote ancestors has been an endeavor for generations of scientists. In Nihewan Basin, northern China, such efforts can be traced back to the 1920s, when a group of French and American scientists recovered Early Pleistocene mammalian fossils there and named the fossiliferous deposits the Nihewan Formation (Barbour et al., 1926). Lithic artifacts in association with mammalian fossils were first found in 1978 at Xiaochangliang (You et al., 1978; Liu et al., 2013). Since then, quite a number of Early Pleistocene Paleolithic sites, notably Donggutuo (Wei, 1985; Schick et al., 1991; Hou, 2008), Cenjiawan (Xie and Cheng, 1990; Ma et al., 2024), Banshan (Wei, 1994) and Feiliang (Xie et al., 1998; Liu et al., 2013) have been identified (Fig. 1). These and several dozen other contemporaneous discoveries have made the basin the densest concentration of early Paleolithic sites outside Africa and a major area of archaeological and paleoenvironmental research in East Asia (Zhu et al., 2004; Deng et al., 2008; Ao et al., 2013; Liu et al., 2021; Tu et al., 2022).

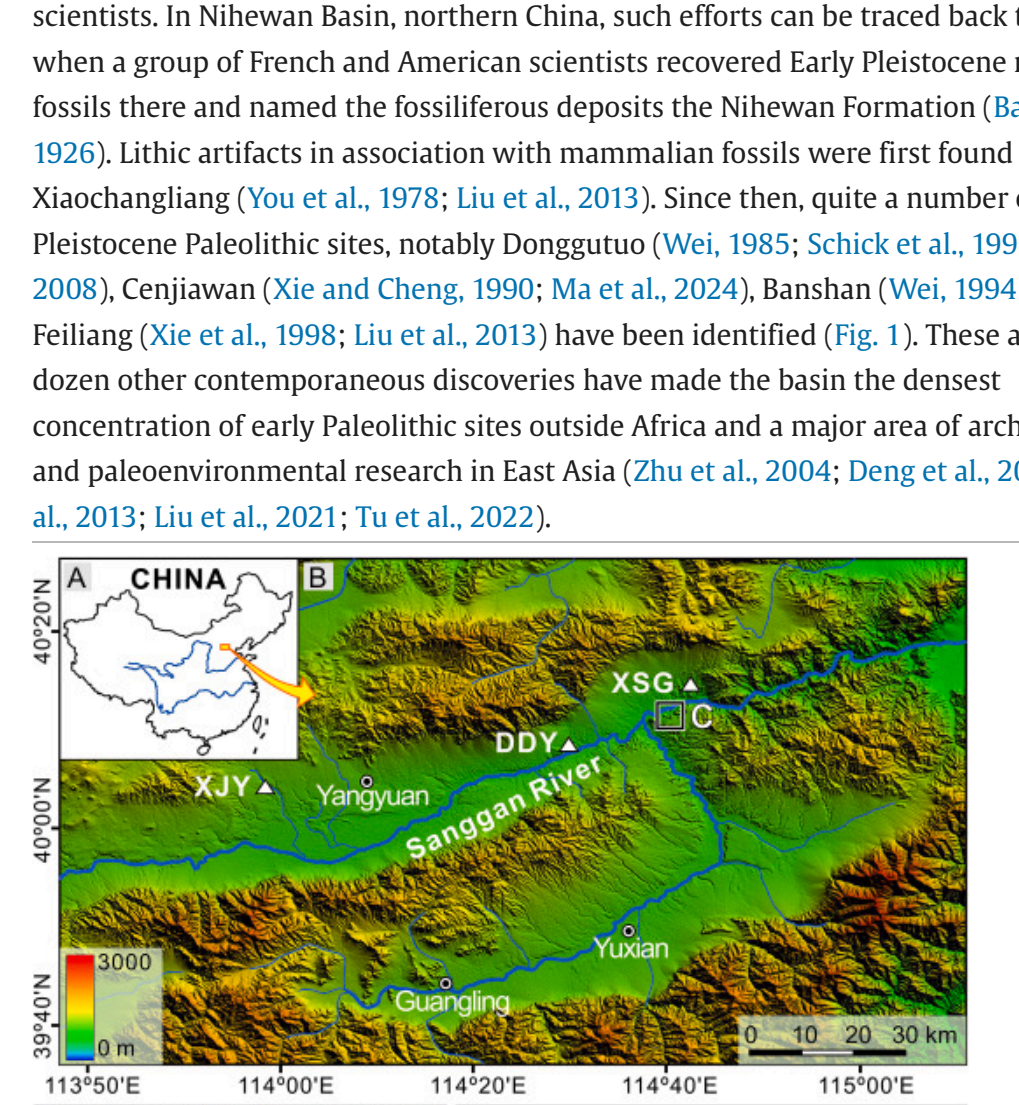

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Fig. 1. Geographical location and sampling cross-sections of Majuangou sites. A. a map of China, showing the location of the Nihewan area. B. a map of the Nihewan Basin, with the locations of MJG and some other Paleolithic or paleontological sites discussed in the paper. C. An enlarged map of the MJG area, showing the location of Banshan and MJG sites, and some nearby sites. D. a photo showing the positions of the excavated horizons and the sampling positions at the Banshan and MJG sites. Abbreviations of the sites: MJG, Majuangou; BS, Banshan; CJW, Chenjiawan; FL, Feiliang; DGT, Donggutuo; XCL, Xiaochangliang; DDY, Dadiyuan, XSG, Xiashagou; XJY, Xujiayao-Houjiayao.

Based on biostratigraphic correlations and preliminary paleomagnetic measurements, at the time of their discovery the sites of Xiaochangliang (You et al., 1978; Tang et al., 1995), Donggutuo (Wei, 1985; Schick et al., 1991) and Cenjiawan (Xie and Cheng, 1990) were all believed to represent the earliest hominin occupations in East Asia. Banshan was biostratigraphically correlated to the upper strata of Donggutuo (Wei, 1994), so the discovery and excavation of Majuangou sites (MJG-I ~ III) more than 20 m directly under Banshan attracted great attention from the prehistoric community (Hebei Provincial Institute of Cultural Relics, 2002; Zhu et al., 2004; Xie et al., 2006) (Fig. 1, Fig. 2). Ages from ~1.8 Ma (Qiu, 2000) to around or even more than 2 Ma were proposed (Cai and Li, 2004; Xie et al., 2006; Cai et al., 2008). Using detailed magnetostratigraphic analyses, Zhu et al. (2004) assigned ages of 1.32, 1.55, 1.64 and 1.66 Ma to Banshan, MJG-I, MJG-II and MJG-III, respectively (Fig. 2). This age sequence has been reinforced by quite a number of magnetostratigraphic studies of almost all the Paleolithic and/or paleontological localities in the basin (e.g., Deng et al., 2006; Deng et al., 2008; Ao et al., 2010; Ao et al., 2013). Together, these have made the Nihewan Basin one of the most intensively studied areas in the world by this method of relative dating. Consequently, the 1.66 Ma old MJG-III has been widely cited as documenting the earliest well-dated human settlement in northeastern Asia (e.g., Dennell and Roebroeks, 2005; Rightmire et al., 2006; Dennell, 2009; Potts and Teague, 2010; Bar-Yosef and Belfer-Cohen, 2013; Antón et al., 2014; Bae, 2024; Dennell, 2024).

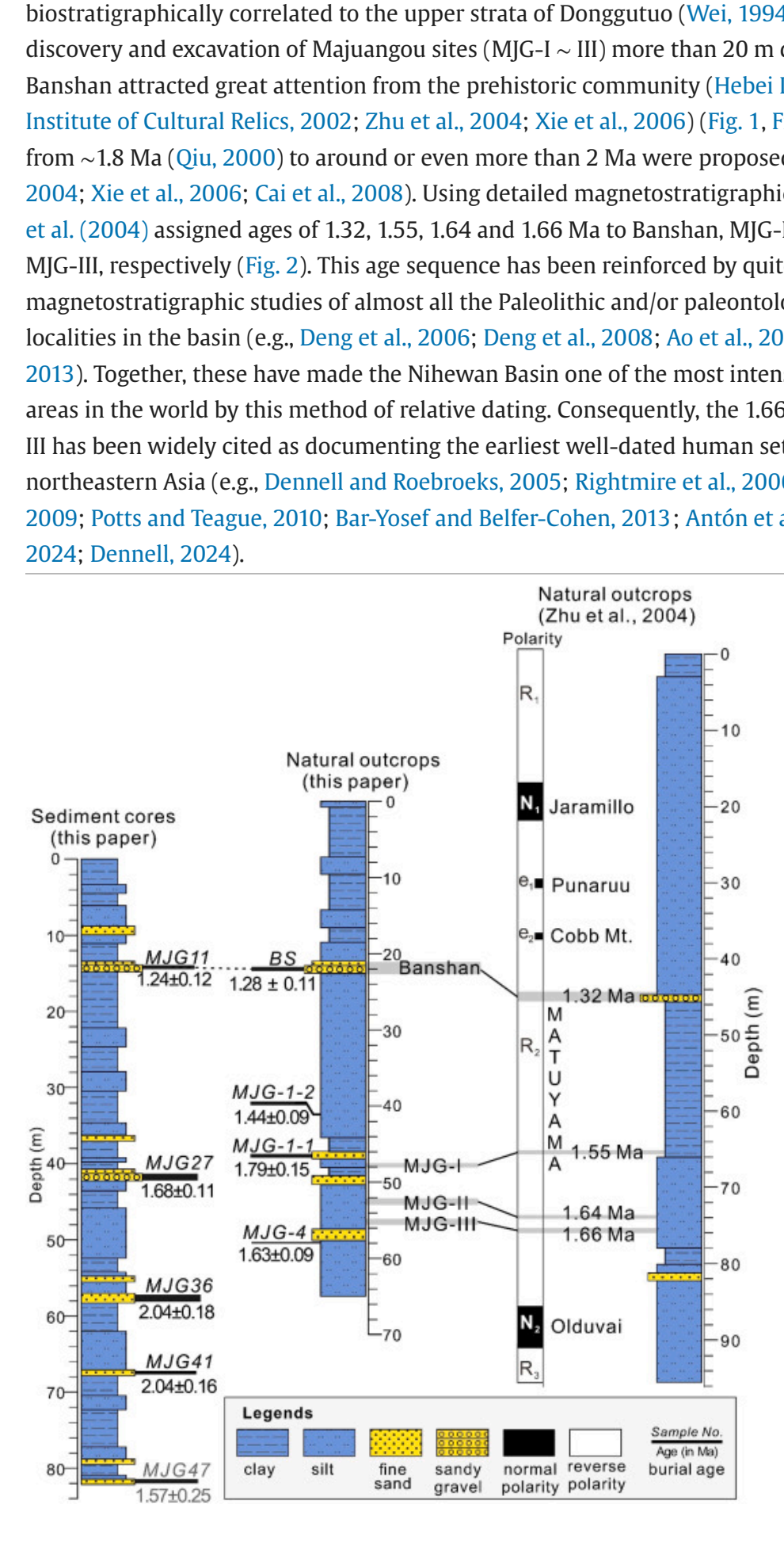

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Fig. 2. Chronostratigraphy of Majuangou sites. Lithostratigraphic column of the sediment cores (left), with the positions of five quartzose samples and their ^{26}Al/^{10}Be burial dates. In the middle is a lithological profile based on a more recent stratigraphic study of the natural out-crops carried out by one of us (F.X.), together with the positions of Banshan, Majuangou-I ~ III and four samples for dating. The stratigraphic and paleomagnetic columns from Zhu et al. (2004) are present on the right side for reference. Note the substantial difference in defining the top of the Majuangou section between the column in the center and the one on the right side. There are also some differences in vertical distances between the cultural layers. We consider that the recently and more carefully measured values given here are accurate, and they are the ones quoted in this paper. The age results in this paper are not sensitive to these minor differences.

In spite of the far-reaching influence of the paleomagnetic time scale, the exact temporal position of the Nihewan sites remain open to further studies. This is because the record of geomagnetic events in fluvio-lacustrine sediments may not be complete. Without at least one robust age control to anchor the stratigraphy, the interpretation of paleomagnetic stratigraphy remains non-unique. In fact, advice in quoting the paleomagnetic dates with prudence can be frequently found in the literature (Dennell, 2009). Moreover, the reliability of this timescale was contested by Cai et al. (2008), as these authors insisted that on microfaunal grounds, MJG-III should be at least 1.8 Ma, possibly as old as 2.2 Ma. On the other hand, much younger ages of 1.36 Ma (Gao et al., 2005) and even of 1.1–1.2 Ma (Ciochon, 2010) have been proposed. Liu et al. (2014) reported ESR ages of Banshan and Majuangou sites that are generally consistent with the ages proposed by Zhu et al. (2004). However, critical comments by Duval (2016) raised concerns regarding the reliability of the derived ages.

To check the ages previously assigned to the Majuangou sites, the application of an independent and well-established radio-isotopic dating method is needed. Here we report the results from ^{26}Al/^{10}Be burial dating of the Majuangou sites that help constrain the chronological framework for early hominin settlement in mainland East Asia.

2. Site context and sampling

The Nihewan Basin is a downfaulted basin located in eastern margin of the Chinese Loess Plateau (Fig. 1). Majuangou (MJG) is a small gully (~0.9 km in length) located near the eastern margin of Nihewan Basin (40°13.517′ N, 114°39.844′ E, 860 m a.s.l., Fig. 1). The gully has cut deeply into the basin's fluvio-lacustrine sediments, offering rare exposures of the remains of early hominin activity recorded in the depositional sequence. Four archaeological horizons in a stacked sequence have been identified along the gully's eastern slope and under its bottom. The highest and thus the most recent one is Banshan, which was discovered in 1990 at a depth of 21.2–22.6 m from the top of the section (Wei, 1994). The Majuangou site (later renamed MJG-I) was discovered two years later at a lower and thus older horizon (47.4–48.0 m) (Hebei Provincial Institute of Cultural Relics, 1998). Continued efforts in searching for evidence of still earlier hominin presence led to the discovery in 2000 of two more cultural layers at levels further below, MJG-II (52.1–53.0 m) and MJG-III (54.7–55.6 m) (Hebei Provincial Institute of Cultural Relics, 2002; Zhu et al., 2004; Xie et al., 2006).

To perform ^{26}Al/^{10}Be burial dating, we collected four quartz sand samples from the cross-sections exposed by previous excavations (Fig. 1D, Fig. S1). At Banshan, the artifacts and mammalian fossils were recovered from a ~70 cm-thick layer of sandy gravel (Wei, 1994). The sample BS was taken from the lowest horizon of this layer, at a depth of ~4.7 m from the slope surface. MJG-1-1 was taken from a ~5 cm thick sandy layer, which is ~1.0 m above the artifact- and fossil-bearing layer of MJG-I. The current burial depth of this layer is ~16.5 m from the surface. MJG-1-2 was taken from a ~10 cm-thick sandy layer about 5.5 m higher than MJG-1-1, with a current burial depth of ~11 m. Another sample, MJG-4, was collected from a sandy sub-layer ~2.7 m below MJG-III, which is currently buried at ~6.8 m below the surface. The positions of all of the cultural and sampling horizons are illustrated in a lithological profile (Fig. 2).

The current burial depths of the cross-section samples range from about 5 to 17 m, not necessarily sufficient to quantitatively shield continued production by secondary cosmic ray muons. Insufficient burial depth can lead to underestimated burial ages due to continued production after deposition (see Dating Methods section), but the degree of underestimation is contingent upon the erosion rate of the gully, a value that is difficult to independently determine. In other words, a sample may be only a few meters below the surface today, but if the gully formed only in the past 50,000 years, it may have spent nearly all of its history tens of meters below the surface, far more shielded from secondary cosmic rays. Because the exact timing of gully incision and erosion is difficult to know, one feasible way to evaluate the accuracy of burial ages of these samples is to date samples from the same layers that are buried more deeply, away from the gully.

To ensure sufficient shielding of the samples for burial dating, two sediment cores, 9 cm in diameter and ~82 m in depth were drilled in parallel from a platform ~14 m above Banshan (Fig. 1D, Fig. S1). Two-meter-long plastic liners were used to avoid distortion and to guarantee a sediment recovery rate as high as 98%. When cut into halves with a thread saw, the deposits are found to comprise mainly silt and clay, but intervals of sand or sandy-gravel deposits are recognizable at depths of 14m, 42m, 57m, 67m and 82m, from which quartz sand samples MJG-11, MJG-27, MJG-36, MJG-41 and MJG-47 were taken, respectively (Fig. 2). The spatial relationship between the samples collected from the excavated pits and sediment cores is illustrated in Fig. S2.

Additionally, to verify whether modern sediment in Nihewan Basin has a burial age near zero, a sand sample was taken from the cultural deposits of Dadiyuan (DDY, ~2.9 m below the surface), a terminal Late Pleistocene Upper Paleolithic site in the basin ~10 km west of Majuangou (Xie et al., 2006) (Fig. 1A).

3. Dating method

3.1. The principles of ^{26}Al/^{10}Be burial dating

Burial dating is based on the cosmogenic radionuclides ^{26}Al (τ_{26} = 1.021 ± 0.024 Ma) and ^{10}Be (τ_{10} = 2.005 ± 0.020 Ma) (Nishiizumi, 2004; Chmeleff et al., 2010; Borchers et al., 2016) that build up in the mineral quartz as it is exposed near the ground surface, and then decay after the sediment is buried underground (see details in Granger and Muzikar (2001) and Granger (2006)).

We use the simple burial dating method, assuming that quartz is derived from a source area that is eroding in steady-state and that continued cosmogenic nuclide production after burial is negligible. The simple burial dating method is typically valid for samples that were buried quickly and that have remained buried at depths of tens of meters. For samples that are not buried deeply enough to be fully shielded from post-depositional production by muons, simple burial dating is known to underestimate the true age and is therefore considered a minimum burial age. Although the isochron burial dating method can circumvent these limitations and provide an accurate age at relatively shallow depths, it generally requires analyzing at least 5–8 individual gravel clasts from the same depth (e.g., Erlanger et al., 2012; Granger et al., 2015; Zhao et al., 2016; Tu et al., 2017; Luo et al., 2020); a lack of quartz gravel at Majuangou, precludes isochron dating there.

3.2. Sample preparation and analysis

Bulk sediment samples were rinsed by water to remove most of the clays, and soaked in HCl to dissolve carbonate components. Materials between 0.2 and 0.5 mm were collected by sieving, then etched in 1% HF-HNO_3 solution repeatedly. After further purification using magnetic and gravimetric separation, sample purity was determined by analyzing Al and other major elements (K, Ca, Na, Ti, Fe) by inductively coupled plasma-optical emission spectrometry (ICP-OES). This work was mostly completed in the pre-treatment laboratory of Nanjing Normal University. The purified quartz was dissolved in 1:5 HNO_3/HF solution after spiked with ~0.3 mg ^{9}Be carrier. An aliquot was taken for Al and Be concentrations by ICP-OES. The remaining solution was evaporated to fumes after addition of 1 ml H_2SO_4 to eliminate fluorides and as a solution keeper. By adding NaOH, iron, titanium, and other elements were removed at pH 14. Al and Be were precipitated at pH ~7.5, and then separated by ion exchange chromatography in oxalic acid. Both elements were precipitated as hydroxides and transformed into oxides over a propane flame. Al_2O_3 and BeO were mixed with niobium and loaded into cathodes for AMS measurements at PRIME Lab, Purdue University. The measured ratios were normalized to standards prepared by K. Nishiizumi (Nishiizumi, 2004; Nishiizumi et al., 2007).

For more technical details of sample pretreatment and Al-Be separation and purification, the readers may refer to Granger et al. (2015). Burial ages were calculated following Granger and Muzikar (2001), with a surface ^{10}Be production rate of 7.9 at/g/yr based on the average of the time-dependent production rate at the site over the past 2 million years using the model of Lifton et al. (2014), and a^{26}Al/^{10}Be surface production rate ratio of 6.8.

4. Results

The ^{26}Al and ^{10}Be concentrations and calculated simple burial ages are presented in Table 1. The $^{26}Al_{[1]}$ values were initially measured with relatively large counting statistics of >10%. The $^{26}Al_{[2]}$ values were obtained by re-measuring the same targets after the introduction of a gas-filled magnet (Fifield et al., 2007) to the AMS at Purdue University. The weighted means of the two measurements were used to calculate the ^{26}Al/^{10}Be ratios and then the age results. Original data such as sample size, ^{9}Be carrier mass, total Al concentration and results of AMS measurements are presented as Table S1 in the supplementary materials.

Table 1. Cosmogenic nuclide concentrations and burial ages of quartz samples from Majuangou and related sites.

Sample	Present depth (m)	$^{26}Al_{[1]}$ (10^6 at/g)	$^{26}Al_{[2]}$ (10^6 at/g)	$^{26}Al_{[w]}$ (10^6 at/g)	^{10}Be (10^6 at/g)	^{26}Al/^{10}Be
DDY[a]	2.9	1.0628 ± 0.0820	1.0658 ± 0.0212	1.0656 ± 0.0205	0.1594 ± 0.0041	6.68 ± 0.21
BS[a]	4.7	0.3952 ± 0.0418	0.3929 ± 0.0143	0.3931 ± 0.0136	0.1085 ± 0.0042	3.62 ± 0.19
MJG 11	14	0.4131 ± 0.0351	0.4106 ± 0.0127	0.4109 ± 0.0120	0.1111 ± 0.0055	3.70 ± 0.21
MJG-1-2[a]	11	0.2850 ± 0.0267	0.2826 ± 0.0084	0.2828 ± 0.0080	0.0840 ± 0.0030	3.37 ± 0.15
MJG-1-1[a]	16.5	0.2286 ± 0.0281	0.2883 ± 0.0126	0.2783 ± 0.0158	0.0982 ± 0.0047	2.84 ± 0.21
MJG 27-1	42	0.4136 ± 0.0415	0.4092 ± 0.0155	0.4097 ± 0.0146	0.1353 ± 0.0071	3.03 ± 0.19
MJG-27-2	42	0.3587 ± 0.0398			0.1290 ± 0.0034	2.78 ± 0.32
MJG-4[a]	6.8	0.2153 ± 0.0347	0.2200 ± 0.0074	0.2198 ± 0.0073	0.0714 ± 0.0021	3.08 ± 0.14
MJG 36-1	57	0.1588 ± 0.0292	0.1749 ± 0.0077	0.1738 ± 0.0074	0.0658 ± 0.0043	2.64 ± 0.20
MJG-36-2	57	0.1500 ± 0.0212			0.0702 ± 0.0030	2.14 ± 0.32
MJG 41	67	0.2234 ± 0.0637	0.2649 ± 0.0109	0.2637 ± 0.0107	0.1056 ± 0.0072	2.50 ± 0.20
MJG 47	82	0.1500 ± 0.0636	0.2125 ± 0.0223	0.2057 ± 0.0210	0.0650 ± 0.0051	3.16 ± 0.41

[a] denotes samples collected from the cross-sections of the excavated pits, while others were derived from sediment cores.

The sample of DDY gives a burial age of 0.02 ± 0.06 Ma (±1σ error range, similarly hereafter), which is consistent with its archaeological features as an Upper Paleolithic site. Based on elevation correlation, the top of cores is ~8 m lower than the top of the natural outcrops (Fig. 2). Thus, the sample MJG-11 is located at the same depth as BS, although it was taken from a layer with smaller particle size and lower gravel density compared to the sandy gravel layer where the sample BS was collected. The samples of MJG-11 and BS give ages of 1.24 ± 0.12 and 1.28 ± 0.11 Ma, respectively. The former is taken from a depth of ~14.2 m in the core, while the latter from a depth of only ~4.7 m on the excavated cross-section. The consistency within error between the two dates supports the suitability of the samples from the excavated cross-sections for dating and suggests negligible post-depositional production.

Replicate analyses of MJG-27 yield ages of 1.64 ± 0.13 and 1.82 ± 0.22 Ma, with a weighted mean of 1.68 ± 0.11 Ma. MJG-1-1 and MJG-1-2 give ages of 1.79 ± 0.15 Ma and 1.44 ± 0.09 Ma, respectively. Within error range, the three results are consistent with their stratigraphical order, as the difference between MJG-1-1 and MJG-27 does not surpass ±1σ. The cultural layer MJG-I, ~1m below sample MJG-1-1, should be older than 1.49 Ma at 95% confidence, considering the 2σ error range of MJG1-1.

MJG-4, 2.7m below the cultural layer MJG-III, gives an age of 1.63 ± 0.09 Ma, providing a close estimate for this cultural layer. Duplicate analyses of MJG-36 give dates of 1.94 ± 0.16 and 2.38 ± 0.29 Ma, with a weighted mean of 2.04 ± 0.18 Ma. The two lowest core samples below cultural horizons, MJG-41 and MJG-47, are dated to 2.04 ± 0.16 and 1.57 ± 0.25 Ma, respectively (Fig. 2). The latter one bears rather large error due mainly to insufficient sample size. Within error range the two age results are consistent with each other and with their stratigraphic position.

5. Discussions

5.1. Reliability of simple burial ages of Majuangou

The reliability of simple burial age hinges on the validity of two major assumptions mentioned above (Granger and Muzikar, 2001). It was suggested that the sandy layers in the Nihewan Beds were most likely transported directly from the surrounding mountains to the ancient lake by alluvial fans when the lake level was low (Yuan et al., 2009; Tu et al., 2022). This inference is supported by the near-zero age of sample DDY in this study, as well as by the consistency between simple burial dates and luminescence ages from the cultural deposits of the late Middle Pleistocene hominin site Xujiayao-Houjiayao at northwest margin of the Nihewan Basin (Tu et al., 2015). Additionally, Tu et al. (2022) performed isochron burial dating on 11 clast samples taken from the sandy-gravel layers in Xiashagou fauna site at northeast margin of the basin, and the internal consistency among these samples suggests that none of them experienced an appreciable prior burial history.

Another issue to consider is whether the sediment was buried deeply and rapidly enough to prevent significant post-burial nuclide production. For all the age results of this paper, including the ones from currently shallowly buried layer from the cross-sections, no correction for post-burial production of cosmogenic nuclides by muons was made. This is supported by the consistency of burial ages from the same layer revealed from the sediment core and cross-sections, suggesting recent incision and/or a high erosion rate of the Majuangou gully. Background erosion rates in this region can be estimated on the order of 800–8000 m/Ma according to soil erosion studies utilizing ^{137}Cs in the northern Loess Plateau (Li et al., 2005; Zhang et al., 2006). Even if the erosion rates were 10 times less in prehistoric times, the correction for insufficient shielding can still be safely ignored. Rapid erosion is also supported by geomorphological observations in the region. The ancient Nihewan Lake dried up around 266 ka ago (Zhao et al., 2010). At that time the fluvio-lacustrine deposits at Majuangou would have accumulated to about the same height as at nearby Haojiatai (Zhu et al., 2004), more than 50 m higher than at present. Since the drying-up of the paleolake, or possibly much more recently after the formation of Malan Loess during the Last Glaciation, at Majuangou not only all of the >50 m thick deposits formed during Brunhes normal epoch have been washed away, but also the gully has cut the Matuyama chron deposits to a depth of more than 60 m. From these data, high erosion rates in the range of 414–11,000 m/Ma can be estimated.

5.2. Implications for the chronostratigraphy of the Nihewan Basin

Reliable dating of the Early Pleistocene Paleolithic/hominin sites East Asia has been a hotspot in archaeological geochronology. In the Nihewan Basin, nearly all of the sites beyond the range of luminescence dating (e.g., ~0.3 Ma) have been dated by the relative method of magnetostratigraphy (Deng et al., 2006; Dennell, 2015, 2024; Yang et al., 2020a). For instance, the cultural layers of Majuangou (1.66–1.55 Ma) (Zhu et al., 2004), Xiaochangliang (1.36 Ma) (Zhu et al., 2001), Xiantai (1.36 Ma)(Deng et al., 2006), Banshan (1.32 Ma) (Zhu et al., 2004), Feiliang (1.2 Ma) (Deng et al., 2007; Ao et al., 2012), Cenjiawan (1.1 Ma) (Wang et al., 2006), and Donggutuo (1.1 Ma) (Wang et al., 2005) have been attributed to the reverse polarity zone between the Jaramillo and Olduvai events, while Xujiayao-Houjiayao (~0.5 Ma) (Løvlie et al., 2001; Wang et al., 2004) and Hougou (0.4 Ma) (Zuo et al., 2011) have been linked to the lower/middle part of the Brunhes chron. The specific numerical age of each site has been assigned by the relative position of the cultural layer with the three key paleomagnetic events, i.e., Brunhes-Matuyama (B/M) boundary (0.77 Ma), Jaramillo (1.07–0.99 Ma) and Olduvai subchron (1.95–1.77 Ma) (Deng et al., 2006; Dennell, 2015, 2024; Yang et al., 2020a). Therefore, the accuracy of these age estimates is dependent on the validity of the correlation between magnetostratigraphy and the Geomagnetic Polarity Time Scale (GPTS), as well as the sedimentary continuity between the cultural layer and specific polarity events. Nevertheless, the presence of several sand and gravel layers intercalated within the Nihewan beds suggests multiple episodes of lake level fluctuations in the basin during the Pleistocene, which may have led to erosion or depositional hiatuses in the stratigraphy, potentially complicating magnetostratigraphic interpretations.

The application of isochron burial dating to two horizons at Xiashagou site has provided independent age controls (2.05 ± 0.38 Ma and 2.43 ± 0.16 Ma, respectively) for the Olduvai Subchron and the Gauss/Matuyama Boundary (2.58 Ma), which represent the most important geomagnetic events in magnetostratigraphy of numerous Paleolithic and vertebrate paleontological sites within the eastern part of Nihewan Basin (Tu et al., 2022). By assigning burial ages ranging from 1.28 ± 0.11 Ma to 1.63 ± 0.09 Ma to the cultural layers of Banshan and Majuangou sites that were bracketed between Jaramillo and Olduvai subchrons, our results provide additional radio-isotopic age constraint for the validity of the two geomagnetic events in this region. Thus for the majority of Paleolithic sites located along the eastern margin of the Nihewan Basin, a robust magnetostratigraphic framework can be established through reliable stratigraphic correlations with the Majuangou and Xiashagou sites.

On the other hand, direct burial dating of each site in the basin remains crucial, particularly when the cultural layer can only be assigned to a broad temporal range based on magnetostratigraphy, such as the normal polarity zone of Brunhes Chron, or the reverse polarity zone between Olduvai and Jaramillo. The Xujiayao-Houjiayao site may be considered as an example. The fossil- and lithic-bearing layer was dated to ~0.5 Ma because it is close to the B/M boundary (Løvlie et al., 2001; Wang et al., 2004). In contrast, the sediment sample and a manuport from the cultural layer was dated to 0.24 ± 0.05 Ma by burial dating (Tu et al., 2015). The age estimates derived from magnetostratigraphy was biased owing to an unrecognized sedimentary hiatus that exists between the cultural layer and B/M boundary (Tu et al., 2015). Another case of burial dating in this region can be found at the Jijiazhuang site in Yuxian Basin, a sub-basin of Nihewan Basin, the cultural layer of which was dated to 0.49 ± 0.10–0.63 ± 0.11 Ma, a period that is challenging for luminescence dating or magnetostratigraphy (Ye et al., 2024). Therefore, the burial dating method still holds significant potential in dating Paleolithic sites in the Nihewan Basin.

5.3. Implications for early human settlement in East Asia

At what time our remote ancestor first settled in East Asia is one of the hotly debated subjects in paleoanthropology. For decades, Dmanisi (~1.85 Ma) was considered as the earliest hominin settlement outside Africa (Ferring et al., 2011), and MJG- III, Gongwangling (~1.6 Ma) and Yuanmou (1.7 Ma) as the first evidence of the hominin emergence in East Asia (Zhu et al., 2004, 2008; Tu et al., 2017; Luo et al., 2020), supporting the framework that our ancestors left Africa ca. 1.8 Ma, and arrived at Asia within 0.2 Ma. Recently, archaeological evidence for much early human presence has been founded in Zarqa Valley (Jordan) at 2.48 Ma (Scardia et al., 2019), Shangchen (China) at 2.12 Ma (Zhu et al., 2018) and Xihoudu (China) at 2.43 Ma (Shen et al., 2020). Although no fossil hominins documenting the earliest human in Asia have been found, on chronological grounds it is likely an early form of *Homo erectus* or another contemporaneous hominin could be considered the maker of those artifacts (Barras, 2018; Bae, 2024). In any case, sites in Nihewan Basin remain crucial in documenting the evidence of human occupation at high-latitude Northeast Asia up to 40°N during the Early Pleistocene (Bae et al., 2018; Yang et al., 2020b; Bae, 2024).

The radio-isotopic ages presented in this paper provide an independent chronological sequence for the Majuangou sites, thereby addressing the previous uncertainties and alternative hypotheses (Cai and Li, 2004; Xie et al., 2006; Cai et al., 2008). The ages of Majuangou sites are contemporaneous with those of the Gongwangling and Yuanmou hominin sites located in North and southern China, respectively (Zhu et al., 2004, 2008; Tu et al., 2017; Luo et al., 2020). They may also correspond to the Javanese *H. erectus* from Sangiran, Indonesia that was previously dated to 1.66 Ma or >1.51 Ma (Swisher et al., 1994; Larick et al., 2001) and recently redated to ~1.3 Ma (Matsu'ura et al., 2020). These sites suggest that early hominins dispersed fairly quickly across high latitude Northeast Asia and insular southeast Asia within the span of only a few hundred thousand years after 1.7 Ma. Questions persist regarding how these ancient populations were able to adapt to diverse habitats, ranging from temperate grasslands and woodlands to tropical forests. The hundreds of meters thick fluvio-lacustrine sediments provide a crucial archive for investigating the paleoclimatic and paleoenvironmental contexts during the period of early hominin occupation, as well as their adaptive technological and behavioral strategies. The new dates for the Majuangou sites presented here represent a significant advancement in addressing these questions.

6. Conclusion

By assigning an age of 1.28 ± 0.11 Ma to Banshan, >1.49 Ma to MJG-I, and ~1.63 ± 0.09 Ma to MJG-III, the present study represents the first application of a radio-isotopic dating method to Majuangou sites. The reliability of the this temporal framework is supported by the near zero burial age of a sediment sample from a nearby terminal Late Pleistocene site, by the conformity between the age and biostratigraphy of two samples from the later Middle Pleistocene site Xujiayao-Houjiayao (Tu et al., 2015), and by the general consistency of the age results with stratigraphic order. The above age results are entirely consistent with the previous age assignments by paleomagnetic analyses (Zhu et al., 2004), and provides the first radio-isotopic dating evidence that early hominins were in the Nihewan Basin in high-latitude northern China by ~1.6 Ma. The new dates for the Majuangou sites also offer independent support for the magnetostratigraphic framework of adjacent Early Pleistocene sites along the eastern margin of the Nihewan Basin, and provide a robust chronological foundation for paleoclimatic and paleoenvironmental studies in this region.

CRediT authorship contribution statement

Hua Tu: Conceptualization, Methodology, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Xinfeng Zhang:** Investigation. **Lan Luo:** Investigation, Methodology. **Fei Xie:** Investigation, Resources. **Fei Han:** Investigation, Methodology. **Zhongping Lai:** Conceptualization, Supervision, Project administration. **Darryl E. Granger:** Methodology, Validation, Writing – review & editing. **Guanjun Shen:** Conceptualization, Supervision, Investigation, Funding acquisition, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The author Zhongping Lai is the Guest Editor for *"Quaternary Science Reviews"* and was not involved in the editorial review or the decision to publish this article.

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Appendix A. Supplementary data

The following is the Supplementary data to this article:

Download: Download Acrobat PDF file (814KB)
Multimedia component 1.

Data availability

Data will be made available on request.

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