Guanjun Shen
*Institute for Coastal and Quaternary Studies, Nanjing Normal University, Nanjing, Jiangsu 210097, P.R. China. E-mail: gjshen@pine.njnu.edu.cn*

Teh-Lung Ku
*Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089-0740, U.S.A. E-mail: rku@usc.edu*

Hai Cheng, R. Lawrence Edwards
*Department of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55455, U.S.A. E-mail: cheng021@gold.tc.umn.edu, edwar001@maroon.tc.umn.edu*

Zhenxin Yuan, Qian Wang*
*Institute of Vertebrate Paleontology and Paleoanthropology, Academia Sinica, Beijing 100044, P.R. China*

Received 22 February 2001
Revision received 20 August 2001 and accepted 5 September 2001

*Keywords:* Zhoukoudian Locality 1, *Homo erectus*, TIMS U-series dating, Speleothem calcite.

# High-precision U-series dating of Locality 1 at Zhoukoudian, China

Thermal ionization mass spectrometric $^{230}Th/^{234}U$ dating has been carried out on intercalated speleothem samples from the limestone cave occupied by *Homo erectus* at Zhoukoudian, China. The samples were recently collected in proper stratigraphic context after detailed field examinations. The results show that the age of the No. 5 Skull from Layer 3 is >400 ka, possibly in the range of about 400–500 ka, and that the hominid fossils from the lower strata are at least 600 ka and possibly >800 ka, much older than previously thought. The near-equilibrium $^{230}Th/^{234}U$ ratios and internal consistency of the dates and stratigraphy lend credence to the results and allow us to comment on their important implications for human evolution.



*Journal of Human Evolution* (2001) **41,** 679–688
doi:10.1006/jhev.2001.0516
Available online at http://www.idealibrary.com on IDEAL®

## Introduction

The discovery in 1929 of the first skull cap of *Homo erectus* at Locality 1 of Zhoukoudian, about 50 km southwest of the city of Beijing, marked a new era in our understanding of the history of human evolution. Excavations at that site have revealed an extraordinary richness of paleoanthropological relics, including six fairly complete hominid crania and other hominid fossils

*Current address: The Sterkfontein Research Unit, School of Anatomical Sciences, University of the Witwatersrand, Johannesburg 2193, South Africa. E-mail: 055qwang@chiron.wits.ac.za

0047–2484/01/120679+10$35.00/0

representing at least 40 individuals, 98 species of nonhominid mammalian fossils, and several tens of thousands of stone artefacts (Pei, 1929, 1931; Black *et al.*, 1933; Jia, 1964; Wu *et al.*, 1985). Numerous burned bones and stones provided strong supporting evidence for early utilization of fire by humans (Wu, 1999), though claims to the contrary have been made (Weiner *et al.*, 1998).

The Zhoukoudian hominid specimens, once named *Sinanthropus pekinensis* and commonly known as "Peking Man", have been widely recognized as representative of *H. erectus* (Weidenreich, 1943). The issue of whether this hominid species was a direct ancestor of later eastern Asian populations or a side branch in human evolution impacts on the two principal current hypotheses about the origin of modern *H. sapiens* (e.g., Wolpoff *et al.*, 1984, 2001; Stringer, 1994, 2000). A reliable chronology for relevant finds is therefore of importance in addressing the question of the phylogenetic status of *H. erectus*.

Early attempts to date the Zhoukoudian site may be traced to $^{230}Th/^{234}U$ ages measured on two fossil bones by Cherdyntsev (1971). In the late 1970s, during the last round of excavation at the site, a multidisciplinary study was organized by the Institute of Vertebrate Paleontology and Paleoanthropology, *Academia Sinica* (Wu *et al.*, 1985). Numerical dating was carried out at several Chinese institutions using different techniques, including U-series disequilibrium (Zhao *et al.*, 1985*a*), fission track (Liu *et al.*, 1985), paleomagnetism (Qian *et al.*, 1985), thermoluminescence (Pei, 1985) and amino acid racemization (Zhou, 1989). As a result, the following age sequence was proposed (Zhao *et al.*, 1985*b*): ca. 700 ka for the lowest fossiliferous horizon (Layer 13), based mainly on paleomagnetic stratigraphy; ca. 500 ka for the lowest stone artefact-containing layer (Layer 10), based on fission track dating of sphene grains extracted from ash deposits, and ca. 230 ka for the uppermost strata (Layers 1–3) based on $^{230}Th/^{234}U$ dating of fossils.

Since then, along with the technical advancement of the dating methods, chronological studies of Zhoukoudian Locality 1 have continued. Yuan *et al.* (1991) applied the method of $^{231}Pa/^{235}U$ to cross-check the $^{230}Th/^{234}U$ dating, and proposed that the age of ca. 230 ka should relate to the topmost level of Layers 1–2, while the age of Layer 3 from which the No. 5 Skull was unearthed (Qiu *et al.*, 1973) should be ca. 290 ka. Guo *et al.* (1991) fission-track dated Layer 4, obtaining an age of $299 \pm 55$ ka. Huang *et al.* (1991), and more recently Grün *et al.* (1997), applied ESR dating to tooth enamel from different layers, proposing age ranges of 282–578 ka and 300–550 ka, respectively, for the hominid remains. On the whole, the newer age results do not significantly alter the generally accepted temporal framework for Locality 1 established earlier, which placed the age of the hominid remains in the range of about 230–500 ka.

However, the validity of the assumptions used in the dating and the accuracy of the derived ages remain problematic. This is particularly so for the closed-system assumptions for U-series dating of fossils, which are known to be susceptible to post-burial U-migration (Bischoff *et al.*, 1988; Rae *et al.*, 1989; Schwarcz & Blackwell, 1992; Shen, 1996*a*). The previous paleomagnetic study may also be suspect in view of the fact that only 27 samples were measured out of a 48 m thick sequence, and that by using only alternative field demagnetization the removal of the reversed hematite overprint might be incomplete (Qian *et al.*, 1985). In checking the previous age assignment of Layers 1–3, Shen & Jin (1991) dated an intercalated flowstone layer (samples BZC-2, 3) from Layers 1–2 at Locus H and obtained a much older date of $421^{+110}_{-50}$ ka (1σ). Since pure, dense and well-preserved speleothem carbonates are more likely to act as a closed system for U-Th isotopes than are fossil bones (Ludwig *et al.*, 1992; Schwarcz, 1992; Shen, 1996*b*), it was suggested that the youngest *H. erectus* at Zhoukoudian (represented by the No. 5 Skull) was at least 100 ka older than previously thought.

As a follow-up study, the flowstone date was re-checked using thermal ionization mass spectrometry (TIMS), which improves greatly the analytical precision over that of $\alpha$-particle counting. A weighted mean of $414 \pm 13$ ka ($2\sigma$) was derived from quadruplicate analyses of BZC-3 (Shen *et al.*, 1996). We have since made further collections and TIMS $^{230}Th/^{234}U$ dating of suitable calcite samples from Locality 1. Detailed field examinations were carried out to ensure that the dated samples have proper stratigraphic context and that they are devoid of calcite crystals of diagenetic origin. The results are now presented in this report.

## Samples

Zhoukoudian Locality 1 was a large cave, about 140 m long from east to west and up to 40 m wide. The multidisciplinary investigations of the cave included a detailed stratigraphic study carried out by Yang *et al.* (1985), based on earlier works of the excavators (e.g., Pei, 1931; Black *et al.*, 1933; Chia, 1959; Chao & Li, 1960; Huang, 1960; Jia, 1964; Qiu *et al.*, 1973). The evolution of the cave in relation to human occupation was reconstructed by Wu & Lin (1983) and Ren *et al.* (1985). All these studies served to guide our sampling strategies for the present study.

At Locus H, five intercalated flowstone layers were reported to be present in the topmost Layers 1–2 deposits (Ren *et al.*, 1985). During our 1995 field study we recognized one additional flowstone layer at the very top, though its lateral extension is fragmented. As shown in Figure 1, sample 95-4 was taken from this newly identified capping flowstone layer. Below about 50 cm of detritus lies the second flowstone layer consisting of two sub-units separated by a depositional hiatus. From the upper sublayer, samples 95-3 and 89-3(top) were taken. The lower sub-layer, from which the previously studied sample BZC-3 came, was re-sampled as 89-3. Two additional samples were retrieved: 95-2 from a stalagmite that formed on top of the second flowstone layer, and 95-1 from the fifth flowstone layer. The latter is composed of quite pure, but loosely cemented calcite crystals without clear depositional laminae, so its *in situ* formation cannot be ascertained. The stratigraphic correlation between Locus H and the well-studied excavation exposure (the preserved West Wall cross-section) was established in the course of an excavation in 1966 led by W. C. Pei (Qiu *et al.*, 1973).

Excavations at East Hillside during 1978–1979, carried out by one of us (Z.X.Y.), unearthed Layers 3 through 6 (Yuan *et al.*, 1985), which correlate well with the corresponding layers on West Wall and on sections revealed by the excavations at eastern part of the Main Excavation Pit during 1958–1959 (Chia, 1959; Chao & Li, 1960; Huang, 1960), although layer thicknesses at different excavation sites differ. At the southern side of East Hillside (Figure 2), the upper part of Layer 5 is composed of six flowstone sub-layers with a total thickness of up to 120 cm. The lower part consists of an indurated carbonate breccia, whose granite-like appearance is characteristic of the locale (Yuan *et al.*, 1985). Samples 95-5, 93-1 and 93-3 were taken from the first, second and fourth sub-layers, respectively, and sample 93-2 was collected from the outer part of a stalagmite on the surface of the flowstone (Figure 2). The stratigraphic positions of these samples are well defined because the flowstone is finely laminated, it lies above the granite-like breccia, and is traceable for about 12 m along the South Wall (Figure 2).

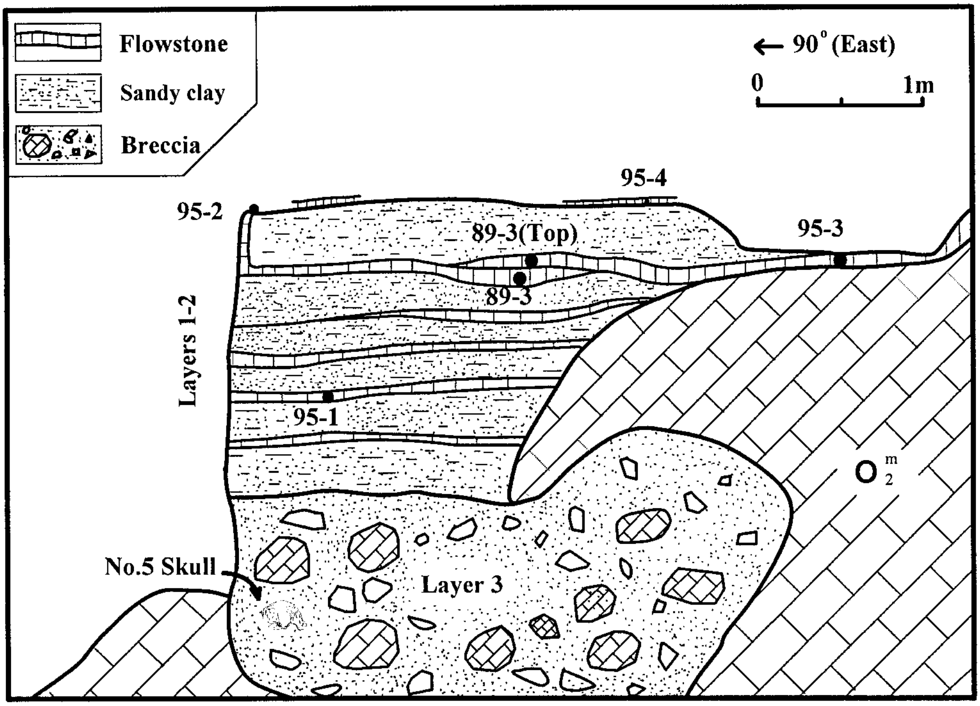


Figure 1. Sketch showing locations of the dated samples from Layers 1–2 at Locus H, Locality 1, Zhoukoudian. Layers 1–2 are poorly fossiliferous, while Layer 3 contains hominid fossils, notably the No. 5 Skull and an abundance of stone artefacts. $O_2^m$ denotes the Middle Ordovician Majiagou Group limestone, in which the cave formed.

Moreover, the east–west depositional continuity at Locality 1 was demonstrated by the longitudinal sections of Pei (1931) and Black *et al.* (1933).

## Methodology

U-series age determinations were performed with TIMS using the procedures of Edwards *et al.* (1986/87) and Cheng *et al.* (2000). The samples were broken into small fragments, cleaned ultrasonically and then hand-picked to avoid pieces of porous and detrital nature. For each analysis, about 2 g were dissolved in $HNO_3$, spiked with $^{229}Th$-$^{233}U$-$^{236}U$, and then purified with ion exchange columns. U was loaded on double Re filaments and Th on single Re filaments covered with coloidal graphite, before measurements were made on a Finnigan MAT 262 mass spectrometer.

The concentrations of $^{233}U$, $^{236}U$ and $^{229}Th$ in the mixed spike solution were calibrated against gravimetrically determined $^{238}U$ and $^{232}Th$ standards. As most of the samples have $^{230}Th$ and $^{234}U$ close to secular equilibrium, uncertainties in the decay constants of $^{234}U$ and $^{230}Th$ may become significant. To address this problem, half-lives of the two nuclides have been re-determined by measuring precisely with TIMS the $^{234}U/^{238}U$ and $^{230}Th/^{238}U$ atomic ratios in four different internal standards thought to have behaved as closed systems for the last $10^6$ years at least, including the inter-laboratory standard HU-1 (Ivanovich *et al.*, 1984). The half-lives thus obtained are $245{,}250 \pm 490$ y ($2\sigma$) and $75{,}690 \pm$

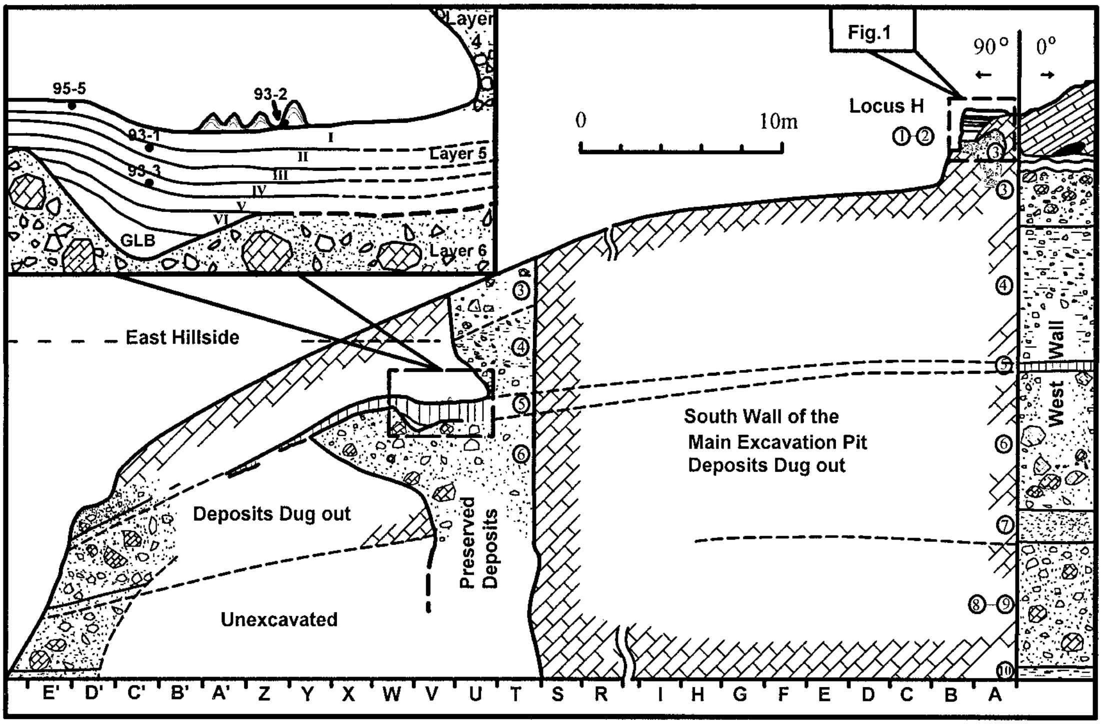


Figure 2. A schematic drawing of profile at Locality 1 showing the South Wall of the Main Excavation Pit, the East Hillside, and a ridge of preserved deposits between the two. At a right angle to the South Wall is the West Wall of the Main Excavation Pit, which is about 40 m thick and exposes Layers 1–13 (increasing in number downward, shown here are Layers 1–10) of the Zhoukoudian Group. Hominid fossils are present at the Main Excavation Pit in Layers 3 through 11 at fifteen widely scattered places designated as Locus A to O (Wu & Dong, 1985). The South Wall is now mainly composed of bare limestone. However, discernible traces of Layer 5 remain, providing stratigraphic continuity throughout the profile. A "stalagmitic floor" running through the longitudinal section has also been clearly shown in Figure 1 of Pei (1931) and in Figure 8 of Black *et al.* (1933). Samples for dating were collected from Layers 1–2 at Locus H (see upper right corner and Figure 1) and from Layer 5 at the East Hillside (see upper left inset, where Roman numerals denote flowstone sub-layers, "GLB" refers to the granite-like breccia mentioned in the text.)

230 y (2σ) for $^{234}$U and $^{230}$Th respectively (Cheng *et al.*, 2000).

## Results and discussion

The isotopic data and calculated ages for 20 analyses on the samples are presented in Table 1. Of the Locus H samples, 95-4 gives a relatively young age of 144 ± 1 ka. The two samples taken from the upper sub-unit of the second flowstone layer, 95-3 and 89-3(top), give comparable ages of 298 ± 7 and 337 ± 8 ka. The four replicate analyses of 89-3 from the lower sub-unit of the second flowstone layer have a weighted mean of 400 ± 8 ka, in good agreement with the previous determination at 414 ± 13 ka (Shen *et al.*, 1996). Thus, there could be a hiatus in deposition between the two sub-units. Samples 95-1 and 95-2 show quite low $^{230}$Th/$^{232}$Th activity ratios of 3–6, signifying a detrital contribution to their $^{230}$Th/$^{234}$U signals and rendering their dates of limited reliability (Table 1). Nevertheless, the near-equilibrium $^{230}$Th/$^{234}$U ratios are consistent with the age assignments of >400 ka for the horizon.

**Table 1** **TIMS U-Series analyses on speleothem samples from Locality 1, Zhoukoudian**

| Sample | $^{238}U$ (ppb) | $^{230}Th/^{232}Th$ | $^{234}U/^{238}U$ | $^{230}Th/^{234}U$ | $^{230}Th$ age (ka) |
|---|---|---|---|---|---|
| | | | *Samples from Layers 1–2, Locus H* | | |
| 95-4 | 1368 (2) | 294 (2) | 1.2008 (0.0015) | 0.7552 (0.0026) | 144 (1) |
| 89-3 (top) | 410.5 (0.6) | 281 (2) | 1.1354 (0.0018) | 0.9927 (0.0037) | 337 (8) |
| 95-3 | 427.0 (0.9) | 55.7 (0.7) | 1.2086 (0.0029) | 0.9855 (0.0045) | 298 (7) |
| 89-3 (I) | 82.2 (0.1) | 233 (2) | 1.1421 (0.0025) | 1.0162 (0.0045) | 391 ($^{+16}_{-15}$) |
| (II) | 75.5 (0.1) | 289 (4) | 1.1399 (0.0028) | 1.0162 (0.0094) | 393 ($^{+35}_{-28}$) |
| (III) | 77.0 (0.1) | 1550 (9) | 1.1393 (0.0020) | 1.0197 (0.0076) | 406 ($^{+33}_{-26}$) |
| (IV) | 71.73 (0.04) | 650 (5) | 1.1449 (0.0016) | 1.0197 (0.0030) | 400 ($^{+12}_{-11}$) |
| 95-1 (I) | 57.1 (0.1) | 3.7 (0.1) | 1.0843 (0.0026) | 1.0305 (0.0125) | |
| (II) | 65.1 (0.1) | 5.6 (0.1) | 1.1014 (0.0030) | 1.0249 (0.0088) | |
| 95-2 (I) | 29.6 (0.1) | 3.1 (0.1) | 1.0817 (0.0035) | 1.0272 (0.0184) | |
| (II) | 28.8 (0.1) | 3.4 (0.1) | 1.0894 (0.0049) | 1.0158 (0.0145) | |
| | | | *Samples from Layer 5, East Hillside* | | |
| 93-2 (I) | 122.4 (0.2) | 455 (4) | 1.0547 (0.0016) | 1.0086 (0.0035) | 486 ($^{+34}_{-28}$) |
| (II) | 32.03 (0.03) | 350 (3) | 1.0972 (0.0031) | 1.0257 (0.0048) | 508 ($^{+68}_{-42}$) |
| 95-5 | 28.8 (0.1) | 6.0 (0.1) | 1.0994 (0.0053) | 1.0262 (0.0100) | |
| 93-1 (I) | 555.4 (0.6) | 2119 (29) | 1.0404 (0.0011) | 1.0174 (0.0036) | >634 |
| (II) | 546.1 (0.8) | 1139 (8) | 1.0419 (0.0015) | 1.0120 (0.0035) | 584 ($^{+104}_{-61}$) |
| (III) | 533.1 (0.6) | 472 (4) | 1.0389 (0.0010) | 1.0146 (0.0033) | 709 ($^{+\infty}_{-126}$) |
| 93-3 (I) | 107.1 (0.1) | 10.8 (0.2) | 1.0404 (0.0027) | 1.0053 (0.0166) | 501 ($^{+\infty}_{-103}$) |
| (II) | 198.8 (0.2) | 43.7 (0.4) | 1.0400 (0.0011) | 1.0166 (0.0034) | 869 ($^{+\infty}_{-282}$) |
| (III) | 612.7 (0.7) | 570 (5) | 1.0381 (0.0011) | 1.0127 (0.0039) | 640 ($^{+\infty}_{-92}$) |

Numbers in parentheses represent 2σ uncertainties in the last digits. Roman numerals in the first column denote replicate analyses on different splits of the same specimen. All isotopic ratios shown are activity ratios. For 95-1, 95-2 and 95-5, age results are not given because of the large uncertainty due to low $^{230}Th/^{232}Th$ ratios. For the analysis of 93-1 (I), the median $^{230}Th/^{234}U$ ratio is higher than, but within 2σ, of the equilibrium value. The age result is calculated from the lower bound on $^{230}Th/^{234}U$ and the higher bound on $^{234}U/^{238}U$.

For the East Hillside samples, analyses on separate chips of 93-2 with different uranium concentrations and $^{234}U/^{238}U$ ratios give consistent ages of $486^{+34}_{-28}$ and $508^{+68}_{-42}$ ka (Table 1). Triplicate analyses on both 93-1 and 93-3 all give near-equilibrium $^{230}Th/^{234}U$ ratios, indicating that the second–fourth sub-layers have ages approaching the limit of the TIMS U-series dating. A date of ca. 600 ka, marking the upper age limit with current measurement precisions, may be derived from the weighted mean of the six $^{234}U/^{238}U$ and $^{230}Th/^{234}U$ activity ratios on 93-1 and 93-3. The stalagmite sample 93-2 (ca. 500 ka) and the flowstone samples 93-1 and 93-3 (ca. 600 ka) may represent different periods of speleothem formation, but considering errors, their ages are not clearly resolvable. The agreement between replicates, the near-equilibrium $^{230}Th/^{234}U$ ratios, and the trends for increasing $^{230}Th/^{234}U$ ages and decreasing $^{234}U/^{238}U$ ratios with depth in a stratigraphic column all indicate the overall reliability of the measurements and the validity of the age interpretation.

Layers 1–3 (Figure 1) have been assigned a single date of ca. 230 ka (Zhao *et al.*, 1985*a*), or a time span between 230 and 290 ka (Yuan *et al.*, 1991). Shen *et al.* (1996) suggested an older date for the deposits from the lower unit of the second flowstone. However, this newly assigned age has not been well received, mainly because of the occurrence of typical Late Pleistocene faunal elements from North China, most notably *Cervus elaphus*. Our present results show that the uppermost 60 cm of deposits at Locus H were, in fact, formed over a fairly long period from 144 to 300 ka. The refined chronology for the topmost strata presented here may conceivably reconcile the U-series dating on calcite and the biostratigraphy.

The ages for the East Hillside samples clearly show the antiquity of Layer 5. Pending further confirmation, the ca. 500 ka horizon represented by the replicate analyses on 93-2 can be taken to mean that all the remains found in Layers 2–4, including the No. 5 Skull from Layer 3, are tightly bracketed between ca. 400–500 ka. The second–fourth sub-layers of the Layer 5 flowstone are at least 600 ka. As many hominid remains were excavated from Layers 8–9, and some even from Layers 10 and 11 (Wu & Dong, 1985), these remains could therefore be significantly older than 600 ka. On the West Wall, Layers 2–4 deposits are about 12 m thick, whereas those in Layers 6–10 are approximately 15 m thick (Yang *et al.*, 1985). By assuming comparable sedimentation rates for deposits above and below Layer 5, the hominids from the lower strata could be 800 ka or older.

The results of this study have important implications. First, human occupation of the Zhoukoudian sites not only occurred much earlier, but also lasted much longer than previously thought. Studies on New Cave (Locality 4), a site located about 70 m to the south of Locality 1, show that human activities there took place earlier than 300 ka and lasted until 120 ka (Shen *et al.*, 1999). These dates and those reported here, taken together, indicate human occupation of Zhoukoudian sites for over half a million years, likely encompassing the transition between late *H. erectus* and early *Homo sapiens* (Clark *et al.*, 1994). During the time span represented by the depositional sequence at Locality 1, progressive changes in faunal composition, artefact inventory and hominid morphology are discernable (Qiu *et al.*, 1973). Such changes are at variance with any proposed model in which *H. erectus* populations in China exhibited a lack of evolutionary change and finally became extinct by replacement.

Second, younger representatives of Chinese *H. erectus* have generally been considered to be contemporaneous with African Middle Pleistocene hominid fossils assigned to *Homo heidelbergensis* (Rightmire, 1996) or to *Homo rhodesiensis* (McBrearty & Brooks, 2000). Bearing more advanced morphological characters, the African specimens are more likely to be the direct ancestor of *H. sapiens* (Rightmire, 1996). Our revision in age of *H. erectus* at Zhoukoudian provides evidence in support of the idea that Asian *H. erectus* and the African *H. heidelbergensis* or *H. rhodesiensis* represent different stages of human evolution, the former predating the latter (Wang & Tobias, 2000). A much older age assignment to the Zhoukoudian hominids also provides a greater lapse between *H. erectus* and *H. sapiens*, making the former more suitable as an ancestral form.

Third, based largely on the previously assigned age of 230 ka for the No. 5 Skull, the youngest member of *H. erectus* at Zhoukoudian, ideas about the co-existence of *H. erectus* and *H. sapiens* in China (Chen & Zhang, 1991) and a slower evolutionary rate for Asian *H. erectus* compared with their African counterparts have been advanced (Clark *et al.*, 1994). Our date of >400 ka for the No. 5 Skull does not support these ideas. We hypothesize that *H. erectus* in China probably did not survive much later than this date. This revised age may also clear up the long-standing puzzle as to why *H. erectus* at Zhoukoudian is apparently contemporaneous with, or even younger than, the morphologically more advanced Dali and Jinniushan skulls (Chen & Zhang, 1991; Chen & Yuan, 1988). Lastly, our results may lead to a revision of the Chinese mid-Pleistocene chronology, given that the biostratigraphy of the Zhoukoudian Locality 1 has been used as a general reference section for contemporaneous deposits in northern China (Yang *et al.*, 1985).

While providing an older age estimate for *H. erectus* at Zhoukoudian, our work suggests that further efforts in searching out additional calcite samples, particularly from along the discernible traces of Layer 5 on the South Wall (Figure 2), for precise U-series dating and stratigraphic correlation are warranted. To ensure the closed-system behavior of the samples, simultaneous high-precision TIMS measurement of $^{231}Pa/^{235}U$ (Edwards *et al.*, 1997) as well as $^{230}Th$-$^{234}U$-$^{238}U$ should be carried out. Given the uncertainties involved in the previous measurements, a systematic re-examination of the paleomagnetic stratigraphy of the Zhoukoudian deposits is called for, to cross-check with the U-series dates and to extend the chronology to the lower strata in the sequence.

## Summary

TIMS $^{230}Th/^{234}U$ dating on speleothem samples from Zhoukoudian Locality 1 show that the age of the No. 5 Skull from Layer 3 is >400 ka, possibly in the range of about 400–500 ka, and that hominid fossils from the lower strata are at least 600 ka, and possibly 800 ka or older. These revised ages imply that (i) human occupation of the Zhoukoudian site occurred much earlier and lasted much longer than previously thought, (ii) Asian *H. erectus* and African *H. heidelbergensis* or *H. rhodesiensis* may represent different stages of human evolution, the former predating the latter, and (iii) hypotheses indicating a co-occurrence of late *H. erectus* and early *H. sapiens* in China and a slower rate of evolution of Asian *H. erectus* compared with their African counterparts need re-evaluation.

## Acknowledgements

This project was jointly supported by the National Natural Science Foundation of China (49363008) and the US NSF (SBR-9420777). The Committee on Scholarly Exchange with China is thanked for sponsoring G.J.S.'s first visit to labs in the U.S.A. during 1993. We would also like to thank Mr Bingxi Cai and Mr Linhong Jin for assistance in sample collection, and Prof. P. V. Tobias and three anonymous referees for constructive suggestions and comments.

## References

Bischoff, J., Rosenbauer, R., Tavoso, A. & Lumley, H. de (1988). A test of uranium-series dating of fossil tooth enamel: results from Tournal Cave, France. *Appl. Geochem.* **3,** 145–151.

Black, D., Chardin, T. de, Young, C. C. & Pei, W. C. (1933). Fossil man in China: The Choukoutian cave deposits with synopsis of our present knowledge of the late Cenozoic in China. *Mem. Geol. Surv. China, Ser. A* **11,** 1–158.

Chao (Zhao), T. K. & Li, Y. H. (1960). Report on the excavation of the Choukoutien *Sinanthropus* site in 1959. *Vert. PalAs.* **2,** 97–99.

Chen, T. M. & Yuan, S. X. (1988). Uranium series dating of bones and teeth from Chinese paleolithic sites. *Archaeometry* **30,** 59–76.

Chen, T. M. & Zhang, Y. Y. (1991). Palaeolithic chronology and possible coexistence of *Homo erectus* and *Homo sapiens* in China. *World Archaeol.* **23,** 147–154.

Cheng, H., Edwards, R. L., Hoff, J., Gallup, C. D., Richards, D. A. & Asmerom, Y. (2000). The half-lives of uranium-234 and thorium-230. *Chem. Geol.* **169,** 17–33.

Cherdyntsev, V. V. (1971). *Uranium-234*. Jerusalem: Israel Program for Scientific Translation.

Chia (Jia), L. P. (1959). Report on the excavation of *Sinanthropus* site in 1958. *Vert. PalAs.* **1,** 21–26.

Clark, J. D., Heinzelin, J. de, Schick, K. D., Hart, W. K., White, T. D., WoldeGabriel, G., Walter, R. C., Suwa, G., Asfaw, B., Vrba, E. & H.-Selassie, Y. (1994). African *Homo erectus*: old radiometric ages and young Oldowan assemblages in the Middle Awash Valley, Ethiopia. *Science* **264,** 1907–1910.

Edwards, R. L., Chen, J. H. & Wasserburg, G. J. (1986/87). $^{234}U$-$^{238}U$-$^{230}Th$ systematics and the precise measurement of time over past 500,000 years. *Earth Planet. Sci. Lett.* **81,** 175–192.

Edwards, R. L., Cheng, H., Murrell, M. T. & Goldstein, S. J. (1997). Protactinium-231 dating of carbonates by thermal ionization mass spectrometry: implications for Quaternary climate change. *Science* **276,** 782–786.

Grün, R., Huang, P. H., Wu, X. Z., Stringer, C. B., Thorne, A. G. & McCulloch, M. (1997). ESR analysis of teeth from the palaeoanthropological site of Zhoukoudian, China. *J. hum. Evol.* **32,** 83–91.

Guo, S. L., Liu, S. S., Sun, S. F., Zhang, F., Zhou, S. H., Hao, X. H., Hu, R. Y., Meng, W., Zhang, P. F. & Liu, J. F. (1991). Fission track dating of 4th Layer of the Peking Man site. *Acta Anthropol. Sinica* **10,** 73–77.

Huang, P. H., Jin, S. Z., Liang, R. Y., Lu, Z. J., Zheng, L. Z., Yuan, Z. X., Cai, B. X. & Fang, Z. M. (1991). Study of ESR dating for burying age of the first skull of Peking Man and chronological scale of the cave deposit in Zhoukoudian site Loc. 1. *Acta Anthropol. Sinica* **10,** 107–115.

Huang, W. P. (1960). Re-study of the CKT *Sinanthropus* deposits. *Vert. PalAs.* **2,** 83–96.

Ivanovich, M., Ku, T. L., Harmon, R. S. & Smart, P. L. (1984). Uranium Series Intercomparison Project (USIP). *Nuclear Instruments and Methods in Physics Research* **2232,** 446–471.

Jia, L. P. (1964). Sinanthropus pekinensis *and its culture*. Beijing: Zhonghua Publishing House.

Liu, S. S., Zhang, F., Hu, R. Y., Liu, J. F., Guo, S. L., Zhou, S. H., Meng, W., Zhang, P. F., Sun, S. F. & Hao, X. H. (1985). Dating Peking Man site by fission track method. In (R. K. Wu, M. E. Ren, X. M. Zhu, Z. G. Yang, C. K. Hu, Z. C. Kong, Y. Y. Xie & S. S. Zhao, Eds) *Multi-disciplinary Study of the Peking Man Site at Zhoukoudian*, pp. 241–245. Beijing: Science Press.

Ludwig, K. R., Simmons, K. R., Szabo, B. J., Winograd, I. J., Landwehr, J. M., Riggs, A. C. & Hoffman, R. J. (1992). Mass-spectrometric $^{230}$Th-$^{234}$U-$^{238}$U dating of the Devils Hole calcite vein. *Science* **258,** 284–287.

McBrearty, S. & Brooks, A. S. (2000). The revolution that wasn't: a new interpretation of the origin of modern human behavior. *J. hum. Evol.* **39,** 453–563.

Pei, J. X. (1985). Thermoluminescence dating of the Peking Man site and other caves. In (R. K. Wu, M. E. Ren, X. M. Zhu, Z. G. Yang, C. K. Hu, Z. C. Kong, Y. Y. Xie & S. S. Zhao, Eds) *Multi-disciplinary Study of the Peking Man Site at Zhoukoudian*, pp. 256–260. Beijing: Science Press.

Pei, W. C. (1929). An account of the discovery of an adult *Sinanthropus* skull in the Choukoutien deposit. *Bull. Geol. Soc. China* **8,** 203–205.

Pei, W. C. (1931). Notice of the discovery of quartz and other stone artifacts in the Lower Pleistocene hominid-bearing sediments of the Choukoutien cave deposit. *Bull. Geol. Soc. China* **11,** 110–146.

Qian, F., Zhang, J. X. & Yin, W. D. (1985). Magnetic stratigraphy from the sediment of West Wall and Test Pit of Locality 1 at Zhoukoudian. In (R. K. Wu, M. E. Ren, X. M. Zhu, Z. G. Yang, C. K. Hu, Z. C. Kong, Y. Y. Xie & S. S. Zhao, Eds) *Multi-disciplinary Study of the Peking Man Site at Zhoukoudian*, pp. 251–254. Beijing: Science Press.

Qiu, Z. L., Gu, Y. M., Zhang, Y. Y. & Zhang, S. S. (1973). New discovery of the fossils and cultural remains of *Sinanthropus pekinensis* from Zhoukoudian. *Vert. PalAs.* **11,** 109–131.

Rae, A., Hedges, R. & Ivanovich, M. (1989). Further studies for uranium-series dating of fossil bones. *Appl. Geochem.* **4,** 331–337.

Ren, M. E., Liu, Z. C., Jin, J. L., Deng, X. Y., Wang, F. Y., Peng, B. Z., Wang, X. Y. & Wang, Z. H. (1985). Development of Zhoukoudian caves and its relation to the life of fossil man. In (R. K. Wu, M. E. Ren, X. M. Zhu, Z. G. Yang, C. K. Hu, Z. C. Kong, Y. Y. Xie & S. S. Zhao, Eds) *Multi-disciplinary Study of the Peking Man Site at Zhoukoudian*, pp. 155–184. Beijing: Science Press.

Rightmire, G. P. (1996). The human cranium from Bodo, Ethiopia: evidence for speciation in the Middle Pleistocene? *J. hum. Evol.* **31,** 21–39.

Schwarcz, H. P. (1992). Uranium-series dating and the origin of modern man. *Phil. Trans. R. Soc. Lond. B* **337,** 131–137.

Schwarcz, H. P. & Blackwell, B. A. (1992). Archaeological applications. In (M. Ivanovich & R. S. Harmon, Eds) *Uranium-series Disequilibrium—Application to Earth, Marine and Environmental Sciences* [2nd edn, pp. 513–552. Oxford: Oxford University Press.

Shen, G. J. (1996*a*). U-series dating of fossil bones: results from Chinese sites and discussion on its reliability. *Chinese J. Geochem.* **15,** 303–313.

Shen, G. J. (1996*b*). $^{227}$Th/$^{230}$Th dating method, methodology and application to Chinese speleothem samples. *Quat. Sci. Rev. (Quat. Geochronol.)* **15,** 699–707.

Shen, G. J. & Jin, L. H. (1991). Re-study of the upper age limit of Peking Man site. *Acta Anthropol. Sinica* **10,** 273–277.

Shen, G. J., Ku, T. L., Gahleb, B. & Yuan, Z. X. (1996). Preliminary results on U-series dating of Peking Man site with high precision TIMS. *Acta Anthropol. Sinica* **15,** 210–217.

Shen, G. J., Yuan, Z. X., Cheng, H. & Edwards, R. L. (1999). New evidence for the chronology of New Cave (Locality 4) at Zhoukoudian. *Longgupo Prehistoric Culture* **1,** 141–147.

Stringer, C. B. (1994). Out of Africa—a personal history. In (M. N. Nitecki & D. V. Nitcki, Eds) *Origins of Anatomically Modern Humans*, pp. 75–84. Boston: Jones & Bartlett.

Stringer, C. B. (2000). Coasting out of Africa. *Nature* **405,** 24–27.

Wang, Q. & Tobias, P. V. (2000). Review of the phylogenetic position of Chinese *Homo erectus* in light of midfacial morphology. *Acta Anthropol. Sinica* **19**(supplement), 23–33.

Weidenreich, F. (1943). The skull of *Sinanthropus pekinensis*: a comparative study of a primitive hominid skull. *Pal. Sin. Ser. D* **10,** 1–484.

Weiner, S., Xu, Q. Q., Goldberg, P., Liu, J. Y. & Bar-Yosef, O. (1998). Evidence for the use of fire at Zhoukoudian, China. *Science* **281,** 251–253.

Wolpoff, M., Hawks, J., Frayer, D. W. & Hunley, K. (2001). Modern human ancestry at the peripheries: a test of the replacement theory. *Science* **291,** 293–297.

Wolpoff, M., Wu, X. Z. & Thorne, A. (1984). Modern *Homo sapiens*: A general theory of hominid evolution involving the fossil evidence from east Asia. In (F. Smith & F. Spencer, Eds) *The Origins of Modern Humans*, pp. 411–483. New York: Alan R. Liss.

Wu, R. K. & Dong, X. R. (1985). Retrospect and prospect of the study of Peking Man. In (R. K. Wu, M. E. Ren, X. M. Zhu, Z. G. Yang, C. K. Hu, Z. C. Kong, Y. Y. Xie & S. S. Zhao, Eds) *Multi-disciplinary Study of the Peking Man Site at Zhoukoudian*, pp. 86–94. Beijing: Science Press.

Wu, R. K. & Lin, S. L. (1983). Peking Man. *Scientific American* **248,** 86–95.

Wu, R. K., Ren, M. E., Zhu, X. M., Yang, Z. G., Hu, C. K., Kong, Z. C., Xie, Y. Y. & Zhao, S. S. (1985). *Multi-disciplinary Study of the Peking Man Site at Zhoukoudian*. Beijing: Science Press.

Wu, X. Z. (1999). Investigating the possible use of fire at Zhoukoudian, China. *Science* **283,** 299.

Yang, Z. G., Mou, J. Z., Qian, F., Wang, X. Y., Niu, P. S., Chen, H. L., Yin, W. D. & Wei, X. S. (1985). Study of the Late Cenozoic strata at Zhoukoudian. In (R. K. Wu, M. E. Ren, X. M. Zhu, Z. G. Yang, C. K. Hu, Z. C. Kong, Y. Y. Xie & S. S. Zhao, Eds) *Multi-disciplinary Study of the Peking Man Site at Zhoukoudian*, pp. 1–85. Beijing: Science Press.

Yuan, S. X., Chen, T. M., Gao, S. J. & Hu, Y. Q. (1991). Study on uranium series dating of fossil bones from Zhoukoudian sites. *Acta Anthropol. Sinica* **10,** 189–193.

Yuan, Z. X., Lin, S. L., Dong, R. & Jin, C. Z. (1985). Report on the excavation of the Peking Man site in 1978–1979. In (R. K. Wu, M. E. Ren, X. M. Zhu, Z. G. Yang, C. K. Hu, Z. C. Kong, Y. Y. Xie & S. S. Zhao, Eds) *Multi-disciplinary Study of the Peking Man Site at Zhoukoudian*, pp. 102–106. Beijing: Science Press.

Zhao, S. S., Xia, M., Zhang, C. H., Liu, M. L., Wang, S. X., Wu, Q. F. & Ma, Z. B. (1985*a*). Uranium-series dating of Peking Man site. In (R. K. Wu, M. E. Ren, X. M. Zhu, Z. G. Yang, C. K. Hu, Z. C. Kong, Y. Y. Xie & S. S. Zhao, Eds) *Multi-disciplinary Study of the Peking Man Site at Zhoukoudian*, pp. 246–250. Beijing: Science Press.

Zhao, S. S., Pei, J. X., Guo, S. L., Liu, S. S., Qian, F., Chou, S. H. & Li, X. G. (1985*b*). Study of chronology of Peking Man site. In (R. K. Wu, M. E. Ren, X. M. Zhu, Z. G. Yang, C. K. Hu, Z. C. Kong, Y. Y. Xie & S. S. Zhao, Eds) *Multi-disciplinary Study of the Peking Man Site at Zhoukoudian*, pp. 239–240. Beijing: Science Press.

Zhou, Y. H. (1989). Amino acid dating of Peking Man and Dingcun Man. *Acta Anthropol. Sinica* **8,** 177–181.