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U-series and radiocarbon analyses of human and faunal remains from Wajak, Indonesia

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ABSTRACT

Laser ablation U-series dating results on human and faunal bone fragments from Wajak, Indonesia, indicate a minimum age of between 37.4 and 28.5 ka (thousands of years ago) for the whole assemblage. These are significantly older than previously published radiocarbon estimates on bone carbonate, which suggested a Holocene age for a human bone fragment and a late Pleistocene age for a faunal bone. The analysis of the organic components in the faunal material show severe degradation and a positive $\delta^{13}\text{C}$ ratio indicate a high degree of secondary carbonatisation. This may explain why the thermal release method used for the original age assessments yielded such young ages. While the older U-series ages are not in contradiction with the morphology of the Wajak human fossils or Javanese biostratigraphy, they will require a reassessment of the evolutionary relationships of modern human remains in Southeast Asia and Oceania. It can be expected that systematic direct dating of human fossils from this area will lead to further revisions of our understanding of modern human evolution.

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Introduction

The human remains that were found in the Javanese Wajak site in 1888 and 1890 have been the subject of controversy since their description as 'Proto-Australians' (Dubois, 1922). Seen as a link between Pleistocene Javanese *Homo erectus* and recent Australian Aborigines, 'Wajak Man' has played an important role in the ideas about multiregional evolution (Weidenreich, 1945; Coon, 1962; Wolpoff et al., 1984) but not everyone agreed (Storm, 1995, 2001). A critical problem was the absence of age determinations (Storm and Nelson, 1992), until Shutler et al. (2004) reported a radiocarbon date, which suggested a Holocene age for 'Wajak Man'. This finding was not in disagreement with Storm's (1995) interpretation of the morphology of the human remains, the fauna and microlithic artifacts.

The Wajak site and hominids

In 1888, while prospecting for marble, B.D. Van Rietschoten found a skull on a mountain slope of the Gunung Lawa in East Java

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near Tjampoer Darat. The skull, now known as Wajak 1 (Fig. 1A), was sent to Eugène Dubois, who at the time was in Sumatra. Dubois (1890) reported that Wajak 1 was found in a rock-fissure filled with breccias, and although bones of animals, presumably deer were present, no other human remains were discovered. Later in 1890, Dubois travelled from Sumatra to Java to excavate the Wajak site. During this excavation he found remains of a second specimen, now known as Wajak 2 (Fig. 1B). Soon afterwards, the remains of a human skeleton were discovered in the sediments of the above-mentioned rock-fissure, which presumably belong to Wajak 2, along with fragments of various mammals. Although Dubois (1922) described the exact location of the Wajak site, it was believed to be lost (Van Stein Callenfels, 1936; Coon, 1962; Jacob, 1967; Van den Brink, 1982) until the site was rediscovered in 1985 by Aziz and De Vos (1989).

Most of the materials excavated from the Wajak site are skeletal remains. The bones show no marks of transportation, which makes it unlikely that they were washed into the site. The bone assemblage contains various animals that are represented by only a few elements of the skeleton. Humans dominate the bone assemblage, with a nearly complete cranium (Wajak 1) and a partial skeleton (perhaps associated with the Wajak 2 cranial remains).

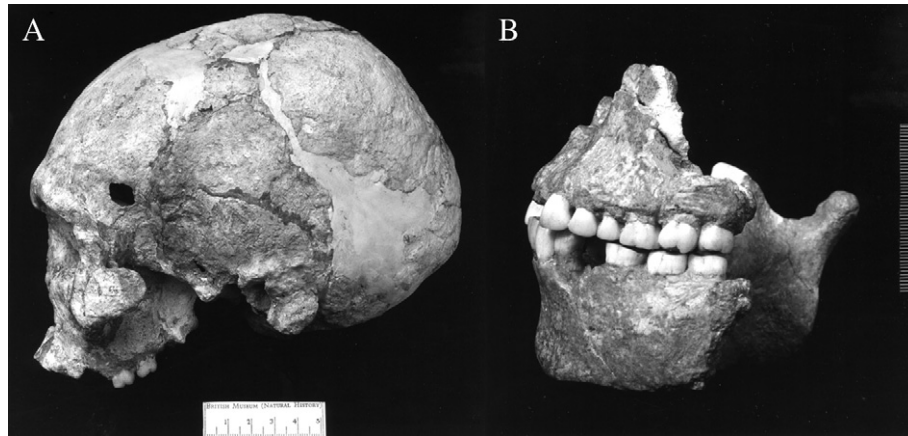


Figure 1. A: Cranium and mandible of Wajak 1, norma lateralis sinistra. B: Maxilla and mandible of Wajak 2, norma lateralis sinistra.

This observation, together with the presence of a few artifacts, possible cut marks (fragment of distal part of metacarpus from a large deer), signs of burning and remains of marine origin indicate that Wajak was a habitation site, a burial, or both (Storm, 1995). Unfortunately, the excavations were not sufficiently well documented to provide further resolution of this issue.

The fauna include *Rusa timorensis*, *Muntiacus muntjac*, *Sus scrofa*, *Tapirus indicus*, *Rhinoceros sondaicus*, *Hystrix javanica*, *Panthera tigris*, *Homo sapiens* and *Presbytis cristatus* (Van den Brink, 1982; Storm, 1995). In addition, the site contained marine invertebrate remains comprised of mollusc shell fragments and spines of sea urchins. All mammals found in the site are still extant, although *T. indicus* is now extinct in Java, *Rhinoceros* is restricted to a reserve in West Java, and *P. tigris* very likely disappeared from Java in the last century (Whitten et al., 1996). The animal bone assemblage of Wajak can be interpreted as stemming from an open woodland fauna (De Vos, 1983, 1985).

During a restudy of the fragmentary bone material from this site, two artifacts were found and interpreted as small blades (Storm, 1992). The Indonesian Epipalaeolithic period, which is partly characterised by the occurrence of microlithic industries, is dated to between 10,000 and 5000 BP (Before Present) (Van Heekeren, 1975).

Storm (2001) combined Javanese biostratigraphy (De Vos, 1983; Sondaar, 1984; Leinders et al., 1985) with dated sedimentological and palynological information (Dam, 1994; Van der Kaars and Dam, 1995) to establish a climatic sequence for Java: before and around 135 ka (thousands of years ago), the climate was considerably drier and hot (the archaic fauna of Ngandong). Between 126 and 81 ka, the climate was primarily humid and warm (the modern fauna of Punung), becoming subsequently drier and cooler (the modern fauna of Wajak) before returning to more interglacial conditions in the Holocene.

There are two aspects of the Wajak skulls that all scientists agree with: they clearly represent *H. sapiens* and are large and very robust (Storm, 1995). Their robustness is the main reason why the Wajak remains were readily linked with other robust skulls in the region, such as those from the more ancient site of Ngandong, and late Pleistocene-early Holocene hominins from Australia (Weidenreich, 1945; Coon, 1962; Wolpoff et al., 1984; Thorne and Wolpoff, 1992). However, others noticed difficulties in the assumption of a direct evolutionary link between Ngandong and Wajak (Jacob, 1967; Santa Luca, 1980; Stringer, 1992; Storm, 1995, 2001).

Previous age estimates

The ages suggested for Wajak ranged from Pleistocene to Holocene (Storm and Nelson, 1992), with an emphasis on the latter.

Dubois (1922) assumed a 'great [Pleistocene] age' based on the observation that the density of the Wajak 2 mandible was about 40% higher than fresh bone. Jacob (1967) claimed that the Wajak fauna was similar to the Mesolithic fauna of Sampung. In conjunction with the degree of fossilisation and low U-concentrations (around 2 ppm), he proposed a Holocene age. Note that the U-concentrations of all bones analysed in this study are significantly higher than 2 ppm (see Figs. 3, 6 and 8, below). Bartstra (1984a, 1984b, 1987) placed the Pacitanian in the late Pleistocene or early Holocene and considered 'Wajak Man' as the maker of this culture. However, the Wajak remains and Pacitanian artifacts do not appear to bear any relation to each other (Storm, 1992, 1995).

Two radiocarbon dates were obtained on fossils from Wajak. A human femur yielded 6560 ± 140 BP (AA7718) and an unspecified faunal bone $10,560 \pm 75$ BP (Shutler et al., 2004). This would place the hominids into the Holocene and the site may have been occupied since the late Pleistocene/Holocene transition. The dates also agree with the proposed Mesolithic nature of the two artifacts.

Materials and methods

Samples

Six different bone fragments were analysed. The three human bones (see Fig. 5, below) consist of two cranial fragments from Wajak 2 (WH1 and WH2) and one cross-section from the mid femoral shaft (WH3). The three other samples were faunal post-cranial bone fragments (WF1 to 3, see Fig. 7, below) selected from the Dubois collection in Leiden. These have no precise provenance and their spatial and temporal relationships to the human material are uncertain.

Experimental and results

In order to assess the fossilization state and age of the human material we applied a series of techniques on small human bone fragments.

Bone preservation and fossilisation A crystallinity index (CI) value of 5.3 was determined using X-ray diffraction (XRD) on mid-cortical bone powder in the British Museum Research Laboratories in London, using the method described by Bartsiakos and Middleton (1992). This high value confirms the observation of Dubois (1922) that the fossilization state of 'Wajak Man' as 'very complete'.

Thin cross sections of femoral cortical bone were produced using a diamond saw. Fig. 2 shows a section of cortical bone including part of the medullary cavity. The bone voids, i.e., the Haversian

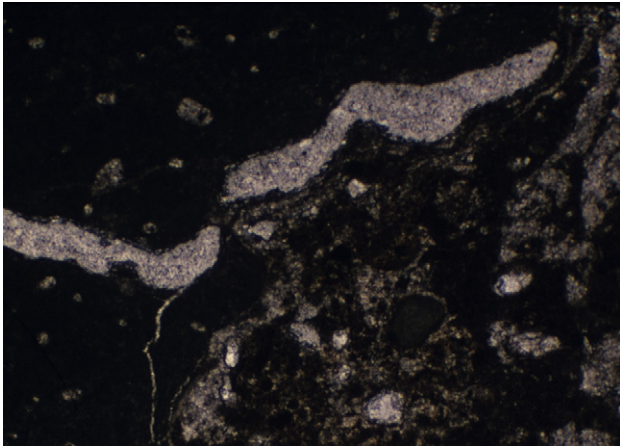


Figure 2. Section of human cortical bone (upper left corner) including a part of the medullary cavity (lower right corner) viewed under a cross polarizing microscope. The horizontal width is about 1 mm. Note the complete destruction of the osteons and their lamellae apart from the Haversian canals that have been filled by calcite. A thin layer of calcite has covered the outer and inner surfaces of bone (shown as a diagonal white line covering the endosteal surface, in the upper right). The cracks have been infilled by calcite too (white line on the left). No calcite has impregnated the bone matrix itself. The crystals of bone mineral have a random orientation. The medullary cavity has been filled by brecciated (calcified) clay (lower right corner).

canals and the postmortem cracks, are filled with calcite. A thin layer of calcite also covers the outer and inner surfaces of bone in places where the periosteum and the endosteum would have been. No calcite has been detected in the bone matrix itself. The bone mineral recrystallised so that the osteons and their lamellae were completely destroyed. The medullary cavity is filled by brecciated, calcified clay. Thus, after deposition in the cave, a thin calcitic layer was first precipitated on the bone surfaces, and then clay covered the medullary cavity internally and the bone externally.

U-series analysis Laser ablation U, Th and U-series analyses were carried out at the Australian National University. For the experimental set-up, see Eggins et al. (2003, 2005), and for applications on human fossils see Grün et al. (2005, 2006, 2008). U and Th concentrations were derived from repeated measurements of the NBS-610 standard, U-isotope ratios from the dentine of a rhinoceros tooth from Hexian (sample 1118, see Grün et al., 1998).

Initially, the human bones were analysed along laser tracks. The results of the laser tracks are greatly scattered (Fig. 3). The large number of pores, which are partly filled with calcite, caused poor counting statistics for U-series age estimates. To avoid the influence of pores and to obtain better general counting statistics, subsequent measurements utilised spot analysis where the laser was kept in one position for 100 s, creating a small pit (132 μm in diameter, approximately 50 μm deep) in the bone by ablation. Fig. 4 shows the ^{230}Th run for the WH3-1, the ablation holes shown in Fig. 5D (below) on the left hand side. ^{232}Th is amplified by a factor of 100 compared to the ^{238}U measurement. It can be seen that only spot #1 of the human sample WH3, very close to the surface of the bone, shows any notable ^{232}Th concentrations. Some of the other ablation pits (e.g., Rhino standard spot #1 and WH3-1 spots #13 and #14) show some minor ^{232}Th elevations at the start of the measurements. These are more likely surface contaminations from the cutting process rather than pore fillings. Nearly all ^{232}Th measurements are close or equal to the background, which is shown in the first 120 cycles. In all measurements (except #1), the elemental $^{238}\text{U}/^{232}\text{Th}$ ratios are well in excess of 1000, which correspond to activity ratios of >3000 . We cannot explicitly quantify the $^{230}\text{Th}/^{232}\text{Th}$ activity ratios as we do not have a matrix matched ^{232}Th standard. However, the very high $^{238}\text{U}/^{232}\text{Th}$ ratios imply that

any corrections for detrital ^{232}Th are not necessary. The laser ablation spots that were partly drilled into the adhering sediments (e.g., Fig. 5A, B) did show elevated ^{232}Th concentrations, but these data points were not further used in the age assessment of the samples.

Note that the U-concentrations are critically dependent on the homogeneity of the material; small filled or unfilled pores will cause an apparent change in the U-concentrations. For example, the peak shapes of the two sets of standards in Fig. 4 (before and after the sample measurement) are quite different and this would lead to significantly different U-concentration assessments, while the $^{230}\text{Th}/^{238}\text{U}$ ratios are the same within counting statistics. The ANU Neptune has only one ion counter, which needs to be used for both ^{230}Th and ^{234}U measurements. In practice, the $^{234}\text{U}/^{238}\text{U}$ ratios in bones change significantly less than the $^{230}\text{Th}/^{238}\text{U}$ ratios. Each line of spot analyses consists of twice as many $^{230}\text{Th}/^{238}\text{U}$ than $^{234}\text{U}/^{238}\text{U}$ analyses, the latter being offset by a few 100 μm (see Figs. 5 and 7). Where several $^{234}\text{U}/^{238}\text{U}$ analyses were equidistant from a $^{230}\text{Th}/^{238}\text{U}$ spot, appropriate averages were used. The spot analyses focused on areas away from the pores.

For the human samples, cross sections were carried out for WH2 and WH3, while the analyses of WH1 focused on the rims. WH1 had some remaining sediment attached. For comparison with the bone material, one set of spots is located in that rim. The results on the human bones are shown in Figs. 5 and 6.

All faunal samples consisted of dense bone so that equally spaced spots along cross sections could be analysed. Note that the second cross section on WF3 is not accompanied by $^{234}\text{U}/^{238}\text{U}$ analyses. Here, the average of the other line was used. The mean and standard deviation of the 16 measurements along the first cross section in WF3 were 1.0300 ± 0.0049 , which shows that the basic assumption, namely that the $^{234}\text{U}/^{238}\text{U}$ ratio changes little in the bones, is justified (all $^{234}\text{U}/^{238}\text{U}$ measurements are within 0.99 and 1.06). The ages estimated along the four measured profiles are shown in Fig. 7.

Bayesian modelling To build a chronology from the U-Series dates, a model was constructed in OxCal version 4.1 (Bronk Ramsey, 2009a) using the General t-type Outlier Model and assuming all samples had a 5% prior probability of being an outlier (Bronk Ramsey, 2009b).

Radiocarbon analysis As the U-series results were considerably older than the previously published ^{14}C ages, an attempt was made to extract collagen for radiocarbon dating from the three faunal samples dated by U-series using the ultrafiltration protocol described in Brock et al. (2010). Briefly, this consists of a series of acid and base washes to remove carbonates and base-soluble organics prior to gelatinization, filtration and ultrafiltration to dissolve the protein and remove large (>60 – $90 \mu\text{m}$) insoluble contaminants and small ($<30 \text{ kDa}$) soluble contaminants, respectively. Collagen yields from the Wajak bones were suspected of being extremely low, and the samples were therefore freeze-dried prior to ultrafiltration. At this point in the process, collagen yields ranged between 0.01 and 0.2 wt% (Table 1), and were too small for ultrafiltering (Wood et al., 2010). Moreover, when the collagen content of bone falls below 1 wt%, its quality is often reduced and radiocarbon dates are often erroneous (Van Klinken, 1999). The residue remaining after the pretreatment of sample N7005 contained just 2% carbon, much less than the approximately 40% expected from collagen (Van Klinken, 1999). As a result, no samples could be reliably radiocarbon dated.

Next, the apatite fraction of WF1 was dated by AMS radiocarbon to examine whether the bones dated by U-Series produced similar ages to those of Shutler et al. (2004). To assess this radiocarbon procedure, the apatite of a woolly rhinoceros bone from MIS

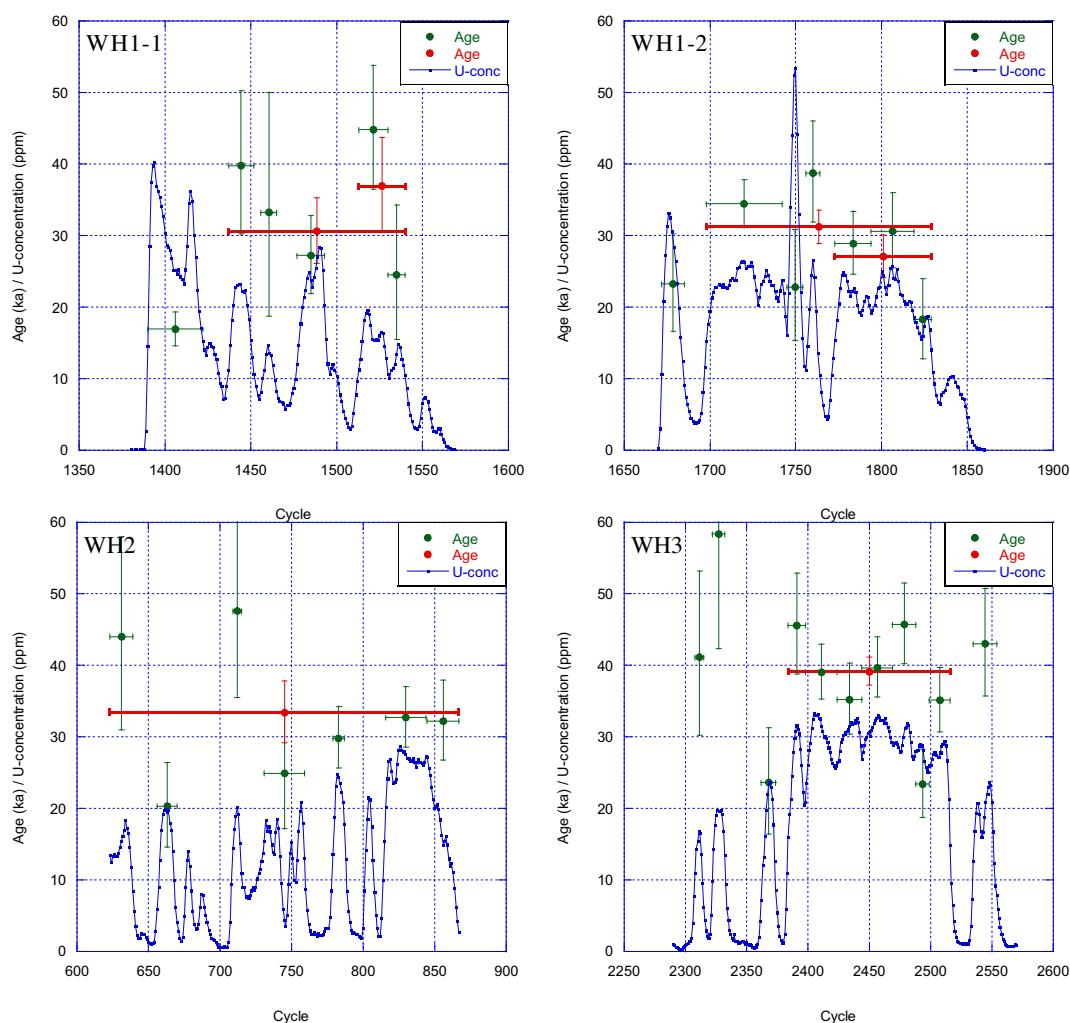


Figure 3. U concentrations and age calculation from continuous laser tracks of WH1, WH2 and WH3. The position of the laser track for WH2 is shown in Fig. 5C.

5e permafrost deposits at Zaglik, near Irkutsk, Russia, was also analysed. Collagen from this bone yielded radiocarbon dates of >50,400 BP with a $\delta^{13}\text{C}$ of -18.7 (OxA-22659). An acid leach method was used to remove secondary carbonates prior to AMS. The two bones were crushed to a fine powder and etched in 10 ml 1 M acetic acid for 10 h in a blood collection Vacutainer®. Evolved

CO_2 was removed every 1–2 h and the headspace placed under a vacuum of 10–3 Torr in an attempt to avoid recrystallisation and to speed up the reaction (Zazzo and Saliège, 2011). Acetic acid was removed and the bone washed five times in MilliQ water prior to freeze drying. 3 ml 85% H_3PO_4 was added to the bone powder and heated at 80°C for 3 h. Evolved CO_2 was collected, graphitized and dated by AMS as described by Fallon et al. (2010). The results are shown in Table 2. Note that the AMS $\delta^{13}\text{C}$ values on graphite are often enriched by 3–4‰ compared to isotope ratio-mass spectrometry.

Discussion of the dating results

In spite of the poor counting statistics, the ablation tracks already indicated that the age of the Wajak fossils was considerably older than suggested by the bone apatite radiocarbon results (Shutler et al., 2004; see Fig. 3). There is no clear relationship between U-concentration and U-series age, and the mean values of the three samples vary between about 30 and 40 ka.

It is expected from the diffusion-adsorption model for U-uptake (Millard, 1993; Millard and Hedges, 1996; Pike, 2000; Pike et al., 2002) that spatially resolved analyses across a homogeneous bone yield U-shaped or constant U-concentration and apparent U-series age profiles. In ideal circumstances, a plot of apparent U-series age versus U-concentration would either be flat or show

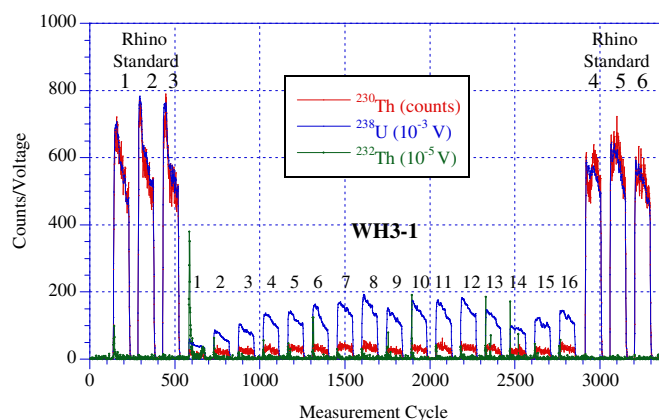


Figure 4. Laser ablation spot analyses of WH3-1 (Row 1 of spots in Fig. 5D).

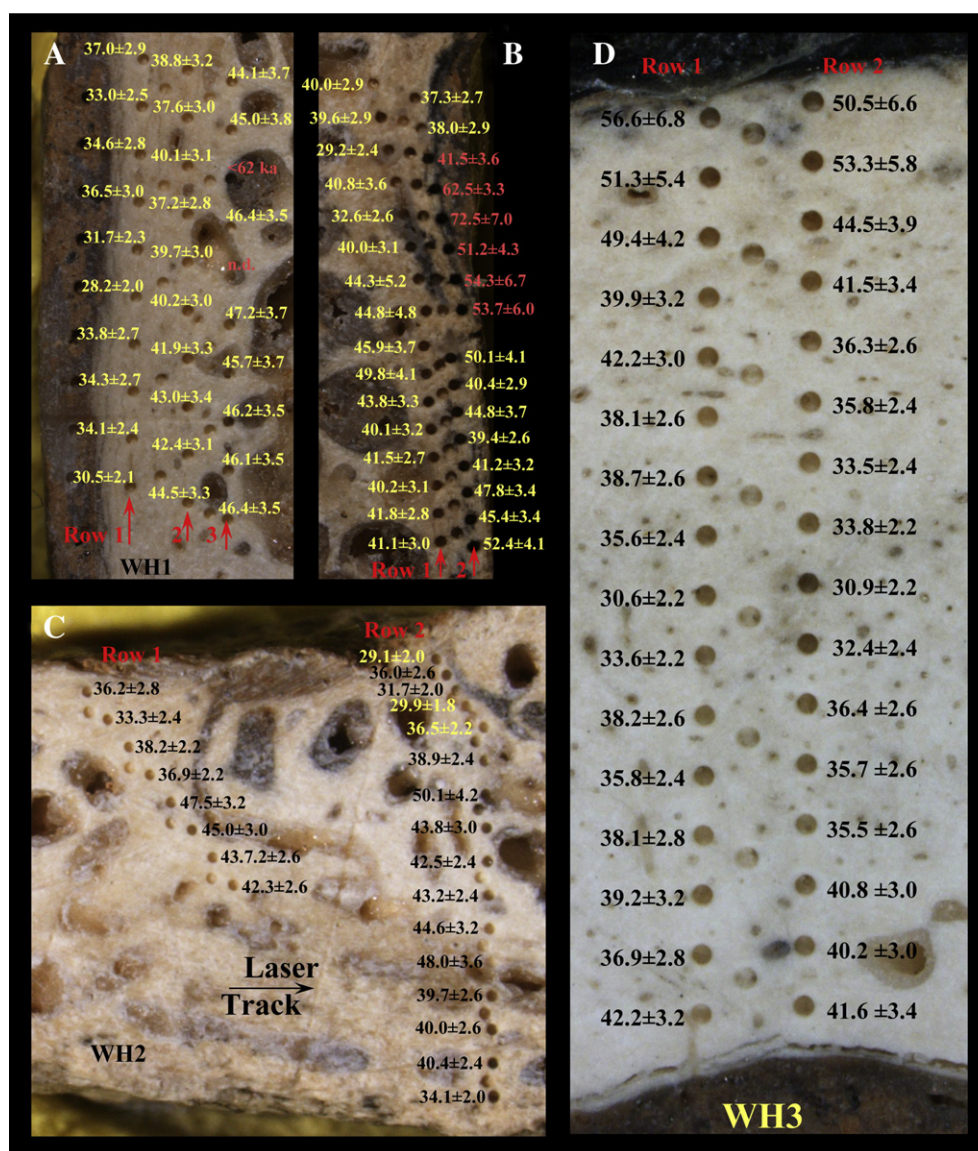


Figure 5. U-series age estimates on the human samples from the Wajak site. WH1 (A, B) and WH2 (C) are cranial fragments and WH3 (D) is a cross-section from the mid femoral shaft. No ages were calculated for the outer rim in 6A, which mainly contains sediment. Red numbers indicate contamination either from sediments or pore fillings. The other colours in the ages were only chosen for better contrast. Track positions in Fig. 6 are indicated by red arrows (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

increasing U-series age estimates with increasing U-concentrations. However, all three faunal bones have sections where the U-series ages increase from the outside towards the inside (e.g., WF1 on both sides, see Figs. 7A and 8A). This could be explained with a secondary U-uptake phase, but this would lead to higher U-concentrations, which is clearly not the case. The only trend that is visible is in WF1 and shows decreasing ages with increasing U-concentrations, perhaps a secondary overprint that did not affect the outermost spot. The assumption of the U-uptake model presented by Sambridge et al. (2012), that the $^{234}\text{U}/^{238}\text{U}$ ratio in the vicinity of the bones' surfaces are constant over time, would have a negligible effect on any age calculations as all measured $^{234}\text{U}/^{238}\text{U}$ ratios are very close to 1 (see above).

One has to keep in mind that, unless a major phase of leaching has taken place, all U-series age estimates on bones are minimum results as the time of U-uptake, rather than the death of the animal, is dated. Only one sample shows some indication for leaching. WF3-1 has a clear trend of increasing U-series ages with decreasing

U-concentrations (see spots 1 to 6 in Fig. 8C). Perhaps the first spot of WF2 shows the same effect. The other samples show decreasing age estimates with decreasing or constant U-concentrations in the volumes close to the outside, which may indicate a secondary overprint with U. The general lower U-concentrations in the volumes closer to the outside may indicate some deterioration of the mineralogical structure of the bone, resulting in a reduction of the internal surface area and ability to adsorb U. Investigations on the cement and dentine of a much older sample shows that U-mobilisation can take place over small distances leading to small scale U-leaching and U-accumulation effects (Duval et al., 2011). The same processes may apply to the Wajak samples. The best U-series result would result from averaging all data.

Excluding the first spot of WF2 and spots 1 to 6 in WF3-1 (which may cause a bias towards older ages due to leaching), the following mean ages are obtained: WF1: 36.5 ± 5.8 ka; WF2: 41.6 ± 6.8 ka; WF3-1: 33.3 ± 2.8 ka and WF3-2: 35.9 ± 5.5 ka (the uncertainties are the standard deviations from the age variations). If the bones

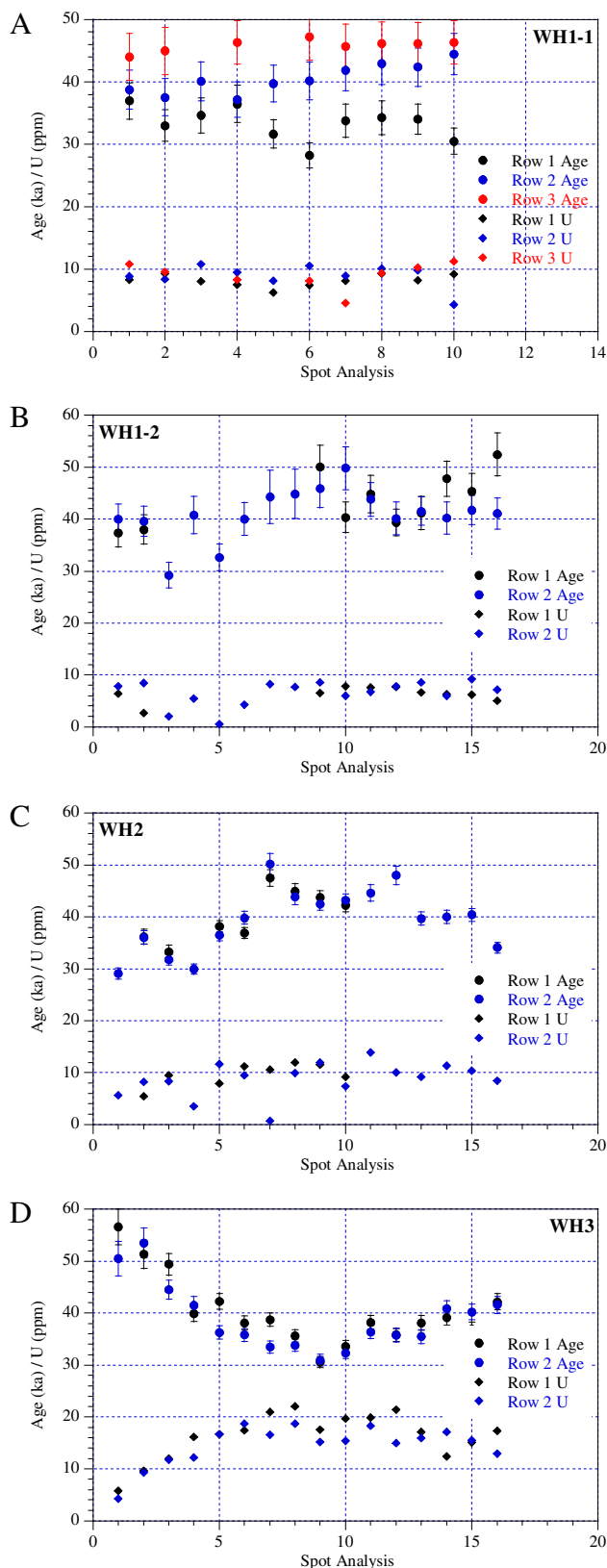


Figure 6. U-concentration and U-series ages of the three human bones for each spot analysis, WH1 (A, B), WH2 (C) and WH3 (D), see Fig. 5.

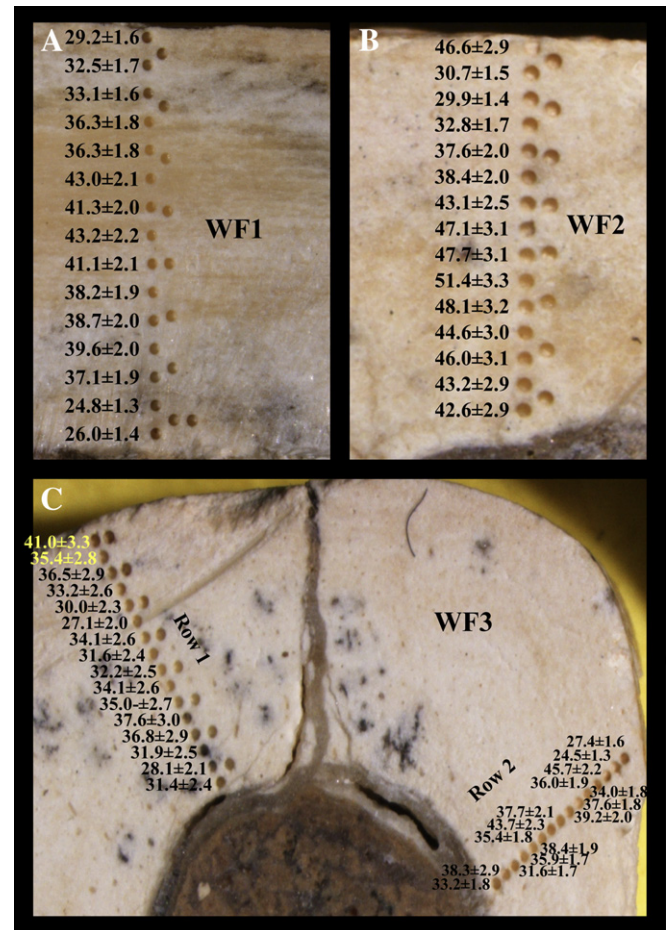


Figure 7. Estimated ages for laser ablation U-series spot analyses of postcranial bone fragments, WF1 (A), WF2 (B) and WF3 (C).

are considered to be of the same age then they should all be older than about 35 ka (derived from WF2). If they are of different ages, then they are certainly all older than 30 ka. While some further selection from the data may decrease the uncertainties of the individual samples, this would not reduce the scatter in the mean ages between the samples.

The human samples show the same trends as the faunal material. In WH1-1, there is a clear trend of older age estimates towards the centre of the bone (see trends from Row 1 to 3 in Figs. 5A and 6A). As seen in WF1, the increasing U-series age estimates are associated with increasing U-concentrations; i.e., it is unlikely to be the result of leaching. For the cranial fragments, one may postulate that the main U migration path into the bones proceeded via the internal pores. But spots near pores in the second row are neither older than the other spots in the same row, nor do they contain more U (see Figs. 5A and 6A). Spots drilled into the calcite either did not allow any age calculations, or were associated with

Table 1
Collagen and carbon yields of three faunal bones from Wajak.

N-number	Sample	Start weight (mg)	End weight (mg)	Collagen yield (%)	C (%)
7001	WF1-A	644	0.2	0.03	N/A
7005	WF1-B	933	1.8	0.19	2%
7002	WF2-A	704	0.1	0.01	N/A
7003	WF3-A	534	0.1	0.02	N/A

Table 2
Radiocarbon age estimates on apatite.

Sample name	S-ANU	^{14}C age (BP)	Starting weight (mg)	Pretreatment yield (mg)	Pretreatment yield (%)	$\delta^{13}\text{C}$ (‰)	C (%)
Zaglik	25,112	27,770 \pm 150	688.7	450.3	65	-11.1 ± 0.3	1.0
WF1A	25,111	14,870 \pm 100	670.3	516.7	77	8.1 ± 3.1	1.0

very large errors (see spots 3 and 5 in the third row of spots in Fig. 5A). At the other side of WH1, there is no relationship between age and sample position or U-concentration (Figs. 5B and 6B), only the spots partially drilled into the sediment show significantly older apparent age estimates (red spots in Fig. 5B). The average age of WH1-1 is 39.5 ± 5.6 ka and WH1-2 42.0 ± 5.1 ka. There is no evidence for leaching in the second cranial bone WH2. Its average age is 39.7 ± 5.7 ka.

WH3 is a cortical bone fragment from the mid shaft of a femur consisting of thick and relatively dense bone without larger pores. The two cross sections show the remarkable reproducibility of the general trends in U-isotope distribution. In both profiles the age of the first five spots may be the result of leaching (see Figs. 5D and 6C, D), the age calculation of the first spot may be biased by some detrital ^{232}Th (Fig. 4). Excluding these results, WH3 has an average age of 36.5 ± 3.2 ka. WH1 and WH2 show consistently older ages than 35 ka, while WH3 could perhaps be 2 ka younger, based on the younger end of the error envelope. Again, one has to keep in mind that all results are minimum age estimates.

If all U-series dates are placed within a single Phase in a Bayesian model in OxCal, the period of bone accumulation is predicted to have ended by 37.4–28.5 ka (95.4% probability; Fig. 9). No outliers are identified by the model, confirming the consistency of the dataset. The length of bone deposition at the site, provided by the Interval function of OxCal, ranged between 0 and 16.2 ka: the bones may all be identical in age, or they could range over more than ten millennia.

One may be tempted to exclude further data points when calculating the averages for the rows of U-series dates, particularly the outer spots of WH1 and WH2. This would result in minimum age estimates in the 45 ka range, changing the Bayesian model. However, at this juncture, the most important point is that all fossils yielded U-series results that are significantly older than previously estimated by radiocarbon. The main interference in radiocarbon dating is most likely massive recent contamination associated with the precipitation of calcite in the pores of the bones. We feel that the large scatter in the U-series age estimates within each bone, perhaps associated with relatively recent U-redistribution, precludes any further speculations about the age of the Wajak hominins (i.e., how much older than 37.4–28.5 ka they are), unless other methods such as ESR can be applied to the dental remains (Joannes-Boyau and Grün, 2011).

The question arises why should the original radiocarbon results be incorrect? The previous result on the human bone is well within the range of reliable radiocarbon dating. Our attempt to extract organic matter from the bones showed that virtually none was preserved in the Wajak bone samples. Contamination, corresponding to around 3% modern, was present in the carbonate fraction of the MIS 5 bone from Zaglik. The $\delta^{13}\text{C}$ of -11.1 ± 0.3 ‰ is 7.6‰ heavier than the collagen, but this difference is more or less expected from the different physiological pathways and fractionation of carbon isotopes in the formation of proteins and hydroxyapatite (around 5‰ e.g., Lee-Thorp et al., 1989) plus offsets between AMS and conventional mass spectrometry on graphite $\delta^{13}\text{C}$ measurements (3–4‰, see above). WF1 yielded a significantly younger age of around 14.9 ka BP. A contamination corresponding to 3% modern carbon would change the age by

about 3 ka only. However, the $\delta^{13}\text{C}$ of $+8.1 \pm 3.1$ ‰ cannot be explained by physiological fractionation of dietary carbon, only by the diagenetic introduction of carbon with a very high $\delta^{13}\text{C}$ values. Values of around 0–+4‰ were found in speleothems between 12 and 30 ka from Java (Westaway et al., 2007a). That makes it very likely that our radiocarbon result was heavily biased by secondary carbonate contaminations, which are clearly visible in WH1 and WH2 (Fig. 5).

The radiocarbon date on the bone AA7718 was based on a thermal release method developed by Haas and Banewicz (1980) and refined by John Head. Unfortunately, the $\delta^{13}\text{C}$ value of -25 ‰ that was used for age calculation was simply assumed. We cannot find any evidence that any $\delta^{13}\text{C}$ values were measured after the initial calculation. In this context it is worthwhile pointing out that the thermal release method yielded very young apparent ages on samples that were known to be beyond the age limits of radiocarbon (Grün et al., 1997). On a series of tooth enamel samples, the thermal release method yielded ages in the range of 5–15 ka BP for thermal release at 600 °C, 6.5 ka BP and 110% modern for 750 °C and 12 ka BP and modern for 900 °C. This shows that the thermal release method can even return apparently modern ages for samples that are known to be older than 40 ka. It seems most likely that the thermal release method yielded an average contamination age, and we find it unlikely that any of the radiocarbon analyses on the Wajak bone samples yielded reliable age estimates.

Implications

The faunal assemblage, reflecting an open woodland environment, fits into the colder and dryer climate that dominated during MIS3. There are no age estimates for the two artifacts (Storm, 1992), making any association between these cultural remains and hominins even more uncertain than between the faunal and human remains. Little is known about the Mesolithic of Java, and it is questionable that small stone tools occurred in Java only during this period, since indications have been found elsewhere in the world of the presence of microliths much earlier, for example during the Upper Palaeolithic in India (Clarkson et al., 2009) or Sri Lanka (Deraniyagala, 1992).

Knowledge about late Pleistocene *H. sapiens* in Indonesia is very limited. Besides the results of this study that suggest a Pleistocene age for Wajak, the only other possible Javanese indication is that from the Punung fauna (Storm et al., 2005). A left upper P³ from this fauna, classified as *Homo*, has mesiodistal and buccolingual dimensions that place it within the range of *H. sapiens*. As the Punung fauna can be dated between 126 and 81 ka ago, as confirmed by the study of Westaway et al. (2007b), this is possibly the oldest *H. sapiens* fossil from Java. Unfortunately, although it was found associated with the Punung fauna, further details about the context are unknown. Moreover, as a single premolar, the possibilities for research into its relationships are limited. Another specimen from this region, the well known Niah Cave ‘Deep Skull’ from Borneo, is evidently of late Pleistocene age, between ca. 46 to ca. 34 ka ago (Harrison, 1965; Barker et al., 2007). Unfortunately, this skull belonged to a young individual that shows post-mortem damage (Brothwell, 1960), which make studies of its affinities difficult.

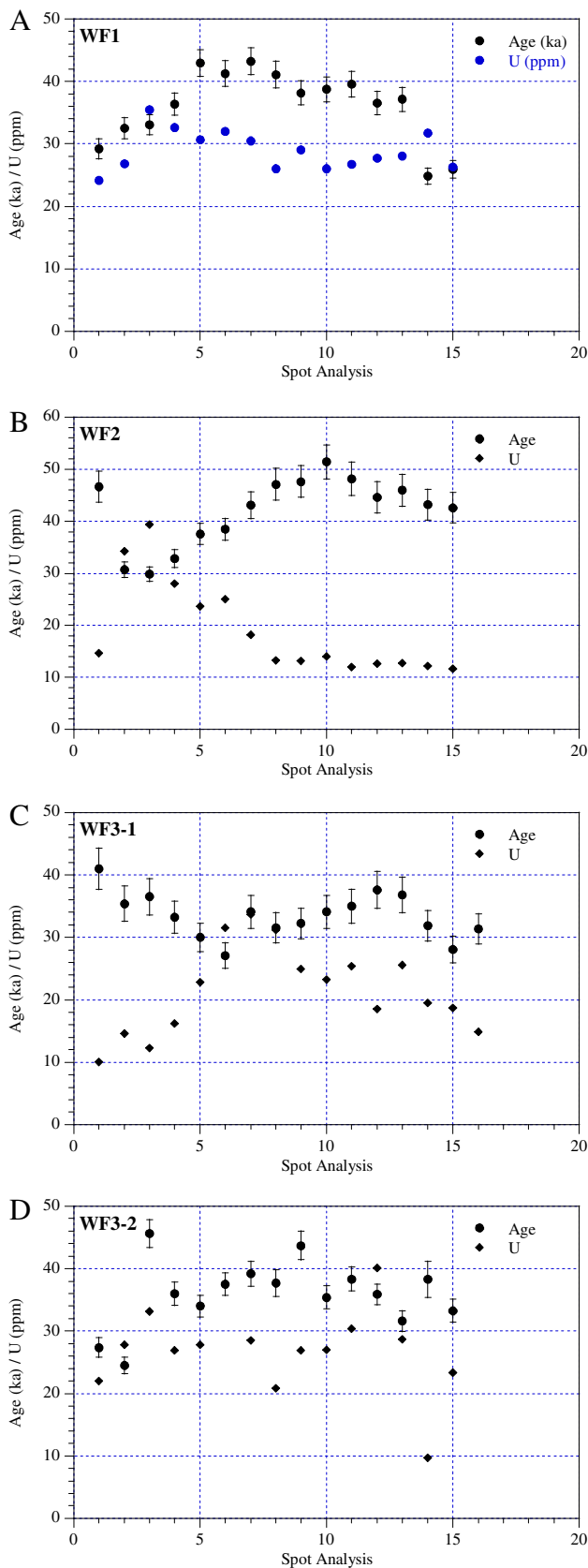


Figure 8. U-concentration and U-series ages of the three faunal bones for each spot analysis, WF1 (A), WF2 (B), WF3 (C, D).

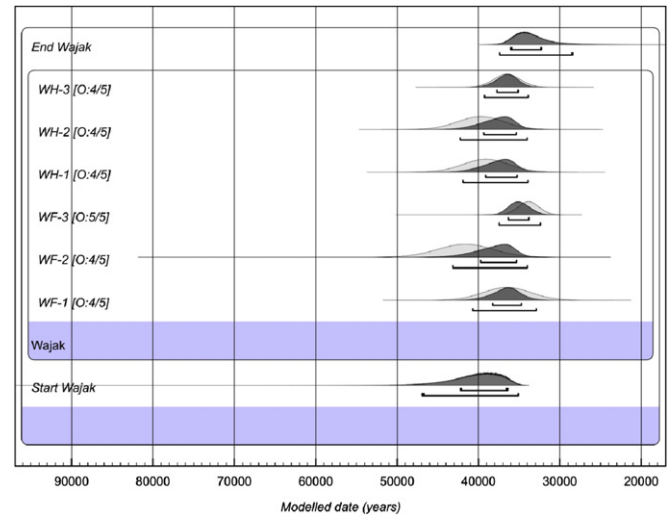


Figure 9. Dates modelled using Bayesian statistics within OxCal v.4.1.6 (Bronk Ramsey, 2009a, 2009b). The pale probability distribution represents the unmodelled date and the darker distribution the modelled date. The 68.2 and 95.4% ranges of the modelled date are given beneath each distribution.

Concluding remarks

It is obvious that U-series dating of bones is not a perfect dating method as there are many factors that have to be taken into account in the interpretation of the analytical data. The major weakness is the fact that U-series analyses on bones usually only provide minimum age estimates. But the results on the Wajak bones also show that radiocarbon, the most widely applied and accepted dating method, may produce results that are serious underestimates. This particularly refers to data from times when rigorous quality assessments had not yet been developed.

On the other hand, new dating results often face opposition from those who prefer to adhere to established schemes for the timing of human evolution. As with dating studies in the late 1980s of the early modern humans in the Levant (Valladas et al., 1988; Stringer et al., 1989) that had a major impact on our understanding of the timing of modern human evolution, the systematic application of dating techniques that can reach beyond the limits of radiocarbon dating will give new insights into the arrival of modern humans in Southeast Asia. Reassessment of young age determinations for the Ngandong hominins from Java (e.g., Indriati et al., 2011) means that the latest presence of archaic humans in the region is still unknown. The Toba eruption at about 73 ka may well have disrupted remaining archaic human populations in Southeast Asia (Williams et al., 2009), but the implication of 'Denisovan' DNA being found in recent Australasian populations (Reich et al., 2010, 2011) is that archaic humans were still resident in Southeast Asia when the ancestors of modern Australasians arrived there. The age estimate of ~67 ka on a small human metatarsal from Luzon (Philippines) indicates an early human presence in that region (Mijares et al., 2010), but the specimen cannot be assigned to species. But given such discoveries, along with those on the island of Flores (Morwood and Jungers, 2009), it seems very likely that intensified archaeological and palaeoanthropological research in the region will provide new fossils and many more 'surprises'. Nevertheless, it is also important to assess the human fossils that have already been excavated, and it is likely that specimens whose ages were obtained using the older methods of radiocarbon dating, or from the dating of associated materials, will turn out significantly older or younger, once they are analysed directly using the latest techniques (Grün, 2006).

Assuming for a moment that the Wajak assemblage is contemporaneous, the new dating results suggesting an age within the late Pleistocene are not in conflict with what we know of the morphology of the human remains, and Javanese biostratigraphy. But of course a great handicap is our lack of knowledge of the original appearance of this site. Luckily, the rediscovery of Wajak (Aziz and De Vos, 1989) means that it is possible to re-excavate, which could provide insight into, for instance, the association between the human, fauna and microlithic remains (Storm, 1992). An age within the late Pleistocene allows a reassessment of the evolutionary relationships of the Wajak fossils. From the perspective of time, the role for Wajak as representing a 'Proto-Australian' (Dubois, 1922) becomes more tenable, as does its claimed resemblance to even older modern human fossils (Stringer, 1992). However, a number of scientists (Jacob, 1967, 1968; Bulbeck, 1982; Wolpoff et al., 1984; Storm, 1995, 2001) have also seen 'Asian' characteristics in the Wajak skulls, and thus an interesting question arises: how old is the Asian face, and where did it originate? Because of the new dating results from Wajak, Indonesia may even contribute to the answer. Moreover, a Pleistocene age for the Wajak human fossils means that they may also be relevant to the ongoing debate about the fate of the Ngandong humans (Bartstra et al., 1988; Swisher et al., 1996; Storm, 2001; Yokoyama et al., 2008; Indriati et al., 2011), the status of the Liang Bua *Homo floresiensis* remains (Morwood and Jungers, 2009), and new evidence of archaic gene flow into recent Australasian populations (Reich et al., 2010, 2011).

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References

- Aziz, F., De Vos, J., 1989. Rediscovery of the Wadjak site (Java, Indonesia). *J. Anthropol. Soc. Nip.* 97, 133–144.
- Barker, G.W.W., Barton, H., Bird, M., Daly, P., Datan, I., Dykes, A., Farr, L., Gilbertson, D., Harrison, B., Hunt, C., Higham, T., Kealhofer, L., Krigbaum, J., Lewis, H., McLaren, S., Paz, V., Pike, A., Piper, P., Pyatt, B., Rabett, R., Reynolds, T., Rose, J., Rushworth, G., Stephens, M., Stringer, C., Thompson, J., Turney, C., 2007. The human revolution in lowland tropical Southeast Asia: the antiquity and behavior of anatomically modern humans at Niah Cave (Sarawak, Borneo). *J. Hum. Evol.* 52, 243–261.
- Bartsiokas, A., Middleton, A.P., 1992. Characterization and dating of recent and fossil bone by X-ray diffraction. *J. Archaeol. Sci.* 19, 63–72.
- Bartstra, G.J., 1984a. Dating the Pacitanian: some thoughts. In: Andrews, P., Franzen, J.L. (Eds.), *The Early Evolution of Man with Special Emphasis on Southeast Asia and Africa*, vol. 69. Cour. Forsch.-Inst. Senckenberg, pp. 253–258.
- Bartstra, G.J., 1984b. Some remarks upon fossil man from Java, his age and his tools. In: Van de Velde, P. (Ed.), *Prehistoric Indonesia. A Reader*. Foris Publications, Dordrecht, pp. 163–177.
- Bartstra, G.J., 1987. Late *Homo erectus* or Ngandong man of Java. *Paleoethist. Groningen* 29, 1–7.
- Bartstra, G.J., Soegondho, S., van der Wijk, A., 1988. Ngandong man: age and artifacts. *J. Hum. Evol.* 17, 325–337.
- Brock, F., Higham, T., Ditchfield, P., Ramsey, C.B., 2010. Current pretreatment methods for AMS radiocarbon dating at the Oxford Radiocarbon Accelerator Unit (ORAU). *Radiocarbon* 52, 103–112.
- Bronk Ramsey, C.B., 2009a. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51, 337–360.
- Bronk Ramsey, C.B., 2009b. Dealing with outliers and offsets in radiocarbon dating. *Radiocarbon* 51, 1023–1045.
- Brothwell, D.R., 1960. Upper Pleistocene human skull from Niah caves, Sarawak. *Sarawak Mus. J.* 9, 323–349.
- Bulbeck, D., 1982. A re-evaluation of possible evolutionary processes in Southeast Asia since the Late Pleistocene. *Bull. Indo-Pacific Prehist. Assoc.* 3, 1–21.
- Clarkson, C., Petraglia, M., Korisettar, R., Haslam, M., Boivin, N., Crowther, A., Ditchfield, P., Fuller, D., Miracle, P., Harris, C., Connell, K., James, H., Koshy, J., 2009. The oldest and longest enduring microlithic sequence in India: 35,000 years of modern human occupation and change at the Jwalapuram Locality 9 rockshelter. *Antiquity* 83, 326–348.
- Coon, C.S., 1962. *The Origin of Races*. Knopf, New York.
- Dam, M.A.C., 1994. *The Late Quaternary Evolution of the Bandung basin, West Java, Indonesia*. Ph.D. Dissertation, Vrije Universiteit.
- De Vos, J., 1983. The Pongo faunas from Java and Sumatra and their significance for biostratigraphical and paleo-ecological interpretations. *Proc. K. Ned. Akad. B* 86, 417–425.
- De Vos, J., 1985. Faunal stratigraphy and correlation of the Indonesian hominid sites. In: Delson, E. (Ed.), *Ancestors: The Hard Evidence*. Alan R. Liss, New York, pp. 215–220.
- Deraniyagala, S.U., 1992. *The Prehistory of Sri Lanka, Part II*. Department of Archaeological Survey, Colombo.
- Dubois, E., 1890. Notes from Dubois. Collection Dubois, National Museum of Natural History, Leiden, unpublished.
- Dubois, E., 1922. The Proto-Australian fossil man of Wadjak. *Java. K. Ned. Akad. Van. Wet. B* 23, 1013–1051.
- Duval, M., Aubert, M., Hellstrom, J., Grün, R., 2011. High resolution, LA-ICP-MS mapping of U and Th isotopes in an Early Pleistocene equid tooth from Fuente Nueva-3 (Orce, Andalusia, Spain). *Quatern. Geochronol.* 6, 458–467.
- Eggins, S.M., Grün, R., Pike, A.W.G., Shelley, A., Taylor, L., 2003. ^{238}U , ^{232}Th profiling and U-series isotope analysis of fossil teeth by laser ablation-ICPMS. *Quatern. Sci. Rev.* 22, 1373–1382.
- Eggins, S.M., Grün, R., McCulloch, M.T., Pike, A.W.G., Chappell, J., Kinsley, L., Shelley, M., Murray-Wallace, C.V., Spötl, C., Taylor, L., 2005. In situ U-series dating by laser-ablation multi-collector ICPMS: new prospects for Quaternary geochronology. *Quatern. Sci. Rev.* 24, 2523–2538.
- Fallon, S.J., Fifield, L.K., Chappell, J.M., 2010. The next chapter in radiocarbon dating at the Australian National University: status report on the single stage AMS. *Nucl. Instrum. Meth. B* 268, 898–901.
- Grün, R., 2006. Direct dating of human remains. *Yearb. Phys. Anthropol.* 49, 2–48.
- Grün, R., Abeyratne, M., Head, J., Tuniz, C., Hedges, R.E.M., 1997. AMS ^{14}C analysis of teeth from archaeological sites showing anomalous ESR dating results. *Quatern. Sci. Rev.* 16, 437–444.
- Grün, R., Huang, P.H., Huang, W., McDermott, F., Stringer, C.B., Thorne, A., Yan, G., 1998. ESR and U-series analyses of teeth from the palaeoanthropological site of Hexian, Anhui Province, China. *J. Hum. Evol.* 34, 555–564.
- Grün, R., Stringer, C., McDermott, F., Nathan, R., Porat, N., Robertson, S., Taylor, L., Mortimer, G., Eggins, S., McCulloch, M., 2005. U-series and ESR analyses of bones and teeth relating to the human burials from Skhul. *J. Hum. Evol.* 49, 316–334.
- Grün, R., Maroto, J., Eggins, S., Stringer, C., Robertson, S., Taylor, L., Mortimer, G., McCulloch, M., 2006. ESR and U-series analyses of enamel and dentine fragments of the Banyoles mandible. *J. Hum. Evol.* 50, 347–358.
- Grün, R., Aubert, M., Joannes-Boyau, R., Moncel, M.H., 2008. High resolution analysis of uranium and thorium concentrations as well as U-series isotope distributions in a Neanderthal tooth from Payre using laser ablation ICP-MS. *Geochim. Cosmochim. Acta* 72, 5278–5290.
- Haas, H., Baniewicz, J., 1980. Radiocarbon dating of bone apatite using thermal release of CO_2 . *Radiocarbon* 22, 537–544.
- Harrison, T., 1965. 50,000 Years of Stone Age Culture in Borneo. Annual Report of the Smithsonian Institution for 1964, 521–530.
- Indriati, E., Swisher III, C.C., Lepre, C., Quinn, R.L., Suriyanto, R.A., Hascaryo, A.T., Grün, R., Feibel, C.S., Pobiner, B.L., Aubert, M., Lees, W., Antón, S.C., 2011. The age of the 20 meter Solo River Terrace, Java, Indonesia and the survival of *Homo erectus* in Asia. *Plos One* 6, 1–10.
- Jacob, T., 1967. Some Problems Pertaining to the Racial History of the Indonesian Region. Drukkerij Neerlandia, Utrecht.
- Jacob, T., 1968. A human wadjakoid maxillary fragment from China. *Proc. K. Ned. Akad. B* 71, 232–235.
- Joannes-Boyau, R., Grün, R., 2011. A comprehensive model for CO_2 ADVANCE |2ADVANCE |u5-ADVANCE |d5 radicals in fossil tooth enamel: implications for ESR dating. *Quatern. Geochronol.* 6, 82–97.
- Lee-Thorp, J.A., Scaly, J.C., van der Merwe, N.J., 1989. Stable carbon isotope ratio differences between bone collagen and bone apatite, and their relationship to diet. *J. Archaeol. Sci.* 16, 585–599.
- Leinders, J.J.M., Aziz, F., Sondaar, P.Y., De Vos, J., 1985. The age of the hominid-bearing deposits of Java: state of the art. *Geol. Mijnbouw* 64, 167–173.
- Mijares, A.S., Détroit, F., Piper, P., Bellwood, P., Grün, R., Aubert, M., Cuevas, N., De Leon, A., Dizon, E., 2010. New evidence for a 67,000 year old human presence at Callao Cave, Luzon, Philippines. *J. Hum. Evol.* 59, 123–132.
- Millard, A.R., 1993. *Diagenesis of Archaeological Bone: The Case of Uranium Uptake*. D.Phil. thesis, University of Oxford.
- Millard, A.R., Hedges, R.E.M., 1996. A diffusion-adsorption model of uranium uptake by archaeological bone. *Geochim. Cosmochim. Acta* 60, 2139–2152.

- Morwood, M.J., Jungers, W.L., 2009. Conclusions: implications of the Liang Bua excavations for hominin evolution and biogeography. *J. Hum. Evol.* 57, 640–648.
- Pike, A.W.G., 2000. Uranium Series Dating of Archaeological Bone by Thermal Ionization Mass Spectrometry. D.Phil. thesis, University of Oxford.
- Pike, A.W.G., Hedges, R.E.M., Van Calsteren, P., 2002. U-series dating of bone using the diffusion-adsorption model. *Geochim. Cosmochim. Acta* 66, 4273–4286.
- Reich, D., Green, R.E., Kircher, M., Krause, J., Patterson, N., Durand, E.Y., Bence, V., Briggs, A.W., Stenzel, U., Johnson, P.L.F., Maricic, T., Good, J.M., Marques-Bonet, T., Alkan, C., Fu, Q., Mallick, S., Li, H., Meyer, M., Eichler, E.E., Stoneking, M., Richards, M., Talamo, S., Shunkov, M.V., Derevianko, A.P., Hublin, J.J., Kelso, J., Slatkin, M., Pääbo, S., 2010. Genetic history of an archaic hominin group from Denisova Cave in Siberia. *Nature* 468, 1053–1060.
- Reich, D., Patterson, N., Kircher, M., Delfin, F., Nandineni, M.R., Pugach, I., Ko, A.M.-S., Ko, Y.-C., Jinam, T.A., Phipps, M.E., Saitou, N., Wollstein, A., Kayser, M., Pääbo, S., Stoneking, M., 2011. Denisova admixture and the first modern human dispersals into Southeast Asia and Oceania. *Am. J. Hum. Genet.* 89, 516–528.
- Sambridge, M., Grün, R., Eggins, S., 2012. U-series dating of bone in an open system: the diffusion-adsorption-decay model. *Quatern. Geochronol.* 9, 42–53.
- Santa Luca, A.P., 1980. The Ngandong Fossil Hominids. A Comparative Study of a Far Eastern *Homo Erectus* Group. Yale University Press, New Haven.
- Shutler Jr., R., Head, J.M., Donahue, D.J., Jull, A.J.T., Barbetti, M.F., Matsu'ura, S., De Vos, J., Storm, P., 2004. AMS radiocarbon dates on bone from cave sites in Southeast Java, Indonesia, including Wajak. *Mod. Quatern. Re.* 18, 89–93.
- Sondaar, P.Y., 1984. Faunal evolution and the mammalian biostratigraphy of Java. In: Andrews, P., Franzen, J.L. (Eds.), *The Early Evolution of Man with Special Emphasis on Southeast Asia and Africa*, vol. 69. Cour. Forsch.-Inst. Senckenberg, pp. 219–235.
- Storm, P., 1992. Two microliths from Javanese Wadjak man. *J. Anthropol. Soc. Nip.* 100, 191–203.
- Storm, P., 1995. The evolutionary significance of the Wajak skulls. *Scripta Geol.* 110, 1–247.
- Storm, P., 2001. The evolution of humans in Australasia from an environmental perspective. In: Dam, R.A.C., van der Kaars, S. (Eds.), *Quaternary Environmental Change in the Indonesian Region*. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* vol. 171, pp. 363–383.
- Storm, P., Nelson, A.J., 1992. The many faces of Wadjak Man. *Archaeol. Ocean.* 27, 37–46.
- Storm, P., Aziz, F., De Vos, J., Kosasih, D., Baskoro, S., Ngiliman, van den Hoek Ostende, L.W., 2005. Late Pleistocene *Homo sapiens* in a tropical rainforest fauna in east Java. *J. Hum. Evol.* 49, 536–545.
- Stringer, C.B., 1992. Reconstructing recent human evolution. *Phil. Trans. R. Soc. B* 337, 217–224.
- Stringer, C.B., Grün, R., Schwarcz, H.P., Goldberg, P., 1989. ESR dates for the hominid burial site of Es Skhul in Israel. *Nature* 338, 756–758.
- Swisher III, C.C., Rink, W.J., Antón, S.C., Schwarcz, H.P., Curtis, G.H., Suprijo, A., Widiastomo, 1996. Latest *Homo erectus* of Java: potential contemporaneity with *Homo sapiens* in Southeast Asia. *Science* 274, 1870–1874.
- Thorne, A.G., Wolpoff, M.H., 1992. The multiregional evolution of humans. *Sci. Am.* 266, 76–83.
- Valladas, H., Reyss, J.L., Joron, J.L., Valladas, G., Bar-Yosef, O., Vandermeersch, B., 1988. Thermoluminescence dating of Mousterian 'Proto-Cro-Magnon' remains from Israel and the origin of modern man. *Nature* 331, 614–616.
- Van den Brink, L.M., 1982. On the mammal fauna of the Wajak Cave, Java (Indonesia). *Mod. Quatern. Re.* 7, 177–193.
- Van der Kaars, W.A., Dam, M.A.C., 1995. A 135,000-year record of vegetational and climatic change from the Bandung area, West-Java, Indonesia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 117, 55–72.
- Van Heekeren, H.R., 1975. Chronology of the Indonesian prehistory. *Mod. Quatern. Re.* 1, 47–52.
- Van Klinken, G.J., 1999. Bone collagen quality indicators for palaeodietary and radiocarbon measurements. *J. Archaeol. Sci.* 26, 687–695.
- Van Stein Callenfels, P.V., 1936. The Melanesoid civilization of Eastern Asia. *Bull. Raffles Mus. B* 1, 41–51.
- Weidenreich, F., 1945. *Apes, Giants, and Man*. University of Chicago Press, Chicago.
- Westaway, K.E., Zhao, J.-x., Roberts, R.G., Chivas, A.R., Morwood, M.J., Sutikna, T., 2007a. Initial speleothem results from western Flores and eastern Java, Indonesia: were climate changes from 47 to 5 ka responsible for the extinction of *Homo floresiensis*? *J. Quatern. Sci.* 22, 429–438.
- Westaway, K.E., Morwood, M.J., Roberts, R.G., Rokus, A.D., Zhao, J.-x., Storm, P., Aziz, F., van den Bergh, G., Hadi, P., Jatmiko, de Vos, J., 2007b. Age and biostratigraphic significance of the Punung Rainforest Fauna, East Java, Indonesia, and implications for *Pongo* and *Homo*. *J. Hum. Evol.* 53, 709–717.
- Whitten, T., Soeriaatmadja, R.E., Afiff, S.A., 1996. *The Ecology of Java and Bali*. Periplus Editions, Hong Kong.
- Williams, M.A.J., Ambrose, S.H., van der Kaars, S., Ruehlemann, C., Chattopadhyaya, U., Pal, J., Chauhan, P.R., 2009. Environmental impact of the 73 ka Toba super-eruption in South Asia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 284, 295–314.
- Wolpoff, M.H., Wu, X. Zhi, Thorne, A.G., 1984. Modern *Homo sapiens* origins: a general theory of hominid evolution involving the fossil evidence from East Asia. In: Smith, F.H., Spencer, F. (Eds.), *The Origins of Modern Humans: A World Survey of the Fossil Evidence*. Alan R. Liss, New York, pp. 411–483.
- Wood, R.E., Higham, T.F.G., Bronk Ramsey, C., 2010. Refining background corrections for radiocarbon dating of bone collagen at ORAU. *Radiocarbon* 52, 600–611.
- Yokoyama, Y., Falguères, C., Sémah, F., Jacob, T., Grün, R., 2008. Gamma-ray spectrometric dating of late *Homo erectus* skulls from Ngandong and Sambungmacan, Central Java, Indonesia. *J. Hum. Evol.* 55, 274–277.
- Zazzo, A., Saliège, J.-F., 2011. Radiocarbon dating of biological apatites: a review. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 310, 52–61.