ary of the subducting slab has a sharp boundary for wave conversions (*18–21*). As the characteristics of the later phase are consistent with those shown in previous studies (*19, 21, 22*), we confirm that the later phase is an $S - P$ converted wave at the upper boundary of the subducting Pacific slab (*21, 22*).

We estimated the distances between the sources and the upper boundary of the subducting slab from this $S - P$ converted phase data using a two-dimensional ray-tracing program (SEIS83) (*23*). The observed $SP - P$ time data show two populations, one of about 2 s and the other greater than 3 s (Fig. 3). These earthquakes with $SP - P$ times of either about 2 s or greater than 3 s are located in the upper seismic zone, at a distance of 15 to 20 km from the upper boundary of the slab, and in the lower seismic zone, at a distance of 40 to 50 km, respectively. This result is consistent with the hypocentral data shown in Figs. 1 and 2 and confirms that the deep seismic zone consists of two layers within the slab.

We calculated the temperature structure in the subducting lithosphere using a two-dimensional model (*24*) in which the rigid oceanic lithosphere is subducting under the arc and mantle flow is induced in the viscous mantle wedge. The calculated temperature structure in Fig. 4 shows that the double seismic zone, which is at depths of 340 to 400 km, is located below the transition zone from α-olivine to β-spinel (*25*). Moreover, the double seismic zone is parallel to the calculated 500° to 550°C isotherms in the subducting lithosphere as well as to the upper surface of the slab.

As shown in Fig. 4, the double seismic zone is located on the α-β phase transition zone and is parallel to the isotherms. These features are consistent with the hypothesis that deep earthquakes are triggered by a phase transition of the metastable olivine phase (*26, 27*) in the range of ~500° to 600°C; this temperature has been estimated to be about 600° to 700°C from experiments (*28*) and the kinetics of olivine-spinel phase transformation (*26, 29*). Seismicity in the Izu-Bonin region shows that the number of earthquakes increases at depths greater than about 300 km and decreases at depths greater than about 450 km. This depth range agrees with that of the metastable zone estimated by thermal modeling.

REFERENCES AND NOTES

1. H. H. Turner, *Mon. Not. R. Astron. Soc. Geophys. Suppl.* **1**, 1 (1922).
2. K. Wadati, *Geophys. Mag.* **1**, 162 (1928).
3. E. Orowan, *Geol. Soc. Am. Mem.* **79**, 323 (1960).
4. B. E. Hobbs and A. Ord, *J. Geophys. Res.* **93**, 10521 (1988).
5. D. T. Griggs, in *Nature of the Solid Earth*, E. C. Robertson, Ed. (McGraw Hill, New York, 1972), pp. 361–384.
6. D. T. Griggs and J. Handlin, *Geol. Soc. Am. Mem.* **79**, 347 (1960).
7. D. T. Griggs and D. W. Baker, in *Properties of Matter Under Unusual Conditions*, H. Mark and S. Frenback, Eds. (Wiley Interscience, New York, 1969).
8. M. Ogawa, *J. Geophys. Res.* **92**, 13801 (1987).
9. P. W. Bridgman, *Am. J. Sci.* **243A**, 90 (1945).
10. S. H. Kirby, *J. Geophys. Res.* **92**, 13789 (1987).
11. S. H. Kirby, W. B. Durham, L. A. Stern, *Science* **252**, 216 (1991).
12. H. W. Green II *et al.*, *Nature* **348**, 720 (1990).
13. T. Iidaka and D. Suetsugu, *ibid.* **356**, 593 (1992).
14. K. Suyehiro and T. Iidaka, in preparation.
15. D. A. Wiens, J. J. McGuire, P. J. Shore, *Nature* **364**, 790 (1993).
16. T. Utsu, *J. Phys. Earth* **23**, 367 (1975).
17. B. L. N. Kennett and E. R. Engdahl, *Geophys. J. Int.* **105**, 429 (1991).
18. I. Nakanishi *et al.*, *Geophys. J. R. Astron. Soc.* **67**, 615 (1981).
19. T. Matsuzawa *et al.*, *ibid.* **86**, 767 (1986).
20. K. Obara and H. Sato, *J. Geophys. Res.* **93**, 15037 (1988).
21. T. Iidaka, *Seismol. Soc. J.* **2**, 154 (abstr.) (1991).
22. J. Stefani *et al.*, *J. Geophys. Res.* **87**, 323 (1982).
23. V. Cerveny and I. Psencik, Program Package (SEIS83) (1983).
24. Y. Furukawa, *J. Geophys. Res.* **98**, 8309 (1993).
25. T. Katsura and E. Ito, *ibid.* **94**, 15663 (1989).
26. C. M. Sung and R. G. Burns, *Tectonophysics* **31**, 1 (1976).
27. L. Liu, *Phys. Earth Planet. Inter.* **32**, 226 (1983).
28. K. Suito, in *High-Pressure Research, Applications in Geophysics*, M. H. Marghnani and S. Akimoto, Eds. (Academic Press, New York, 1977), pp. 255–266.
29. D. C. Rubie *et al.*, *J. Geophys. Res.* **95**, 15829 (1990).
30. T. Iidaka *et al.*, *ibid.* **97**, 15307 (1992).
31. K. Suyehiro and I. S. Sacks, *Bull. Seismol. Soc. Am.* **67**, 1051 (1979).
32. R. Jeanloz and S. Morris, *Annu. Rev. Earth Planet. Sci.* **14**, 377 (1986).
33. B. Parsons and J. G. Sclater, *J. Geophys. Res.* **82**, 803 (1977).
34. R. D. Jarard, *Rev. Geophys.* **24**, 217 (1986).

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Age of the Earliest Known Hominids in Java, Indonesia

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$^{40}Ar/^{39}Ar$ laser-incremental heating of hornblende separated from pumice recovered at two hominid sites in Java, Indonesia, has yielded well-defined plateaus with weighted mean ages of 1.81 ± 0.04 and 1.66 ± 0.04 million years ago (Ma). The hominid fossils, a juvenile calvaria of *Pithecanthropus* and a partial face and cranial fragments of *Meganthropus*, commonly considered part of the Asian *Homo erectus* hypodigm, are at least 0.6 million years older than fossils referred to as *Homo erectus* (OH-9) from Olduvai Gorge, Tanzania, and comparable in age with the oldest Koobi Fora *Homo cf. erectus* (*Homo ergaster*) in Kenya. These ages lend further credence to the view that *Homo erectus* may have evolved outside of Africa. If the ancestor of *Homo erectus* ventured out of Africa before 1.8 Ma, the dispersal would have predated the advent of the Acheulean culture at 1.4 Ma, possibly explaining the absence of these characteristic stone cleavers and hand axes in East Asia.

The discovery in 1891 of a fossil hominid skull cap and femur in middle Pleistocene deposits exposed along the Solo River at Trinil, Java (Fig. 1), opened one of the most interesting chapters in the search for fossil hominids. At a time when little was known of our ancestors other than Neanderthal and Cro-Magnon man from Europe (*1*), Eugene Dubois set out from Holland to find Darwin's missing link. Dubois' remarkable discovery led him to propose a new species, *Anthropopithecus erectus*, which he subsequently referred to as *Pithecanthropus erectus* (*2*). Although Dubois himself later questioned the hominid affinities of his new species, subsequent work has placed the Trinil find within our own genus, renaming it *Homo erectus* (*3*).

By the mid-1900s, the central focus of hominid evolution shifted to the African continent, where the discovery of Pliocene fossil hominids and artifacts in direct association with datable volcanic rocks established Africa as the center for the origin of humans (*4*). In the 1960s and 1970s, the discovery of pre-Neanderthal hominids in Africa (*5–7*) and possibly Europe (*7*) referable to *H. erectus* sparked renewed interest in the type *H. erectus* of Java (*7–9*). In the Koobi Fora region of Kenya, specimen KNM-ER 3733 is now considered to have an age of slightly greater than 1.77 Ma, indicating that it represents perhaps the oldest hominid fossil referable as ancestral *H. erectus* (*7, 10*) (Fig. 2). The oldest stone "cleavers" and "hand axes," characteristic of the Acheulean culture, associated with Afri-

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can *H. erectus* are firmly established at no older than 1.4 Ma (*11*) (Fig. 2). Despite numerous *H. erectus* finds in Java and China since Dubois' initial discoveries, Acheulean tools have yet to be discovered in Asia (*12*).

Reports of Plio-Pleistocene fossil hominids in Java and China continue to appear in the literature (*13–20*). However, the lack of datable volcanic material in China and the debate over the provenience and age of hominid fossils in Java has led to the conclusion that most of the Asian hominids are younger than about 1.2 to 1.0 Ma (*12, 21–26*). In Java, much of the disagreement over the age of some of the hominid fossils centers on differences of opinion as to which formation the find site should be attributed. Most workers agree that most of the hominid fossils have been collected from the middle Pleistocene Kabuh Formation (*6, 15*). However, a few are reported to have been collected from stratigraphically lower deposits attributed to the Plio-Pleistocene Pucangan Formation (*6*), considered by some workers to be as old as 2.0 Ma (*14, 17–20*). These age assignments are, however, based primarily on regional correlations of the Kabuh and Pucangan formations over wide geographic areas in Java.

The oldest reported Java hominids come from two geographically separated outcrops of Pucangan deposits. The first is the site of the "Mojokerto child" (Mojokerto 1, or Perning 1), a well-preserved juvenile calvaria attributed to *P. modjokertensis* and discovered near the village of Perning in 1936 (*14, 27, 28*) (Fig. 1). The second area is the central part of the Sangiran dome, where two specimens of *Meganthropus* (S27 and S31) were recovered in the late 1970s (*16, 17, 26*) (Fig. 1). *Meganthropus* S27 consists of a relatively complete, albeit crushed, face and associated cranial fragments, whereas S31 consists of part of a cranium. To address the uncertainties associated with the age of the earliest Asian hominids we obtained $^{40}Ar/^{39}Ar$ ages for volcanic units in direct association with the hominid find sites, thus avoiding circuitous age guesses based on regional lithologic correlations.

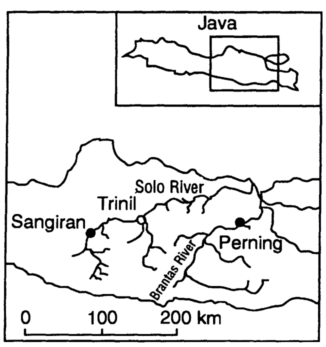

Fig. 1. Map of Java, Indonesia, showing the hominid localities of Sangiran (S27 and 31), Perning (Mojokerto 1), and Trinil (type *H. erectus*).

The Mojokerto calvaria was collected from a small excavation dug in 1936 by Tjokrohandojo, a local collector for the geologist Duyfjes (*27*), and subsequently described by von Koenigswald (*29*). The site, plotted on a geologic map by Duyfjes (*27*) and, more recently, by Kumai and co-workers (*28*), was reported to have come from a hard continental conglomeratic volcanic sandstone at a depth of 1 m below the surface. In 1975, Jacob revisited the Mojokerto site with Tjokrohandojo to reconfirm Duyfjes' 1936 locality description.

Duyfjes (*27*) considered the continental strata from which the Mojokerto calvaria was recovered to be a volcanic facies of the Pucangan Formation. In the Sangiran area, the Pucangan Formation has been argued to be of Plio-Pleistocene age on the basis of foraminifera and diatoms in marine intercalations in the Pucangan and underlying marine Kalibeng formations (*19, 20*). A Plio-Pleistocene age for the volcanic facies of the Pucangan was supported by a K-Ar date of 1.9 ± 0.5 Ma (*14*) for a pumice tuff at Perning. However, this date has not been given much credence because of its high error and because of confusion over the proximity of the dated sample to the Mojokerto calvaria (*12, 13, 21*). More recently, the volcanic deposits at Mojokerto have been reinterpreted as belonging to the Kabuh Formation (*30*), considered in the Sangiran area to be of middle Pleistocene age (*6, 15*). This age assignment was supported by the correlation of the normal geomagnetic polarity determined for the Mojokerto site (*27*) with the Jaramillo geomagnetic event dated elsewhere at ~1.0 Ma (*31*).

Field reconnaissance of the Perning area in 1992 and 1993 revealed that the site recorded by Duyfjes (*27*) from which the Mojokerto calvaria was collected contained volcanic pumice suitable for radioisotopic dating. Confirmation that this was the site reported by Duyfjes (*27*) comes from similarly appearing volcanic pumice and volcaniclastic matrix that still infill the cranial vault of the Mojokerto calvaria. No other stratum in the Mojokerto area was found to contain similar appearing pumice or volcanic matrix. Microprobe analyses of hornblende from pumice collected from the Mojokerto site and those from the cranial vault indicate similar compositions, further corroborating the find site of the Mojokerto calvaria (Table 1). We were unable, however, to obtain sufficient hornblende from the Mojokerto calvaria for $^{40}Ar/^{39}Ar$ dating.

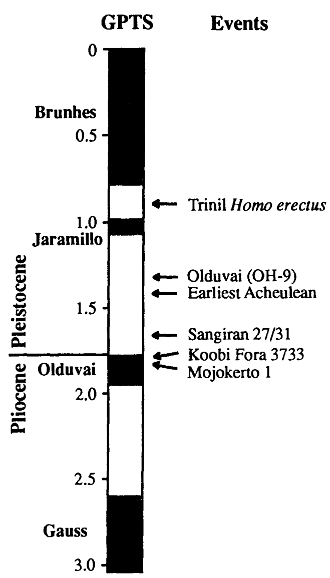

Fig. 2. Chronology of hominid fossils and events in Java, Indonesia, and East Africa discussed in the text, plotted on the geomagnetic polarity time scale (GPTS) (*31*).

Two $^{40}Ar/^{39}Ar$ laser-incremental heating analyses (*32*) of hornblende from both the pumice and associated volcanic matrix collected at the Mojokerto site yielded four indistinguishable plateau ages of 1.81 ± 0.07, 1.79 ± 0.07, 1.80 ± 0.07, and 1.82 ± 0.09 Ma (Fig. 3 and Table 2). The weighted mean age of the four plateaus is 1.81 ± 0.04 Ma. An isochron of the combined plateau data from four analyses gives a similar age of 1.82 ± 0.03 Ma [$^{40}Ar/^{36}Ar$ intercept of 293.5 ± 5.1, mean square weighted deviation (MSWD) = 0.15].

We also collected six oriented samples for paleomagnetic analyses from two volcaniclastic clay layers interbedded in the conglomeratic volcanic sandstone at the Mojokerto site. Thermal demagnetization of these samples yielded a normal geomagnetic polarity residing in magnetite with a slight reversed hematite overprint. Our results agree with a normal polarity assignment for Mojokerto (*24*). However, the paleopole direction obtained by thermal demagnetization of the samples suggests that the previously reported transitional direction for the

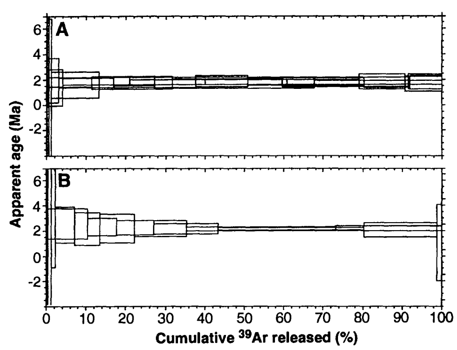

Fig. 3. $^{40}Ar/^{39}Ar$ age spectra obtained from incremental-laser heating of hornblende from pumice and volcanic matrix associated with hominid fossils: (**A**) Mojokerto 1 (sample 92JV-23B; weighted mean plateau age of 1.81 ± 0.04 Ma) and (**B**) Sangiran 27 (sample 92JV-4; weighted mean plateau age of 1.66 ± 0.04 Ma) from Java, Indonesia.

site is a result of incomplete removal of the reversed hematite overprint with the use of alternating field (AF) demagnetization methods only. In conjunction with our $^{40}Ar/^{39}Ar$ ages reported here, we reinterpret the normal geomagnetic polarity of the Mojokerto site as the Olduvai geomagnetic subchron (*31*).

In Sangiran, we concentrated on the putative age of *Meganthropus* specimens S27 (*16*) and S31 (*17*) collected after the excavation of an irrigation canal dug in 1974 on the south side of the central part of the dome. Both S27 and S31 were recovered from the same site approximately one year apart in clays mapped as the lower part of the Pucangan Formation (*16–18, 25*). The find site of these hominids has been plotted on geologic maps of the area and placed in stratigraphic sections by Jacob (*16*), Sartono (*17, 18*), and Itahara (*25*).

A volcanic pumice-rich layer crops out 2 m above the horizon that yielded *Meganthropus* S27 and S31. Two laser-incremental heating $^{40}Ar/^{39}Ar$ analyses (*32*) on hornblende from pumice handpicked from this layer yielded two well-behaved spectra with plateau ages of 1.66 ± 0.04 and 1.66 ± 0.07 Ma (Fig. 3 and Table 2) with a weighted mean age of 1.66 ± 0.04 Ma. An isochron of the combined plateau data from the two analyses gives an age of 1.65 ± 0.03 Ma ($^{40}Ar/^{36}Ar$ intercept = 295.8 ± 1.2, MSWD = 0.10). No paleomagnetic data are available for the S27-S31 site, although much of the Pucangan Formation in the Sangiran area has reversed magnetic polarity (*22, 26*). In conjunction with the $^{40}Ar/^{39}Ar$ age obtained here, we suggest that the S27-S31 site occurs within the Matuyama geomagnetic interval (*31*).

Our ages indicate that the earliest known Java hominids are 0.6 to 0.8 million years older than the type *H. erectus* from Trinil (*33*), at least 0.6 million years older than the inferred age of *H. "erectus"* (OH-9) from Olduvai Gorge, Tanzania (*7*), and of comparable age to the oldest specimens of *H. cf. erectus* (=*H. ergaster*) from the Koobi Fora region of Kenya (*7–10*). These dates further indicate that hominids ventured out of Africa much earlier than previously thought (Fig. 2).

Whether the hominids from the Pucangan Formation in Java are *H. erectus* is an ongoing debate. One side views all of the Asian and African material as variants of a single species, *H. erectus* (*7*). However, this view does not reflect the wide range of morphological variation seen in the Javanese hominids. On the other hand, it is difficult to reconcile the number of hominid species proposed in an opposing view in which the earliest Javanese hominids are *M. palaeojavanicus* and *P. dubius*, with the latter purportedly evolving into *P. modjokertensis* (or *P. robustus*) and *P. erectus* (*15, 16, 34*). The youngest of the Javanese hominids are called *H. erectus soloensis* or, by some, *H. sapiens soloensis* (*15, 16, 34*). Others have argued for australopithicine affinities for *P. dubius* (*35*) and renamed *Meganthropus* as *Australopithecus palaeojavanicus* (*13, 17, 18*). In this view the geologically younger and morphologically more derived specimens are referred to as *H. robustus, H. erectus trinilensis* (*H. erectus erectus*), and *H. erectus ngandongensis* (*soloensis*) (*13, 17, 18*). In light of the new ages reported here, a complete restudy of these hominids is needed to determine the origin of the Javanese *H. erectus* and its taxonomic affinity with similar-age hominids of Africa.

The determination of which hominid species ventured out of Africa depends largely on the taxonomic affinity of some of the Javanese and African hominids. Recent systematic studies indicate that many of the

Table 1. Microprobe analyses of individual hornblende grains from pumices collected at the Mojokerto find site and from the fossil hominid calvaria.

Oxide	Range of mean weight percent	
	Field site	Calvaria
SiO_2	44.3–45.8	44.9–46.8
FeO	13.3–14.3	12.7–13.7
CaO	10.9–11.2	10.8–11.2
Al_2O_3	8.63–9.63	7.91–9.35
MgO	13.0–13.7	13.3–14.6
TiO_2	1.38–1.81	1.38–1.57
MnO	0.39–0.77	0.43–0.70
NaO_2	1.26–1.87	1.16–1.44
F	0.14–0.17	0.11–0.15
K_2O	0.24–0.48	0.20–0.44
Cl	0.05–0.10	0.06–0.11

Table 2. $^{40}Ar/^{39}Ar$ plateau data from laser-incremental heating of Java hornblendes.

Analysis	Percent ^{39}Ar	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{40}Ar^{*}/^{39}Ar$	Percent $^{40}Ar^{*}$	Age [Ma (± SD)]
Mojokerto 1 site (sample 92JV-23B, pumice)							
6772-01C	3.9	24.479	10.589	0.0774	2.486	10.1	1.353 (0.730)
6772-01D	16.7	8.524	11.274	0.0203	3.461	40.3	1.883 (0.147)
6772-01E	19.3	5.517	11.574	0.0107	3.327	59.8	1.810 (0.098)
6772-01F	21.3	5.732	12.210	0.0116	3.332	57.6	1.813 (0.102)
6772-01G	17.6	5.514	9.887	0.0102	3.319	59.8	1.806 (0.106)
6772-01H	11.5	5.949	10.673	0.0119	3.331	55.6	1.812 (0.297)
6772-01I	9.5	8.908	6.188	0.0215	3.072	34.3	1.672 (0.303)
6772-02B	11.9	4.990	14.723	0.0111	2.928	58.1	1.593 (0.529)
6772-02C	25.5	5.147	13.365	0.0100	3.300	63.5	1.796 (0.205)
6772-02D	13.1	5.701	13.224	0.0113	3.478	60.5	1.893 (0.218)
6772-02E	29.0	4.748	11.801	0.0080	3.376	70.5	1.837 (0.150)
6772-02F	10.8	5.167	8.561	0.0089	3.260	62.7	1.774 (0.214)
6772-02G	8.5	6.208	23.558	0.0164	3.337	52.9	1.816 (0.305)
Mojokerto 1 site (sample 92JV-23B, matrix)							
6777-01C	11.6	11.039	10.141	0.0289	3.343	30.1	1.814 (0.186)
6777-01D	20.5	22.149	10.494	0.0670	3.222	14.4	1.749 (0.257)
6777-01E	27.7	7.300	10.645	0.0163	3.380	46.0	1.834 (0.111)
6777-01F	32.0	4.947	9.806	0.0082	3.339	67.1	1.812 (0.197)
6777-01G	8.0	7.567	6.400	0.0164	3.262	42.9	1.770 (0.269)
6777-02B	2.5	25.938	8.383	0.0781	3.554	13.6	1.929 (0.894)
6777-02C	13.7	11.338	11.344	0.0307	3.197	28.0	1.735 (0.201)
6777-02D	10.5	9.718	11.564	0.0246	3.414	34.9	1.853 (0.191)
6777-02F	40.3	5.906	12.016	0.0126	3.197	53.7	1.735 (0.217)
6777-02G	32.4	7.540	10.761	0.0173	3.314	43.6	1.799 (0.081)
Sangiran 27 site (sample 92JV-4, pumice)							
7427-01D	1.1	87.565	19.352	0.2694	9.662	10.9	6.889 (4.117)
7427-01E	4.8	39.318	21.529	0.1301	2.652	6.6	1.893 (0.677)
7427-01F	6.3	44.388	21.170	0.1487	2.203	4.9	1.573 (0.627)
7427-01G	8.9	47.712	20.519	0.1596	2.246	4.6	1.604 (0.552)
7427-01H	13.2	10.044	20.308	0.0320	2.280	22.4	1.628 (0.306)
7427-01I	37.7	4.881	19.663	0.0145	2.214	44.8	1.581 (0.096)
7427-01J	26.8	4.207	20.858	0.0125	2.244	52.6	1.602 (0.106)
7427-02D	9.8	86.981	19.466	0.2905	2.761	3.1	1.971 (0.573)
7427-02E	7.3	33.674	22.178	0.1120	2.400	7	1.714 (0.340)
7427-02F	9.4	58.988	19.821	0.1973	2.313	3.9	1.651 (0.278)
7427-02G	16.1	22.170	19.882	0.0731	2.220	9.9	1.586 (0.188)
7427-02H	36.8	14.864	20.580	0.0485	2.234	14.8	1.595 (0.069)
7427-02I	18.5	7.886	20.376	0.0253	2.088	26.1	1.491 (0.289)
7427-02J	1.2	3.651	20.751	0.0155	0.765	20.7	0.546 (1.455)

African and European hominids referred to as *H. erectus* lack the key derived characters that unite Asian *H. erectus* (*9*). The absence of these characters, together with the presence of shared derived cranial features seen in *H. sapiens* but not in the Asian *H. erectus*, led to the inclusion of many of the early African specimens, such as the Koobi Fora specimens KNM-ER 3733 and KNM-ER 3883, in a different antecedent species, *H. ergaster* (*9*). The question about the existence of *H. erectus* sensu strictu in Europe (*36, 37*) and uncertainties about the relation of younger and more derived hominids, such as OH-9 from Olduvai Gorge (*7, 9*), with *H. ergaster* make it unclear whether *H. erectus*, sensu strictu, might be endemic to Asia (*8, 9*).

If *H. ergaster* is the sister taxon of *H. sapiens* (*9*), the linear evolution of *H. habilis* to *H. erectus* and finally *H. sapiens* may be overly simplistic. For example, if all of the later African specimens referred to as *H. erectus*, such as OH-9, are actually *H. ergaster*, then clearly *H. erectus* represents a side branch of hominid evolution in Asia. If the evolution of *H. erectus* was in Asia and these younger African specimens are also *H. erectus*, such an affiliation suggests that the species somehow ventured back into Africa around 1.2 Ma.

The absence of Acheulean cleavers and hand axes in Asia has been an intriguing feature that separates the African and Asian *H. "erectus"* cultures. The concept of a "Movius Line" separating the African Acheulean and Asian Bamboo cultures has been attributed to paleoenvironmental and paleoecological differences between Asia and Africa (*12, 38*). Our $^{40}Ar/^{39}Ar$ ages lead to an alternative view that the ancestor of *H. erectus* ventured out of Africa before Acheulean tools were developed. The Acheulean culture first appears in Africa about 1.4 Ma (*11*), at least 0.4 to 0.5 million years after the ancestor of *H. erectus* had ventured out of Africa (Fig. 2). Such a view argues, of course, that once leaving Africa, *H. erectus*, sensu strictu, remained somewhat endemic in Asia, representing perhaps a distinct lineage in hominid evolution (*8, 39*). In this scenario, the appearance of Acheulean tools in the middle Pleistocene of Europe, as well as of India, could reflect a younger, more recent dispersal out of Africa.

REFERENCES AND NOTES

1. W. King, *Q. J. Sci.* **1**, 88 (1864); P. Broca in *Reliquiae acquitanicae*, E. Lartet, H. Christy, T. R. Jones, Eds. (Williams and Norgate, London, 1865), pp. 97–122.
2. E. Dubois, *Versl. Mijnw. Batavia* **3**, 10 (1892); *Batavia: Landesdruckerei* (1894); *Bull. Soc. Belg. Geol.* **9**, 151 (1895).
3. F. Weidenreich, *Am. Anthropol.* **42**, 375 (1940).
4. L. S. B. Leakey, J. F. Evernden, G. H. Curtis, *Nature* **191**, 478 (1961).
5. M. D. Leakey, *Olduvai Gorge* (Cambridge Univ. Press, Cambridge, 1971), vol. 3.
6. M. H. Day, *Guide to Fossil Man* (Cassel, London, ed. 4, 1986).
7. G. P. Rightmire, *The Evolution of* Homo erectus (Cambridge Univ. Press, Cambridge, 1990).
8. P. J. Andrews, *New Sci.* **3**, 24 (1984); P. J. Andrews, *Cour. Forschungsinst. Senckenberg* **69**, 167 (1984).
9. B. Wood, *Hominid Cranial Remains*, vol. 4 of *Koobi Fora Research Project* (Clarendon, Oxford, 1991); B. Wood, *Nature* **355**, 783 (1992).
10. C. S. Feibel, F. H. Brown, I. McDougall, *Am. Phys. Anthropol.* **78**, 595 (1989).
11. B. Asfaw *et al.*, *Nature* **360**, 732 (1992).
12. G. G. Pope, in *The Evolution of the East Asian Environment*, R. O. Whyte, Ed. (Hong Kong Univ. Press, Hong Kong, 1984), vols. 1 and 2, pp. 822–847; *Mod. Quat. Res. Southeast Asia* **9**, 65 (1985); *Annu. Rev. Anthropol.* **17**, 43 (1988).
13. S. Sartono, *Mod. Quat. Res. Southeast Asia* **8**, 129 (1984); *ibid.* **9**, 115 (1985); S. Matsu'ura, in *Primate Evolution*, vol. 1 of *Proceedings of the Tenth Congress of the International Primatological Society 1985, Nairobi, Kenya*, J. G. Else and P. C. Lee, Eds. (Cambridge Univ. Press, Cambridge, 1986), pp. 115–128.
14. T. Jacob and G. H. Curtis, *Contrib. Univ. Calif. Archeol. Res. Facil.* **11**, 50 (1971).
15. T. Jacob, *Hum. Evol.* **2**, 473 (1973).
16. ——, in *Current Argument on Early Man*, L.-K. Königsson, Ed. (Pergamon, Oxford, 1980), pp. 170–179.
17. S. Sartono, *Congrès International de Paléontologie Humaine* (Prétirage, Nice, 1982), p. 491.
18. ——, *Mod. Quat. Res. Southeast Asia* **4**, 19 (1978).
19. D. Ninkovich and L. H. Burckle, *Nature* **275**, 306 (1978).
20. D. W. Orchiston and W. G. Seisser, *Mod. Quat. Res. Southeast Asia* **7**, 131 (1982).
21. J. de Vos, in *Ancestors: The Hard Evidence*, E. Delson, Ed. (Alan R. Liss, New York, 1985), pp. 215–220.
22. F. Sémah, *Mod. Quat. Res. Southeast Asia* **7**, 151 (1982); M. Hyodo *et al.*, *Anthropol. Sci.* **10** (no. 2), 157 (1993).
23. F. Sémah, in (*17*), pp. 542–558.
24. ——, S. Sartono, Y. Zaim, T. Djubiantono, *Mod. Quat. Res. Southeast Asia* **6**, 103 (1981); F. Sémah, A. M. Sémah, S. Sartono, Y. Zaim, T. Djubiantono, *l'Anthropologie* **85/86**, 509 (1982).
25. M. Itihara *et al.*, in *Quaternary Geology of the Hominid Fossil-bearing Formations in Java*, N. Watanabe and D. Kadar, Eds. (Geological Research and Development Centre special publication 4, Bandung, Indonesia, 1985), pp. 11–44.
26. Y. Shimizu et al., *ibid.*, pp. 275–307.
27. J. Duyfjes, *Ing. Ned. Indie* **3**, 136 (1936); *Dienst. v. d. Mijn. Ned. Indie Geol. Kaart* **1**, 1 (1938).
28. H. Kumai *et al.*, in (*25*), pp. 55–62.
29. G. H. R. von Koenigswald, *Ing Ned. Indie* **3**, 149 (1936).
30. S. Sartono, *Mod. Quat. Res. Southeast Asia* **6**, 91 (1981).
31. S. C. Cande and D. V. Kent, *Geophys. Res.* **97**, 13917 (1992).
32. The $^{40}Ar/^{39}Ar$ methods and analytical procedures used in this study follow the work of A. Deino and R. Potts [*J. Geophys. Res.* **95**, 8453 (1990)]; A. Deino *et al.* [*J. Geol.* **98**, 567 (1990)]; C. C. Swisher III and D. R. Prothero [*Science* **249**, 760 (1990)]; C. C. Swisher III *et al.* [*ibid.* **257**, 954 (1992)]; P. R. Renne and A. R. Basu [*ibid.* **253**, 176 (1991)]; and A. R. Basu, P. R. Renne, D. B. DasGupta, F. Teichmann, and R. J. Povede [*ibid.* **261**, 902 (1993)].

   Individual pumice fragments were handpicked and trimmed to remove any adhering volcanic matrix. The pumice was crushed gently and sieved to obtain the coarsest hornblende. The hornblende was cleaned with distilled water in an ultrasonic cleaner to remove any attached pumice and clay. The freshest and most euhedral appearing hornblende were handpick-viewed through a binocular microscope, with those hornblende crystals containing large or abundant inclusion being avoided. Microprobe analysis of the hornblende yielded K_2O values averaging 0.35%, with CaO values around 11.0%.

   The $^{40}Ar/^{39}Ar$ irradiation parameter *J* was determined from replicate analyses of single crystals of the co-irradiated monitor mineral, Fish Canyon sanidine, with an age of 27.84 Ma. This age is similar to that recommended by G. T. Cebula, *et al.* [*Terra Cognita* **6**, 139 (1986)] but modified slightly as a result of in-house intercalibration at the Geochronology Center with MMhb-I with a published age of 520.4 ± 1.7 Ma by S. D. Samson and E. C. Alexander [*Chem. Geol. Isotope Geosci. Sect.* **66**, 27 (1987)]. Sample 92JV-23B was irradiated for 1.5 hours in the Denver TRIGA Reactor: $J = 0.0003018 \pm 0.00000025$ and $^{40}Ar/^{36}Ar$ mass discrimination $= 1.006 \pm 0.00024$. Sample 93JV-4 was irradiated for 1.5 hours in the Oregon TRIGA Reactor: $J = 0.000396 \pm 0.0000003$ and $^{40}Ar/^{36}Ar$ mass discrimination $= 1.011 \pm 0.0002$. The *J*s contain all analytical uncertainties, but not to include all errors associated with the absolute age of the monitor mineral. Ca and K corrections were determined from laboratory salts: $(^{36}Ar/^{37}Ar)_{Ca} = 2.742 \times 10^{-4} \pm 9.7 \times 10^{-6}$, $(^{39}Ar/^{37}Ar)_{Ca} = 6.852 \times 10^{-4} \pm 2.4 \times 10^{-5}$, and $(^{40}Ar/^{39}Ar)_K = 9.0 \times 10^{-4} \pm 3.0 \times 10^{-4}$. Decay constants are those recommended by R. H. Steiger and E. Jager [*Earth Planet. Sci. Lett.* **36**, 359 (1977)] and G. B. Dalrymple [*Geology* **7**, 558 (1979)].

   Approximately 0.5 mg of hornblende from each of the Java samples was incrementally heated by a stepwise increase of the output from a defocused Ar-ion laser beam. Each increment was held for 45 s, and the released gases were purified by two scanning auger electron spectroscopy C-50 getters operated at approximately 400°C. The Ar isotopes were measured in an on-line mass analyzer product 215 noble-gas mass spectrometer operated in the static mode, with the use of automated data collection techniques.

   The plateau ages are calculated as the weighted (by inverse variances) mean of all increments defining the plateau, and the uncertainties that accompany the plateau ages are standard errors. All of the spectra are essentially flat, yielding plateaus that comprise more than 90% of the total ^{39}Ar released. Definition of the obtained plateaus follows R. J. Fleck *et al.* [*Geochim. Cosmochim. Acta* **41**, 15 (1977)]. The low temperature increments, consisting of less than 2% of the total ^{39}Ar released, contain large analytical errors due to high atmospheric Ar contamination and are consequently omitted from the plateaus. The uncertainties associated with the individual incremental apparent ages are 2σ errors, while those that accompany the calculated weighted mean ages of the plateau increments and weighted means of the replicate analyses are standard errors, following J. R. Taylor [*An Introduction to Error Analysis* (Oxford Univ. Press, Oxford, 1982)].
33. C. C. Swisher III *et al.*, unpublished data.
34. G. H. R. von Koenigswald, *Proceedings of the VIII International Congress of the Anthropological Ethnology Society 1968* (Scientific Council of Japan, Tokyo, 1969), vol. 1, pp. 104–105; B. Campbell, in *Classification and Human Evolution*, S. L. Washburn, Ed. (Methuen, London, 1964), pp. 50–74.
35. J. L. Franzen, in (*21*), pp. 221–226.
36. C. Stringer, *Anthropologie* **19**, 3 (1981).
37. F. C. Howell, in *Evolution of African Mammals*, V. J. Maglio and H. B. S. Cooke, Eds. (Harvard Univ. Press, Cambridge, MA, 1978), pp. 154–248.
38. H. L. Movius Jr., *Trans. Am. Philos. Soc.* **38**, 329 (1948).
39. C. Stringer, in *Hominid Evolution and Community Ecology*, R. Foley, Ed. (Academic Press, London, 1984), pp. 55–83.

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