Early Pleistocene $^{40}Ar/^{39}Ar$ ages for Bapang Formation hominins, Central Jawa, Indonesia

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The Sangiran dome is the primary stratigraphic window for the Plio-Pleistocene deposits of the Solo basin of Central Jawa. The dome has yielded nearly 80 *Homo erectus* fossils, around 50 of which have known findspots. With a hornblende $^{40}Ar/^{39}Ar$ plateau age of 1.66 ± 0.04 mega-annum (Ma) reportedly associated with two fossils [Swisher, C.C., III, Curtis, G. H., Jacob, T., Getty, A. G., Suprijo, A. & Widiasmoro (1994) *Science* 263, 1118–1121), the dome offers evidence that early *Homo* dispersed to East Asia during the earliest Pleistocene. Unfortunately, the hornblende pumice was sampled at Jokotingkir Hill, a central locality with complex litho-stratigraphic deformation and dubious specimen provenance. To address the antiquity of Sangiran *H. erectus* more systematically, we investigate the sedimentary framework and hornblende $^{40}Ar/^{39}Ar$ age for volcanic deposits in the southeast quadrant of the dome. In this sector, Bapang (Kabuh) sediments have their largest exposure, least deformation, and most complete tephrostratigraphy. At five locations, we identify a sequence of sedimentary cycles in which *H. erectus* fossils are associated with epiclastic pumice. From sampled pumice, eight hornblende separates produced $^{40}Ar/^{39}Ar$ plateau ages ranging from 1.51 ± 0.08 Ma at the Bapang/Sangiran Formation contact, to 1.02 ± 0.06 Ma, at a point above the hominin-bearing sequence. The chronological sequence of $^{40}Ar/^{39}Ar$ ages follows stratigraphic order across the southeast quadrant. An intermediate level yielding four nearly complete crania has an age of about 1.25 Ma.

geochronology | human evolution | *Homo erectus* | Southeast Asia | tephrostratigraphy

Within the Solo basin of Central Jawa, an abrupt change from lacustrine to fluvial sedimentation marks the contact between the Pucangan and the overlying Kabuh Formations. Within the Sangiran dome, the primary stratigraphic window for the basin, these deposits are known as the Sangiran and Bapang Formations, respectively (1). Although the upper units of the Sangiran Formation have yielded *Homo erectus* fossils, Bapang sediments have produced many more and indicate a hominin species well established on the Sundan subcontinent. The Bapang Formation represents an aggraded fluvial system built up in a number of energetic cycles. The sediments themselves were derived from the eruptions of one or more volcanoes east of the basin and from the weathering of carbonate–silicate highlands uplifting north and south (Fig. 1*b*).

Bapang Sedimentary Cycles

At the two Bapang village reference sections (Bpg A and Bpg B), five complete normally graded cycles are visible, referred to here as C1 to C5 (Fig. 2). Each cycle has two distinct sedimentary facies, commencing with an a-facies below and terminating with a b-facies above. The a-facies beds comprise poorly sorted planar- and cross-bedded gravels and sands. Clasts consist of andesite and rounded dacitic pumice as well as microcrystalline quartz derived from carbonate rocks. C1a, the lowest level of which defines the traditional "Grenzbank" (GB), includes a greater range of clast sizes scoured from locally underlying deposits, including clay cobbles from the adjacent lacustrine sediments, foraminifera from marine rocks, and andesite boulders from laharic deposits. The a-facies sediments have interbedded ashy tuffaceous lenses, locally termed "tuffs" (1). Notable are the C1a Lowest Tuff (LtT) that appears only at Bapang, and the C2a tuffaceous silt level found at Bapang and Sendangbusik. The latter feature is closely associated with hominin fossils (Fig. 2).

The b-facies beds are poorly to moderately sorted tuffaceous silts and sands consisting of altered volcanic glass with interspersed angular to subangular crystals and altered lithic clasts. Bedding in the b-facies sediments is planar to massive, with rare cross bedding. Three of the poorly sorted, tuffaceous b-facies have previously been called the Lower (C1b), Middle (C2b), and Upper (C4b) "Tuffs" (1). The Middle Tuff (MT) is the most widely distributed and variable. At Bapang and Pucung, MT is distinct, fine-grained, homogeneous, and surface-scoured. It constitutes a tuffaceous silt zone at Tanjung, and is reworked within a sandy, braided fluvial C2b unit at Sendangbusik and Grogolwetan.

The upper reaches of the major b-facies units exhibit features of subaerial weathering. Among them are small, vertically oriented, tubes with dense lateral distribution that appear to be root casts for grassy plants and burrows for small insects. The presence of grassy plants is corroborated by extant pollen profiles (2). These tubes and other open spaces are commonly lined with microlaminated clay. At Bapang and Pucung, the MT shows light paleosol development. At Pucung, Upper Tuff (UT) overlies a distinct clay-rich lens whose organic component may represent a paleosol A-horizon. At the bases of C2a, C3a, and C5a, renewed fluvial action scoured the surfaces of LT, MT, and UT, respectively. As weathering features do not extend up into the overlying a-facies unit, they must antedate the subsequent erosion.

The paired facies indicate a fluvial regime of energetic basal stream channel deposits overlain by lower-energy stream and overbank sediments. The series fines generally from bottom to top. Epiclastic pumice is found in each a-facies, with typical grain sizes decreasing from pebble- to cobble-sized in the lower two cycles to granule- to pebble-sized in the upper cycles. Course pumice has short residence times in energetic fluvial systems such as these. Therefore, its presence in the a-facies is consistent with deposition shortly after eruption.

Abbreviations: Ma, million years ago or million years; MT, Middle Tuff; UT, Upper Tuff; MSWD, mean square of weighted deviates.

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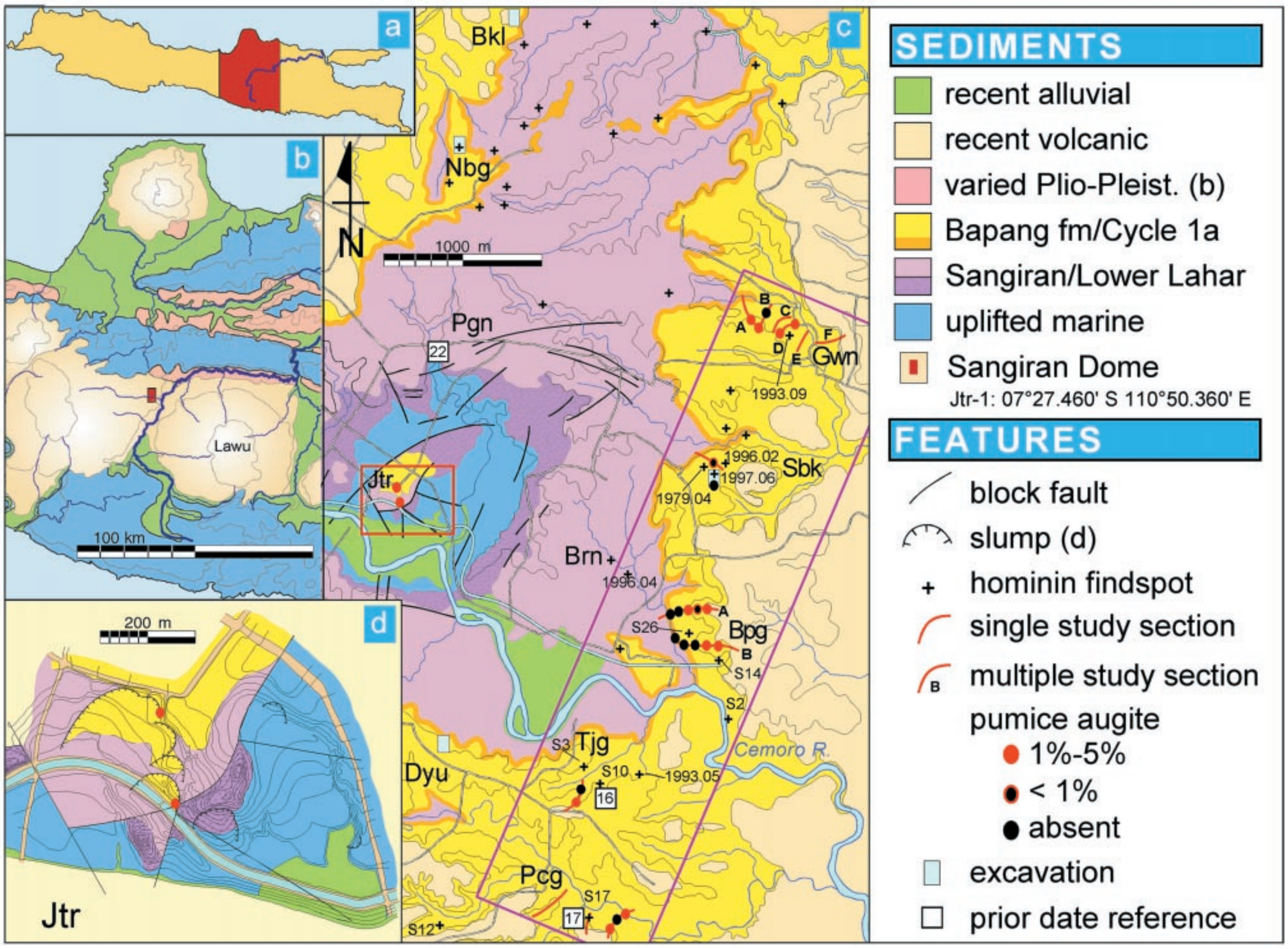

Fig. 1. (*a*) Jawa, Republic of Indonesia. (*b*) Solo Basin. The basin is a segment of Jawa's east–west trending Central Depression, the current magmatic zone of the Indonesian volcanic island arc. Supplying the Sangiran dome's Bapang Formation sedimentary sequence were volcanic cones building east and west and marine carbonate–silicate highlands emerging north and south. (*c*) Sangiran Dome. Southeast quadrant box shows locations for study sections, pumice samples, hominin findspots, and previous dates. +, documented hominin findspot (28, 29). Labeled findspots are discussed in the text or presented in Fig. 2. ''S'' prefix represents old colloquial ''Sangiran'' numbers used for fossils found into the mid 1970s. More recent findspots carry year and month of discovery along with a village locality prefix: Bkl, Brangkal; Brn, Bukuran; Bpg, Bapang; Dyu, Dayu; Gwn, Grogolwetan; Jtr, Jokotingkir Hill; Nbg, Ngebung; Pcg, Pucung; Pgn, Pablengan; Sbk, Sendangbusik; Tjg, Tanjung. (*d*) Jokotingkir Hill (central dome box). The lower red oval represents the Jtr-1 canal level pumice lens sampled for $^{40}Ar/^{39}Ar$ hornblende age analysis within a slumped Bapang Formation sediment block (longitude and latitude in legend). The upper red oval marks a pumice lens at the top of this block sampled for augite content and hornblende color only. Hominin fossils S27 and S31 were recovered during canal excavations within 150 m west–northwest of Jtr-1.

The a-facies yield megafauna fossils in coarse sediment lenses, especially at unit bases. The b-facies sediments are devoid of megafauna. The richest a-facies "bone beds" lie in C1a, and are attributable to the Trinil H.K. fauna. C2a through C5a contain Kedung Brubus stage fossils, as identified by de Vos *et al.* (3). The sedimentary cycles aid in interpreting dome hominin fossil taphonomy. Highly fragmented gnathic remains have been found most commonly in C1 sediments [12 specimens from the "Grenzbank" (GB) itself]. C2a and C3a present more cranial elements in more complete form. C5a yields the stratigraphically highest hominin fossil (calotte S3) in a notably good state of preservation. The overall change in fossil fragmentation patterns correlates with diminishing fluvial energy throughout the sedimentation sequence.

Across the southeast quadrant, C2a sediments have conserved a number of well known cranial and dental fossils, including cranium S17 at Pucung, and occipital fragments Sbk-1979.04 (variously referred to as S37a/b and as S39 and S40a) as well as incisor Sbk-1997.06 at Sendangbusik (4). Recently, three more adult cranial fossils have been documented *in situ* (Figs. 1 and 2): cranium Tjg-1993.05 (5), calotte Gwn-1993.09 (6), and calotte Sbk-1996.02 (7). A fourth important specimen, occipital Brn-1996.04, has been found in Sangiran Formation sediments near Bapang village. Within a scope of research that covers the entire hominin-bearing Bapang sedimentary sequence in the southeast quadrant, we focus on sediments surrounding the C2a specimens, which are anatomically more complete and stratigraphically better documented than most dome finds.

Tephrochronology

Pumice clasts are associated with all a-facies fossil beds and they have a relatively uniform mineralogy throughout the sedimentary sequence, suggesting that they erupted from a single volcano. Petrographic examination of thin-sections taken from 25 representative pumice clasts shows 10–20 vol. % complexly zoned euhedral to subhedral plagioclase phenocrysts and 3–7 vol. % euhedral to subhedral hornblende phenocrysts. Euhedral to subhedral magnetite phenocrysts, often associated with apatite, compose up to 2 vol. %. In most samples, phenocrystic phases show eruption shattering, and groundmasses are gener-

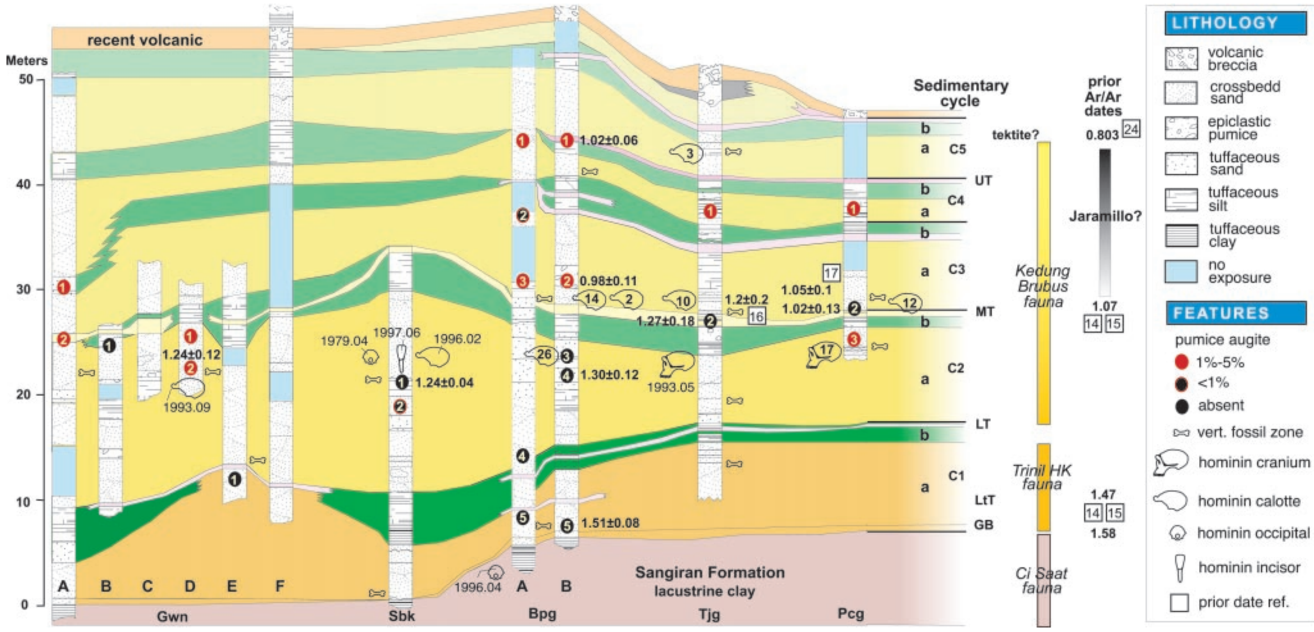

Fig. 2. Bapang Formation tephrostratigraphy. Sedimentary cycles: orange/yellow, a-facies; green, b-facies. Shading indicates the pattern of sediment fining from bottom to top. Numbered ovals mark epiclastic pumice sites sampled for augite content, hornblende color, and $^{40}Ar/^{39}Ar$ age analysis. From left to right, sections run north to south for a total of 4 km (no horizontal scale). The Grogolwetan and Bapang localities have lettered multiple sections. Pumice with hornblende $^{40}Ar/^{39}Ar$ ages $\leq$ 1.1 Ma has 1–5 vol. % augite phenocrysts. Pcg-2, the exception (no augite), has an age of 1.02 $\pm$ 0.13 Ma. Pumice with hornblende $^{40}Ar/^{39}Ar$ ages $\geq$ 1.25 Ma lacks augite. Pumice from Gwn D-2 (1.24 $\pm$ 0.12 Ma) has $<$1% augite microphenocrysts. At Grogolwetan, C2a pumice lens Gwn D-2 lies 50 cm above the cranium findspot. At Sendangbusik, C2a pumice lens Sbk-1 is in direct association with an incisor, a calotte, and two large occipital–parietal fragments, representing three individuals. The isotope correlation age (1.24 $\pm$ 0.04 Ma) is shown for Sbk-1. At Bapang, B-1 represents UT (C4b), the only fine-grained tephra to give a reliable $^{40}Ar/^{39}Ar$ age (1.02 $\pm$ 0.06 Ma). The C3a B-2 plateau age (0.98 $\pm$ 0.11 Ma) is statistically indistinguishable from the UT age. C2a pumice at B-4 correlates stratigraphically with calotte S26. C1a pumice lens B-5 lies 130 cm above the Bapang/Sangiran contact. At Pucung, pumice lens Pcg-2 lies in association with a C3a fossil concentration.

ally colorless glass with abundant vesicles. Also relatively common are microlites of plagioclase, hornblende, and apatite. Clays or calcite partially replace groundmass glass in a few samples. The mineral abundances resemble those found in pumice clasts of the Lawu cone, 30 km to the east (8).

Although the background mineralogy of the pumice clasts is homogenous, augite content and hornblende color vary with stratigraphic position (Fig. 2). Pumice sampled in C1a (below MT) generally lacks augite phenocrysts and has bright green hornblende, whereas pumice sampled in C3a and C4a (above MT) has 1–5 vol. % euhedral to subhedral augite and brownish-green hornblende. Pumice in C2a (MT) is transitional for augite content. With one exception, the mineralogy of the b-facies tuffaceous sediments typically does not match that of the a-facies. This probably reflects fluvial reworking of older tephras and soils as well as in place alteration and soil formation. In exception, the augite content and hornblende color observed in tuffaceous silt at Bpg B-1 (UT) match those of pumice clasts sampled in similar stratigraphic position (Bpg A-1, Tjg-1, and Pcg-1).

Plagioclase is the dominant phenocryst in the Bapang pumices, and it has been successfully dated in other volcanic settings (9). Nevertheless, age determinations using plagioclase can be erroneous (10, 11). We analyzed both plagioclase and hornblende separates from site Bpg B-1 to assess the utility of each mineral for geochronology in the Sangiran dome (see Table 3 and Fig. 6, which are published as supplemental data on the PNAS web site, www.pnas.org). Whereas two Bpg B-1 hornblende splits yielded flat age spectra with analytically identical plateau ages [1.04 $\pm$ 0.04 mega-annum (Ma) and 0.99 $\pm$ 0.04 Ma], the plagioclase separate produced a discordant age spectrum. The plagioclase results most likely reflect the presence of extraneous argon

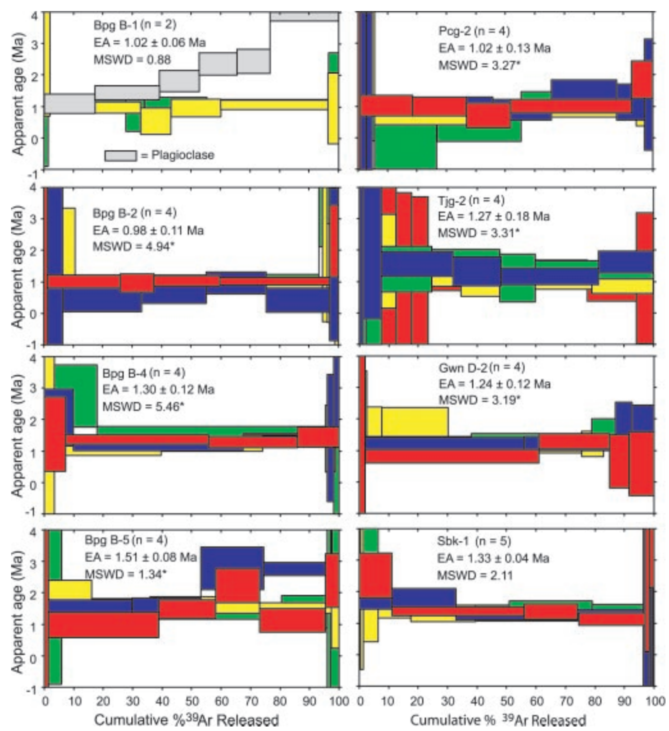

Fig. 3. $^{40}Ar/^{39}Ar$ age spectra diagrams for replicate (n) hornblende analyses. EA, Eruption Age. Overall, the replicate analyses are reproducible and have flat age spectra. Both plagioclase and hornblende separates were analyzed from site Bpg B-1. In contrast to the hornblende from this sample, the plagioclase yielded a highly discordant spectrum.

Table 1. Compilation of hornblende $^{40}Ar/^{39}Ar$ plateau and total gas age results

Sample	Weight, mg	Plateau age, Ma	Plateau MSWD	No. steps on plateau	% ^{39}Ar in plateau	Total gas age, Ma
Jtr-1a	9.82	1.19 ± 0.10	5.60*	3	96.1	3.12 ± 0.24
Jtr-1b	8.81	1.07 ± 0.04	0.37	3	100	1.09 ± 0.10
Jtr-1c	14.83	1.20 ± 0.11	9.67*	2	82.5	2.39 ± 0.16
Bpg B-1a	17.96	1.04 ± 0.04	0.47	6	100	1.06 ± 0.14
Bpg B-1b	17.51	0.99 ± 0.04	1.83	6	100	0.98 ± 0.14
Bpg B-2a	33.06	1.06 ± 0.05	0.65	5	93.4	1.16 ± 0.16
Bpg B-2b	11.02	0.94 ± 0.04	1.12	6	100	1.10 ± 0.20
Bpg B-2c	9.52	0.67 ± 0.09	1.11	6	100	0.64 ± 0.34
Bpg B-2d	15.53	1.02 ± 0.04	0.13	5	97	1.08 ± 0.14
Pcg-2a	179.25	1.13 ± 0.08	2.59*	7	94.5	0.72 ± 0.28
Pcg-2b	36.68	0.86 ± 0.07	0.93	5	100	0.88 ± 0.68
Pcg-2c	17.28	1.13 ± 0.07	1.55	7	100	1.07 ± 0.34
Pcg-2d	20.89	0.97 ± 0.06	0.55	5	92.7	1.07 ± 0.32
Tjg-2a	12.64	1.21 ± 0.14	0.21	8	100	1.3 ± 2.7
Tjg-2b	19.24	1.05 ± 0.09	0.59	6	100	1.4 ± 1.5
Tjg-2c	23.77	1.44 ± 0.11	0.46	6	100	1.7 ± 1.7
Tjg-2d	18.47	1.37 ± 0.08	1.23	6	100	1.48 ± 0.38
Gwn D-2a	142.14	1.22 ± 0.05	1.74	4	69.9	1.43 ± 0.37
Gwn D-2b	41.79	1.36 ± 0.06	1.5	5	100	1.43 ± 0.75
Gwn D-2c	31.16	1.20 ± 0.07	0.21	5	100	1.26 ± 0.84
Gwn D-2d	38.1	0.98 ± 0.12	3.14*	5	100	1.03 ± 0.81
Sbk-1a	14.44	1.44 ± 0.05	1.52	4	93.6	1.87 ± 0.81
Sbk-1b	17.64	1.27 ± 0.05	1.28	6	96.6	1.48 ± 0.25
Sbk-1c	12.25	1.27 ± 0.05	0.25	5	67.2	1.52 ± 0.27
Sbk-1d	17.34	1.33 ± 0.04	1.73	4	87.4	1.53 ± 0.16
Sbk-1e	16.94	1.31 ± 0.04	2.17	5	100	1.41 ± 0.14
Bpg B-4a	7.96	1.57 ± 0.09	0.01	2	82.1	1.78 ± 0.22
Bpg B-4b	18.84	1.19 ± 0.04	1.05	5	98.6	1.21 ± 0.31
Bpg B-4c	15.27	1.33 ± 0.06	1.84	5	100	1.40 ± 0.18
Bpg B-4d	16.01	1.35 ± 0.04	0.45	4	100	1.37 ± 0.13
Bpg B-5a	10.9	1.38 ± 0.08	0.19	5	100	1.45 ± 0.32
Bpg B-5b	17.37	1.56 ± 0.05	0.2	6	100	1.65 ± 0.65
Bpg B-5c	21.83	1.54 ± 0.09	0.07	3	53.1	2.69 ± 0.37
Bpg B-5d	18.21	1.37 ± 0.19	4.21*	5	95.3	1.44 ± 0.63

Plateau and total gas age errors are 1σ. Total gas ages and errors are weighted by the % ^{39}Ar released.
*MSWD falls above the 95% confidence interval and therefore errors are multiplied by the square root of the MSWD.

inherited from either incompletely degassed xenocrysts or from the magmatic system.

Hornblende generally separated as pure, coarse-grained phenocrysts. The color, morphology, and grain size for each separate was consistent and therefore suggested the existence of a single magmatic hornblende population. In addition, prior K-Ar and $^{40}Ar/^{39}Ar$ ages for Sangiran dome pumice samples were determined on hornblende, allowing direct comparison with our results. Most b-facies sediments contained only a few small hornblende phenocrysts of varying color, morphology, and degree of alteration, all indicators of mixed provenance. As already noted, unaltered hornblende was separable from tuffaceous silt at site Bpg B-1.

Eight hornblende separates were analyzed from the southeast quadrant and one more from Jokotingkir Hill in the central dome. For each, two to five aliquots were tested for homogeneity and analytical reproducibility (Fig. 3 and supplemental data). For the majority of laser-heated samples, ≈10–20 mg of mineral were heated in six steps. The blank corrections for ^{40}Ar and ^{36}Ar were highly variable, ranging from less than 1% up to ≈50% and age calculation was sensitive for steps with high blank corrections. Nevertheless, as correction sensitivity was highly variable for steps yielding similar ages, no apparent systematic error can be associated with potential blank inaccuracy. The age spectra were generally well behaved (Table 1 and Figs. 3 and 4; also see supplemental data). Weighted mean combination of plateau ages for each sample indicate eruption ages from 1.51 ± 0.08 to 0.98 ± 0.11 Ma (Fig. 3). These results conform to the stratigraphic position of the pumice samples (Fig. 2). The scatter for some of the replicate plateau age results (Table 1) could indicate minor xenocryst and/or excess argon contamination.

Isotope correlation diagrams (Fig. 4) were produced by combining all data from each replicate experiment and removing statistical outliers (12) until the mean square of weighted deviates (MSWD) fell within the 95% confidence intervals (13). The isotope correlation ages agree generally with the plateau ages (Tables 1 and 2). However, samples Jtr-1 and Sbk-1 yielded apparent excess argon intercepts and isotope correlation ages (Jtr-1 = 0.93 ± 0.05, Sbk-1 = 1.24 ± 0.04 Ma) that are 2σ younger than their combined plateau ages (Jtr-1 = 1.10 ± 0.07, Sbk-1 = 1.33 ± 0.04 Ma). Thus, isotope correlation results may best estimate the eruption ages for Jtr-1 and Sbk-1, which conform well to the chronological trend of the plateau ages.

Our results corroborate prior K-Ar and bulk sample $^{40}Ar/^{39}Ar$ analyses of Sangiran pumice hornblende. The Bpg B-5 sample age (1.51 ± 0.08 Ma) matches previous $^{40}Ar/^{39}Ar$ results of 1.47 Ma and 1.58 Ma for the lowest Bapang sediments (14, 15). The Tjg-2 site age (1.27 ± 0.18 Ma) corroborates a K-Ar age (1.2 ± 0.2 Ma) determined in association with the S10 findspot (16). At Pucung, the S17 findspot lies ≈5 m below MT. Pumice

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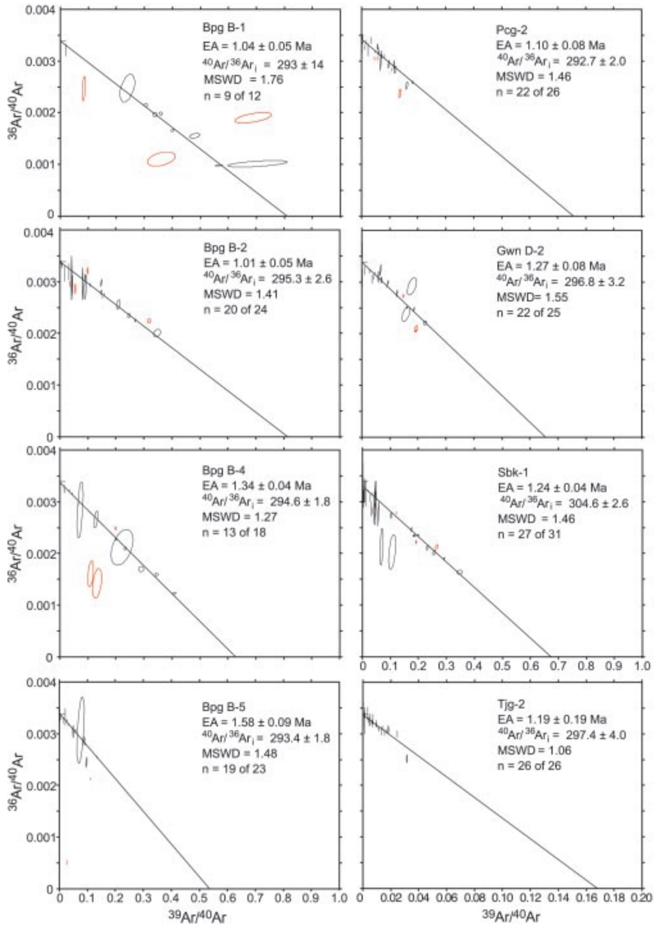

Fig. 4. Isotope correlation diagrams for hornblende isotopic results. Plots show combination of all data from each set of replicate analyses. Data shown in red are statistical outliers to the regression line as determined by the elimination methods of Deino and Potts (12).

collected at the findspot (Pcg-2) produced an $^{40}Ar/^{39}Ar$ age (1.02 ± 0.13 Ma) statistically identical with a K-Ar age (1.05 ± 0.1 Ma) on pumice collected 12 m above the S17 findspot (17). Swisher (14, 15) has a seven-age average (1.07 Ma) for apparently similar pumice levels above MT.

When the hornblende $^{40}Ar/^{39}Ar$ age sequence and the pumice mineralogy are linked and fit into the context of the Bapang sedimentary cycles, a basic pattern emerges. Cycle 2b (MT) appears to separate a long early period of relatively energetic fluvial sedimentation from a later but more contracted period of finer deposition. Pumice clasts in C1a have green hornblende, lack augite, and have ages of about 1.5 Ma. C2a pumice has transitional mineral contents and ages of about 1.25 Ma. C3a, C4a, and C5a have pumice clasts with brown tinted hornblende and augite with ages of about 1.0 Ma. These data suggest deposition of C1 pumice shortly after an eruption, perhaps of the Lawu center, at about 1.5 Ma. C2 pumice was deposited about 0.25 Ma later after a second eruption. Pumice from C3, C4, and C5 were from one eruption or a series of closely timed eruptions at about 1 Ma. The consistency between the ages and the stratigraphy precludes recycling of pumice from an extinct eroding volcanic edifice.

Discussion

The tephrostratigraphy of the hominin-bearing sedimentary sequence of the Bapang Formation in the southeast quadrant of the Sangiran Dome provides the best means to understand the age of *H. erectus* on the Sundan subcontinent. Two other recent attempts to assign age to Sangiran fossils show the difficulty of working outside this restricted sedimentary context. One involves the $^{40}Ar/^{39}Ar$ age of pumice sampled in the central part of the dome (18). The second attempt involves the use of Australasian strewnfield tektites as a stratigraphic maker in Bapang sediments (19).

Across the dome, the Bapang Formation C1a unconformably overlies the Sangiran (Pucangan) Formation itself comprising three units. The upper unit has *ca.* 75 m of lacustrine sediments that contain tuffaceous lenses but no pumice (1). The upper reaches of the lacustrine unit have produced the endemic island-type Ci Saat fauna, which has just a small number of terrestrial vertebrates including *H. erectus* (3). Occipital Brn-1996.04 was found some 10 m below the lacustrine unit's top, and is therefore older than 1.51 ± 0.08 Ma.

The second unit comprises *ca.* 35 m of brackish and marine clays that hold no terrestrial fauna and no pumice. The lowest unit is the Lower Lahar, a *ca.* 30-m-thick deposit of volcanic breccia. The Lower Lahar unit contains small amounts of epiclastic pumice and a sparse and very fragmentary fauna with no hominins (20). The marine carbonate Puren (Kalibeng) Formation is found below the Lower Lahar.

At the base of Jokotingkir Hill in the central dome, block faulting during the Middle Pleistocene has laterally juxtaposed Bapang, Sangiran, and Puren sediments. In 1978, maxilla S27 (no publication) and calotte S31 (21) were each retrieved without provenance during hill base canal excavations. At this locale,

Table 2. Summary of hornblende $^{40}Ar/^{39}Ar$ plateau age determinations

Sample	Weighted mean plateau age, Ma	Weighted mean plateau age MSWD	Isotope correlation age, Ma	$^{40}Ar/^{36}Ar_i$	Isotope correlation age MSWD	# Steps for isochron	Chosen Eruption age, Ma
Jtr-1	1.10 ± 0.07	1.11	0.93 ± 0.05	323.3 ± 4.4	2.32	8 of 15	0.93 ± 0.05
Bpg B-1	1.02 ± 0.06	0.88	1.04 ± 0.05	293 ± 14	1.76	9 of 12	1.02 ± 0.06
Bpg B-2	0.98 ± 0.11	4.94*	1.01 ± 0.05	295.3 ± 2.6	1.41	20 of 24	0.98 ± 0.11
Pcg-2	1.02 ± 0.13	3.27*	1.10 ± 0.08	292.7 ± 2.0	1.46	22 of 26	1.02 ± 0.13
Tjg-2	1.27 ± 0.18	3.31*	1.19 ± 0.19	297.4 ± 4.0	1.06	28 of 28	1.27 ± 0.18
Gwn D-2	1.24 ± 0.12	3.19*	1.27 ± 0.08	296.8 ± 3.2	1.55	22 of 25	1.24 ± 0.12
Sbk-1	1.33 ± 0.04	2.11	1.24 ± 0.04	304.6 ± 2.6	1.46	27 of 31	1.24 ± 0.04
Bpg B-4	1.30 ± 0.12	5.45*	1.34 ± 0.04	294.6 ± 1.8	1.27	13 of 18	1.30 ± 0.12
Bpg B-5	1.51 ± 0.08	1.34	1.58 ± 0.09	293.4 ± 1.8	1.48	19 of 23	1.51 ± 0.08

Plateau age determined from weighted mean combination of individual plateau ages for each sample. Weighted mean plateau age and isotope correlation age errors are 2σ. For isotope correlation age determination method see supplemental data.
*MSWD falls above the 95% confidence interval and therefore errors are multiplied by the square root of the MSWD.

Swisher *et al.* (18) sampled "A volcanic pumice rich layer [that] crops out 2 m above the horizon that yielded *Meganthropus* S27 and S31." Swisher *et al.* (18) further report a step-heated bulk sample hornblende $^{40}Ar/^{39}Ar$ age of 1.66 ± 0.04 for this sediment and the fossils.

Based on attempts to replicate Swisher *et al.*'s (18) procedures, we make two observations. First, if the material analyzed was indeed pumice, it cannot have derived from hominin-bearing lacustrine sediments traditionally termed "Pucangan"—they hold no epiclastic pumice. Second, although there is an epiclastic pumice lens 2 m above the canal bed at the base of Jokotingkir Hill (Jtr-1), it lies fully within a published slumped block of Bapang sediment (1). The sediment is silty and contains no foraminifera, most likely indicating C2a or higher Bapang character. Our $^{40}Ar/^{39}Ar$ ages (plateau and isotope correlation) for Jtr-1 (Table 2) resemble C3a and C4a ages from the southeast quadrant.

Sémah *et al.* (22) observe that Swisher *et al.*'s (18) bulk sample hornblende $^{40}Ar/^{39}Ar$ age (18) matches their single grain hornblende $^{40}Ar/^{39}Ar$ age (1.66 ± 0.04 Ma) for the Lower Lahar at Pablengan, 1 km north. Because the Lower Lahar is a massive volcanic breccia, it may hold hornblende of widely varying ages. Sémah *et al.* (22) also report a single grain age of 1.77 ± 0.04 Ma for this unit (22). Although the Lower Lahar may indeed contain hornblende of highly varying ages, French and American $^{40}Ar/^{39}Ar$ results on similar dome hornblende diverge consistently (23). In any event, the ages of fossils S27/S31 remain unresolved.

The age of Australasian strewnfield tektites has been refined recently to 0.803 Ma (24). At this age, the tektites should provide a key stratigraphic marker for *H. erectus* in Southeast Asia (19). Nevertheless, the presence of these objects in the hominin-bearing sediments of Sangiran must be questioned. Tektites are usually found in sediments younger than their own isotopic age (25) and, in the dome, they are commonly found on current erosional surfaces. The first programmed geological excavations in the dome claimed to find two tektites in Bapang sediments; one at Brangkal and the other at Pucung (1). However, detailed documentation was never provided. Moreover, in the last 10 years, programmed fieldwork has been carried out at multicomponent archaeological and paleontological sites at Ngebung (26), at Brangkal, Dayu, and Ngledok (27), and at Sendangbusik (4). Although these more recent excavations have been intensive and meticulous throughout the lower and middle Bapang sequence (C1–C3), they have not recovered tektites. Without stratigraphic confirmation and with mounting evidence for Early Pleistocene-aged hominin-bearing Bapang sediments, it is likely that the tektite level lies in C5b or higher deposits. We suggest that the Australasian event essentially postdates the sedimentary context for the early Sundan hominins.

Conclusions

We have reported a sequence of fluvial sedimentary cycles related to the calc-alkaline eruptions of the Indonesian magmatic arc in the Solo basin of Central Jawa. The sediments, known locally as the Bapang (Kabuh) Formation, constitute the youngest hominin-bearing strata of the Sangiran dome. Each sedimentary cycle has a lower a-facies deposited by highly charged migrating stream channels, and an upper b-facies deposited by quieter overbank sedimentation. In the b-facies, light soil developments, root traces, and pollen diagrams suggest the presence of grassy environments on these floodplains. In the classical taphonomic conundrum, the b-facies overbank settings likely reflect preferred occupation surfaces whereas the a-facies gravels have concentrated paleontological remains into coarser lenses.

We have also reported taphonomic and mineralogical trends, as well as hornblende $^{40}Ar/^{39}Ar$ ages that closely follow the Sangiran dome stratigraphic sequence. These data reflect a fluvial regime in which pumice was transported from its volcanic source rapidly enough to prevent significant mixing of old and young minerals. In total, the Bapang $^{40}Ar/^{39}Ar$ ages indicate that *H. erectus* occupied the Solo basin for at least a half million years beginning 1.5 Ma.

We have also shown that Swisher *et al.*'s pumice-derived $^{40}Ar/^{39}Ar$ age of 1.66 ± 0.04 Ma cannot be linked with the S27 and S31 fossils as claimed (18). Nevertheless, the stratigraphically oldest hominin fossil from the southeast quadrant, occipital Brn-1996.04, underlies C1a by about 10 m. As there is a significant erosional break across the dome just below C1a, the age of this specimen and other Sangiran (Pucangan) Formation hominin fossils is greater than 1.5 Ma.

ANTHROPOLOGY

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