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LETTERS

Hominins on Flores, Indonesia, by one million years ago

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Previous excavations at Mata Menge and Boa Lesa in the Soa Basin of Flores, Indonesia, recovered stone artefacts in association with fossilized remains of the large-bodied *Stegodon florensis florensis*[1–9]. Zircon fission-track ages from these sites indicated that hominins had colonized the island by 0.88 ± 0.07 million years (Myr) ago[6]. Here we describe the contents, context and age of Wolo Sege, a recently discovered archaeological site in the Soa Basin that has *in situ* stone artefacts and that lies stratigraphically below Mata Menge and immediately above the basement breccias of the basin. We show using ^{40}Ar/^{39}Ar dating that an ignimbrite overlying the artefact layers at Wolo Sege was erupted 1.02 ± 0.02 Myr ago, providing a new minimum age for hominins on Flores. This predates the disappearance from the Soa Basin of 'pygmy' *Stegodon sondaari* and *Geochelone* spp. (giant tortoise), as evident at the nearby site of Tangi Talo, which has been dated to 0.90 ± 0.07 Myr ago[10]. It now seems that this extirpation or possible extinction event and the associated faunal turnover were the result of natural processes rather than the arrival of hominins[9]. It also appears that the volcanic and fluvio-lacustrine deposits infilling the Soa Basin may not be old enough to register the initial arrival of hominins on the island.

There has been a long history of palaeontological and archaeological research in the ~200-km^2 Soa Basin of western central Flores (Fig. 1), where the geological sequence is divided into two main stratigraphic units[6,11,12] (Fig. 2). The oldest unit, the Ola Kile Formation, is the basement bedrock and comprises massive and resistant andesitic breccias and volcanic mudflows with minor interbedded tuffaceous siltstones, sandstones and lava flows. A fission-track date from near the top of the Ola Kile Formation provides a minimum age of 1.86 ± 0.12 Myr for this unit[6]. Successional volcanic and fluvio-lacustrine deposits of the ~100-m-thick Ola Bula Formation unconformably overlie the Ola Kile Formation, and have previously yielded fission-track ages in ascending order of between 0.96 ± 0.09 and 0.65 ± 0.06 Myr (ref. 6). The basal tuff interval of the Ola Bula Formation is dominated by volcanic mudflows and ignimbrites, with minor conglomerate lenses and tuffaceous siltstones. This volcanic tuff-dominated facies grades upwards into a sandy interval characterized by fluvio-lacustrine tuffaceous sand layers interbedded with lacustrine tuff and tuffaceous silt, and minor fluvial conglomerate lenses and mudflows[6].

Wolo Sege (8° 41′ 26′′ S, 121° 5′ 59′′ E) is situated in the tuff interval at the base of the Ola Bula Formation (Fig. 2), with alternating tuffaceous silt, ignimbrite and weathered pumice deposits exposed to the north, west and south. The site occurs in the southeastern corner of a cattle yard at the head of a small gully, which is naturally enclosed on three sides by a 3-m-high vertical rock scarp. The gully is approximately 500 m east of, and 10 m stratigraphically below, Mata Menge (Fig. 2), as indicated by elevation in combination with lateral tracing of the tuffaceous units. Mata Menge contains *S. florensis florensis* fossils and stone artefacts in fluvio-lacustrine sediments dated to between 0.88 ± 0.07 and 0.80 ± 0.07 Myr ago[4,5,13,14]. A small, dry streambed extends east from the gully, draining into a channel that cuts into the Ola Kile Formation, which also outcrops in the western corner of the cattle yard.

During an archaeological survey of the area in September 2005, several large, water-worn stone artefacts were found on the surface of the Wolo Sege cattle yard. These seem to have eroded from a 1-m-thick conglomerate lens exposed in the southeastern scarp. A tuffaceous horizon near the base of the Ola Bula Formation, exposed in another cattle yard 50 m south of, and 7 m stratigraphically below, Mata Menge, had previously yielded a fission-track age of 0.94 ± 0.06 Myr (ref. 6; Fig. 2), and Wolo Sege was likely to be older. With this in mind, we conducted a small excavation to determine whether the site contained *in situ* stone artefacts and to obtain samples for dating.

A 2 m × 1.5 m section of the scarp was excavated to enable us to sample the conglomerate and underlying tuffaceous siltstone down to the Ola Kile Formation (Fig. 2c and Supplementary Fig. 1). The

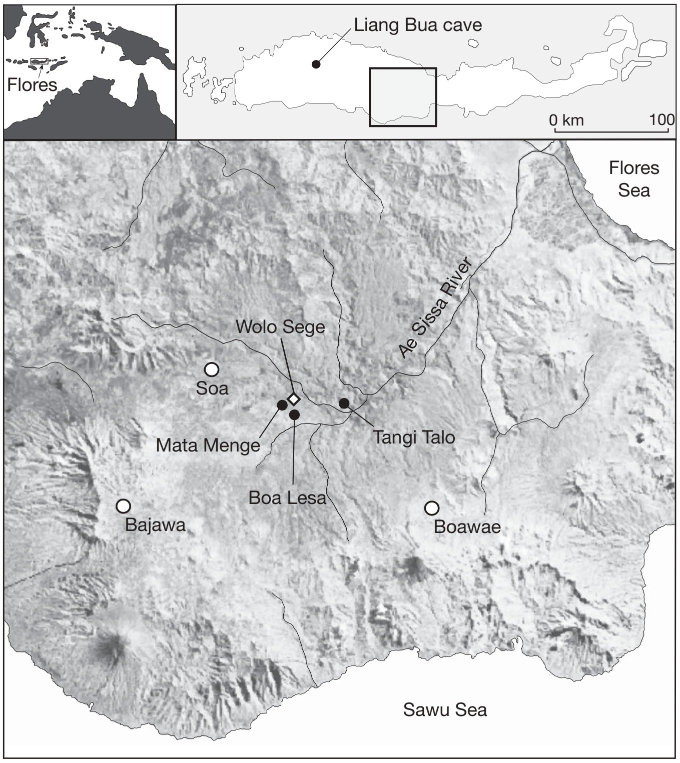

Figure 1 | Map of Flores showing the location of Wolo Sege. Also shown are other key early- or middle-Pleistocene archaeological and palaeontological localities in the Soa Basin mentioned in the text, and the late-Pleistocene Liang Bua cave in western Flores. (Base maps courtesy of D. Hobbs.)

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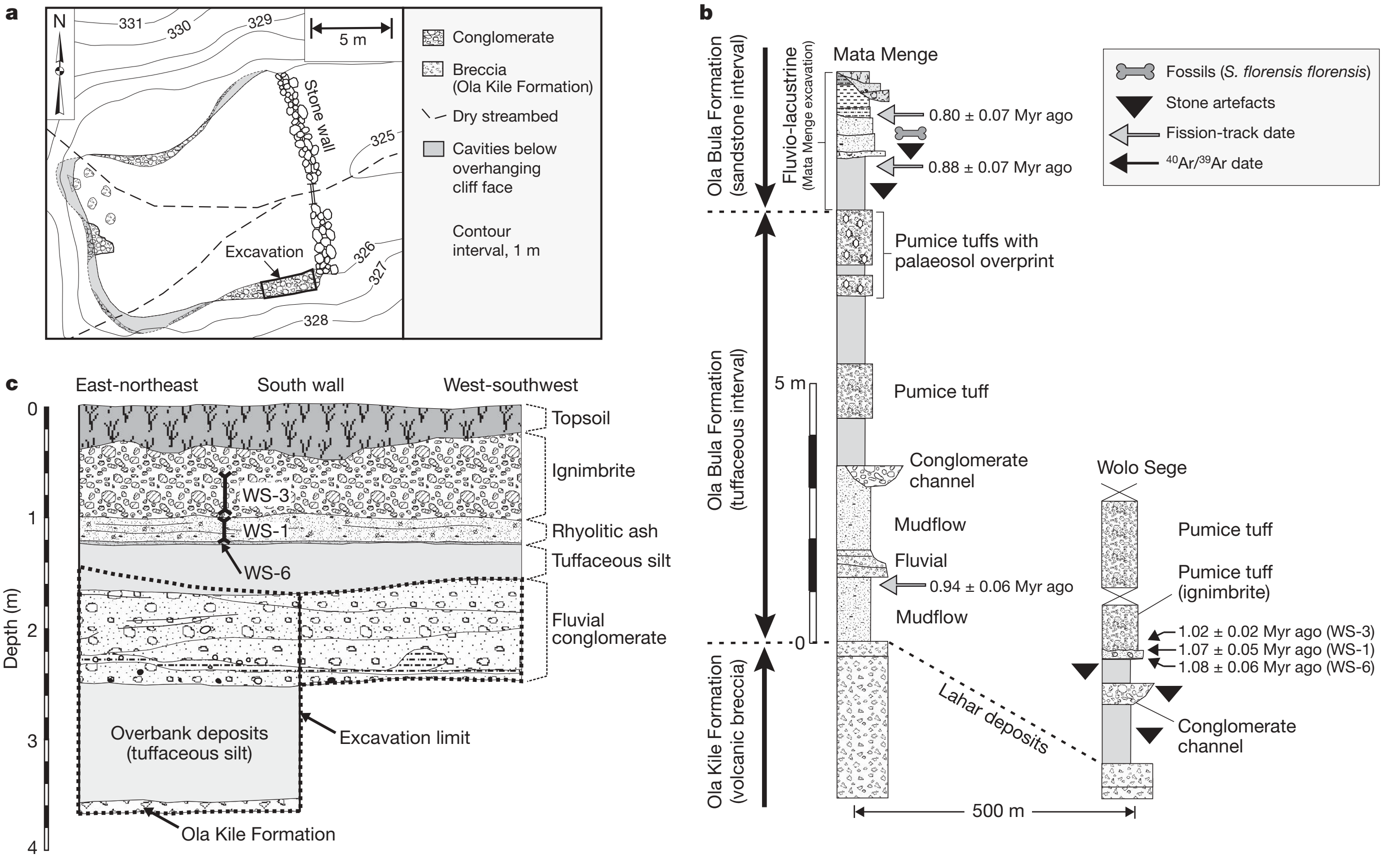

Figure 2 | Geological and stratigraphic context of Wolo Sege. a, Plan view of the excavation within the cattle yard; the gully in which the yard is situated lies in the junction between two incised stream beddings flowing from west to east. **b,** Location of the Wolo Sege and Mata Menge strata within the geological sequence of the Soa Basin. **c,** Stratigraphic profile of the excavations and locations of samples (WS-1–WS-6) taken for ^{40}Ar/^{39}Ar dating. *In situ* stone artefacts were recovered from the tuffaceous silt underlying the pumice tuff/ignimbrite ($n = 1$), the fluvial conglomerate ($n = 45$) and the tuffaceous silt (overbank deposit; $n = 2$) overlying the Ola Kile Formation. The earliest fission-track date from the Ola Bula Formation is 0.96 ± 0.09 Myr and comes from the site of Ngampa in the eastern part of the Soa Basin[6].

excavation was then extended 2 m to the west along the exposed conglomerate layer. The vertical rock face above the excavation was also cleaned and recorded. In descending order, the stratigraphy comprises topsoil, ignimbrite, fine-grained air-fall rhyolitic ash with accretionary lapilli (Fig. 2c, WS-1), a tuffaceous siltstone overbank deposit, fluvial conglomerate and tuffaceous silts, which directly overlie laharic breccias of the Ola Kile Formation.

The Wolo Sege excavation yielded no faunal remains, but 45 *in situ* stone artefacts were recovered from the conglomerate and two fine-grained metavolcanic flakes were excavated from the lower tuffaceous siltstone layer ~15–20 cm above the Ola Kile Formation (Fig. 3e, f). A single volcanic flake was also recovered from the upper overbank deposit during extraction of sediment for dating. The Wolo Sege stone artefacts are predominantly small and morphologically undifferentiated flakes struck from cobbles by direct hard-hammer percussion (Fig. 3; see also Supplementary Fig. 2), but include a bifacially and centripetally worked 'radial' core, similar to those characteristic of the Mata Menge assemblage of stone artefacts[13–16].

Significantly, the Wolo Sege artefacts exhibit taphonomic alteration in accordance with the relevant sedimentary facies: the majority of artefacts from the conglomerate feature slight (17.8%, $n = 8$) to heavy (75.6%, $n = 34$) surface abrasion and edge damage indicating fluvial transportation[17], whereas those from the underlying tuffaceous silt are relatively fresh and unabraded. The artefacts have thus evidently been moved from their original places of discard by hydraulic processes; however, it is clear that they are not intrusive from overlying sediments. The ignimbrite layer overlying the artefact-bearing deposits comprises an 80-cm-thick solidified and undisturbed rock mass through which the artefacts are very unlikely to have intruded (Fig. 2). With the exception of the two metavolcanic flakes, the basal tuffaceous silt deposits are completely devoid of clasts measuring more than a few millimetres in diameter.

Using a Nu Instruments Noblesse multi-collector noble-gas mass spectrometer at the Quaternary Dating Laboratory, Roskilde University, we carried out a total of 98 ^{40}Ar/^{39}Ar laser-fusion age determinations on single and multiple hornblende crystals in two samples from the accretionary-lapilli-bearing ash deposit, and one sample from the overlying ignimbrite (Fig. 2c). The two ash layers (WS-1 and WS-6) and the ignimbrite (WS-3) yielded model ages of 1.07 ± 0.05 Myr, 1.08 ± 0.06 Myr and 1.02 ± 0.02 Myr, respectively (Supplementary Fig. 3). The ages agree within their errors, indicating that the three units could be part of the same eruptive event. The majority of age measurements ($n = 76$) were made on hornblende from the ignimbrite as it contained larger crystals (up to 5 mm in length) than the other units, making it more suitable for single-crystal analysis owing to the higher argon content. In an ^{39}Ar/^{40}Ar–^{36}Ar/^{40}Ar correlation plot, regression of the WS-3 data ($n = 69$ of 76 analyses) yielded an isochron age of 1.02 ± 0.02 Myr with an ^{40}Ar/^{36}Ar intercept of 297 ± 4, which is within error of the atmospheric ratio (Fig. 4). This high-precision isochron result provides a robust minimum age for the underlying deposits and stone artefacts.

Previously, the earliest stone artefacts at Mata Menge, associated with the fossilized remains of *S. florensis florensis*, as well as the absence of artefacts from Tangi Talo with its pygmy *S. sondaari* and giant tortoise, suggested hominin colonization of Flores between ~0.9 and 0.88 Myr ago[3–6,10] (Fig. 5). On this basis, the faunal turnover that occurred in the Soa Basin at this time was attributed to the arrival of this new predator, although it may have been hastened by a major

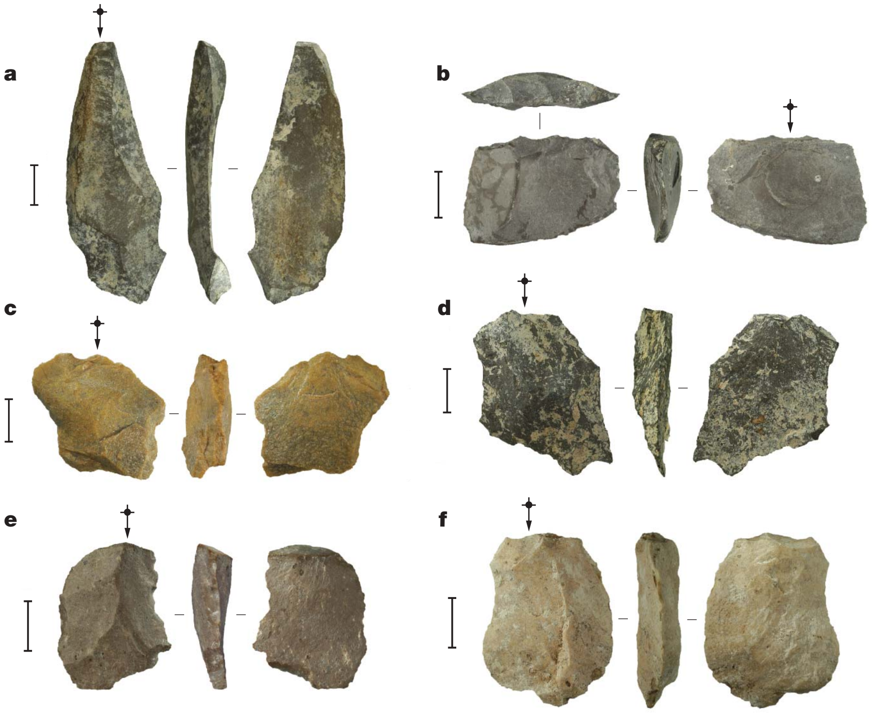

Figure 3 | Stone artefacts from Wolo Sege. a, **b**, **e**, **f**, Fine-grained metavolcanic flakes; that in **e** has been retouched unifacially along the left lateral margin towards the dorsal surface. **c**, Chalcedony flake. **d**, Medium-grained volcanic flake. Forty-four stone artefacts were excavated from the conglomerate and basal tuffaceous silt at Wolo Sege in 2005, including the retouched flake (**e**), a radial core, a flake fragment and one undiagnostic implement (probably a flake); a further three *in situ* artefacts were recovered from the conglomerate during section-cleaning (**a**), and one during extraction of sediment for dating, giving a total assemblage of 48 artefacts. Local volcanic/metavolcanic fluvial cobbles (average maximum dimension, 78.6 ± 38.9 mm; range, 40–220 mm) of varying quality comprise the dominant (95.8%) raw materials, although high-quality chert (2.1%) and chalcedony (2.1%) are also present. Arrows indicate the percussion axes of the flakes. Scale bars, 10 mm. (Photo by M. W. Moore.)

volcanic eruption that blanketed the area[9,18,19]. It is now clear, however, in light of the evidence from Wolo Sege, that hominins were present on Flores by 1 Myr ago. This suggests that the non-selective, mass death of *S. sondaari* and giant tortoise, associated with stratigraphic evidence for a major volcanic eruption at Tangi Talo ~0.9 Myr ago[10], could represent a localized or regional extinction, and that the faunal turnover may have been a result of climate change, volcanic activity or some other natural process or event (Fig. 5).

On a final note, the Wolo Sege stone artefacts, which currently comprise the oldest evidence for hominins on Flores, occur to the base of the volcanic and fluvio-lacustrine deposits that infill the Soa Basin[6,11]. If hominins arrived significantly earlier than 1 Myr ago, as primitive morphological traits of the late-Pleistocene endemic species

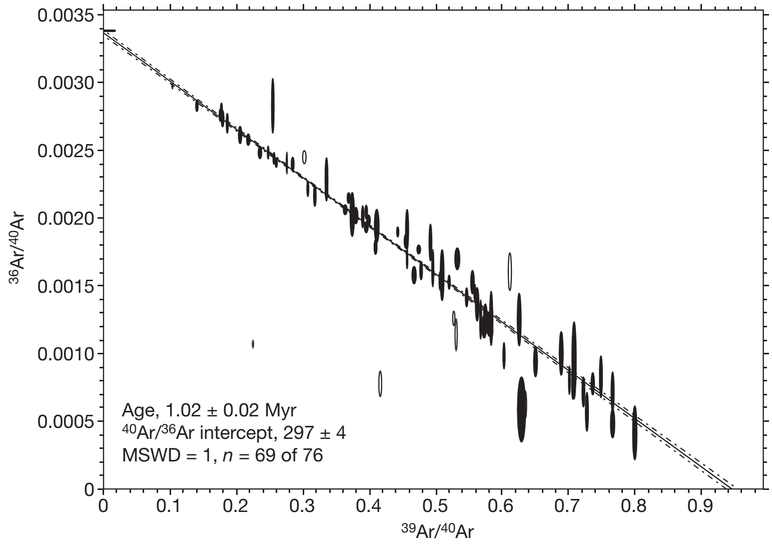

Figure 4 | Inverse isochron plot for ignimbrite WS-3 data with error ellipses representing individual hornblende analyses. The isochron age is indistinguishable from the weighted mean of the fusion-model ages. Of the 76 analyses, seven (unfilled ellipses) were rejected as outliers on the basis of their large contribution to the weighted sum of squares of the linear regression of the data (solid line). Dashed lines indicate the 2-s.d. error envelope of the resultant best-fit line. The seven outliers may reflect the effects of excess ^{40}Ar or, alternatively, are inherited xenocrysts. MSWD, mean sum of weighted deviates.

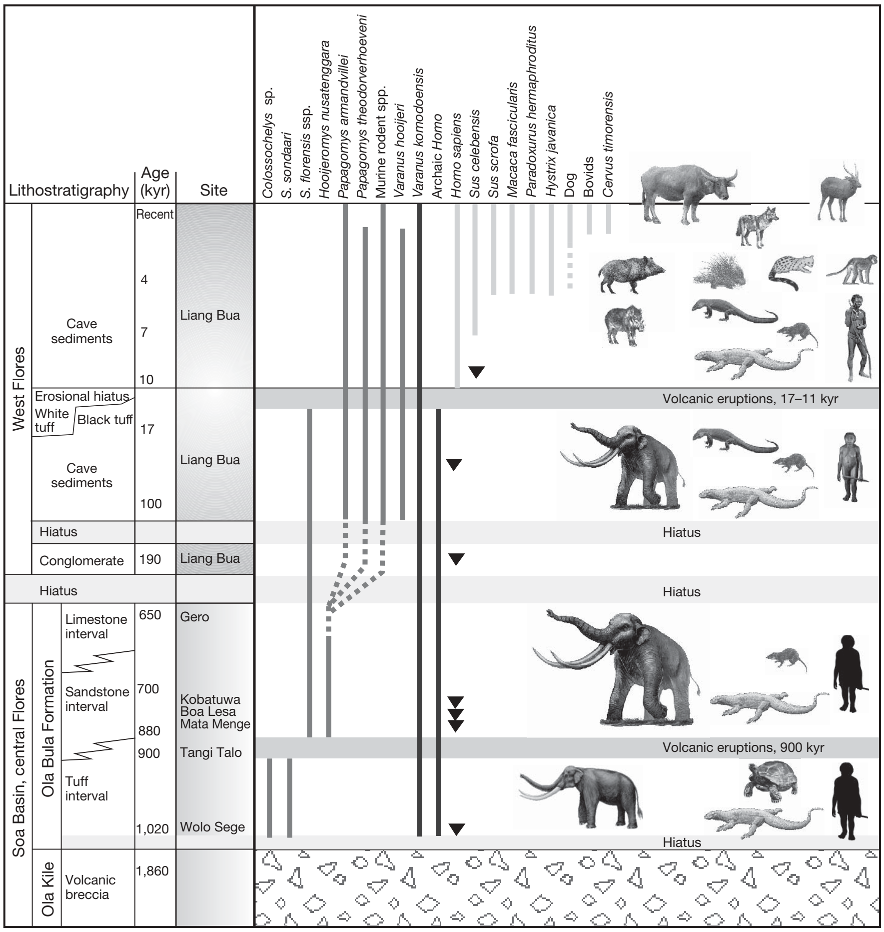

Figure 5 | The faunal sequence on Flores. The sequence is characterized by long-term phylogenetic continuity, but includes two major faunal turnovers. The first, associated with evidence for a major volcanic eruption ~900 kyr ago, involved the extirpation or extinction of the diminutive *S. sondaari* and giant tortoise. This was followed by the appearance of the large-bodied *S. florensis florensis* and giant rat, as is evident at many fossil sites in the Soa Basin from 880 kyr ago. Evidence from Wolo Sege now indicates that this first faunal turnover did not coincide with the arrival of hominins. The second faunal turnover, including the disappearance of *S. florensis insularis* and *Homo floresiensis* at Liang Bua, was also associated with a major volcanic eruption, ~17 kyr ago[2]. This preceded the first evidence, from ~11 kyr ago, for modern humans, who subsequently introduced a range of animals to the island. The only species that seems to continue throughout the entire sequence is the Komodo dragon, an opportunistic predator and scavenger. The black triangles denote stone artefacts, proxy evidence for hominins. (*H. floresiensis* icon by Atelier Daynes.)

Homo floresiensis[20–22] may indicate[23–28], then the sedimentary formations of the Soa Basin may be too young to provide evidence for the initial arrival of hominins on Flores, which must therefore be sought in other parts of the island.

METHODS SUMMARY

We extracted hornblende from the samples by crushing and sieving, using magnetic separation and sodium polytungstate heavy liquid, and finally by hand-picking. Crystals were leached in HNO_3 and dilute hydrofluoric acid to remove adhering glass. Samples were loaded into holes drilled into 18-mm-diameter aluminium sample disks and irradiated for 2 h in the cadmium-shielded CLICIT facility at the Oregon State University TRIGA reactor, along with Alder Creek sanidine (ACs-2; 1.194 Myr old[29]), as the neutron-fluence monitor mineral. An aliquot of the ignimbrite sample WS-3 was included in a second, shorter, irradiation of 0.25 h. Before the fusion analysis, we degassed the crystals using a defocused, low-power laser to preferentially remove adhering and loosely bound argon. Fusion was carried out at a power of 4–8 W using a 50-W Synrad CO_2 laser. The sample gas was cleaned by means of a small-volume (450-cm^3) all-metal extraction line with two water-cooled SAES GP 50 getter pumps and a cold finger at $-115\,^{\circ}C$.

The argon isotopic analyses were made on a fully automated Nu Instruments Noblesse multi-collector noble-gas mass spectrometer equipped with a Faraday detector and three ETP ion-counting electron multipliers. Analyses were carried out by measurement of ^{40}Ar and ^{39}Ar on the high-mass electron multiplier, ^{38}Ar and ^{37}Ar on the axial electron multiplier and ^{36}Ar on the low-mass electron multiplier, with baselines measured every other cycle. Blank measurements were made before each fusion analysis, typical values being $<1 \times 10^{-16}$ mol for ^{40}Ar and $<5 \times 10^{-18}$ mol for ^{36}Ar. We corrected combined instrumental mass fractionation and detector bias by repeated measurement of 1×10^{-14} mol argon (air) aliquots on the different electron multipliers, following protocols described in Methods. Corrections for interfering isotopes produced by nucleogenic reactions during irradiation were based on published data[30], with the exception of the value used for the $^{36}Ar/^{37}Ar$ production ratio of ^{40}Ca (0.000270 ± 0.0000002), which was determined at the Quaternary Dating Laboratory, Roskilde University, using natural fluorite irradiated at the Oregon State University TRIGA reactor (January 2009). Data collection and reduction were carried out using the program MASS SPEC (A. Deino, Berkeley Geochronology Center; for full argon isotopic analyses, see Supplementary Table 1).

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions A.B. located and excavated the Wolo Sege site and analysed the stone artefacts. G.D.v.d.B. mapped, described and interpreted the stratigraphic units and prepared Fig. 5 (with M.J.M.), and I.K. supervised the excavation. G.M.J. identified and sampled Wolo Sege ash layers suitable for dating and carried out the mineral separation. M.S. carried out the ^{40}Ar/^{39}Ar multi-collector dating experiments. M.J.M. and F.A. are the Chief Investigator and the Australian and Indonesian Institutional Counterpart in this ARC project, respectively, and provided support and advice for the Wolo Sege excavation.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Any enquiries for additional information and data relating to the Quaternary Dating Laboratory ^{40}Ar/^{39}Ar ages should be addressed to M.S. (storey@ruc.dk). Correspondence and requests for materials should be addressed to A.B. (abrumm@uow.edu.au).

METHODS

^{40}Ar/^{39}Ar method. The ^{40}Ar/^{39}Ar dating was carried out at the Quaternary Dating Laboratory, Roskilde University, using the following methods. Hornblende crystals (0.5–5 mm) were extracted from the Wolo Sege ash layers (WS-1 and WS-6) and ignimbrite (WS-3) using crushing, sieving, magnetic separation, sodium polytungstate heavy liquid and, as the final step, hand-picking. The crystals were gently leached in HNO_3 and dilute hydrofluoric acid to remove adhering glass. The mineral grains were loaded into wells drilled into 18-mm-diameter aluminium sample disks, which were then stacked, wrapped in aluminium foil and sealed in a quartz glass tube. The samples were irradiated in two batches in the cadmium-shielded CLICIT facility at the Oregon State University (OSU) TRIGA reactor, along with Alder Creek sanidine (ACs-2; 1.194 Myr old[29]), as the neutron-fluence monitor in the calculation of *J* (see equation (1), below). Sample irradiation maps are shown in Supplementary Fig. 4. Sample batch QL-OSU-16 was irradiated for 2 h on 30 March 2009. An aliquot of WS-3 hornblende was included in a later, much shorter, irradiation (sample batch QL-OSU-17) of 0.25 h on 17 July 2009, to test the long-term reproducibility of the age determinations and using a different set of irradiation conditions. The shorter irradiation, of QL-OSU-17, gave a value of ^{40}Ar*/^{39}Ar for ACs-2 close to 10 (^{40}Ar*, radiogenic ^{40}Ar), and reduced the magnitude of nucleogenic interference corrections, principally the production of ^{36}Ar from ^{40}Ca, in the age calculation by a factor of ~8 relative to results from the QL-OSU-16 samples.

Before the fusion analysis, the hornblende crystals were first heated using a defocused 50-W Synrad CO_2 laser operated at a power of 2 W, to preferentially remove adhering and loosely bound argon. Fusion was then carried out at a power of 4–8 W with a focused laser beam. Clean-up of the gas sample was by means of a small-volume (450-cm^3) all-metal extraction line with two water-cooled SAES GP-50 getter pumps and a cold finger at -115 °C. The majority of fusion analyses carried out were on single crystals, primarily to avoid mixing of ages through possible xenocryst contamination. For the smallest-sized crystals, however, it was necessary to fuse up to ten grains to obtain enough gas to allow reasonably precise argon isotopic measurements to be made.

The argon isotopic analyses were made on a Nu Instruments Noblesse multi-collector noble-gas mass spectrometer equipped with a Faraday detector and three ETP ion-counting electron multipliers. Because of the relatively small ^{40}Ar signal sizes ($<$150,000 counts per second) yielded by the Wolo Sege hornblende crystals, peak intensities were measured only on the electron multipliers. To negate any unforeseen fractionation effects associated with the mass spectrometer's electrostatic quad lenses (zoom optics), analyses of unknowns, blanks and monitor minerals were carried out in identical fashion, by measuring ^{40}Ar and ^{39}Ar on the high-mass ion counter (HiIC), ^{38}Ar and ^{37}Ar on the axial ion counter (AxIC) and ^{36}Ar on the low-mass ion counter (LoIC), with baselines measured every other cycle. Measurement of the ^{40}Ar, ^{38}Ar and ^{36}Ar ion beams was carried out simultaneously and followed by measurement of ^{39}Ar and ^{37}Ar. Beam switching was achieved by varying the field of the mass spectrometer magnet and with minor adjustment of the quad lenses. All signals were corrected using previously determined detector dead-time constants (HiIC, 27.2 ns; AxIC, 37.1 ns; LoIC, 23.7 ns). Blank determinations, following identical clean-up and measurement routines to the unknowns, were made before each fusion analysis and have typical values of $<1\times10^{-16}$ mol for ^{40}Ar and $<5\times10^{-18}$ mol for ^{36}Ar. For calculation of *J*, multiple aliquots of ACs-2 spatially distributed around the unknowns were run and the *J* value of the unknown calculated either by averaging or from applying a plane-fitting algorithm to the *J* values of the different monitor positions.

In comparison with single-collector peak-switching measurements, multi-collection allows more data to be gathered in a fixed time, but for accurate and reproducible age determinations the method requires that the relative efficiencies of the different detectors be well known. The ^{40}Ar/^{36}Ar and ^{40}Ar/^{38}Ar ratios of 1×10^{-14} mol argon aliquots, delivered from a calibrated air pipette during the course of the analyses, were measured using the following detector configurations: $(^{40}\mathrm{Ar}/^{36}\mathrm{Ar})_{\mathrm{HiIC/LoIC}}$, $(^{40}\mathrm{Ar}/^{38}\mathrm{Ar})_{\mathrm{HiIC/AxIC}}$ and $(^{40}\mathrm{Ar}/^{36}\mathrm{Ar})_{\mathrm{HiIC/AxIC}}$.

^{40}Ar, ^{38}Ar and ^{36}Ar. Observed ^{40}Ar/^{36}Ar and ^{40}Ar/^{38}Ar ratios were corrected for instrument mass fractionation and detector efficiencies using equations of the following form: true ratio (unknown) = observed ratio (unknown) × mean [true ratio (std)/observed ratio (std)]. For these a separate correction factor (mean[true ratio (std)/observed ratio (std)]) was calculated for each detector–isotope combination. Atmospheric ratios of $(^{40}\mathrm{Ar}/^{36}\mathrm{Ar})_{\mathrm{air}} = 295.5 \pm 0.5$ and $(^{40}\mathrm{Ar}/^{38}\mathrm{Ar})_{\mathrm{air}} = 1575 \pm 2$ were used. Typically, 2 s.e.m. of eight to ten $(^{40}\mathrm{Ar}/^{36}\mathrm{Ar})_{\mathrm{HiIC/LoIC}}$ ratio determinations was 0.3–0.4%.

^{37}Ar. The observed $(^{40}\mathrm{Ar}/^{37}\mathrm{Ar})_{\mathrm{HiIC/AxIC}}$ ratio was corrected by applying the average of the two means $(^{40}\mathrm{Ar}/^{38}\mathrm{Ar})_{\mathrm{HiIC/AxIC}}/1{,}575$ and $(^{40}\mathrm{Ar}/^{36}\mathrm{Ar})_{\mathrm{HiIC/AxIC}}/295.5$.

^{39}Ar. The mass fractionation correction required to convert $(^{40}\mathrm{Ar}/^{39}\mathrm{Ar})_{\mathrm{HiIC/HiIC}}$ to the true ^{40}Ar/^{39}Ar ratio was ignored. The only effect of this is a small systematic error in the *J* value derived from the monitor minerals, but because both monitor and unknown minerals are handled in the same way, the effect cancels out when the ages for the unknowns are calculated as follows:

$$t = \frac{1}{\lambda_t} \ln\left[J \frac{^{40}\mathrm{Ar}^*}{^{39}\mathrm{Ar}} + 1 \right]$$

where

$$J = \frac{e^{\lambda T} - 1}{^{40}\mathrm{Ar}^*/^{39}\mathrm{Ar}} \tag{1}$$

Corrections for interference isotopes produced by nucleogenic reactions during irradiation are based on published data[30], with the exception of the value used for the ^{36}Ar/^{37}Ar production ratio of ^{40}Ca (0.000270 ± 0.0000002), which was determined at the Quaternary Dating Laboratory, Roskilde University, using natural fluorite irradiated at the OSU TRIGA reactor in January 2009, following the start of a new fuel cycle. Data collection and reduction were carried out using the program MASS SPEC (A. Deino, Berkeley Geochronology Center). Full argon isotopic analyses for unknowns, and the monitor minerals used in the calculation of *J*, are given in Supplementary Table 1.