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Earliest known hominin activity in the Philippines by 709 thousand years ago

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Excavation methods.

The Main Excavation comprises four 2x2 m quadrants arranged in 'T' shape (Extended Data Fig. 1). Excavation took place in 10-cm spits, separating the sediments from distinct stratigraphic layers where appropriate. The excavation was undertaken with bamboo sticks to prevent damage to the fossils and stone artefacts. All sediments were dry and wet sieved. The first quadrant was dug in 2014 at the site where a concentration of fossils and stone artefacts was found on the surface, including a *Celebochoerus cagayanensis* canine fragment[1]. This quadrant, referred to as the test excavation or South Quadrant (S-Q), had reached a depth of 1.2 m when the first rhinoceros fossils were found embedded in a silty clay plug that had filled in an ancient channel with a sandy bottom. The trench was then extended with two 2x2 m quadrants adjacent and directly to the north and northwest of S-Q. (N-Q and NW-Q, respectively). More fossils of a single rhinoceros skeleton and also stone artefacts were excavated along the same erosive contact between a sandy channel base (Unit A) and a clayey channel fill deposit (Unit F). From the southern baulk of S-Q a 1 m wide connection with slot Trench H was made to examine the continuation of sedimentary layers in the Main Excavation and Trench H.

In 2015 the Main Excavation was further extended to the east with a 2x2 m quadrant (NE-Q) east of N-Q, in order to trace the fossil bearing horizon in an eastern direction, and to expose a larger area of the undulous fossil-bearing surface. Also, S-Q was excavated further to a maximum depth of 1.8 m to examine a larger portion of the sandy layers (Unit A) below the fossil-bearing horizon.

The three-dimensional coordinates of all artefacts and fossil bones (Extended Data Fig. 3) (and the orientation, dip and plunge of long bones) were recorded with a Leica© Total station. The rhinoceros bones where retrieved one by one after having been first protected with a layer of petroleum jelly, a layer of plastic bags and an outer layer a plaster of Paris armed with bamboo sticks to consolidate the samples for transport. Fine cleaning with water and a soft brush and consolidation of the bones with a 20% paraloid B72 solution was achieved in the zooarchaeology laboratory of the Archaeological Studies Program of the University of the Philippines Diliman using a magnifying glass.

Sedimentology

Stratigraphically, the site layers pertain to the upper part of the Awidon Mesa Formation, a Pleistocene sequence of alluvial stream deposits intercalated with volcaniclastic and pyroclastic deposits. The depositional environment of the Awidon Mesa Fm was characterized by braided rivers on an alluvial fan system that formed in response to uplift in the Cordillera Central to the West[2,3]. The apex of this fan was near the point where the present paleo-Chico River Valley widens into the Cagayan Valley (West to the Pangul Anticline) (Fig.1). During periods of volcanic activity in the catchment area of the Chico River, large amounts of pyroclastic flows and lahars were fed onto this alluvial fan system. The ignimbritic layers are characterized by a dacitic composition, and one of the defining characteristics of the Awidon Mesa Fm is the occurrence of reworked bipyramidal volcanic quartz crystals in the clastic sediments. Continued east-west compressional deformation led to the uplift of the Pangul Anticline to the South and West of the excavation area, as well as the Cabalwan and other north-south trending anticlines in the Cagayan Valley. This deformation phase is thought to have redirected the Chico River to the north in its present-day configuration, thus bringing deposition on the westward prograding alluvial fan system as exposed in the Cabalwan Anticline, to a halt.

The Kalinga site layers were grouped into stratigraphic units based on differences in texture, sedimentary structures, and consolidation, where each unit was thought to represent common facies associations indicative for specific depositional environments. Samples were taken for grainsize analysis from the baulks of the Main Excavation and Trench H (Extended Data Fig. 1).

Grainsize analyses were performed at the sedimentology laboratory of the School of Earth and Environmental Sciences at the University of Wollongong, Australia. Small amounts of each sample were put in plastic flasks with distilled water, which were then placed in an ultrasonic bath to loosen the sediment over a period of 2 hrs. The samples were then sieved through 1 mm mesh and analysed with a Malvern Mastersizer 2000©. The minerals content of the archaeological layer Unit F was obtained from X-ray Powder Diffraction (XRD) on 30g sub-samples placed into a Brucker© D2 Phaser diffractometer at the UMR 5143 laboratory of the Muséum National d'Histoire Naturelle in Paris, France. The occurrences of crystal minerals in the fossiliferous clay were identified by matching the XRD pattern with reference patterns of pure substances (Extended Data Fig. 4).

The fossiliferous clay (Unit F) unconformably overlies a coarse to medium sandy, indurated fluvial layer (Unit A) with cross bedding and scour and fill structures. A concave channel has cut down into this fluvial unit. Fossils and stone artefacts were found concentrated directly above the deepest part of the erosional surface, and are embedded in and covered by a massive, very poorly sorted fine-grained mudflow layer (Unit F), which has filled in the channel (Extended Data Figs. 1 & 3). This archaeological layer is a very poorly sorted, up to 3.25 m thick, muddy unit. In the Main Excavation, Unit F is cut by the modern topography and a 10 to 60 cm thick recent topsoil has overprinted the interval directly beneath the ground surface. Unit F is made up of predominantly silty clay with variable admixtures of sand – including slightly rounded bipyramidal and non-euhedral quartz– and rounded pebbles, which are predominantly dacites. The XRD spectrum of the fossiliferous clay points to a high concentration of volcanic-derived minerals including saponite, which often forms as a result of the alteration of volcanic glasses[4,5] (Extended Data Fig. 4). The overall very poor sorting (Extended Data Fig. 1) indicates that Unit F was deposited by a mudflow filling in a pre-existing fluvial channel (most probably following a volcanic eruption), which is further substantiated by the higher concentration of pebbles in the lower part of Unit F and the absence of pollen.

Geochronological framework

We applied three different geochronological methods, each of which are based on different physical principles. $^{40}Ar/^{39}Ar$ dating was performed on plagioclases from Unit A and Unit G and Electron Spin Resonance (ESR) dating was applied to bipyramidal quartz crystals from these same two units. Thirdly, Uranium-Thorium ESR (ESR/U-series) dating method was applied to rhino fossil tooth enamel recovered from Unit F. The results obtained for each method account for different geological processes. In the case of $^{40}Ar/^{39}Ar$, the obtained ages correspond to the crystallization age of the plagioclases. Since the sedimentary units from which the crystals were extracted are not primary voclanoclastic deposits but instead fluvial layers, the true depositional ages of these units must be younger than the Ar-Ar ages we obtained [6]. Therefore, they provide a maximum age for the sedimentological formation from which they have been extracted. In contrast, ESR applied on optically bleached quartz provide the age of deposition of the sedimentary quartz subsequent to their transportation, which resulted in resetting their geochronometer[7]. The ESR/U-series dating method on the fossil rhino tooth dates the death and burial of this animal within the sedimentary unit. Furthermore, the geological age of death of the rhinoceros corresponds to the age of the apparent butchery marks on its bones. Therefore, the age of hominin presence in Kalinga site is given by the ESR/U-series age of 709±68, and is bracketed by the ESR on quartz ages obtained on the underlying and overlying sedimentary units, which are between 727±30 and 701±70, respectively. It would be expected that the $^{40}Ar/^{39}Ar$ ages provide older ages, which correspond to a volcanic eruption after which the crystal minerals were reworked into the sedimentary units. Therefore they provide a maximum possible age for the site. These different geochronological methods as applied to different archaeological materials are all coherent with deposition of the fossils and artefacts just after the Brunhes-Matuyama boundary, which is further substantiated by the palaeomagnetism results and the presence of a reworked Australasian tektite in the bone-bed Unit F.

ESR/U-series dating on tooth enamel

A combined Electron Spin Resonance (ESR) and Uranium-series (U-series) approach was applied on a rhinoceros' right maxillary third premolar (Archaeological number: II-2014-J1-095; sample code: CGY1501) excavated from the archaeological layer Unit F, following the protocol described by Bahain and co-authors[8]. After mechanical separation of the dental tissues, the enamel was cleaned using a dental drill to remove any contamination of sediment or dentine. For the calculation of the beta contribution, the initial enamel thickness was measured to 1505±376 µm, and, following enamel preparation, the removed thickness was measured to 351±88 µm on the dentine side and 45±12 µm on the sediment side. The enamel was then ground and sieved. The 100-200 µm fraction was used for equivalent dose (D_E) determination: it was split in ten aliquots, nine of them were irradiated by a γ ^{60}Co source at doses ranging from 260 to 12500 Gy. The ESR intensity of each aliquot was then measured using a Bruker© EMX ESR spectrometer and a dose-response curve was built from the data set for the tooth. D_E was determined using a single saturating exponential function from the eight first aliquot intensities according to the protocol proposed by Duval and Grün[9] (Extended Data Fig. 6). Radioelement contents of the dental tissues and associated sediments were measured by γ-ray spectrometry and U-series were performed on each dental tissue. The γ dose was measured in the laboratory from three sediment samples taken from the homogeneous clayey Unit F at proximity of the analysed tooth and the obtained value has been combined with the γ dose measured *in situ* from sandy Unit A as this underlying sedimentary layer contributed for a small amount to the total dose received by the tooth as observed on the site. Therefore, the γ dose used for the calculation of the age from the tooth combined 5% of the γ dose from layer A3, 65% from layer F1 and 30% from layer F2 (Extended Data Figure 1a).

The uranium (U) and thorium (Th) isotopic analyses on the dental tissues were performed on a Neptune© Multi-Collector Inductively Coupled Plasma Mass Spectrometer (MC-ICPMS) at Nanjing Normal University, Republic of China. The chemical protocol used for sample preparation follows the method described by Shao and co-authors[10]. The uranium and thorium fractions were separated from each other and from the matrix material using some UTEVA® resin columns and were dissolved in a mixture of 0.1N HNO3 and 0.01N HF for MC-ICPMS analysis. The radioelements content of the sediments are listed in Supplementary Information Table 2. No ^{238}U decay chain was observed. Uranium was measured statistically by ^{233}U, ^{235}U, ^{236}U and ^{238}U on Faraday cups and ^{234}U simultaneously on a secondary electron multiplier (SEM). Thorium was analysed with ^{230}Th and ^{229}Th alternately on the SEM and ^{232}Th on a Faraday cup. The uranium isotopic ratios of the standard uraninite HU-1 were measured before and after each uranium and thorium isotopic measurement. Mass fractionation was corrected by comparing the measured ^{238}U/^{235}U to the value of 137.760 for the HU-1 standard and to the value of 137.818 for natural samples[11] with an exponential law. The mass fractionation for uranium and thorium are assumed to be equivalent. The SEM to Faraday cup yield was assessed by the δ^{234}U measured in the HU-1 standard. Hydride interferences, machine abundance sensitivity and amplifier gains were evaluated every day prior to sample measurements. The ^{230}Th/U ages were calculated using half-lives of 75,584 years and 245,620 years for ^{230}Th and ^{234}U, respectively[12]. The ESR/U-series ages were calculated with the "ESRUS" Matlab software written by Qingfeng Shao[13]. Lastly, dose rates (D_a) contributions, U-uptake parameters and ESR/U-series ages were calculated applying the classical US model[14], which provided an age of 709 ± 68 (1σ) ka for the rhinoceros tooth. These results are presented in Extended Data Table 1.

ESR dating on fluvial quartz

ESR dating was applied on fluvial quartz grains collected from two samples, one taken in Unit A (Layer A_4) and the other one in Unit G (Layer G_1) encapsulating the archaeological bone-bed Unit F. The volcanic bipyramidal quartz crystals from Unit F were also analysed but did not return any exploitable result due to their shape (not reducible into powder), size and strong angular dependence. The ESR method is based on the measurement of the accumulated natural radiation dose resulting from environmental radioactivity[15]. ESR dating of quartz uses radiation sensitive paramagnetic centres such as aluminium or titanium[16,17] and relies on the resetting of any previously present signal by sun light exposure at the time of deposition[7]. An age is derived by assessing the total dose received by the sample since its deposition divided by the dose rate which is obtained from all environmental radiation sources including cosmic rays. The analysis was done at the Geochronology laboratory of the UMR 7194, Muséum National d'Histoire Naturelle of Paris, France.

Both ESR signals of the aluminum (Al) and titanium (Ti) centres were studied (Extended Data Fig.6 c-f). The extraction and preparation protocol of quartz grains is described in Voinchet and co-authors[18]. After extraction, each sample was split into eleven aliquots. Nine of them were irradiated with a γ ^{60}Co source (Commissariat à l'Énergie Atomique, Saclay, France) emitting 1.25 MeV radiation with a dose rate of about 200 Gy/h. The nine additive doses are 264, 431, 653, 1048, 1663, 2640, 4460, 8010, 12500Gy. One aliquot was conserved as natural reference and the eleventh aliquot was exposed during 1600h to light in a Dr Honhle© SOL2 solar simulator (light intensity between 3.2 and 3.4 105 Lux) in order to determine the unbleachable portion of the ESR-Al signal. Each series of eleven aliquots was measured at least three times by ESR at 107K using a Bruker© EMX spectrometer and every measure of each aliquot was undertaken three times after an approximatively 120° rotation of the tube in the ESR cavity, in order to consider angular dependence of the signal due to sample heterogeneity.

For the aluminium ESR centre study, the acquisition parameters used were : 5 mW microwave power, 1024 points resolution, 20 mT sweep width, 100 kHz modulation frequency, 0.1 mT modulation amplitude, 40 ms conversion time, 20 ms time constant and 1 scan. The signal intensity was measured between the top of the first peak at g=2.018 and the bottom of the 16th peak at g=2.002 of the Aluminum hyperfine structure[18]. For the Titanium centre, the acquisition parameters used were : 10 mW microwave power, 1024 points resolution, 20 mT sweep width, 100 kHz modulation frequency, 0.1 mT modulation amplitude, 40 ms conversion time, 20 ms time constant and 2 scans. The signal intensity was measured using the Ti-Li option D[20]. Equivalent doses (D_E) were then determined from the obtained ESR intensities versus the dose growth curves using a coupled exponential and linear function[21,22] with Microcal OriginPro 8 software with $1/I^2$ weighting. In the age calculation, the dose rates D_a were calculated from the radionuclides contents of the sediments and taking into account the *in situ* gamma-rays data and the location of the samples in the stratigraphic sequence.

The dose rate (D_a) provided by the sediment surrounding the sample was obtained from the sum of the alpha, beta, gamma and cosmic-ray contributions. We have at present no means to know precisely when the erosion took place and since when the archaeological material became buried under less than 7m of sediment. Therefore, a depth of 2.60m, which is the thickness between the base of layer A4 and the top of layer G1 still covering Unit A and F where the sample was taken, was used for the cosmic dose rate estimation of Unit A. A depth of 3.40m was used for the cosmic dose rate estimation of Unit G which corresponds to the thickness measured between the base of layer G1 and the laminated silty layer J4 considering that part of Unit J still covers Unit G where the sample was taken. A cosmic dose estimated from a depth of 7m would increase the age for the Unit A by 13% and by 16% for Unit G. Gamma dose rate was determined by *in situ* measurements using an Ortec Digidart LF gamma spectrometer (Canberra©). These gamma doses were estimated using the threshold approach[23]. External alpha and beta contributions were calculated from the sediment radioelement contents (U, Th and K) as determined in the laboratory by high resolution and low back ground gamma-spectrometry[24]. Age calculations were performed using the dose-rate conversions factors from Guérin and co-authors[25], a k-value of 0.15 ± 0.1 [7,26], alpha and beta attenuations from Brennan and co-authors[27,28], water attenuation formulae from Grün[29] and a cosmic dose rate calculated from the equations of Prescott and Hutton[30]. Because the analyzed sediments are of fluvial origin deposited under tropical conditions, the water content should have never been less than 10%. Furthermore, because the analyzed sandy sediments do not show any large hydromorphic features, the water content should have never been higher than 20% which is the field capacity for fine sandy loam[31]. The measured water content of Unit A and G, respectively 15% ± 5 and 13% ± 5, are in accordance with these expected parameters and were used for calculation of the ages. Our calculations show that an increase in assumed water content from 10% to 20% would result in an increase in the calculated mean age of 12 to 14% for both sandy units. The internal dose rate was considered as negligible because of the low contents of radionuclides usually found in quartz grains[32,33]. ESR age estimates are given with one sigma error range.

During the analysis of the samples, an unusual behaviour of aluminium ESR centres was observed, consisting in a total resetting of the signal after the laboratory bleaching simulation, which is more usually observed for titanium centers. The Al bleach aliquot signal is therefore not measurable as it is obliterated by noise (Extended Data Fig. 6 a). This noise might be due to the presence of silica in a different structure than alpha quartz within the sediments. The analyzed quartz appears to be very smooth bi-pyramidal quartz. Here the aluminium and titanium centres showed the same behaviours under bleaching which lead to close D_E values for the two centres (Extended Data Fig. 6 c-f). Observation of this similarity during the bleaching process encouraged consideration of a weighted average age for each stratigraphic layer.

The weighted average ages were calculated using IsoPlot 3.0[34] and given at 95 % probability including *J* uncertainty. Weighted mean ages are 727 ± 30 ka (1σ, Full external uncertainty, Mean Square Weighted Deviation (MSWD) = 0.013 and Probability fit (P) = 0.91) for unit A and 701 ± 70 ka (1σ, Full external uncertainty, Mean Square Weighted Deviation = 0.18 and Probability fit = 0.67) for unit G. These dates bracket the age of the archaeological remains (Supplementary Information Table 1).

Argon/Argon dating

Two sandy layers, Unit A (Layer A_4) and Unit G (Layer G_1) were selected for the laser fusion $^{40}Ar/^{39}Ar$ single-crystal dating method. After crushing and sieving, feldspars ranging from 500 µm up to 1 mm in size were handpicked under a binocular microscope and then slightly leached for 5 minutes in 7% HF acid. A total of thirty crystals were handpicked after leaching and eight of them were separately loaded in a single aluminium disk for each sedimentary Unit. The samples were irradiated for 60 minutes (IRR 106) in the β1 tube of an OSIRIS reactor (Commissariat à l'Énergie Atomique, Saclay, France). After irradiation, the samples were transferred into a copper sample holder and then loaded individually into a differential vacuum Cleartran© window. Crystals were individually fused using a Synrad CO2 at 10-15 % nominal power (c.a 25 W). The Ar isotopes were counted using a VG5400 mass spectrometer equipped with a single ion counter (Balzers© SEV 217 SEN), following the procedures outlined in Nomade and co-authors[35]. Each Ar isotope measurement consisted of 20 cycles of peak switching of the argon isotopes. Neutron fluence (*J*) was monitored by co-irradiation of Alder Creek sanidine (ACs-2 [36]) that were placed in the same pit as the sample during irradiation. The *J* value for each sample was determined from analyses of two ACs-2 single crystal measurements. The corresponding *J* values were calculated using ACs-2 at 1.185 Ma[37], the total decay constant of Min and co-authors[38] and the $^{40}Ar/^{36}Ar$ atmospheric ratio of 298.56 [39]. Procedural blanks were measured every two or three unknowns, depending on the sample beam size previously measured. For a typical 9-min static blank, the backgrounds were generally between 2.0–2.2 × 10^{-17} and 5.0–6.0 × 10^{-19} mol for ^{40}Ar and ^{36}Ar, respectively. The precision and accuracy of the mass discrimination correction was monitored by weekly measurements of various beam sizes of atmospheric air (see Nomade and co-authors[34], for full experimental description). Individual crystal measurements, *J* values as well as nucleogenic production ratios used to correct for reactor-produced Ar isotopes from K and Ca are reported in Supplementary Information Table 3 and 4.

For the two investigated sedimentary layers (Unit A and Unit G) the probability diagrams were simple and point towards one single homogeneous crystal population identical within uncertainties allowing us to calculate a valid weighted mean age. A population is considered to be relevant when the weighted mean age of these crystals present the following statistical characteristics: MSWD (Mean Square Weighted Deviation) < 1.5, Probability fit ≥ 0.1. These weighted average ages are calculated using IsoPlot 3.0 [40] and given at 95 % probability including *J* uncertainty throughout the text. *J* values are: $J = 3.2730.10^{-4} \pm 0.00000098$ and $J = 3.3420.10^{-4} \pm 0.00000201$, for Unit A and G respectively. Weighted mean ages are 1050 ± 28 ka (1σ, Full external uncertainty, MSWD = 0.23 and P = 1.0) and 1007 ± 29 ka (1σ, Full external uncertainty, MSWD = 0.72 and P = 0.7) for Unit A and Unit G, respectively. No excess argon was highlighted by the inverse isochrones that both present a $^{40}Ar/^{36}Ar$ initial intercept (i.e. 296.8 ± 4 and 298.8 ± 9; 2σ) equivalent within uncertainties to the atmospheric ratio[39]. The full data can be found in the Extended Data Fig. 5 and Supplementary Information Table 4**.**

Palaeomagnetic dating

An oriented block sample for palaeomagnetic dating purposes was obtained from the north baulk of Trench H south of the Main Excavation (Fig. 1; Extended Data Fig. 1). Due to the scarcity of suitable undisturbed fine-grained layers only one stratigraphic layer was sampled. The sample was taken from a 15-20 cm thick, well-sorted, laminated silty layer exposed in the lower part of Unit G (Layer G_2). The sample was taken using a cubic, sealable plastic container of 10x10x10 cm, fitted over a cube-shaped pedestal that was carved to fit the container. The block sample was tightly sealed and oriented using a

Brunton compass, corrected for local declination, and transported to the Centre for Geological Survey in Bandung, Indonesia, for further analysis. All treatments and measurements were performed in the magnetically shielded room at the Palaeomagnetic Laboratory in the Centre for Geological Survey. Six cube-shaped sub-samples or specimens, each with a volume of ~10 cm^3, were cut from the block sample. Magnetic Remanence directions of the specimens were determined using two different methods. Five specimens (HT1A-D and HT-1K) were demagnetized using Alternating Field (AF) using a Schonstedt© GSD-1 AF demagnetizer, with intervals of 0.5, 1, 2.5, and 5 mT, up to peak fields of 90-100 mT. A single specimen (HT-1E) was demagnetized using a MMTD-80 Thermal Demagnetizer© (TD), with intervals of 20º C, 30º C to 50º C up to a maximum of 580° C. Direction and intensity measurements were performed using a AGICO© JR-6A Spinner Magnetometer.

Progressive demagnetization curves, stereoplots and Zijderveld diagrams of all the six analysed specimens are shown in Extended Data Fig. 7 a-e. The Zijderveld diagrams show that most specimens appear to have only a single Natural Remanent Magnetization (NRM) component. Only two specimens (HT-1B and HT-1K) had a secondary magnetic component, which was easily removed. The stereoplots demonstrate that all specimens show little change in NRM direction during stepwise demagnetization. This could indicate a very strong secondary magnetization that influenced all specimens. However, progressive alternating field demagnetization at 50 – 60 mT reduced the intensity to only ~10% of the total intensity before demagnetization, showing that secondary magnetization was eliminated and Characteristics Remanent Magnetizations (ChRMs) was acquired. All ChRMs progressed to the origin of the orthogonal vector projections at higher field strengths.

To further test that the ChRMs were successfully isolated, one specimen was demagnetized using TD (specimen HT-1E). The TD treatment also resulted in a single magnetic component with little change in the NRM direction during progressive heating up to 580º C, when magnetic intensity was reduced to ~10 % of the total intensity prior to demagnetization (see Extended Data Fig. 7-f).

Supplementary Information Table 5 shows the magnetic intensities of all six analysed specimens before and after intensity saturation was achieved, as well as the mean ChRMs directions for each specimen. Mean ChRMs directions were determined using Puffin Plot Software[41] and super IAPD 2000 that uses principal component analysis[42] and calculates site and mean directions following Fisher[43]. The maximum angular deviation was set at < 5°. The mean ChRMs direction of the six specimens combined was close to the present-day Normal polarity (Dm = 352.5°, Im = 25.4°; Extended Data Fig. 7 g-h). Applying the criteria for palaeomagnetic data reliability of Butler[44] this outcome is reliable (R = 5.97, k = 156.27, α95 = 5.4°).

Non-destructive characterization of the tektite

The earliest records of tektites recovered from the Philippines were from Rizal Province, Northeast of Manila, and were described by Henry Otley Beyer in 1928. Beyer was an anthropologist and archaeologist from the University of the Philippines, and, in 1962 published a book covering his collected papers on the topic. Following this publication, all tektites from the Philippines were referred to as rizalites, and all present similar physical characteristics resulting from brittle spalling. Rizalites chemical signatures are also identical to the other tektites originating from the Australasian strewn field, an impact that took place somewhere between Southern China and the Bay of Tonkin west of the Cagayan Valley 786+/-2 ka ago[45].

Visual inspection of the black glass recovered from the Unit F bone-bed (Extended Data Fig. 8a) reveals a near spherical ellipsoid of 9.43 g, with surface aspects and ornamentation typical of tektites (Extended Data Figure 1f & 8a), and in particular those from the Philippines. The surface aspect shows no fluvial transport but there is evidence of etching by soil acid resulting from a long term residence in the sediment. The nearest source for obsidian from Kalinga is located 120 km to the Northwest where green glass is outcropping. Black obsidian in the Philippines is only known to the South of Manila[45]. Furthermore, no microcrystals, typical of obsidian, are observed in the Kalinga glass when examined in transmitted light under cross polarizer microscopy.

The field magnetic susceptibility (χ) of the Kalinga glass, measured with a MFK1 Agico Kappabridge, has a value of 77 $\times 10^{-9}$ m^3/kg while obsidian with χ below 100 are extremely rare, and usually not black. The measured value on the Kalinga glass is in good agreement with Australasian tektite data[45] which shows a range from 57 to 103 $\times 10^{-9}$ m^3/kg and an average of 82 $\pm$ 10 $\times 10^{-9}$ m^3/kg (n=152) according to the literature[46] and a mean of 87 $\pm$ 6 $\times 10^{-9}$ m^3/kg and a range from 69 to 129 $\times 10^{-9}$ m^3/kg based on our own measurements on a sample of 1500 specimens. The only other tektites within that range are from the Ivory Coast (1.1 Ma) and Texas (35 Ma)[47].

Saturation isothermal remanence magnetism (SIRM) shows that low susceptibility in obsidian is mostly due to ferromagnetic inclusions, which are unlike the paramagnetic iron diluting the tektite glass. While SIRM in tektites is usually below 10^{-6} Am^2/kg (maximum 4.10^{-6} Am2/kg [48]), SIRM in low susceptibility obsidian is above 10^{-3} Am^2/kg with the lowest measured value being above 10^{-5} Am^2/kg on samples from Lipari (Italy)[49]. The Kalinga sample yield an SIRM of $0.65.10^{-6}$ Am^2/kg (measured with a 2G cryogenic magnetometer after a 3 T field application), which is typical of tektites, including Australasites. This evidence serves to further exclude volcanic glass.

µXRF spectra obtained using a Horiba XGT700 instrument (30 kV, 100 µm spot, 200 s counting time) yielded the following major element semi-quantitative composition in wt.%: SiO2 75.2, Al2O3 11.7, Fe2O3 4.9, CaO 4.8, K2O 2.5, TiO2 0.71, MnO2 0.12 (Extended Data Fig. 8b). This composition is consistent with previous analyses, being at odds with an obsidian composition (which is characterized by lower Fe and higher K values). Comparison with a shard of Australasite from China measured under the same experimental conditions yielded comparable values except for CaO (Extended Data Fig. 8c). However, this variability is not exceptional in the Australasian strewn field, and the Kalinga CaO is within the 3.5% of average data published[50].

We conclude therefore, based on visual inspection, magnetic measurements and local geological context, that the Kalinga glass is a tektite belonging to the Australasian strewn field dated at 0.79 Ma[45].

Tektite strewn fields are very rare (four have been officially accepted, and two are under study from Central and South America), the Australasian field being by far the largest in the world, and the only one from Asia. The possibility that the Kalinga sample belongs to another, unknown tektite strewn field rather than to the Australasian field is therefore unlikely.

The presence of an Australasian tektite in the bone-bed along with normal polarity palaeomagnetism in the sedimentary unit directly overlaying the bone-bed suggests an age for the fossil and archaeological remains of Kalinga site that is younger than the Lower-Middle Pleistocene boundary. This is in agreement with the ESR ages obtained on quartz from Unit A and G and on the fossil tooth enamel from Unit F. Because the ESR method is measuring the age of the last deposition of the fossils and sediments, we retain those dates when estimating the minimum age of the Kalinga site. In contrast, the $^{40}Ar/^{39}Ar$ method focuses on dating the origin of the volcanic plagioclase crystals and therefore represents a maximum age for the Kalinga archaeological site. The combination of the methods applied to different materials therefore constrain the age of the archaeological findings at Kalinga and suggest they are not older than 777 ka (ESR/U-series on enamel lower tail probability at 1 sigma) and not younger than 631 ka (ESR/U-series on Unit G quartz upper tail probability at 1 sigma).

Palaeobotanical analyses

A waterlogged wood fragment was found during the 2014 field season in the clayey matrix of the archaeological Unit F next to one of the ribs of the rhinoceros fossil (Extended Data Fig. 1e). This wood was brought for analysis to the Forest Products Research and Development Institute of the University of the Philippines Los Baños. It was positively identified as *Diospyros* sp. of the family Ebenaceae based on parenchyma cells shape in transverse, tangential and radial sections. This genus groups plants ranging from small shrubs to large trees. The majority of the species of the genus *Diospyros* are native to the tropics but are now rarely found in the low-altitude forests in the Philippines. Six species are presently found in the Cagayan Valley with habitat ranging from low-medium elevation primary forests to low-medium elevation limestone and dipterocarp forests[51].

Five sediment samples of approximately 100g each were taken for palynological analysis from Unit F in the excavation profile NE/East. All the samples were taken from freshly scraped stratigraphic profiles, sampling from bottom to top with 10cm interval using a repeatedly cleaned trowel. The samples were treated and processed with the protocol described by Sémah[52] at the palynology laboratory of the Institut de Recherche pour le Développement (IRD) in Bondy, France. The sediments were found to be barren of any pollen.

The absence of any pollen and the presence of a waterlogged wood fragment in the clayey Unit F dating back to between 731±31 and 706±70 ka is consistent with the interpretation on the deposition process of Unit F as a mudflow consecutive to a volcanic eruption. The presence of volcanic ash in the mudflow Unit F would have indeed both favoured the preservation of organic fragments such as wood and prevented the preservation of pollen.

Faunal analysis

Along with the partial *Rhinoceros philippinensis* fossil skeleton (Extended Data Figure 2a), Unit F contained other vertebrate fossils concentrated near the base. This fauna is briefly described here and compared to older surface findings to better outline the now extinct Middle Pleistocene fauna of The Philippines.

An intermediate *Stegodon* molar fragment (II-2014-J1-437) has two slightly worn ridges preserved, both bearing five apical mammillae (Extended Data Figure 2e). The smooth lateral surfaces and heavy cement suggests it represents an upper or lower m1, m2 or m3. Van den Bergh (1999: 58)[53] noted that a limited number of mamillae, between 4 and 7 per ridge, is a plesiomorphic trait. In the contemporary fauna from Java, *Stegodon trigonocephalus*, individual ridges have 9 to 15 mammillae. The maximum width of the largest ridge of the Kalinga specimen is 55 mm, its corresponding mesiodistal length is 18.8 mm and its height is 40.5 mm. These measurements are only indicative considering the unknown serial number of the molar. In von Koenigswald[54] and de Vos and Bautista[55], description of the surface megafaunal remains from The Philippines, only one species of *Stegodon* is recognized for the archipelago namely *Stegodon luzonensis*, as proposed by von Koenigswald in 1956. The dimensions and number of mammillae of the specimen from Kalinga fit within the variability of these specimens (width of lower m3 (NMP-593) = 59 mm; unworn height = 41 mm) and is therefore here attributed to *Stegodon* cf. *luzonensis*.

A complete second right upper molar (II-2014-J1-344), four upper molar fragments (II-2014-J1-345, II-2014-J1-346, II-2014-J1-347, and II-2014-J1-577) and a proximal fragment of a left radius (II-2014-J1-488), all of Cervidae were recovered (Extended Data Figure 2c,d). The complete second right upper molar is unworn and shows an intact entostyle and bucco-lingually compressed mesial and distal fossa, both of which features are comparable to what is seen in *Cervus*. The parastyle further presents a distal cleft comparable to what is found in *Cervus mariannus*. The length of the upper second molar is 17.3 mm, its mesial width is 18.5 mm and its distal width is 18.1 mm. These dimensions are within the range of *Cervus mariannus* (length range: 15.1-18.3 mm, mesial width range: 15.8-18.7 mm, distal width range: 15.3-18.7 mm), and appear larger than the two other species presently known from The Philippines: *Cervus alfredi* (length range: 13.5-17.3 mm, mesial width range: 15-15.7 mm, distal width range: 14.1-15.5 mm) and *Axis calamianensis* (length range: 13.3-17.8 mm, mesial width range: 11.5-12.7 mm, distal width range: 11.8-13.3 mm). Furthermore, these dimensions are larger than other extant and fossil Cervidae species from Southeast Asia, including *Muntiacus muntjak*, *Axis lydekkeri*, *Axis lydekkeri ngebuensis*, and smaller than the dimensions of *Cervus unicolor*[56].

Although there have been several claims for Pleistocene Cervid fossils in The Philippines, the literature does not provide enough detail regarding the findings, nor does the literature include a morphological description or geological provenance, as noted by de Vos and Bautista[55]. Currently, only fragments of antlers are present in the collections of the National Museum of The Philippines from surface discoveries. De Vos and Bautista[55] conclude that, based on the size of these museum fragments, they pertain to a small Cervid, presumably *Axis*. Our observations are that we can quite confidently attribute the Cervidae material from Kalinga to the Philippine brown deer *Cervus mariannus*, which is presently the only known species from Luzon Island. It therefore appears that this species, endemic to The Philippines, was already present in the archipelago at least 650,000 years ago.

A varanid fibula (II-2014-J1-350) and a femur fragment (II-2014-J1-351) were recovered from Unit F (Extended Data Figure 2b). Both the fibula and the femur have three-quarters of the distal portion of the shaft preserved. The *Varanus salvator* complex has been recently split into eight to eleven species based on colour and scales number[57]. Of these, three species have been described from Luzon Island, *Varanus marmoratus*, *Varanus olivaceus* and the recently newly discovered species from the Sierra Madre, *Varanus bitatawa*[58]. The morphology of the two bones from the Kalinga site is simple and their general shape is similar to the one of the monitor lizard complex, *Varanus salvator*[59], without any possible distinction between the different species. The dimensions of the fibula (maximum width: 10.9 mm) and the femur (maximum width: 19.2 mm) are slightly smaller than that of modern adult monitor lizard dimensions (fibula maximum width range: 11.89-15.46 mm and femur maximum width range: 16.30-21.41 mm). If our varanid fossil bones are of a monitor lizard, they constitute the oldest of this species complex ever recovered from The Philippines. In addition to these varanid fossils, other reptilian fossils excavated from Unit F comprise carapace fragments of Geoemydidae (Extended Data Figure 9).

The Kalinga site has a clear endemic unbalanced fauna where carnivores are absent which is typical of islands from all around the world (Extended Data Fig. 9). Furthermore, this faunal composition of Luzon during the Pleistocene is biased in favour of taxa with overseas dispersal abilities, including proboscideans, deer and pigs, while most other mainland taxa are missing.

Bone modifications

All the bones were examined under low magnification using a DinoLite digital microscope. The bones with surface modifications were then examined under a light microscope under different magnifications and photographs were taken. Additionally, the surface of some of the bones were casted using a Provil Novo light regular silicon, and the epoxy resin replicas were digitized using an Alicona InfiniteFocus, which was preferred to scanning electron microscopy for its better resolution and precision. Identification and description of anthropogenic marks were made following the combination of criteria listed by Dominguez-Rodrigo and co-authors[60].

Within the faunal assemblage excavated from Kalinga Unit F, 13 of the *Rhinoceros philippinensis* fossils show clear marks of hominin activity. One percussion mark was observed on each of the humeri (Fig. 3a,c), in both opposite elements characterized by large conchoidal scar typical of direct percussion on a bone surface with a stone usually made with the aim to reach the marrow[61]. One of these impacts further produced a bone flake that is still adhering to the right humerus, which is further evidence of the anthropogenic origin of this bone surface modification as demonstrated through experiments[61]. A total of 27 cut marks were confidently identified on 11 of the rhinoceros fossil bones (one metacarpal and ten ribs). On the contrary, four ribs presented evidence for abrasion by sediment and/or trampling, while no carnivore marks could be identified on any of the bones. All the groves we identified as anthropogenic marks – whether they are on the metacarpal or on the ribs – exhibit five out of six diagnostic criteria for butchery marks as listed by Dominguez-Rodrigo and co-authors[60], such as V-shape cross-sections, hertzian cones, asymmetrical profiles, barbs and shoulder effects. Not observed with high confidence were microstriations in the bottom of the grooves which are nevertheless rarely preserved on archaeological material[60] (Fig. 3). Of the anthropogenic marks, four cut marks were observed on the right metacarpal IV and 23 cut marks were observed on 10 ribs. Of the latters, seven were located on a ventral surface, 12 were on a lateral surface, two were on an anterior and two on posterior surfaces of ribs. Seven cut marks were positioned close to the proximal extremity of ribs and six were close to the distal extremity of ribs. All those marks are oriented transversely to the long axis of the ribs.

While cut marks have a mean length of 8.7 mm and a width of 0.4 mm, abrasion striations are shorter and narrower (mean length is 3.3 mm and mean width is 0.2 mm). The abrasion marks on the rhinoceros bones are also more superficial than the anthropogenic cut marks. Furthermore, while cut-marked bones had one to a maximum of four larger parallel groves on either surface, the abrasion striations on bones were multiple and multidirectional (Fig. 3c2). The abrasion marks were located on the ventral surfaces of two ribs, on the lateral surface of one rib and on the anterior surface of another rib.

Taking into account the presence of clear percussion marks, the criteria recently defined By Dominguez-Rodrigo and co-authors[60] for the recognition of cut marks, the special position of the marks on the fossil rhinoceros skeleton and on the individual bones, and considering the shape and size of the other groove marks apparently caused by abrasion by the sediments, the presence of cut marks would appear evident. Several studies have recorded higher frequencies of V-grooves in cut marks as compared to striations caused by trampling or sediment abrasion, which are non-organized. Berhensmeyer[62] noted that isolated marks can be misinterpreted as cut marks, but that multiple organized marks, positioned on specific areas such as metapodials[63], can be confidently attributed to cut marks. In addition, Crader[64] observed a higher frequency of cut marks on the ribs of single-carcass bone scatters of butchered elephants rather than on other skeletal elements. Therefore, the location of the cut marks on the Kalinga rhinoceros skeleton support their identification as such, and this evidence supports the conclusion that the rhinoceros carcass had been subjected to butchery activity by hominins.

Lithic technology

The lithic assemblage has been produced from siliceous and igneous rocks by means of various knapping aptitudes and record clear technical attributes (butt, percussion cones)[65]. The knapping techniques include the use of direct hard hammer stone percussion, both bipolar and tangential, and this is also evidenced by crush marks on the distal extremity of two dacitic pebbles. The knapping strategies are oriented towards short and non-organized reduction sequences, resulting in non-standardized flake morphologies and dimensions, and without any intentional retouch usually referred to as expedient technology. The flakes are sometimes elongated and trapezoid, sometimes short, triangular and canted (*déjeté*). All six cores have a residual cortex with at least two short debitage phases (maximum three removals) with bipolar and linear removal directions. The striking platforms are always built on the previous negatives or fracture plans. The knapping angles are uniformly close to 90°, and the negative flake scars show both a bulb resulting from direct freehand percussion and its counter shock resulting from the use of an anvil. The lithic industry excavated in Kalinga is therefore diverse in its techniques and final products.

A diversity of the artefacts is characteristic of the Southeast Asian lower Palaeolithic which is broadly defined as Acheulean (mode 2) for its large cutting tools such as handaxes but which is also frequently composed of smaller, often unretouched flakes[66]. While they have been found primarily outside clear stratigraphic context[67], the Javanese horsehooves, bolas and polyhedrons, along with handaxes and the small 'Sangiran flakes' were recovered in a well-dated 800 ka old layer[68] at Ngebung 2 site of the Sangiran Dome[69,70]. This assemblage of stone tools is associated with faunal remains – some intentionally broken – that can be attributed to the Trinil H.K. fauna[71], and with a *Homo erectus* molar[72]. Further to the East, In the So'a Basin of Flores Island, mostly unretouched small flakes (2 to 4 cm) are dated to one million years[73]. These artefacts, produced through percussion on anvil, are described as similar to the 700 ka old flakes recovered on the same island and associated with a *Homo floresiensis*-like hominin at the So'a Basin site of Mata Menge[74]. Similarly, small unretouched flakes produced by anvil percussion have also been recovered from the Kalinga site, and are of the same age.

It is also noteworthy that, as in Kalinga site, lithic artefacts associated with tektites have been recovered to the north of the Philippines in the Bose Basin in China[75]. These artefacts are typical Acheulean (mode 2) tools including handaxes.

Although not found in stratigraphic context, Acheulean (mode 2) industry is also present in the Philippines at the Arubo 1 site[76]. This assemblage has been assumed to be lower Palaeolithic, and contains a handaxe, and what Pawlik[77] interprets as a horsehoof-like core and a "quasi-Levallois" flake, all of which were found eroding from the present day soil[78]. A total of fifteen tools were identifiable unifacial and bifacial cores and flakes out of 197 lithic artefacts. A further handaxe, likewise not recovered from a clear stratigraphic context, was found by V.J. Paz in the Dewil Valley on Palawan Island (as cited by Dizon and Pawlik[79]). Peterson[80] re-studied the likewise undated Novaliches dam area stone artefacts found in the 1930's by Otley H. Beyer in North Manila and considered them as similar to the Bacsonian and Hoabinhian industries which are both younger than the Kalinga site. The so-far oldest prehistoric site of the Philippine archipelago, the Callao Cave, where a 67 ka old hominin third metatarsal was also discovered, has delivered no lithic artefacts but some cut marks identified on some of the cervid bones that originate from the same sedimentary breccia layer although they are seemingly younger[81].

Due to a tendency for a lack of constrained dating of artefacts recovered from regional context, only limited comparisons of the well-dated Kalinga lithic material can be made. We note, however, the predominance of unifacial technology in Island Southeast Asia, the recurrence of anvil percussion and the production of small unretouched flakes along with larger implements. In comparison to the well-published Arubo 1 site, large cutting tools account for a small proportion of the assemblage, which is furthermore mostly composed of shatter fragments (182 pieces out of 197 artefacts). Shatter fragments showing some characteristic features have been described in Liang Bua as common byproducts of percussion on anvil[82]. More insights on the shatter fragments from Arubo 1 would therefore certainly better highlight similarities and dissimilarities with the Kalinga material in which percussion on anvil has been positively identified.

Stone artefacts associated with very large game butchery in Lower Palaeolithic sites like in Kalinga are generally small-sized. Experiments have demonstrated that a small number of simple flakes is sufficient to butcher a very large carcass, such as an elephant[83,84]. Most archaeological sites that have yielded a single carcass of a very large game animal, whether in Africa or Europe, have a limited number of stone tools, and, as noted by Isaac[85] and more recently by Delagnes and co-authors[86], typically less than one hundred pieces. For example, this is the case at Fuente Nueva 3 with 17 flakes[87], Castel di Guido with 96 flakes[88], La Polledrara with 61 artefacts[89], Notarchirico with 42 chert and limestone artefacts[90], Southfleet Road with about a hundred artefacts[91], 14 flint and quartzite artefacts from Ambrona[92] and 34 flint and quartzite artefacts from Aridos 2[93]. Only a few Lower to early Middle Pleistocene sites including evidence of very large game butchery have delivered more than a hundred artefacts: Koobi Fora's FxJj 3 site (also named Hippopotamus/artefact site or HAS) with 122 recovered stone-tools[85], Barranc de la Boella - Pit 1 with 125 recovered lithic artefacts[94], Aridos 1 with 331 recovered artefacts[93] and Ficoncella with 409 lithic implements of which 296 represent small flakes[95]. The same observations are true for more recent sites dating back to the late Middle Pleistocene[96]. Our findings at the Kalinga site are overall coherent with these observations: the number of lithic implements directly associated with the rhinoceros carcass is limited, less than a hundred pieces, the raw materials are varied and most of the flakes are small and unretouched.

Supplementary Table 1 | ESR results obtained on quartz extracted from sediments. Analytical uncertainties and ages are given with ±1σ. Water contents (%) were estimated by the difference in mass between the natural sample and the same sample dried for a week in an oven at 50°C. Dose rates were determined using dose rate conversion factor updated by Guerin and co-authors[25]. Alpha and beta attenuations were estimated for the selected grain sizes from the tables of Brennan[103]; k-value of 0.15 [7], cosmic dose rate calculated from the equations of Prescott & Hutton[30]. We have at present no means to know precisely when the erosion took place and since when the archaeological material became buried under less than 7m of sediment. Therefore, a depth of 2.60m, which is the thickness between the base of layer A4 and the top of layer G1 still covering Unit A and F where the sample was taken, was used for the cosmic dose rate estimation of Unit A. A depth of 3.40m was used for the cosmic dose rate estimation of Unit G which corresponds to the thickness measured between the base of layer G1 and the laminated silty layer J4 considering that part of Unit J still covers Unit G where the sample was taken. A cosmic dose estimated from a depth of 7m would increase the age for the Unit A by 13% and by 16% for Unit G. The bleaching rate δ_{bl} (%) is determined by comparison of the ESR intensities of the natural and bleached aliquotes (δ_{bl}= $((I_{nat}-I_{bl})/I_{nat})$x100). Mean age are weighted average calculation using Isoplot software.

	D_α (µGy/a)	D_β (µGy/a)	D_γ + cosmic (µGy/a)	Dγ (µGy/a)	D cosmic (µGy/a)	D_a (µGy/a)	Water %	δ_{bl} %	D_E (Gy)	Age (ka)	Mean age (ka± 1σ)
Unit A -Al	7 ± 1	189±12	220±11	86±9	134±6	416±16	15	100	303±10	728±28	727±30
Unit A -Ti	7 ± 1	189±12	220±11	86±9	134±6	416±16	15	100	305±11	733±32	
Unit G -Al	9 ± 1	224±13	195±10	47±6	148±8	428±17	13	100	293±20	685±49	701±70
Unit G -Ti	9 ± 1	224±13	195±10	47±6	148±8	428±17	13	100	306±21	717±50	

Supplementary Table 2 | Radioelements content of the different Kalinga sedimentary units measured by ESR. ^{226}**Ra/**^{238}**U and** ^{222}**Rn/**^{238}**U are activity ratios.**

	^{238}U (ppm)	^{232}Th (ppm)	^{40}K (%)	^{226}Ra/^{238}U	^{222}Rn/^{238}U
Unit A	0.270 ± 0.054	1.059 ± 0.074	0.272 ± 0.009	1.010 ± 0.137	0.944 ± 0.056
Unit F [1]	1.852 ± 0.121	3.154 ± 0.144	1.899 ± 0.026	1.035 ± 0.200	0.869 ± 0.093
Unit G	0.277 ± 0.049	0.894 ± 0.063	0.222 ± 0.008	0.931 ± 0.127	0.887 ± 0.051

[1] Mean values from three sediment samples

Supplementary Table 3 | $^{40}Ar/^{39}Ar$ individual age obtained on large transparent plagioclase crystals (1-1.5mm) for each units investigated.

Lab. code	^{40}Ar (moles)	^{36}Ar V	±σ36 V	^{37}Ar V	±σ37 V	^{38}Ar V	±σ38 V	^{39}Ar V	±σ39 V	^{40}Ar V	±σ40 V	D[(1)]	±%2 σD	%^{40}Ar*	Age (Ka)	±σ	K/Ca	± 1σ
									UNIT A									
N1440-01	4.469E-16	1.161E-06	3.028	0.0007286	1.167	0.0000003	5.195	3.368E-05	0.945	3.262E-04	0.301	1.01117	0.1	18.86	1110.6	± 192.7	0.0077	± 0.0001
N1440-02	6.957E-16	1.862E-06	0.830	0.0010018	0.671	0.0000010	3.362	3.810E-05	0.528	5.078E-04	0.148	1.01122	0.1	12.73	1036.3	± 81.9	0.0063	± 0.0001
N1440-03	3.029E-16	8.823E-07	1.251	0.0009109	1.000	0.0000007	3.404	3.618E-05	0.412	2.211E-04	0.347	1.01114	0.1	27.23	1014.7	± 62.5	0.0066	± 0.0001
N1440-04	2.204E-16	6.547E-07	1.171	0.0007606	0.721	0.0000006	3.373	2.861E-05	0.347	1.608E-04	0.432	1.01114	0.1	31.70	1088.2	± 56.0	0.0063	± 0.0001
N1440-05	2.030E-16	5.466E-07	0.724	0.0005167	0.722	0.0000005	4.152	2.474E-05	0.134	1.482E-04	0.468	1.01113	0.1	29.12	1060.1	± 38.7	0.0080	± 0.0001
N1440-06	1.268E-16	3.406E-07	5.007	0.0003089	0.925	0.0000002	6.634	1.429E-05	1.323	9.253E-05	0.614	1.01111	0.1	27.67	1089.6	± 219.6	0.0077	± 0.0001
N1440-07	1.557E-16	4.503E-07	1.994	0.0006225	0.781	0.0000005	4.051	2.953E-05	0.670	1.136E-04	0.675	1.01112	0.1	43.34	1013.7	± 60.5	0.0079	± 0.0001
									UNIT G									
N1438-01	2.477E-16	8.033E-07	2.644	0.0017906	0.827	0.0000016	2.194	8.396E-05	0.445	1.808E-04	0.740	1.01114	0.1	78.82	1053.8	± 51.5	0.0078	± 0.0001
N1438-02	1.629E-15	4.102E-06	0.783	0.0005999	0.675	0.0000011	2.216	2.287E-05	1.007	1.189E-03	0.195	1.01141	0.1	2.69	872.6	± 292.7	0.0063	± 0.0001
N1438-03	4.261E-16	1.339E-06	1.085	0.0017111	0.773	0.0000011	2.867	6.298E-05	0.509	3.111E-04	0.334	1.01117	0.1	33.36	1028.0	± 50.5	0.0061	± 0.0001
N1438-04	3.685E-16	1.269E-06	2.244	0.0021880	0.688	0.0000015	2.582	8.559E-05	0.555	2.690E-04	0.350	1.01117	0.1	50.64	991.3	± 65.8	0.0065	± 0.0001
N1438-05	1.853E-16	5.135E-07	2.342	0.0004342	0.770	0.0000004	4.186	1.723E-05	1.020	1.353E-04	0.665	1.01113	0.1	22.78	1113.9	± 136.6	0.0066	± 0.0001
N1438-06	1.374E-16	5.063E-07	3.076	0.0009813	0.786	0.0000007	6.187	4.016E-05	0.819	1.003E-04	0.684	1.01111	0.1	59.43	924.1	± 76.1	0.0068	± 0.0001
N1438-07	4.927E-16	1.343E-06	0.686	0.0008393	0.766	0.0000006	4.860	3.495E-05	0.525	3.596E-04	0.260	1.01118	0.1	14.81	947.9	± 59.0	0.0069	± 0.0001
N1438-08	2.684E-16	7.181E-07	4.124	0.0006374	0.768	0.0000005	3.405	2.751E-05	1.135	1.959E-04	0.592	1.01114	0.1	27.18	1203.9	± 203.2	0.0072	± 0.0001

Supplementary Table 4 | $^{40}Ar/^{39}Ar$ background corrections.

Lab. Code	^{36}Ar	±σ36	^{37}Ar	±σ37	^{38}Ar	±σ38	^{39}Ar	±σ39	^{40}Ar	±σ40
	V	V	V	V	V	V	V	V	V	V
					UNIT A					
N1440-01	1.689E-07	7.430E-09	1.348E-08	6.848E-09	2.819E-08	1.381E-08	1.278E-07	1.265E-07	3.752E-05	4.502E-07
N1440-02	1.689E-07	7.430E-09	1.348E-08	6.848E-09	2.819E-08	1.381E-08	1.278E-07	1.265E-07	3.752E-05	4.502E-07
N1440-03	1.689E-07	7.430E-09	1.348E-08	6.848E-09	2.819E-08	1.381E-08	1.278E-07	1.265E-07	3.752E-05	4.502E-07
N1440-04	1.704E-07	1.687E-09	2.668E-08	4.376E-09	7.665E-08	1.134E-08	7.640E-08	9.932E-09	3.637E-05	3.637E-07
N1440-05	1.704E-07	1.687E-09	2.668E-08	4.376E-09	7.665E-08	1.134E-08	7.640E-08	9.932E-09	3.637E-05	3.637E-07
N1440-06	1.704E-07	1.687E-09	2.668E-08	4.376E-09	7.665E-08	1.134E-08	7.640E-08	9.932E-09	3.637E-05	3.637E-07
N1440-07	1.704E-07	1.687E-09	2.668E-08	4.376E-09	7.665E-08	1.134E-08	7.640E-08	9.932E-09	3.637E-05	3.637E-07
					UNIT G					
N1438-01	2.374E-07	8.451E-09	1.100E-08	1.099E-08	4.761E-08	1.409E-08	2.128E-06	1.609E-07	5.169E-05	6.203E-07
N1438-02	2.374E-07	8.451E-09	1.100E-08	1.099E-08	4.761E-08	1.409E-08	2.128E-06	1.609E-07	5.169E-05	6.203E-07
N1438-03	2.400E-07	9.456E-09	4.211E-08	1.049E-08	3.247E-08	7.501E-09	8.900E-07	9.345E-08	4.515E-05	6.411E-07
N1438-04	2.400E-07	9.456E-09	4.211E-08	1.049E-08	3.247E-08	7.501E-09	8.900E-07	9.345E-08	4.515E-05	6.411E-07
N1438-05	2.400E-07	9.456E-09	4.211E-08	1.049E-08	3.247E-08	7.501E-09	8.900E-07	9.345E-08	4.515E-05	6.411E-07
N1438-06	1.445E-07	5.347E-09	1.750E-08	5.565E-09	1.046E-08	7.008E-09	7.160E-08	5.513E-08	3.088E-05	3.705E-07
N1438-07	1.445E-07	5.347E-09	1.750E-08	5.565E-09	1.046E-08	7.008E-09	7.160E-08	5.513E-08	3.088E-05	3.705E-07
N1438-08	1.088E-07	7.398E-09	1.100E-08	1.099E-08	4.364E-08	6.895E-09	7.173E-08	7.166E-08	2.445E-05	3.619E-07

Supplementary Table 5 | Magnetic intensities and Characteristics Remanent Magnetization directions before and after demagnetization.

No	Specimen	Intensity (A/m)		Remanence direction (ChRMs)	
		Before demagnetization	After demagnetization	Mean declination	Mean Inclination
1	HT-1A (AF)	35.93 E -03	2.595 E -03	353.4	22.6
2	HT-1B (AF)	62.48 E -03	5.736 E -03	356.6	20.2
3	HT-1C (AF)	71.24 E -03	5.081 E -03	356.3	32.2
4	HT-1D (AF)	47.90 E -03	4.327 E -03	348.2	27.2
5	HT-1K (AF)	72.78 E -03	4.250 E -03	356.8	27.1
6	HT-1E (TD)	36.95 E -03	2.723 E-03	343.8	23

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