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1 **Earliest known hominin activity in The Philippines by 709 thousand years ago.**

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33 More than 60 years ago, stone tools and mega fauna remains were discovered on the Southeast
34 Asian islands of Flores, Sulawesi and Luzon, and a Middle Pleistocene colonization by *Homo*
35 *erectus* was initially proposed for these islands¹⁻⁴. However, until the discovery of *Homo floresiensis*
36 in 2003, claims for the presence of archaic hominins on Wallacean islands were hypothetical due
37 to the absence of *in situ* fossils and/or stone artefacts excavated from well-documented
38 stratigraphic contexts, or because secure numerical dating methods of sites were lacking. As a
39 consequence, these claims were generally treated with scepticism⁵. Recent excavations at Kalinga
40 in the Cagayan Valley of northern Luzon in The Philippines have yielded 57 stone-tools associated
41 with an almost complete disarticulated skeleton of *Rhinoceros philippinensis* showing clear signs
42 of butchery, together with other fossil fauna remains attributed to stegodon, Philippine brown
43 deer, fresh-water turtle and monitor lizard. All finds originate from a clayey bone bed dated to
44 between 777 thousand and 631 thousand years ago using electron-spin resonance method applied
45 on tooth enamel and fluvial quartz. This evidence pushes back the proven period of colonization⁶
46 of The Philippines by hundreds of thousands of years, and furthermore suggests that early
47 overseas dispersal in Island South East Asia (ISEA) by premodern hominins took place several
48 times during the Early and Middle Pleistocene¹⁻⁴. The Philippines therefore may have played a
49 central role in southward movements into Wallacea, not only of Pleistocene mega fauna⁷, but also
50 archaic hominins.

51 The most recent recoveries in Flores^{8,9} and Sulawesi¹⁰ (Indonesia) provide a unique
52 documentation of over-seas hominin dispersal during the early Middle Pleistocene. An early presence
53 in The Philippine archipelago has been speculated since the 1950s, with the reporting of presumably
54 Pleistocene mega-faunal remains and 'Palaeolithic' industries consisting of chopping-tools and flakes
55 (the 'Cabalwanian' and 'Liwanian' Industries respectively) from surface finds and excavations in the
56 Cagayan Valley basin of northern Luzon^{3,4}. Despite the fact that these early discoveries took place more
57 than 60 years ago, no direct association between mega-fauna and lithic industries has ever been
58 documented since then, and no secure numerical dating of both fossil fauna and lithics has been available

59 for this region¹¹. To date, the discovery of a human metatarsal in Callao Cave in northern Luzon⁶,
60 directly dated at 66.7 ± 1.0 ka, represented the oldest evidence for the peopling of The Philippines.

61 In 2013, a survey of the Cagayan Valley near the Rizal Municipality (Kalinga Province) led to
62 the discovery of a concentration of vertebrate bones and stone artefacts scattered on the surface near
63 what became our new excavation site. The Kalinga site ($17^{\circ}33'45.0318''\text{N}$; $121^{\circ}33'35.7372''\text{E}$) (Fig.
64 1,b) has been excavated annually since 2014 and has resulted in the discovery of *in situ* mega-fauna and
65 associated stone artefacts. The substrate consists of the upper part of the Awidon Mesa Formation, a
66 400m thick sequence of alluvial stream deposits (mainly sandstones and claystones) intercalated with
67 volcanoclastic and pyroclastic layers (Fig. 1a). These sediments were deposited on an alluvial fan system
68 in braided streams of the paleo-Chico River as a consequence of uplift in the Central Cordillera to the
69 west^{12,13}. During a poorly constrained Pleistocene phase of folding in response to east-west compression,
70 alluvial fan deposition in the Kalinga area came to a halt.

71 We conducted the main 16m² excavation at the head of a modern, dry stream valley, north of a
72 small hill and down to a maximum depth of 2m (Fig. 1c, see Supplementary Information: excavation
73 methods and Sedimentology). A 25m x 1m slot trench was excavated down the hill to the Main
74 Excavation. Together, these excavations revealed a total of 7.5m of stratigraphy comprising four main
75 sedimentary units, in ascending order: Unit A, Unit F, Unit G and Unit J (Fig. 1d,e; Extended Data Fig.
76 1). An almost complete disarticulated skeleton of *Rhinoceros philippinensis* (Extended Data Fig.2) was
77 found embedded in the basal sediments of Unit F lying across the base of an erosional channel surface
78 that cuts down vertically into sandy Unit A. This channel was filled with an up to 3.25m thick mudflow
79 (Unit F; see Extended Data Fig. 3 and 4), which covered the bones, along with an *in situ* tektite as well
80 as 57 stone-tools and sparse fossils of other animals (*Geoemydidae*, *Varanus* cf. *salvator*, *Stegodon* cf.
81 *luzonensis* and *Cervus* cf. *mariannus*) (see Supplementary Information: Faunal analysis). The
82 archaeological layer (Unit F) is conformably overlaid by a ~1.15m thick, sterile, cross-bedded coarse
83 sandy fluvial unit with silty lenses (Unit G), which is in turn conformably overlaid by Unit H, a 2.5m
84 thick silty pedogenised layer with rhyzoliths.

85 The 57 stone artefacts account for six cores, 49 flakes and two possible hammer stones, all
86 originating from Unit F (Fig.2, see Supplementary Information: Lithic analysis). With the exception of
87 the two possible hammer stones (Fig.2b), all artefacts lack a patinated lustre and have a fresh appearance,
88 indicating that any transport was minimal. The knapping strategies were oriented towards short and
89 unorganized core reduction, resulting in non-standardized flake morphologies and dimensions, and all
90 artefacts were lacking any intentional retouch. The Kalinga lithic assemblage is diverse in its techniques,
91 technology and final products, and appears similar to the chert industry described at Arubo 1 site¹⁴ (See
92 Supplementary Information: Lithic technology). Also recovered from the Unit F excavation area was a
93 600g pebble among hundreds of pebbles all lighter than 200g, and which we interpret as a possible
94 manuport.

95 Among the more than 400 bones recovered from Unit F, the most striking remains are a
96 disarticulated, ~75% complete skeleton of a single *Rhinoceros philippinensis* individual (Fig. 3;
97 Extended Data Fig. 2). The bones were found lying on top of the erosional surface down-cutting Unit
98 A, and were embedded in the basal clayey sediments of Unit F along the deepest part of the paleo-
99 channel bed (Extended Data Fig. 3). Although none of the rhinoceros bones were found articulated, the
100 recovered skeletal elements occur within a 3m x 2m area, suggesting that disarticulation occurred sub-
101 aerially and that transport prior or during deposition of mudflow Unit F was minimal.

102 Thirteen of the excavated rhino bones, all of which in life had a thin cover of soft tissue (i.e. the
103 ribs and metacarpals)^{15,16}, display cut marks (Fig. 3; Extended Data Fig. 2). Both rhinoceros humeri have
104 similar percussion marks on the anterior surface for the right humerus and on the posterior surface for
105 the left humerus, and both were presumably made with the intention to smash the bones and gain access
106 to the marrow¹⁷. This percussion action resulted in the breakage of the left humerus into five pieces,
107 which is the only bone found fragmented – and yet the fragments were still clustered together within a
108 small 1m² area of the excavation. On the right humerus, however, percussion did not result in
109 fragmentation of the bone (Fig. 3).

110 To constrain the age of the bone-bed and the stone artefacts it contained, we applied three
111 different dating methods to various materials (Fig. 1). Single crystal ⁴⁰Ar/³⁹Ar dating was applied to

112 plagioclase crystals from the sandy units directly below and above the archaeological Unit F and yielded
113 two statistically undistinguishable weighted mean ages of 1050 ± 28 ka and 1007 ± 29 ka, respectively
114 (1σ confidence interval) (see Supplementary Information: $^{40}\text{Ar}/^{39}\text{Ar}$ dating and Extended Data Fig. 5).
115 These $^{40}\text{Ar}/^{39}\text{Ar}$ dates yielded an age for the formation of the volcanic plagioclase crystals. Quartz grains
116 from the same two sandy units were also dated using the Electron Spin Resonance (ESR) method¹⁸, and
117 resulted in a maximum depositional age of 727 ± 30 ka for the deposition of Unit A, and a minimum
118 depositional age of 701 ± 70 ka for Unit G (1σ confidence interval) (see Supplementary Information:
119 ESR dating).

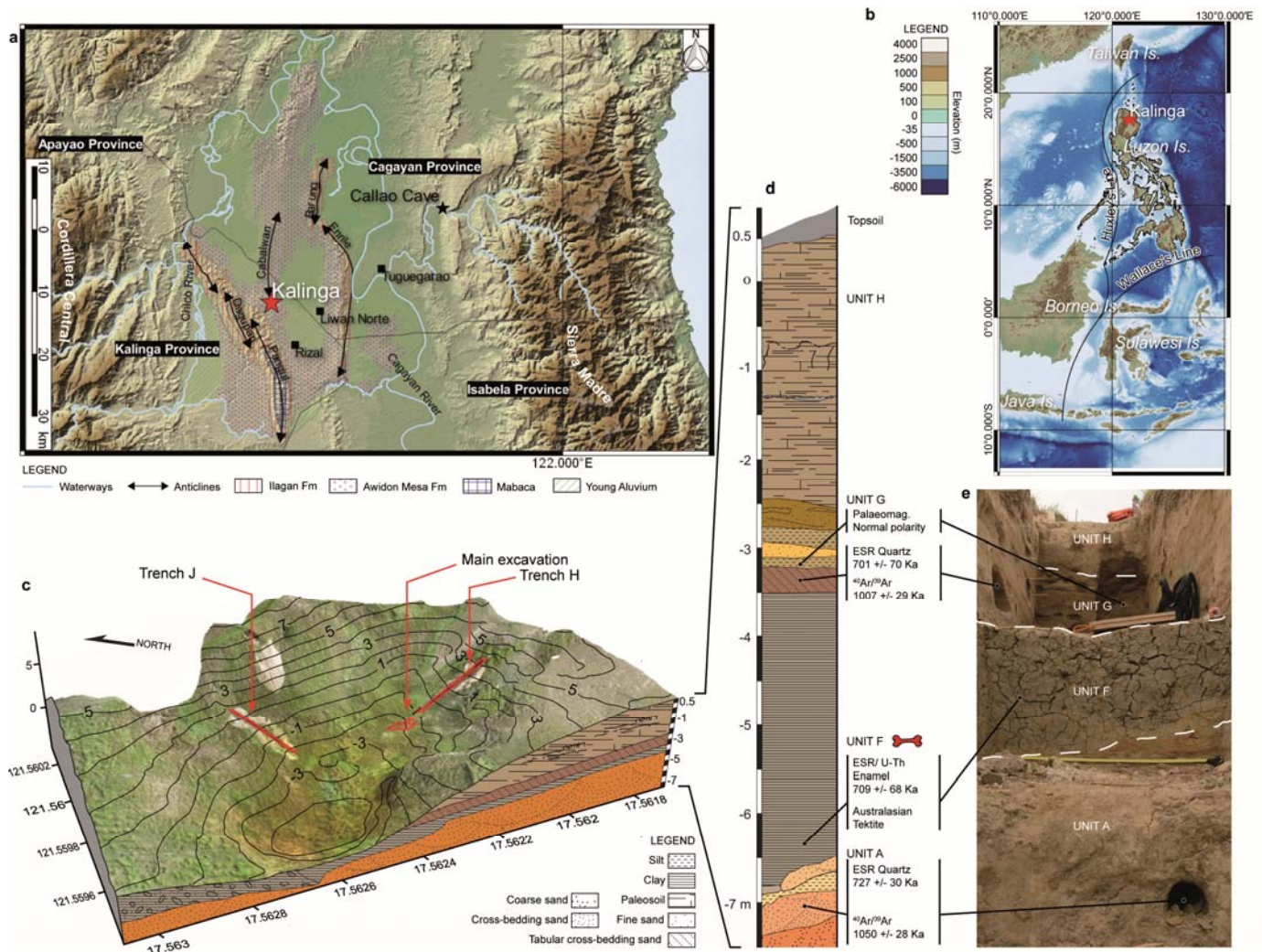
120 To directly constrain the age of the rhinoceros skeleton and the cut-marks, we applied
121 ESR/uranium-series dating on the enamel of the rhinoceros's right maxillary third premolar from the
122 Unit F bone-bed. The tooth yielded an age of 709 ± 68 ka (1σ confidence interval), which is in agreement
123 with the ESR results on quartz (Fig. 1; see Supplementary Information: ESR-uranium series dating,
124 Extended Data Fig. 6, Extended Data Table 1 and Supplementary Information Table 1). In addition, a
125 palaeomagnetic sample was taken from a laminated silty lens in the lower part of Unit G and was found
126 to have a normal magnetic polarity (see Supplementary Information: palaeomagnetic dating and
127 Extended Data Fig. 7). The presence in Unit F of a reworked Australasian tektite (see Supplementary
128 Information: Non-destructive characterization of the tektite, Extended Data Fig. 8), which was formed
129 during a major meteoritic impact just before the onset of the Brunhes Normal polarity epoch at 781
130 $\text{ka}^{19,20}$, also provides further support for these closely grouping dating results. These results further
131 suggest that the volcanic plagioclase crystals from unit G on which the $^{40}\text{Ar}/^{39}\text{Ar}$ date was obtained were
132 reworked from older volcanoclastic deposits, and therefore provide a maximum age for the sequence
133 (see Supplementary Information: Sedimentology). Taken together with the ESR dating results, it follows
134 that the rhinoceros skeleton was buried by a mudflow at least 631 thousand years ago.

135 Our excavations at Kalinga and the numeric dating results clearly provide the first securely dated
136 evidence for human colonization of The Philippines by the early Middle Pleistocene, and long before
137 the appearance of modern humans in both the local context and wider ISEA region²¹. Although the
138 identity of these archaic toolmakers remains unknown, it is likely that they dispersed over at least one

139 sea barrier to reach Luzon Island²². The most likely points of origin are Borneo through Palawan to the
140 west, or China through Taiwan to the north, this latter island being connected to mainland Asia during
141 periods of low sea-level²³. The Middle Pleistocene fauna from the Awidon Mesa Formation contains a
142 wider range of vertebrates than the Pleistocene faunas from two islands to the south of The Philippines
143 that have both yielded evidence for the occupation by premodern humans, Sulawesi⁹ and Flores²⁶
144 (Extended Data Fig. 9). Overseas dispersal throughout Wallacea of land mammals, including hominins,
145 could have been primarily but not exclusively in a north to south direction, following the major surface
146 current flow patterns.

147 Beyond the chronological gap yet to be filled, a question clearly linked to our discovery is the
148 origin of the Callao Cave hominin dated at 66.7 ± 1 ka. This diminutive Callao hominin may represent
149 a direct descendent from a Pleistocene migration stock related to these early Kalinga toolmakers –
150 similar to what happened on Flores Island – or may be derived from a more recent migration wave of
151 anatomically modern humans^{6,21,24,25}.

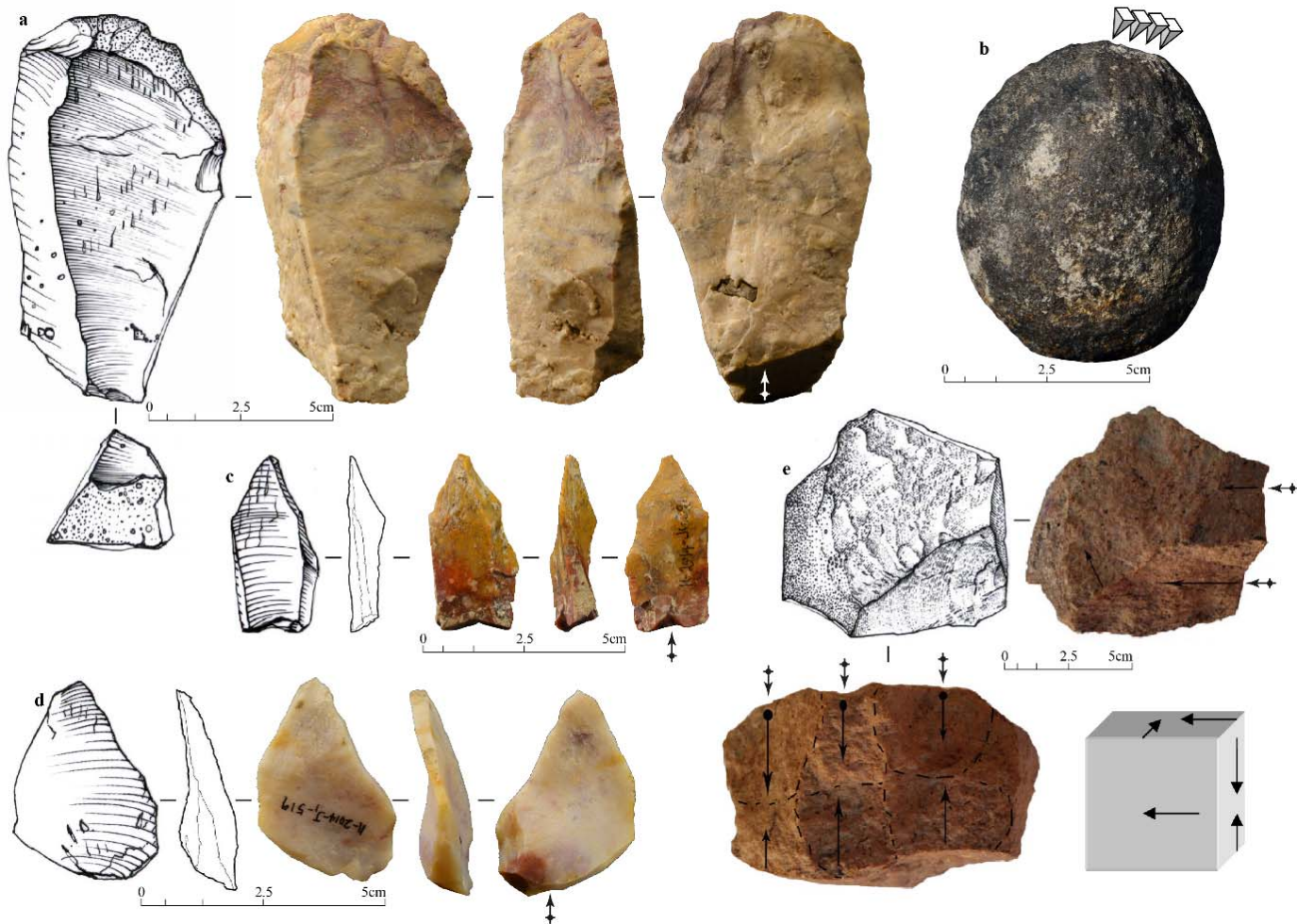
152 Despite the current evidence, it still seems too farfetched to suggest that *Homo erectus*, or
153 another as yet unknown Pleistocene ancestral candidate for the Kalinga toolmakers (e.g.
154 ‘Denisovans’²⁷), were able to construct some sort of simple watercraft and deliberately cross sea barriers
155 to reach these islands²⁸. However, considering evidence of over-seas dispersal during the Middle
156 Pleistocene is increasing in number^{29,30}, such a hypothesis cannot currently be rejected.



157

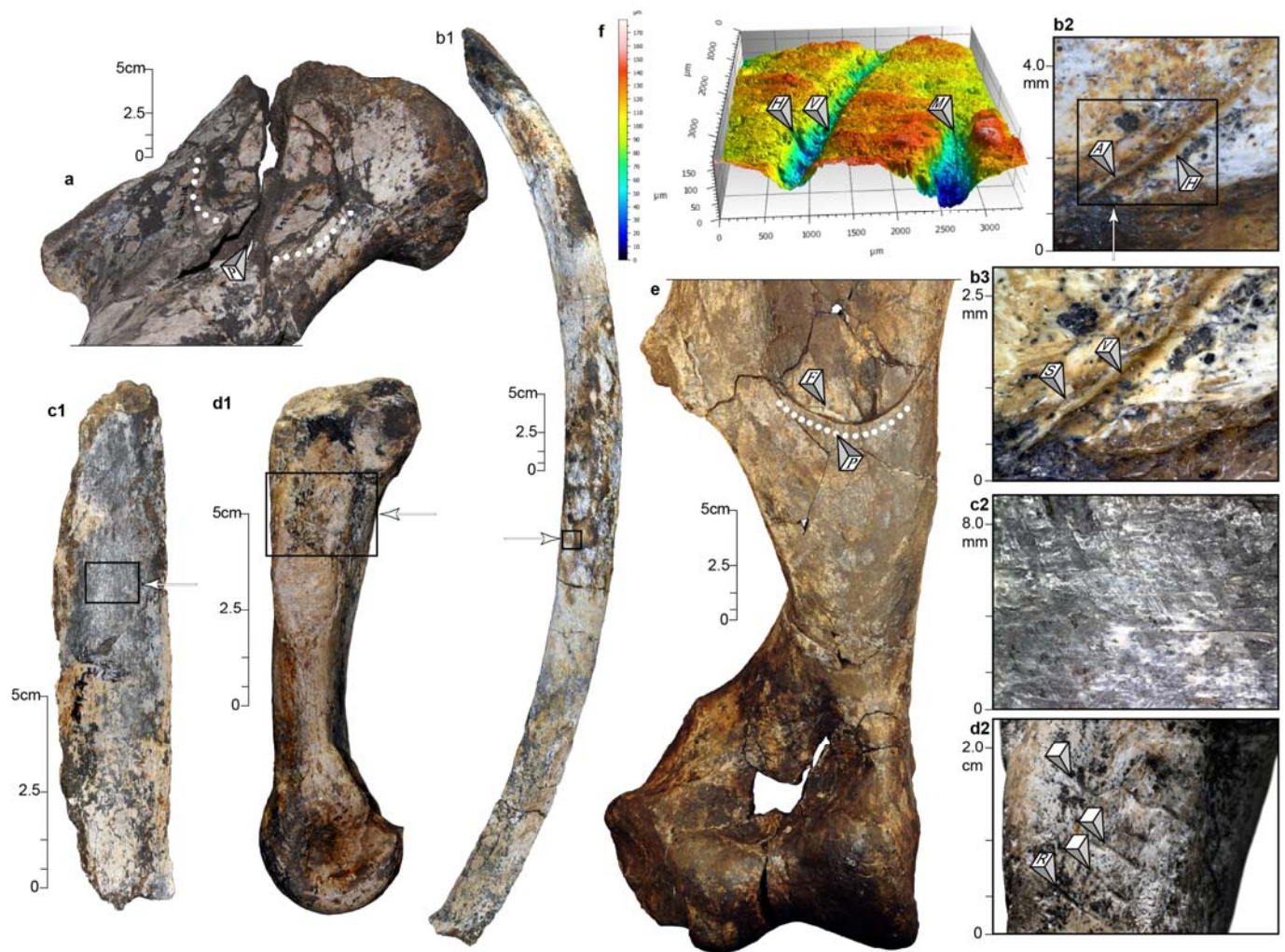
158 **Figure 1 | Geology and sedimentology of the Kalinga Excavation site.** a, Digital elevation map of the Cagayan Valley
 159 surrounding the Rizal municipality (located in b, Northern Luzon Island, east of Huxley's and north of Wallace's Lines). The
 160 Kalinga site (red star) is located at the southern tip of the weakly folded Cabalwan Anticline. Geological units of the area
 161 bounded by the Cagayan River on the East and the Chico River on the West are after Mathisen (1981)¹³. Stratigraphically, the
 162 site layers pertain to the upper part of the Awidon Mesa Formation, a Pleistocene sequence of alluvial stream deposits
 163 intercalated with volcanoclastic and pyroclastic deposits. The depositional environment of the Awidon Mesa Formation was
 164 characterized by braided rivers on an alluvial fan system that formed in response to uplift in the Cordillera Central to the
 165 West^{12,13}. c, Contour map of the Main Excavation and the adjoining slot Trench H along the small valley where the Kalinga site
 166 is located. d, Detailed stratigraphy of the excavation with the absolute ages of the sedimentary units. Unit A constitutes a fining
 167 upward complex of sandy to silty cross-bedded fluvial sediments. The top of Unit A is eroded and cuts down vertically over at
 168 least 2.5 m. This erosive channel is filled with Unit F, a poorly sorted mudflow deposit with a maximum thickness of 3.25 m.
 169 The rhino skeletal elements and most of the stone artefacts were found lying directly above the erosional contact, and were
 170 found embedded in the clayey mud of Unit F. Unit F is conformably overlaid by a sequence of horizontally layered coarse
 171 sandy to silty layers (Unit G), which is in turn conformably overlaid by a thick sequence of silty deposits overprinted by

- 172 paleosols (Unit H). e, Southward view of Trench H showing the lower and upper contacts between mudflow Unit F and sandy
- 173 Unit G and between sandy Unit A and mudflow Unit F.



174

175 **Figure 2 | Lithic artefacts from Kalinga. a**, Cortical flake on chert (II-2014-J1-362; L= 100, B= 55, Th=33mm); **b**, possible
 176 hammerstone on dacite (II-2014-J1-371), although its highly eroded aspect precludes any definitive conclusion; **c**, Siret
 177 kombewa flake on jasper (II-2014-J1-391; L=40, B=18, Th=8mm) having a longitudinal and oblique fracture on the inferior
 178 two-thirds of the left side resulting from a knapping accident while flaking; **d**, double-backed flake on flint (II-2014-J1-519);
 179 **e**, core on quartz (II-2014-J1-396) -showing clear marks of knapping on anvil- with its diachritic diagram.



180

181 **Figure 3 | Different types of marks at the surface of the bones.** a, Left humerus (II-2014-J1-368) found broken into three
 182 fragments in the excavation with an anthropogenic conchoidal percussion mark (P) on its anterior surface most likely produced
 183 to get access to the marrow; **b1**, **b2** and **b3**, sub-complete rib (II-2014-J1-475), having a diagnostic anthropogenic cutmark with
 184 V-shape cross-section (V), hertzian cones (H), asymmetrical profile (A) and shoulder effect (S) on its lateral surface resulting
 185 from defleshing. Black stains are also present inside the cutmark resembling the ones observed on the surface of the rib and are
 186 the result of taphonomic processes that occurred after this cutmark was made (see Fernández-Jalvo and Andrews, 2016: 156)¹⁷;
 187 **c1** and **c2**, rib fragment (II-2014-J1-403) having a shiny surface on its lateral face resulting from multiple multidirectional
 188 striations, presumably due to trampling; **d1** and **d2**, right metacarpal IV (II-2014-J1-282) with parallel and rectilinear
 189 anthropogenic cutmarks (R) on its medial surface presumably generated during disarticulation; **e**, right humerus (II-2014-J1-
 190 289) with an anthropogenic conchoidal percussion mark (P) similar in size and shape to the percussion mark on the left humerus,
 191 but located on its posterior surface and more distally and associated with a small adhered bone flake (F) (see Fernández-Jalvo
 192 and Andrews, 2016: 298)¹⁷; **f**, three-dimensional surface topography of another rib (II-2014-J1-466) showing a linear mark (on
 193 the left) with V-shaped cross-section (V) of anthropogenic origin, as well as hertzian cones (H) and a linear mark (on the right)

194 with a base as broad as the heights of the walls of the groove, commonly attributed to trampling but also with asymmetrical walls
195 and possible microstriations in the bottom (M) of the groove, commonly attributed to anthropogenic marks.

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260

261

262 **Supplementary Information** is available in the online version of the paper.

263

264

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281

282

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284 collaboration with N.A., G.L. and P.A. The site stratigraphy was recorded and analysed by G.v.d.B.
285 Samples for ESR/U-series dating were analysed by J-J.B., Q.S. and C.F. Samples for ESR dating on
286 quartz were analysed by P.V. Samples for $^{40}\text{Ar}/^{39}\text{Ar}$ dating were analysed by S.N. and A.P. D.Y.
287 analysed samples for palaeomagnetism. The lithic material was studied by H.F. and G.C.
288 Palaeobotanical remains were analysed by A-M.S. and C.K. The faunal and taphonomical analysis was
289 conducted by T.I., K.M., M.R. and N.A. T.I. and G.v.d.B. wrote the manuscript

290

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292 www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome
293 to comment on the online version of the paper. Correspondence should be addressed to T.I.
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295

296 **Extended data legends**

297 **Extended Data Figure 1 | Geology and sedimentology of the Kalinga Excavation site.** **a**, Detailed stratigraphic drawing of
298 Trench H also showing the East wall of the S quadrant of the main Excavation. The sedimentary patterns are the same as in
299 Figure 1. Representative logarithmic grainsize diagrams are shown for samples from each sedimentary unit; **b**, Detailed
300 stratigraphic drawing of the Main Excavation walls; **c**, Overview towards the northwest of the quadrants N and NW of the
301 Main Excavation in 2015. The concentration of faunal remains and stone tools lying at the base of Unit F is exposed, just
302 above the eastward sloping erosional contact with Unit A; **d**, Detailed view of quadrant NW showing the position of a flake
303 lying next to the rhinoceros left femur; **e**, Detail of quadrant N showing the piece of waterlogged wood fragment (yellow
304 outline) recovered near a rhinoceros rib extremity (blue outline); **f**, Detail of quadrant NE showing the tektite recovered in
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307 the rhinoceros and position of the taphonomical marks. A total of 97 fragments of ribs of all sizes have been recovered and
308 not all of them could be clearly positioned on the skeleton. We estimate that about 75% of the skeleton has been recovered. **b**,
309 Fibula of *Varanus salvator*. **c**, Radius of a Cervidae. **d**, Molar of *Cervus cf. mariannus*. **e**, Molar fragment of *Stegodon cf.*
310 *luzonensis*.

311 **Extended Data Figure 3 | Digital Elevation Model (DEM) of the Main Kalinga Excavation**, showing the contact surface
312 topography between Unit A and Unit F and the vertical projections (black squares) of the archaeological materials (coloured
313 points) on this surface. This DEM has been produced by interpolation through a kriging method from 37 three-dimensional
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316 lying across the base of the clayey Unit F along this channel, between 0.7m and 1.3m deep.

317 **Extended Data Figure 4 | X-ray diffraction pattern of powdered Unit F clays.** CPS is counts per second. Cu K-alpha
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319 eye. Bipyramidal quartz, albite, hornblende, nontronite and saponite all have a volcanic origin. Albite are plagioclase feldspar
320 frequent in pegmatites. Hornblende is a common silicate mineral in igneous and metamorphic rocks. Nontronite is an iron-
321 rich smectite type of clays which can be produced by hydrothermal alteration. Similarly, the smectite mineral saponite results
322 from alteration of volcanic glass. The mineral composition of Unit F supports the interpretation as a mudflow set in a
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326 Individual ages in **a** are $\pm 1\sigma$.

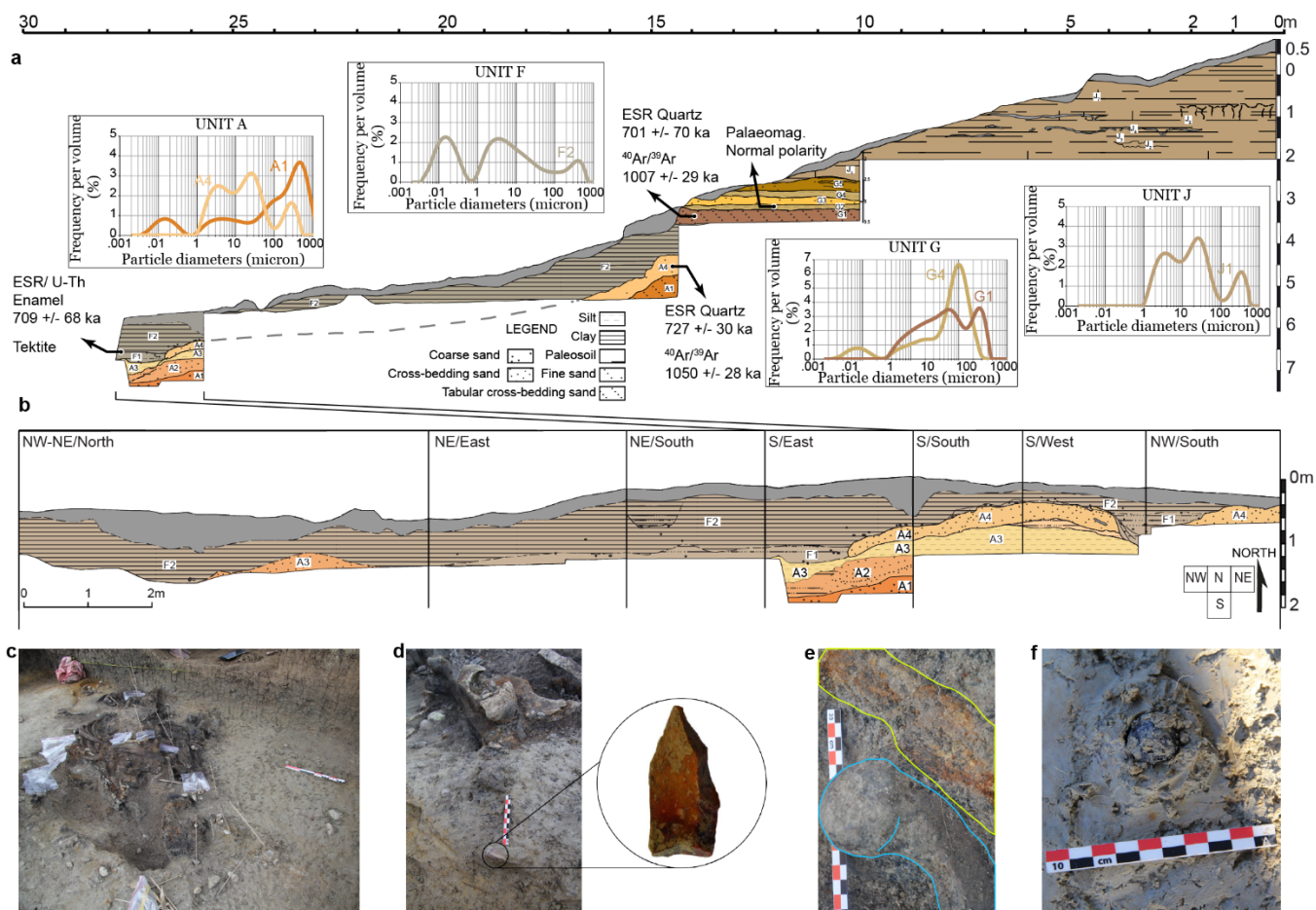
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329 A quartz showing that Al signal is not totally reset although not measurable because extremely weak and covered by noise. **b,**
330 ESR Dose-response curve obtained for the rhinoceros tooth (Archaeological number: II-2014-J1-095; sample code:
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333 bars account for the standard deviation around the mean for each measurement. The red curve is for the dose-response curve.
334 The blue curves account for the 95% confidence interval of the dose-response curve. **c-f,** ESR Dose Response curves, for
335 Aluminium (Al) and Titanium-Lithium (Ti-Li) centers of layers G1 and A4. Vertical bars account for the standard deviation
336 around the mean for each measurement. The red curve is the dose-response curve. The blue curves account for the 95%
337 confidence interval of the dose-response curve.

338 **Extended Data Figure 7 | Progressive demagnetization curves (lower left of each panel), equal area projection**
339 **stereoplots (upper left) and Zijdeveld diagrams (right) for the six analysed specimens from Layer G2. a-e:** specimens
340 treated by alternating field demagnetization; **f,** specimen HT-1E treated by thermal demagnetization. Open circles in the
341 Zijdeveld diagrams represent the inclination while closed circles represent declination. Open and closed circles in the equal
342 area projection (stereoplot) represent the upper and lower hemisphere, respectively. Equal-area projections of the mean
343 ChRMs directions of all analysed specimens, **g,** before and **h,** after demagnetization. Solid squares represent the upper
344 hemisphere. Black cross indicates the mean ChRMs direction of the six specimens combined, surrounded by the $\alpha 95$ circle.
345 Red cross represents the present-day magnetic direction.

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348 Kalinga tektite glass composition through μ XRF with an australasite tektite from China measured in the same conditions (red
349 squares) and with an average australasite composition (blue diamonds) following Koeberl⁵⁰.

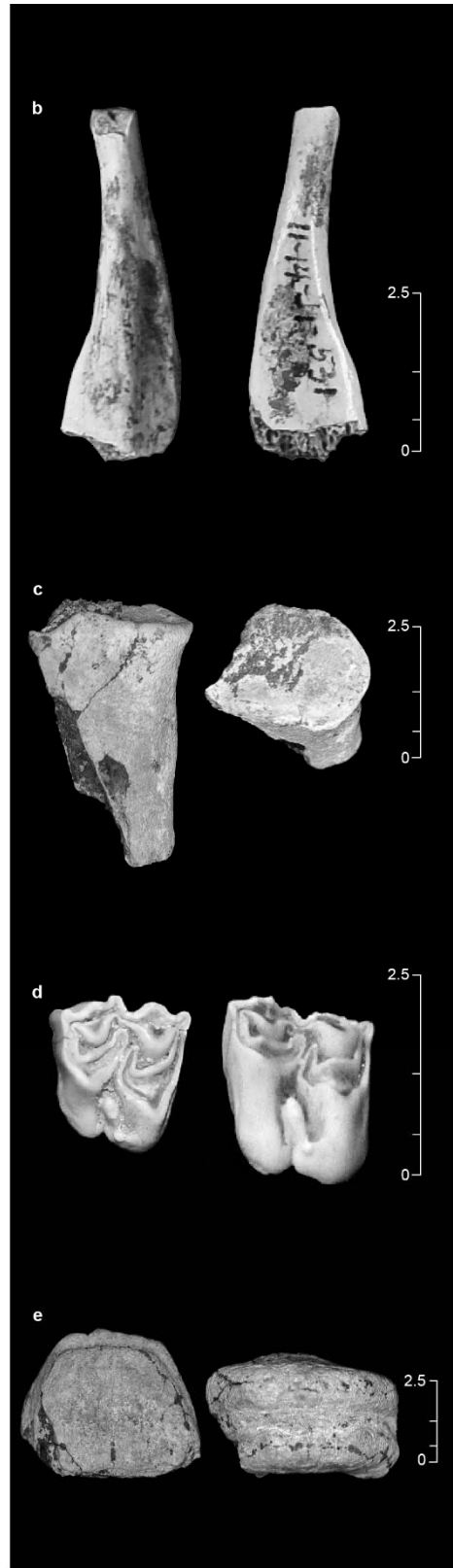
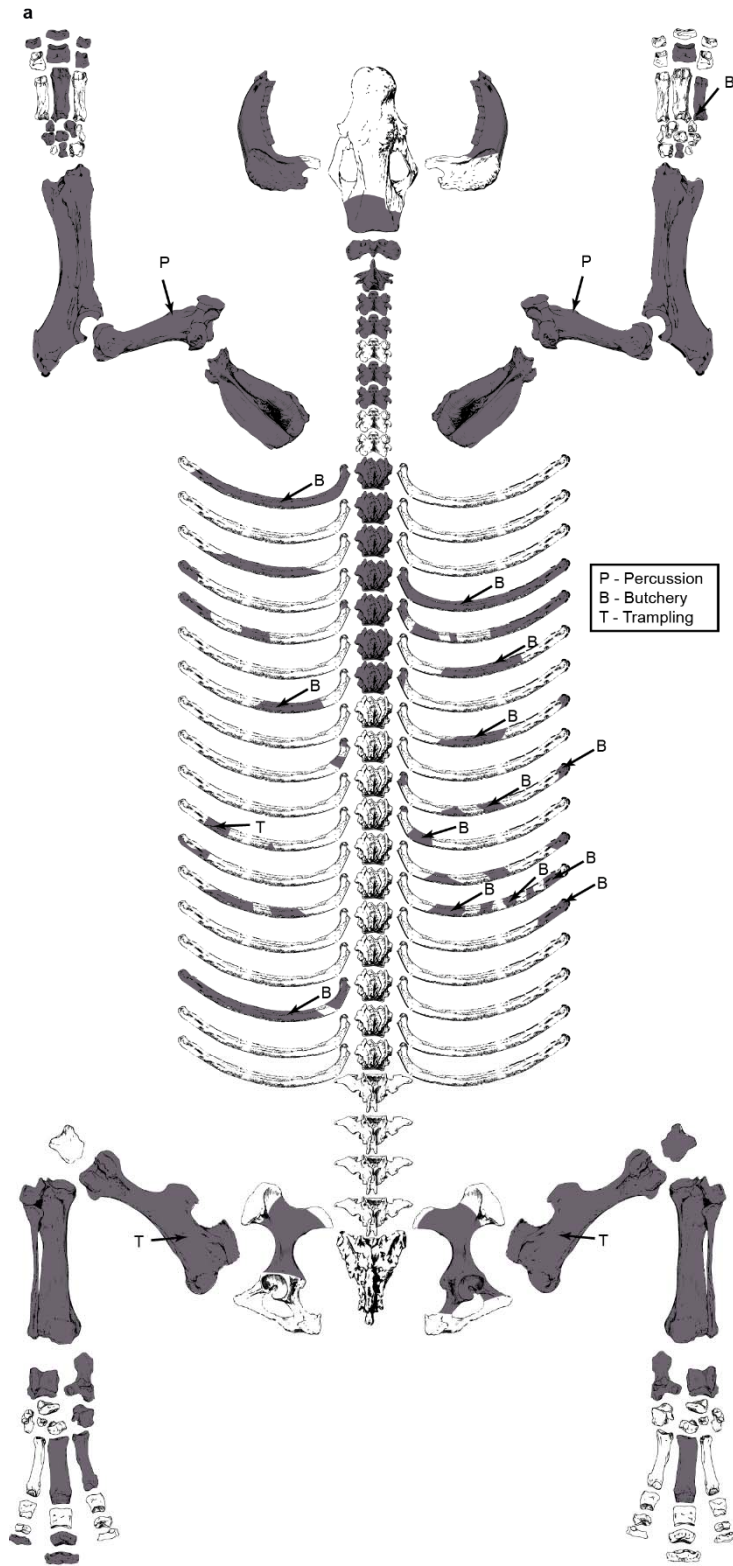
350 **Extended Data Figure 9 | Fauna diversity of the Kalinga site as compared to contemporaneous faunas from other**
351 **islands in the region.** Contemporaneous to those faunas are ‘classic’ *Homo erectus* faunas on Java Island⁹⁷, the Mata Menge
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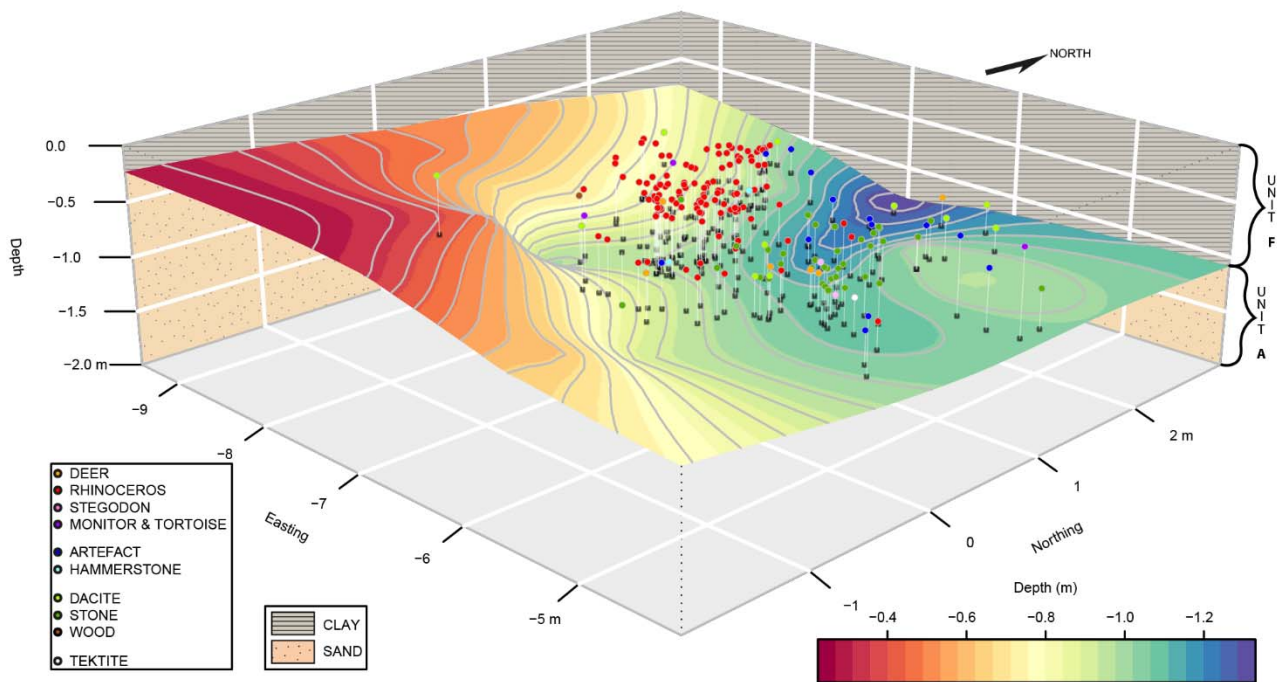
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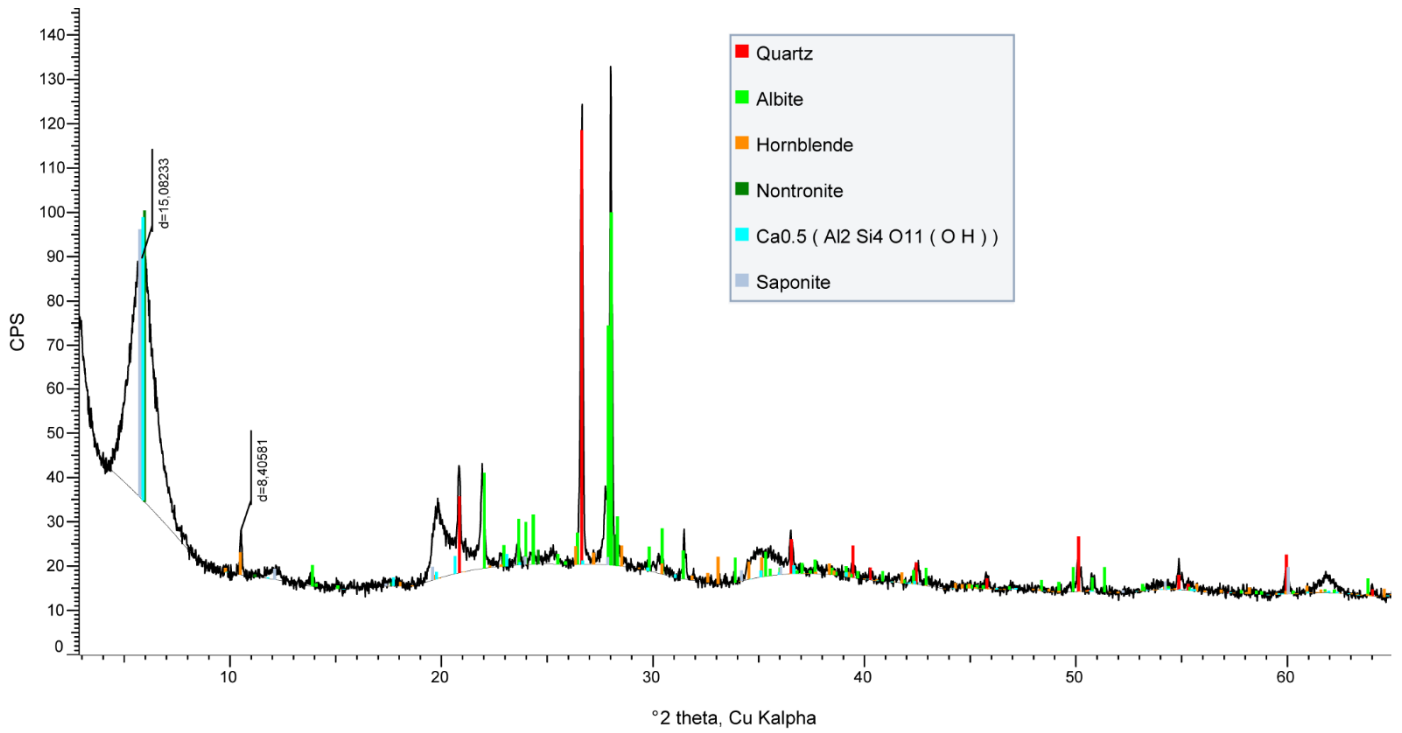
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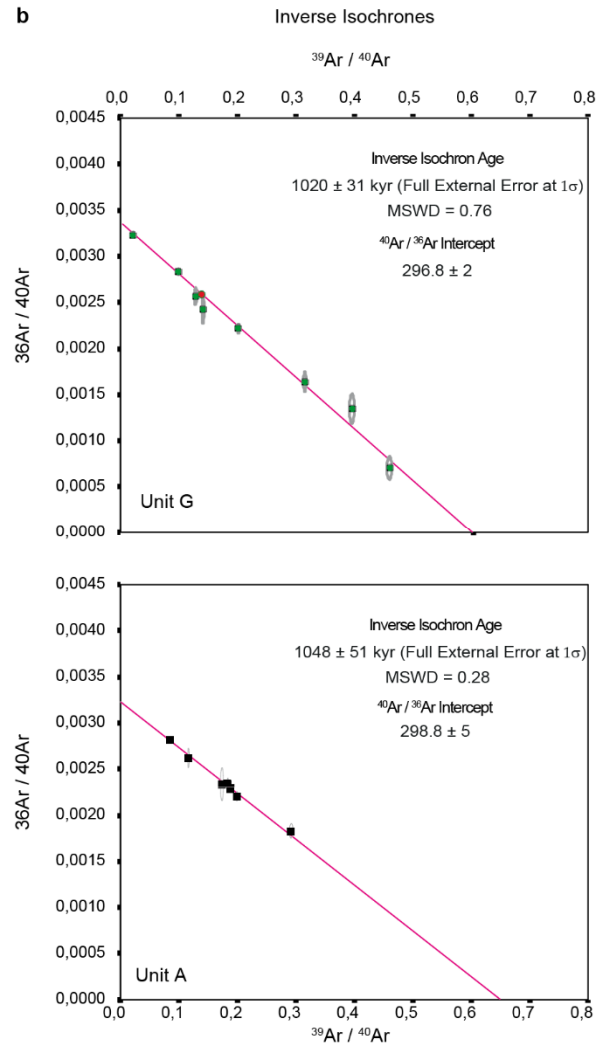
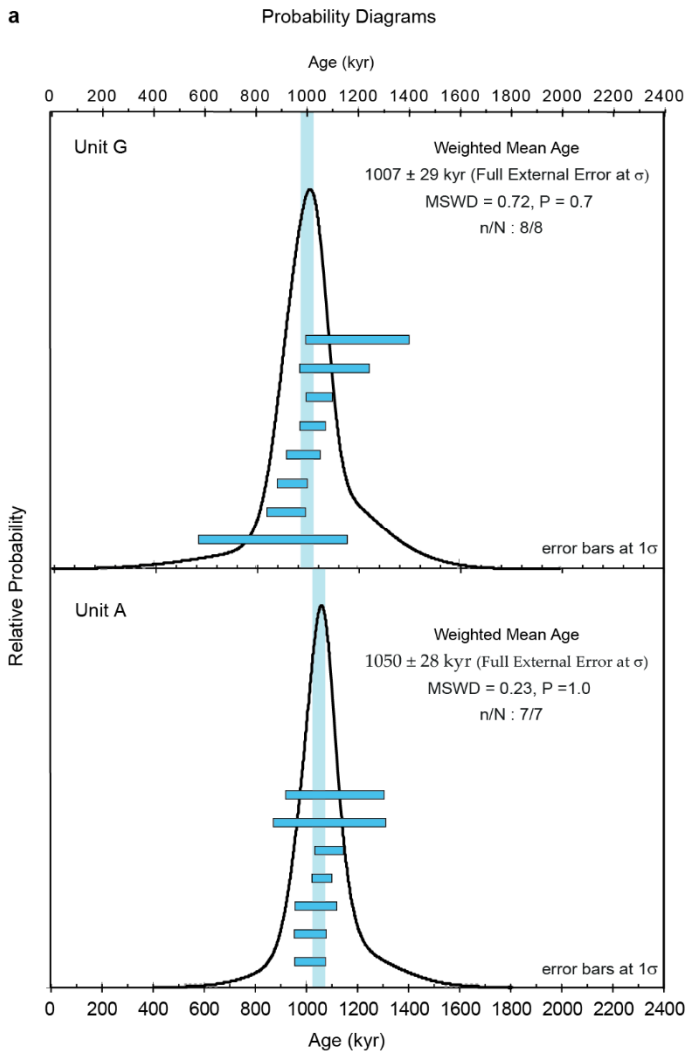
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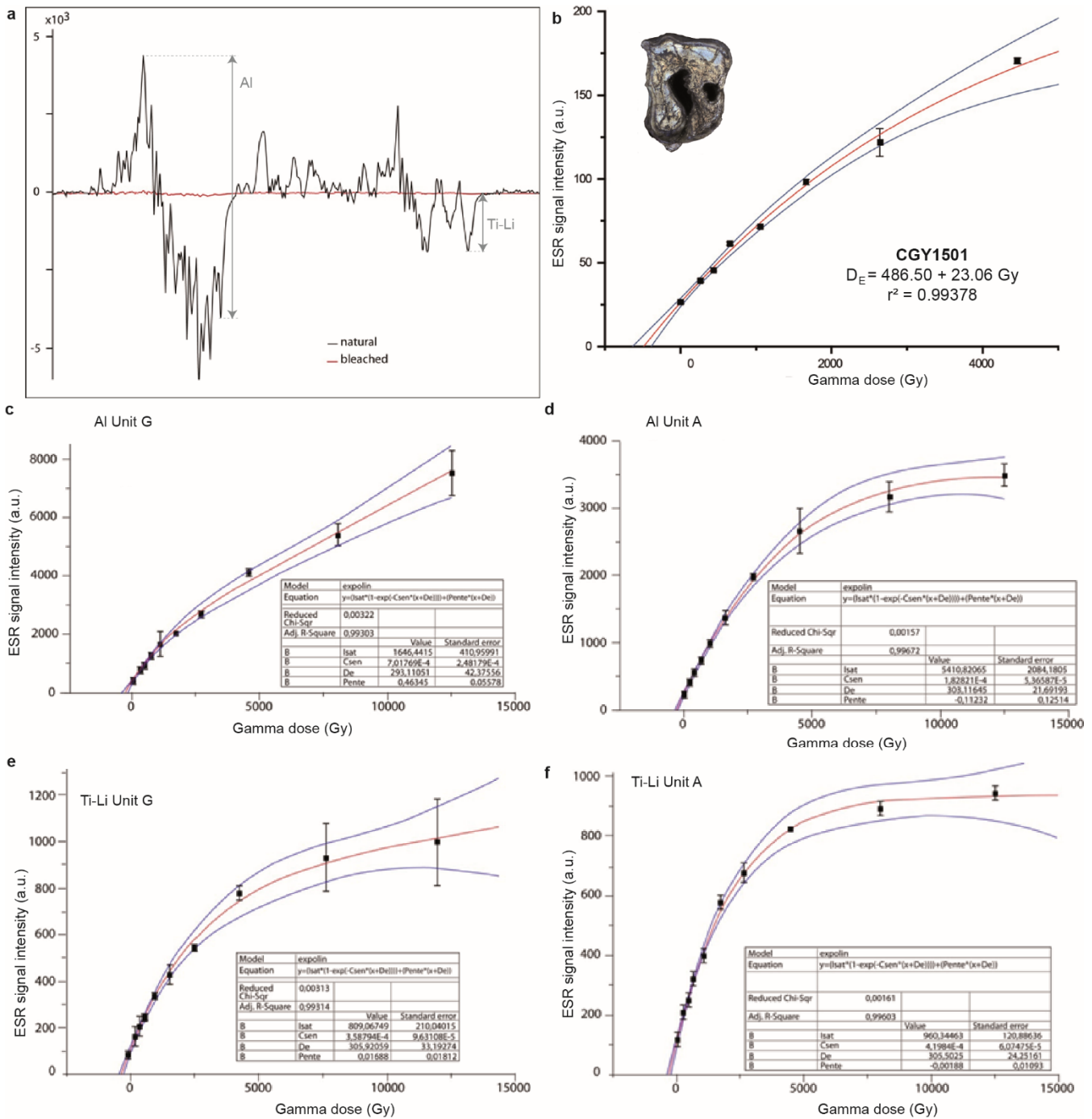
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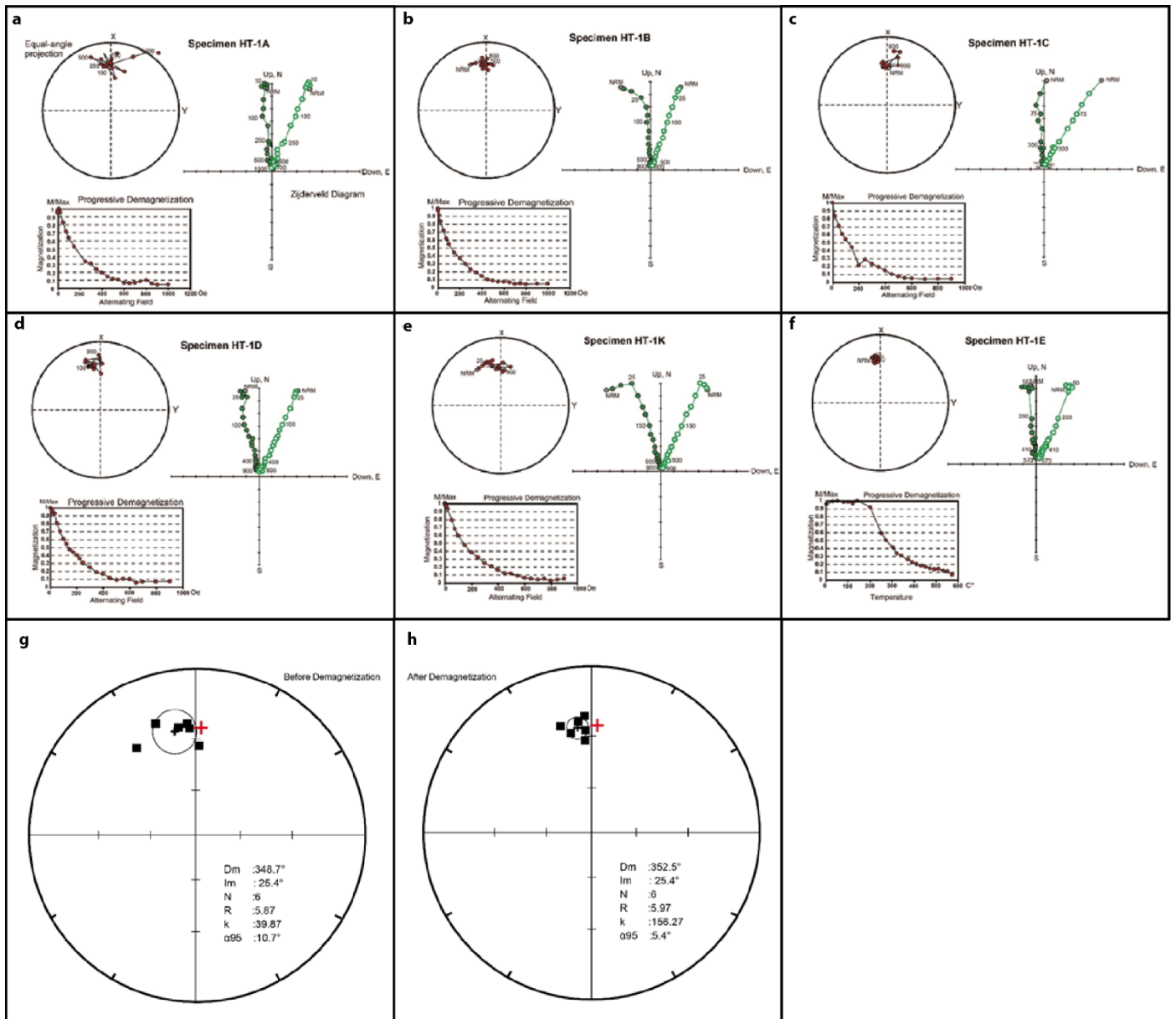
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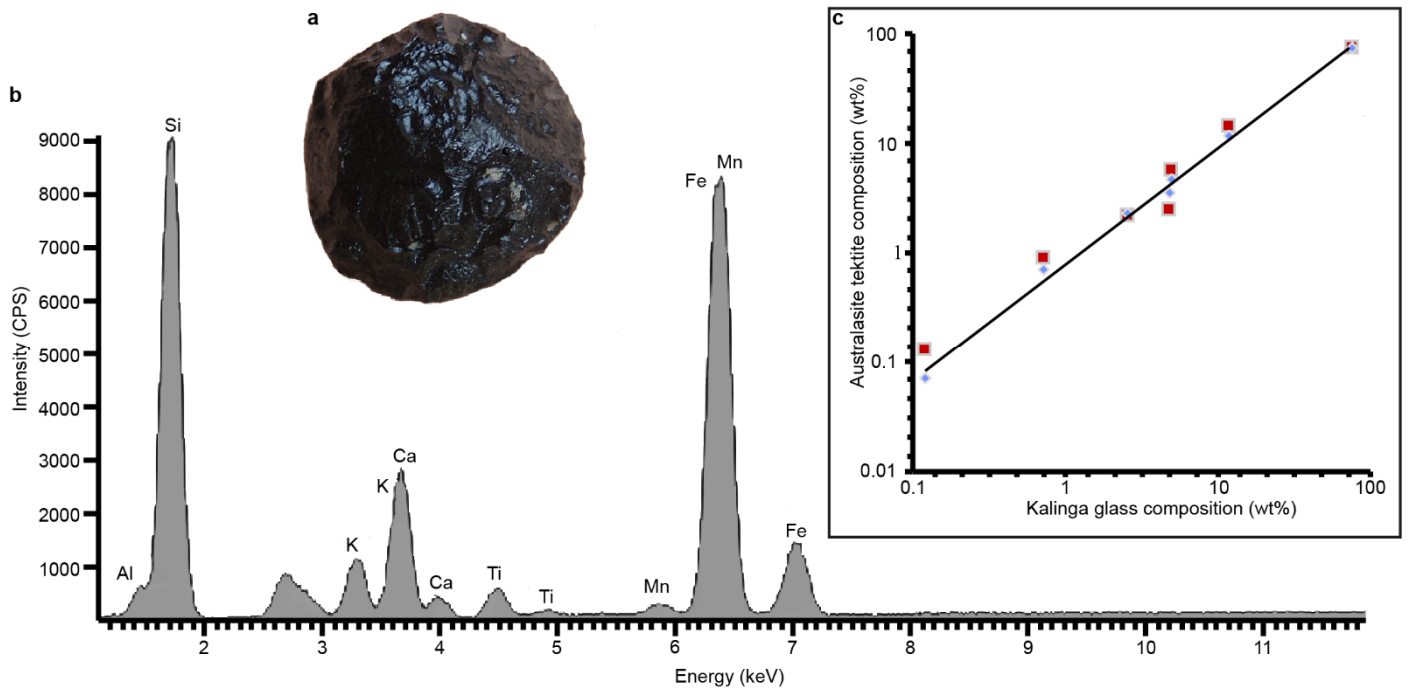
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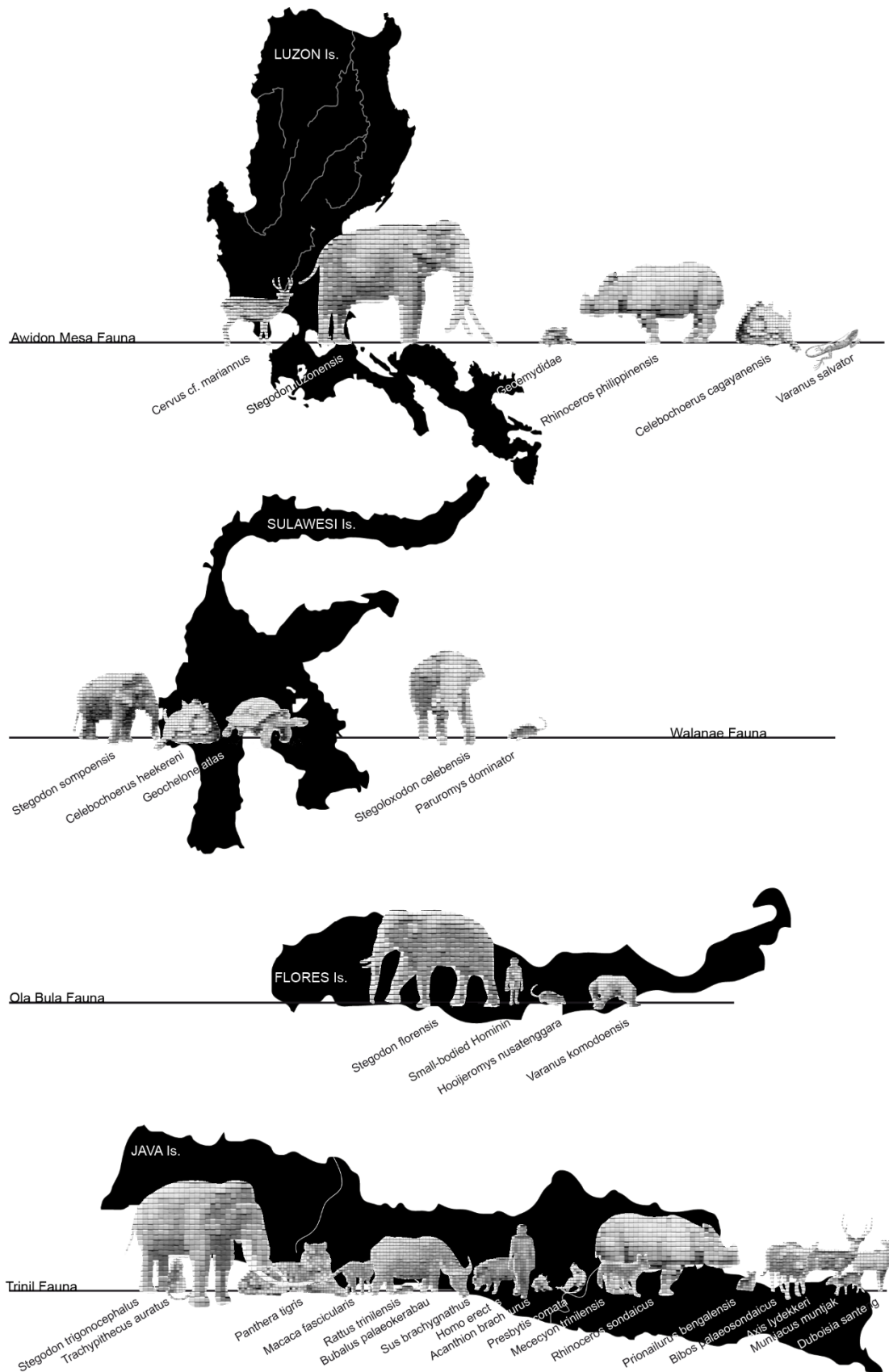
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Extended Data Table 1 | ESR/U-series results for the rhinoceros tooth. a, U-series data for the tooth CGY1501. b, ESR/U-series data and age.

a

Sample	Tissue	U (ppm)	$^{234}\text{U}/^{238}\text{U}$	$^{230}\text{Th}/^{232}\text{Th}$	$^{230}\text{Th}/^{234}\text{U}$	$^{2220}\text{Rn}/^{230}\text{Th}$	Apparent U-series
							ages ¹ (ka±2σ)
IPH-2015-09 CGY1501	dentine	52.3336 ± 0.1692	1.3701 ± 0.0062	141.40	0.8950 ± 0.0051	1.000	220.70 ± 3.28
(R-2014-JI- 095)	enamel	0.2356 ± 0.0001	1.2564 ± 0.0009	48.96	0.8147 ± 0.0014	0.976	164.86 ± 0.96

¹Apparent U-series obtained for dental tissues should be regarded as minimum age estimates

b

Sample	Tissue	Palaeodose	U uptake	D_{α}	$D_{\beta 1}$	$D_{\beta 2}$	D_{γ}	D_{total}	ESR/U-series
		D_E (Gy)	parameter p	Internal ¹ (μGy/a)	(μGy/a)	(mGy/a)	(γ + cosmic) ³ (μGy/a)	total (μGy/a)	US ⁴ (ka±1σ)
IPH-2015-09 CGY1501	dentine	486.50 ± 23.06	-0.1636 ± 0.0893	47 ± 8	208 ± 35	50 ± 4	387 ± 16	692 ± 38	709 ± 58
(R-2014-JI- 095)	enamel		0.3834 ± 0.1530						

Eventual radium and radon losses from the dental tissues were estimated from cross-checked γ and α data¹⁰¹. Dose conversion factors of Guérin and co-authors²⁵ were used. Water contents of 0±0%, 7±5% and 10±5% were used for enamel (fixed), dentine (fixed) and sediments (difference in mass between the natural sample and the same sample dried for a week in an oven at 50°C) respectively.

¹ A k-value of 0.13 ± 0.02 was used following Grün and Katzenberger-Appel¹⁰².

² The enamel thickness removed during preparation process was taken into account in the beta contribution calculation¹⁰³. The following values were used for the age calculation: 1505±376μm, 351±88μm and 45±12μm for the initial thickness, thickness after preparation on the dentine side and on the sediment side respectively.

³ Cosmic dose was estimated from depth using the Prescott and Hutton's formulae³⁰. Because 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, a depth of 2.75m was used for the cosmic dose rate estimation as an intermediate value between the 7m of sediments that once covered the archaeological layer and the present 70cm to 1.20m depth at which the archaeological material was recovered, and as an average between the once full thickness of the archaeological layer and its present thickness where the archaeological material was recovered. A cosmic dose estimated from a depth of 7m would result in a 10% older age for the Unit F and a cosmic dose estimated from a depth of 1m would result in a 7% younger age for the Unit F.

⁴ Uncertainties on the ESR/U-series ages were calculated using Monte-Carlo approach following Shao and co-authors¹⁰⁴

SUPPLEMENTARY INFORMATION

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 fragment¹. 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 were 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 volcanoclastic 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 grain size analysis from the baulks of the Main Excavation and Trench H (Extended Data Fig. 1).

Grain size 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 mineral content of the archaeological layer Unit F was obtained from X-ray Powder Diffraction (XRD) on 30g sub-samples placed into a Bruker[®] 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.

We applied three different geochronological methods, each of which are based on different physical principles. ⁴⁰Ar/³⁹Ar 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/Th) dating 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 $^{40}\text{Ar}/^{39}\text{Ar}$, the obtained ages correspond to the crystallization age of the plagioclases. Since the sedimentary units from which the crystals were extracted are not primary volcanoclastic deposits but instead fluvial layers, the true depositional ages of these units must be younger than the Ar-Ar ages we obtained⁶. 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 geochronometer⁷. The ESR-U/Th 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/Th 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 $^{40}\text{Ar}/^{39}\text{Ar}$ 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.

Combined ESR and 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-authors⁸. 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 were determined using a single saturating exponential function from the eight first aliquot intensities according to the protocol proposed by Duval and Grün⁹ (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-authors¹⁰. 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 ²³⁸U decay chain was observed. Uranium was measured statistically by ²³³U, ²³⁵U, ²³⁶U and ²³⁸U on Faraday cups and ²³⁴U simultaneously on a secondary electron multiplier (SEM). Thorium was analysed with ²³⁰Th and ²²⁹Th alternately on the SEM and ²³²Th 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 ²³⁸U/²³⁵U to the value of 137.760 for the HU-1 standard and to the value of 137.818 for natural samples¹¹ 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 $\delta^{234}\text{U}$ measured in the HU-1 standard. Hydride interferences, machine abundance sensitivity and amplifier gains were evaluated every day prior to sample measurements. The ²³⁰Th/U ages were calculated using half-lives of 75,584 years and 245,620 years for ²³⁰Th and ²³⁴U, respectively¹². The ESR-U/Th ages were calculated with the “ESRUS” Matlab software written by Qingfeng Shao¹³. Lastly, dose rates (D_a) contributions, U-uptake parameters and ESR/U-series ages were calculated applying the classical US model¹⁴, which provided an age of 709 ± 68 (1 σ) 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 A₄) and the other one in Unit G (Layer G₁) 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 radioactivity¹⁵. 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 deposition⁷. 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-authors¹⁸. After extraction, each sample was split into eleven aliquots. Nine of them were irradiated with a γ 60Co 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 approximately 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 structure¹⁸. 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 D²⁰. 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 approach²³. 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-spectrometry²⁴. Age calculations were performed using the dose-rate conversions factors from Guérin and co-authors²⁵, 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 Grün²⁹ and a cosmic dose rate calculated from the equations of Prescott and Hutton³⁰. 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 loam³¹. The measured water content of Unit A and G, respectively $15\% \pm 5$ and $13\% \pm 5$, 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 aluminum 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 3.0³⁴ 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 A₄) and Unit G (Layer G₁) were selected for the laser fusion ⁴⁰Ar/³⁹Ar single-crystal dating method. After crushing and sieving, feldspars ranging from 500 μ m 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 β 1 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-authors³⁵. 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 Ma³⁷, the total decay constant of Min and co-authors³⁸ and the ⁴⁰Ar/³⁶Ar atmospheric ratio of 298.56³⁹. 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 $2.0\text{--}2.2 \times 10^{-17}$ and $5.0\text{--}6.0 \times 10^{-19}$ mol for ⁴⁰Ar and ³⁶Ar, 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-authors³⁴, 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 3.0⁴⁰ 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 ⁴⁰Ar/³⁶Ar initial intercept (i.e. 296.8 ± 4 and 298.8 ± 9 ; 2σ) equivalent within uncertainties to the atmospheric ratio³⁹. 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 G₂). 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 $\sim 10 \text{ cm}^3$, 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 20° C, 30° C to 50° 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 Zijdeveld diagrams of all the six analysed specimens are shown in Extended Data Fig. 7 a-e. The Zijdeveld 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 $\sim 10\%$ 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 580° C, when magnetic intensity was reduced to $\sim 10\%$ 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 Software⁴¹ and super IAPD 2000 that uses principal component analysis⁴² and calculates site and mean directions following Fisher⁴³. The maximum angular deviation was set at $< 5^\circ$. The mean ChRMs direction of the six specimens combined was close to the present-day Normal polarity ($D_m = 352.5^\circ$, $I_m = 25.4^\circ$; Extended Data Fig. 7 g-h). Applying the criteria for palaeomagnetic data reliability of Butler⁴⁴ this outcome is reliable ($R = 5.97$, $k = 156.27$, $\alpha_{95} = 5.4^\circ$).

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 \pm 2 ka ago⁴⁵.

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 Manila⁴⁵. 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 $77 \times 10^{-9} \text{ m}^3/\text{kg}$ 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 data⁴⁵ which shows a range from 57 to $103 \times 10^{-9} \text{ m}^3/\text{kg}$ and an average of $82 \pm 10 \times 10^{-9} \text{ m}^3/\text{kg}$ (n=152) according to the literature⁴⁶ and a mean of $87 \pm 6 \times 10^{-9} \text{ m}^3/\text{kg}$ and a range from 69 to $129 \times 10^{-9} \text{ m}^3/\text{kg}$ 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 $10^{-6} \text{ Am}^2/\text{kg}$ (maximum $4.10^{-6} \text{ Am}^2/\text{kg}$ ⁴⁸), SIRM in low susceptibility obsidian is above $10^{-3} \text{ Am}^2/\text{kg}$ with the lowest measured value being above $10^{-5} \text{ Am}^2/\text{kg}$ on samples from Lipari (Italy)⁴⁹. The Kalinga sample yield an SIRM of $0.65.10^{-6} \text{ Am}^2/\text{kg}$ (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.

μ XRF 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 published⁵⁰.

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 Ma⁴⁵. 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 $^{40}\text{Ar}/^{39}\text{Ar}$ 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/Th on enamel lower tail probability at 1 sigma) and not younger than 631 ka (ESR-U/Th 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 forests⁵¹.

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 Sémah⁵² 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 mammillae, 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 Koenigswald⁵⁴ and de Vos and Bautista⁵⁵, 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 Bautista⁵⁵. Currently, only fragments of antlers are present in the collections of the National Museum of The Philippines from surface discoveries. De Vos and Bautista⁵⁵ 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 number⁵⁷. 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-authors⁶⁰.

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 marrow⁶¹. 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 experiments⁶¹. 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 grooves 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-authors⁶⁰, 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 material⁶⁰ (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 latter, 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 grooves 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-authors⁶⁰ 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. Berhensmeyer⁶² noted that isolated marks can be misinterpreted as cut marks, but that multiple organized marks, positioned on specific areas such as metapodials⁶³, can be confidently attributed to cut marks. In addition, Crader⁶⁴ 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 flakes⁶⁶. While they have been found primarily outside clear stratigraphic context⁶⁷, the Javanese horsehooves, bolas and polyhedrons, along with handaxes and the small ‘Sangiran flakes’ were recovered in a well-dated 800 ka old layer⁶⁸ 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. fauna⁷¹, and with a *Homo erectus* molar⁷². 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 years⁷³. 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 Menge⁷⁴. 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 China⁷⁵. 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 site⁷⁶. This assemblage has been assumed to be lower Palaeolithic, and contains a handaxe, and what Pawlik⁷⁷ interprets as a horsehoof-like core and a “quasi-Levallois” flake, all of which were found eroding from the present day soil⁷⁸. 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 Pawlik⁷⁹). Peterson⁸⁰ 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 younger⁸¹.

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 anvil⁸². 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 Isaac⁸⁵ and more recently by Delagnes and co-authors⁸⁶, typically less than one hundred pieces. For example, this is the case at Fuente Nueva 3 with 17 flakes⁸⁷, Castel di Guido with 96 flakes⁸⁸, La Polledrara with 61 artefacts⁸⁹, Notarchirico with 42 chert and limestone artefacts⁹⁰, Southfleet Road with about a hundred artefacts⁹¹, 14 flint and quartzite artefacts from Ambrona⁹² and 34 flint and quartzite artefacts from Aridos 2⁹³. 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-tools⁸⁵, Barranc de la Boella - Pit 1 with 125 recovered lithic artefacts⁹⁴, Aridos 1 with 331 recovered artefacts⁹³ and Ficoncella with 409 lithic implements of which 296 represent small flakes⁹⁵. The same observations are true for more recent sites dating back to the late Middle Pleistocene⁹⁶. 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 $\pm 1\sigma$. 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-authors²⁵. Alpha and beta attenuations were estimated for the selected grain sizes from the tables of Brennan¹⁰³; k-value of 0.15⁷, cosmic dose rate calculated from the equations of Prescott & Hutton³⁰. 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 ($\delta_{bl} = ((I_{nat} - I_{bl}) / I_{nat}) \times 100$). Mean age are weighted average calculation using Isoplot software.

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

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

	^{238}U (ppm)	^{232}Th (ppm)	^{40}K (%)	$^{226}\text{Ra}/^{238}\text{U}$	$^{222}\text{Rn}/^{238}\text{U}$
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 | $^{40}\text{Ar}/^{39}\text{Ar}$ individual age obtained on large transparent plagioclase crystals (1-1.5mm) for each units investigated.

Lab. code	^{40}Ar (mol es)	^{36}Ar V	$\pm\sigma_3$ 6 V	^{37}Ar V	$\pm\sigma_3$ 7 V	^{38}Ar V	$\pm\sigma_3$ 8 V	^{39}Ar V	$\pm\sigma_3$ 9 V	^{40}Ar V	$\pm\sigma_4$ 0 V	$D^{(1)}$	$\pm\%2$ σ_D	$\%^{40}\text{A}$ r^*	Age (Ka)	$\pm\sigma$	K/C a	$\pm 1\sigma$
UNIT A																		
N14 40- 01	4.469 E-16	1.161 E-06	3.0 28	0.0007 286	1.1 67	0.0000 003	5.1 95	3.368 E-05	0.9 45	3.262 E-04	0.3 01	1.011 17	0.1	18.86	111 0.6	\pm 192 .7	0.00 77	\pm 0.00 01
N14 40- 02	6.957 E-16	1.862 E-06	0.8 30	0.0010 018	0.6 71	0.0000 010	3.3 62	3.810 E-05	0.5 28	5.078 E-04	0.1 48	1.011 22	0.1	12.73	103 6.3	\pm 81. 9	0.00 63	\pm 0.00 01
N14 40- 03	3.029 E-16	8.823 E-07	1.2 51	0.0009 109	1.0 00	0.0000 007	3.4 04	3.618 E-05	0.4 12	2.211 E-04	0.3 47	1.011 14	0.1	27.23	101 4.7	\pm 62. 5	0.00 66	\pm 0.00 01
N14 40- 04	2.204 E-16	6.547 E-07	1.1 71	0.0007 606	0.7 21	0.0000 006	3.3 73	2.861 E-05	0.3 47	1.608 E-04	0.4 32	1.011 14	0.1	31.70	108 8.2	\pm 56. 0	0.00 63	\pm 0.00 01
N14 40- 05	2.030 E-16	5.466 E-07	0.7 24	0.0005 167	0.7 22	0.0000 005	4.1 52	2.474 E-05	0.1 34	1.482 E-04	0.4 68	1.011 13	0.1	29.12	106 0.1	\pm 38. 7	0.00 80	\pm 0.00 01
N14 40- 06	1.268 E-16	3.406 E-07	5.0 07	0.0003 089	0.9 25	0.0000 002	6.6 34	1.429 E-05	1.3 23	9.253 E-05	0.6 14	1.011 11	0.1	27.67	108 9.6	\pm 219 .6	0.00 77	\pm 0.00 01
N14 40- 07	1.557 E-16	4.503 E-07	1.9 94	0.0006 225	0.7 81	0.0000 005	4.0 51	2.953 E-05	0.6 70	1.136 E-04	0.6 75	1.011 12	0.1	43.34	101 3.7	\pm 60. 5	0.00 79	\pm 0.00 01
UNIT G																		
N14 38- 01	2.477 E-16	8.033 E-07	2.6 44	0.0017 906	0.8 27	0.0000 016	2.1 94	8.396 E-05	0.4 45	1.808 E-04	0.7 40	1.011 14	0.1	78.82	105 3.8	\pm 51. 5	0.00 78	\pm 0.00 01
N14 38- 02	1.629 E-15	4.102 E-06	0.7 83	0.0005 999	0.6 75	0.0000 011	2.2 16	2.287 E-05	1.0 07	1.189 E-03	0.1 95	1.011 41	0.1	2.69	872. 6	\pm 292 .7	0.00 63	\pm 0.00 01
N14 38- 03	4.261 E-16	1.339 E-06	1.0 85	0.0017 111	0.7 73	0.0000 011	2.8 67	6.298 E-05	0.5 09	3.111 E-04	0.3 34	1.011 17	0.1	33.36	102 8.0	\pm 50. 5	0.00 61	\pm 0.00 01
N14 38- 04	3.685 E-16	1.269 E-06	2.2 44	0.0021 880	0.6 88	0.0000 015	2.5 82	8.559 E-05	0.5 55	2.690 E-04	0.3 50	1.011 17	0.1	50.64	991. 3	\pm 65. 8	0.00 65	\pm 0.00 01
N14 38- 05	1.853 E-16	5.135 E-07	2.3 42	0.0004 342	0.7 70	0.0000 004	4.1 86	1.723 E-05	1.0 20	1.353 E-04	0.6 65	1.011 13	0.1	22.78	111 3.9	\pm 136 .6	0.00 66	\pm 0.00 01
N14 38- 06	1.374 E-16	5.063 E-07	3.0 76	0.0009 813	0.7 86	0.0000 007	6.1 87	4.016 E-05	0.8 19	1.003 E-04	0.6 84	1.011 11	0.1	59.43	924. 1	\pm 76. 1	0.00 68	\pm 0.00 01
N14 38- 07	4.927 E-16	1.343 E-06	0.6 86	0.0008 393	0.7 66	0.0000 006	4.8 60	3.495 E-05	0.5 25	3.596 E-04	0.2 60	1.011 18	0.1	14.81	947. 9	\pm 59. 0	0.00 69	\pm 0.00 01
N14 38- 08	2.684 E-16	7.181 E-07	4.1 24	0.0006 374	0.7 68	0.0000 005	3.4 05	2.751 E-05	1.1 35	1.959 E-04	0.5 92	1.011 14	0.1	27.18	120 3.9	\pm 203 .2	0.00 72	\pm 0.00 01

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

Lab. Code	^{36}Ar	$\pm\sigma_{36}$	^{37}Ar	$\pm\sigma_{37}$	^{38}Ar	$\pm\sigma_{38}$	^{39}Ar	$\pm\sigma_{39}$	^{40}Ar	$\pm\sigma_{40}$
	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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