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Co-occurrence of Acheulian and Oldowan artifacts with *Homo erectus* cranial fossils from Gona, Afar, Ethiopia

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Although stone tools generally co-occur with early members of the genus *Homo*, they are rarely found in direct association with hominins. We report that both Acheulian and Oldowan artifacts and *Homo erectus* crania were found in close association at 1.26 million years (Ma) ago at Busidima North (BSN12), and ca. 1.6 to 1.5 Ma ago at Dana Aoule North (DANS) archaeological sites at Gona, Afar, Ethiopia. The BSN12 partial cranium is robust and large, while the DANS cranium is smaller and more gracile, suggesting that *H. erectus* was probably a sexually dimorphic species. The evidence from Gona shows behavioral diversity and flexibility with a lengthy and concurrent use of both stone technologies by *H. erectus*, confounding a simple “single species/single technology” view of early *Homo*.

INTRODUCTION

The Gona Project study area, Afar, Ethiopia, has yielded numerous Oldowan archaeological occurrences from 2.6 to 2.0 million years (Ma) ago (1). Study of sediments younger than 2.0 Ma ago at Gona can contribute to understanding Mode 2 (Acheulian) technological emergence and evolution and the makers of this technology (2). We previously reported a pelvis from Gona, furthering our understanding of *Homo erectus* pelvic morphology and evolutionary biology (3). Here, we report combined Oldowan (Mode 1) and Acheulian (Mode 2) stone tool assemblages and hominin cranial fossils found in direct association that derive from stratigraphic levels dating to 1.26 Ma ago at Busidima North (BSN12) and approximately 1.6 to 1.5 Ma ago at Dana Aoule North (DANS) (4, 5) (Figs. 1 and 2 and figs. S1 and S2), which illuminate *H. erectus* variability and behavioral flexibility.

RESULTS

DAN5 and BSN12 sites at Gona: Stratigraphy and archaeology

Abundant stone artifacts, fossil fauna, and a homininal partial calvarium (BSN12/P1) were found at BSN12 (Figs. 3 and 4) in direct association with the Boolihinan Tuff (BHT) (4). Mode 1 artifacts were recovered in situ from the BHT, and glass shards of tephra that geochemically match the BHT were found cemented onto the BSN12/P1 parietal and on both Mode 1 and Mode 2 artifacts (Figs. 3 and 4, fig. S1, sections S1 to S4, and auxiliary data file 1A). Twenty-eight meters of reverse magnetized sediments overlie the BHT, capped by an additional 18+ m of normally magnetized sediments that we assign to the upper Matuyama and Brunhes Chrons, respectively (Fig. 2 and auxiliary data file 1B). Normally magnetized sediments occur 6 m below the BHT, which we interpret to represent the Olduvai Subchron (1.95 to 1.78 Ma ago) (4). The BHT shows strong geochemical affinities with a tuff from Melka Kunture, Ethiopia, dated to 1.262 ± 0.034 Ma ago (1σ uncertainty on ages reported here and elsewhere in text) (5) (auxiliary data file 1, A and B, and sections S1 to S3), consistent with its stratigraphic position in the middle of the Matuyama Chron.

At the DAN5 locality, ~5.7 km northeast of BSN12 (figs. S2 to S5), a well-preserved hominin cranium DAN5/P1 (Fig. 3) and both Mode 1

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and Mode 2 artifacts associated with cutmarked bones (sections S4 and S5) were found eroding in weakly developed paleosols that were later buried and overprinted by a well-developed vertic paleosol (Fig. 2, fig. S4, sections S6 and S7, and auxiliary data file 1, C to E, for paleosol descriptions of both the DAN5 and BSN12 sites). Although much of the cranium was found on the surface, the occipital and left maxilla were found in situ, along with six manuports and one Oldowan core (figs. S2 to S5). Freshly eroded Mode 1 and Mode 2 artifacts and fauna were also collected at the DAN5 hominin site, DAN5-South (~140 m south-southwest), and DAN5-West (~50 m west-northwest), all within the same general stratigraphic context, and subsequent site visits yielded additional freshly eroded artifacts and fauna bearing evidence of stone tool cutmarks. All the DAN5 area artifacts and fossils were found in close proximity and from the same stratigraphic interval within a fining upward sequence (Fig. 2 and figs. S2 to S5).

The DAN5 artifacts and fossils come from a siltstone unit in reversed magnetized sediments 6.5 m above the top of the Olduvai Subchron and 10.5 m below the base of the Jaramillo Subchron (4), with a well-developed, 8- to 9-m-thick, cumulic paleosol separating the artifacts and cranium from the normally magnetized stratigraphic interval above (Fig. 2). The DAN5 artifacts and cranium are constrained between 1.78 and 1.07 Ma. Using average local sedimentation rates (auxiliary data file 1B), the age estimate of DAN5 can be interpolated and narrowed to ~1.6 to 1.5 Ma (4). This estimate is reasonable, given the thick paleosol and gravel that separate DAN5 from the base of the Jaramillo Subchron above and the stratigraphic proximity to the underlying Olduvai Subchron (Fig. 2 and sections S1 to S3).

The DAN5 and BSN12 stone tool assemblages include Mode 2 handaxes and picks (“large cutting tools” or LCTs) and Mode 1 artifacts (unshaped cores and débitage) (Fig. 4, Table 1, and section S4).
The two Gona sites highlighted here were close to riverine sources of raw materials containing trachyte, rhyolite, and basalt cobbles from which most of the artifacts were made. The DAN5 LCTs share broad similarities with those from other early Acheulian sites, such as Konso (Ethiopia) (6) and Kokiselei (Kenya) (7), but differ in some details (table S1). About half of the DAN5 and BSN12 handaxes were made on cobbles, whereas a majority of the handaxes at the 1.75-Ma and younger Konso sites were flake-based (6). A majority of the DAN5 handaxes (87%) were bifacially worked, with better representation of unifacial flaking at Konso. The early Konso handaxes also appear to be longer on average and slightly thinner than those of DAN5. The differences between the Gona and Konso assemblages probably reflect a strong preference for more open dry and wet grassland habitats, consistent with the bulk geochemistry and δ13C values from associated soil carbonates (16) and fossil teeth (auxiliary data file 1, F to H). In summary, the paleoenvironmental information indicates that hominin toolmakers lived in close proximity to ancient rivers, with riparian woodlands adjacent to open habitats.

DAN5 and BSN12 hominin crania

The larger BSN12/P1 (Fig. 3, fig. S6, sections S8 and S9, and table S2) adult calvarium includes portions of the right orbital margin, frontal squama, and left parietal. The BSN12/P1’s robust supraorbital torus is less arched and thickens laterally where it is joined by the temporalis lines. There is slight sagittal keeling of the vault with some thickening at bregma and parasagittal flattening of the parietal. Endocranial volume is estimated to be between 800 and 900 ml. The robusticity of the supraorbital torus suggests that the individual was male.

The more complete DAN5/P1 cranium includes much of the vault and maxillae with right P4-M1 and left P3-M3 (Fig. 3, fig. S7, sections S8 and S9, and tables S2 and S3). The vault is globular with an arcing supraorbital torus that thins laterally and projects anteriorly forming a well-defined post-toral sulcus. The small endocranial volume (~598 ml) makes it the smallest adult erectin known from Africa (fig. S7). The vault lacks evidence of sagittal keeling although there is a midline parietal swelling above lambda. The vault is thickened at asterion, and lambda and angular tori are present. The anterior margin of the zygomatic root is transversely oriented, and the absence of anterior inflation of the maxillary sinus produces a deep canine fossa. Although the canine is missing, its alveolus is short and ends below the nasal floor indicating a small root. The combination of a gracile neurocranium and face along with a small canine alveolus suggests that this individual was female.

The smaller more gracile DAN5/P1 and the larger more robust BSN12/P1 crania share derived anatomical features diagnostic for *H. erectus*, yet they differ in several ways (e.g., overall size, details of supraorbital torus robusticity and morphology, sagittal and coronal contours of the vault, degree of midline keeling, and course of the temporalis lines) that require further comment (see sections S8 and S9). The DAN5/P1 cranium bears similarity to the 1.85- to 1.76-Ma Dmanisi crania (8, 9), the 1.6- to 1.5-Ma juvenile KNM-ER 42700 (10), and the small 0.95-Ma Olorgesailie [KNM-OL 45500 (11)] *H. erectus* crania, and it differs from the typical Asian *H. erectus* crania by having a smaller endocranial volume, a weakly flexed occipital, and lack of continuous mound-like occipital torus—characters that may correlate with overall size (10, 12). The BSN12/P1 fossil is similar to the more robust African specimens such as Olduvai Hominid 9, the ca. 1.1-Ma specimens from Middle Awash, Ethiopia [BOU-VP-2/66 (13)] and Buia, Eritrea [UA-31 (14)], and those from Indonesia and eastern Asia by having a longer and lower vault with a thickened supraorbital torus. This anatomical variation in the Gona specimens can be interpreted in several ways. First, the older DAN5/P1 individual may retain more primitive anatomy (e.g., smaller size, gracile vault, and thin supraorbital tori) than the younger BSN12/P1 fossil, and this variation is due to secular anagenetic evolutionary trends within African *H. erectus*. Alternatively, the size and anatomical variation observed in the Gona specimens is primarily a consequence of sexual dimorphism within a single species. Last, these fossils might reflect a degree of taxonomic diversity previously unrecognized in the Afar for the genus *Homo* (15).

Paleoenvironmental settings

At DAN5, the combination of stratigraphic proximity to a thick cobble conglomerate, the associated fauna (table S4), and data from paleosols is consistent with an ancient landscape that included riparian woodlands with edaphic grasslands (sections S6 and S7 and auxiliary data file 1, C to E). The fauna recovered from the BSN12 site (table S4) shows a strong preference for more open dry and wet grassland habitats, consistent with the bulk geochemistry and δ13C values from associated soil carbonates (16) and fossil teeth (auxiliary data file 1, F to H). In summary, the paleoenvironmental information indicates that hominin toolmakers lived in close proximity to ancient rivers, with riparian woodlands adjacent to open habitats.

The stable isotope values of the DAN5/P1 maxillary right first molar (δ13C = −9.2‰ and δ18O = −2.0‰) are consistent with a diet dominated by C3 plants or, alternatively, broad spectrum omnivory (e.g., eggs, insects, and browsing herbivores). The δ13C value from DAN5/P1 is among the lowest δ13C values for early Pleistocene *Homo* teeth that have been sampled (17, 18). It is within the range of δ13C values from *Homo* for specimens older than 1.65 Ma ago (−9.9 to −3.9‰, identified to *Homo* sp. indet. from the Turkana Basin and *Homo rudolfensis* from the Malawi Rift), but it is lower than the δ13C values for *Homo* < 1.65 Ma ago, which have only been reported from the Turkana Basin (−4.3 ± 1.1‰; range, −5.6 to −2.6‰; n = 10). While the low δ13C value from DAN5/P1 is noteworthy given higher δ13C values from contemporaneous *Homo* in Turkana (indicating consumption of more C4 resources there), in our view, there is not enough isotopic data for *Homo* from this time period to make further interpretations from this single Gona sample. However, if this low δ13C value from DAN5/P1 were more broadly represented in subsequent sampling, then it would be indicative of a broad, varied diet. Additional isotopic data from more specimens and from a greater geographic range are needed to put the data from DAN5/P1 into context.
DISCUSSION

At this time, we interpret the marked anatomical variability between DAN5/P1 and BSN12/P1 to be a consequence of a widely dispersed, long-lived, sexually dimorphic species. The earlier Dmanisi sample also shows a remarkable degree of size and sexual dimorphism within a sample of *H. erectus* (8, 9). The broad dispersion and probable low population density of *H. erectus* created opportunities for developing regional anatomical morphs due to periods of interrupted gene flow. As shown by recent studies of ancient DNA, hominins can and will recognize each other as viable mates even after many hundreds of thousands of years of separation (19), such that a temporary interruption in gene flow does not necessarily result in speciation. This interrupted mixing of genes between small, dispersed groups can lead to a highly polymorphic species that will share many major anatomical and behavioral attributes but still express a great degree of phenetic variation.

The archaeological record at Gona is broadly consistent with this scenario, as the co-occurrence of Mode 1 and Mode 2 stone tools with *H. erectus* over time suggests variably conserved behavioral traits and traditions among small, dispersed populations. Early Acheulian sites almost always have Mode 1 cores and flakes found in association with LCTs, with varying abundances documented at sites such as Konso (6), Kokiselei (7), and Melka Kunture (Garba IV D site) (20). In addition, it is our observation at Gona and elsewhere that many archaeological sites dating to 1.6 to 0.5 Ma ago only contain Mode 1 stone tools, although these sites are probably underreported. The
Gona evidence suggests that most of these Mode 1 sites were created by *H. erectus* (sensu lato), not a different hominin species, particularly in areas that do not preserve evidence of other hominins in the Middle Pleistocene, such as the Afar.

Seeing the expression of *H. erectus* stone tool technology as variable, flexible [e.g., (21)], and a reflection of many different factors (such as site sampling sizes, tool function, distance to stone raw material sources, environmental variability, population size, degree of contact with other groups, etc.) can help demystify this observed pattern, as well as observations of seemingly "advanced" LCTs (i.e., symmetrical, thin, and/or invasively flaked) found alongside "crude" LCTs (e.g., at FLK-West, BSN12, and DAN5) and the lack of LCTs at some sites outside of Africa.

Some early hominin populations, including small groups of *H. erectus*, left Africa, making it to Eurasia by ~1.8 Ma ago [e.g., at Dmanisi (22)]. Given the early age of the Dmanisi site, it is possible that the population that left for Eurasia departed Africa by ~1.8 to 1.9 Ma ago, i.e., before the development of the Acheulian. Thus, the group(s) that remained in Africa most likely developed Acheulian technology, which was later carried along via subsequent waves of migrations to Asia [e.g., (23)]. Some researchers (7) also hypothesized that multiple hominin species may have been responsible for two distinct contemporary technologies. To the contrary, we argue here that the same hominin species, *H. erectus*, that remained in Africa invented the Acheulian, variably and flexibly using both Mode 1 and Mode 2 stone technologies, a view also shared by others [e.g., (6)].

At a basic level, Acheulian toolmakers created handaxes and picks using large-sized raw materials, with complex execution demanding advanced hierarchical organization (24), while also creating Mode 1 stone tools, whenever sharp-edged cutting flakes were needed. Stone tool function could be a particularly important factor in the variable expression of stone technologies. Cutmarks or hammerstone-percussed bones were not identified on the abundant BSN12 fossils. The DAN5 fauna, however, yielded two bones with modifications, showing disarticulation and defleshing from a large range of animal sizes (fig. S8, section S5, and table S5), consistent with the evidence of hominin animal consumption at FLK-West at Olduvai Bed II (Tanzania) (25). The evidence from Gona suggests that *H. erectus* had population-level behavioral diversity and flexibility, with a lengthy and concurrent use of both Mode 1 and Mode 2 technologies, the variable expression of which deserves continued research. Thus, further field investigations will be important to find additional fossil hominins and their cultural remains in the 2.0- to 1.0-Ma time interval.

### MATERIALS AND METHODS

**Methods**

**Microprobe analysis**

Tuffs were first treated with 2 M HCl to remove any carbonate, briefly rinsed in 2% HF, and washed in distilled water. Glass were separated into size fractions of >120, 60 to 120, and <60 μm. All glass analyses were carried out using a Cameca SX-100 electron microprobe located at New Mexico Institute of Mining and Technology following sample preparation as described in (26). Samples were examined using backscattered electron imagery, and selected particles were quantitatively analyzed. Elements analyzed include Na, Mg, Al, Si, P, S, Cl, K, Ca, Ti, Mn, and Fe. An accelerating voltage of 15 kV and a probe current of 10 nA were used. Beam sizes of between 10 and 20 μm were used to avoid Na volatilization (27). Analytical details have been listed in footnotes of auxiliary data file 1A. We noted that analyses of many

| Artifact type | BSN12 in context | BSN12 surface | BSN12 total | DANS-M in context | DANS-M surface | DANS (S & W) in context | DANS (S & W) surface | DANS total |
|---------------|-----------------|---------------|-------------|-------------------|----------------|--------------------------|----------------------|------------|
| Handaxes      | 1               | 2             | 3           | 3                 | 3              | 6                        | 3                    | 15         |
| Picks         | 1               | 0             | 1           | 3                 | 0              | 1                        | 1                    | 5          |
| Cleavers      | 0               | 0             | 0           | 0                 | 0              | 0                        | 0                    | 0          |
| Retouched     | 0               | 0             | 0           | 0                 | 0              | 1                        | 2                    | 3          |
| large flakes/ | 1               | 5             | 6           | 0                 | 0              | 0                        | 1                    | 1          |
| knives        |                 |               |             |                   |                |                          |                      |            |
| Mode 1 cores  | 12              | 25            | 37          | 3                 | 5              | 3                        | 9                    | 20         |
| Whole flakes  | 10              | 90            | 100         | 0                 | 3              | 3                        | 15                   | 21         |
| Retouched     | 1               | 5             | 6           | 0                 | 0              | 0                        | 1                    | 1          |
| flakes/scrapers |             |               |             |                   |                |                          |                      |            |
| Flake fragments | 10             | 39            | 49          | 0                 | 4              | 3                        | 13                   | 20         |
| Core fragments | 1               | 2             | 3           | 0                 | 1              | 0                        | 1                    | 2          |
| Cobbles       | 0               | 0             | 0           | 6                 | 0              | 3                        | 6                    | 15         |
| Broken/split | 3               | 0             | 0           | 0                 | 0              | 0                        | 0                    | 0          |
| cobbles       |                 |               |             |                   |                |                          |                      |            |
| Totals        | 39              | 163           | 202         | 15                | 16             | 20                       | 53                   | 104        |
of these tephra have been reported in previous publications but all analyses of all relevant tephra were repeated using the above procedures. Trace element analysis on a single bulk sample of volcanic ash, treated as described above, was carried out using the x-ray fluorescence method at the Washington State University Peter Hooper GeoAnalytical Lab, described in detail at that laboratory’s website. Powdered rock samples were fluxed with lithium tetraborate, fused into a glass bead, and then analyzed using a Thermo ARL Advant’XP+ automated sequential wavelength spectrometer. Intensities of all elements were corrected automatically for line interference and absorption effects using the fundamental parameter method. Precision of the method is typically better than 5% (relative standard deviation) for all trace elements. Because only a single sample was analyzed for trace elements, these data are included as a footnote to auxiliary data file 1A.

Paleomagnetism

Claystone and siltstone layers were sampled for paleomagnetic analyses. Four oriented samples were collected from each sedimentary horizon. In summary, 87 horizons were sampled in Dana Aoule, Busidima, and Asbole areas (auxiliary data file 1B). These data were initially reported in (4) and (3) although we report the compiled datasets and sampling locations here (Fig. 2 and auxiliary data file 1B). All samples were thermally demagnetized in ≥12 temperature steps ranging up to 580°C, and characteristic remnant magnetization (ChRM) directions for each sample were determined by principal components analysis (28). Site-mean ChRM directions were calculated using Fisher’s statistics (29). Ages for geomagnetic chrons and subchrons of teeth were performed using a Kiel Device and a Thermo Delta Plus gas-source mass spectrometer at the University of Utah, and a common acid bath device and a common acid bath device at Johns Hopkins University. Isotopic analyses were performed using a Kiel Device and a Thermo Delta Plus gas-source mass spectrometer at the University of Arizona, a common acid bath device and Finnigan MAT 252 mass spectrometer at the University of Utah, and a common acid bath device and a Thermo MAT 253 mass spectrometer at Johns Hopkins University. All measurements were made relative to working carbonate and enamel reference material, and typical precision of replicate analyses was 0.1‰ for both δ13C and δ18O measurements.

Paleosols

Trenches in the paleosols were excavated at the DAN5 and BSN12 sites, and soil stratigraphic units were designated to identify unique paleosols, often based on evidence of paleosol burial or reversals in particle size (31). Paleosols associated with the DAN5 and BSN12 sites were described in the field using Natural Resources Conservation Service techniques (32). Samples from the DAN5 and BSN12 paleosols were selected for soil morphological and geochemical analyses to characterize the physical and chemical processes, provide inference into type of surface vegetation, and estimate paleoclimate.

Paleosol clods were selected from bulk samples and measured for bulk density using the wax clod method (33). The results are reported in grams per cubic centimeter and used to estimate relative changes in strain. Aliquots of bulk paleosol samples were submitted to ALS Chemex for geochemical characterization of major, trace, and rare earth elements using lithium borate fusion and inductively coupled plasma atomic emission spectroscopy and inductively coupled plasma mass spectrometry.

The DAN5 and BSN12 bulk density and geochemical data were used to determine the extent and magnitude of weathering. Mobile element additions and losses were calculated using the mass transfer coefficient, τ (34, 35)

\[ \tau = \frac{C_{i,w} - C_{i,p}}{C_{i,p}} \]

where \( C \) is the mobile, \( j \), or immobile, \( i \), element concentration in the weathered, \( w \), or parent, \( p \), material. When \( \tau = 0 \), element \( j \) has not been added or removed from the profile with respect to \( i \). When \( \tau = -1 \), 100% of the element \( j \) has been removed compared to \( i \). In this study, Zr was assumed to be immobile. The \( \varepsilon \) for each depth interval, \( z \), is the relative change in volume, \( V \), between the parent and weathered portion of the profile

\[ \varepsilon_i(z) = \frac{V_w - V_p}{V_p} = \frac{C_{i,p} - C_{i,w}}{C_{i,w}} \]

The \( \varepsilon \) was estimated using bulk density and immobile element data, \( C_{i,p} \) and \( C_{i,w} \) in the right-hand side of Eq. 2. The \( \varepsilon \) incorporated into Eq. 1 normalizes the volumetric changes that can occur during weathering, for example, dilation and collapse. The strain correction can be substantial (36). We estimated the paleo-pH and mean annual precipitation using bulk geochemistry from uppermost B horizons (37, 38).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/10/eaaw4694/DC1

Supplementary Text

Section 51. Geologic context of sites
Section 52. Geochemistry of the BHT and stratigraphic implications
Section 53. Age determination of sites
Section 54. Additional details of the archaeological samples
Section 55. DANS hominin-modified bones
Section 56. Paleosols
Section 57. Ecological reconstructions
Section 58. Additional anatomical descriptions of the hominin fossils
Section 59. DANS/P1 endocast
Section 510. Taxonomic allocation of the BSN12/P1 and DANS/P1 specimens
Fig. S1. Setting of the BSN12 site.
Fig. S2. Map of the DANS area.
Fig. S3. Photographs of the original DANS-Main discovery site.
Fig. S4. DANS-Main area after surface brush and excavation in 2000.
Fig. S5. DANS-Main area in 2008.
Fig. S6. BSN12/P1 partial cranium.
Fig. S7. DANS/P1 partial cranium.
Fig. S8. Modified fossil bones from the DANS site complex.
Table S1. Comparison of the BSN12 and DANS artifacts with Konso.
Table S2. Metrical description of DANS/P1 and BSN12/P1 specimens.
Table S3. Summary maxillary dental metrics (means and ranges) for taxa discussed in the main text.
Table S4. Fauna list from the BSN12 and DANS levels of the Busidima Formation, Gona.
Table S5. Taphonomic sample of fauna recovered from DANS.
Auxiliary data file 1. Geology master data.
References (39–56)
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