Supporting Information

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SI Text

SI Materials and Methods. Fossilized bones from all three Middle Awash Plio-Pleistocene occurrences described in the present study were initially examined in 1990 (and subsequently) by naked eye, then hand lens, and binocular microscope (Nikon SMZ645). Selected specimens were also evaluated via SEM and, more recently, digital microscope (Keyence VHX-600 3CCD). Images were generated by the latter instruments and standard digital photography under directional light.

We then assessed individual marks on selected specimens with a confocal profilometer. Molds were made with President MicroSystemTM (Coltène-Whaledent) regular body dental impression material after cleaning the fossil surfaces with cotton swabs soaked in distilled water (acetone was used for cleaning bone surfaces with consolidant or matrix). Positive casts were then poured using Epo-Tek 301 epoxy resin and hardener (Epoxy Technology). Multiple adjoining scans were taken at 20x magnification using a Sensofar Plμ Neox Confocal Imaging Profiler housed in the Paleoanthropology Imaging Lab at the University of Tübingen. Scans were analyzed using the SensoMAP software, powered by Mountains Technology[R] from Digital Surf. Profiles of linear scores were taken at two loci along every linear groove, at 25%, 50%, 75% of the total length, plus the deepest point.

Fossil mark profiles were compared with marks from experimental crocodile feeding and stone-tool-assisted butchery. Profiler samples from Njau's crocodile feeding experiments were analyzed as high-resolution casts (1, 2). Experimental butchery was conducted on a skinned sheep half-carcass (retaining hind limbs) with the intention of both disarticulating and defleshing. Simple flakes (some retaining cortical surface) were knapped by YS on rhyolite cobbles and were completely unmodified. Residual meat was removed from bones using standard maceration protocol—a 24 hr storage at 50° Celsius, followed by cleaning with a solution of 5‰ KOH, which does not affect the bone surface.

SI Approaches to the identification and illustration of bone surface modifications.

The quest for methods to provide certainty of diagnosis at the level of the individual mark has been a long one in zooarchaeology. Early approaches at agent identification employed dental impression compounds to mold and then generate epoxy casts for visualization and measurement of linear groove cross-sections (3). Despite Binford and Stone's warning of a "high-tech" craze (4, p. 472) four decades ago, adoption of SEM soon became the analytical and illustrative standard, allowing assessment of micromorphological attributes of individual marks (5-8). Later, hand lens magnification (10x-16x) under strong incident light, supplemented by low power binocular microscopy were suggested as adequate for systematic study of bone modification (9).

The more recent application of confocal microscopy and profilometry data (today's faster and cheaper SEM substitute) in bone surface modification studies (e.g., 10) has further enhanced identification, visualization, and measurement of individual marks. However, such narrow, even microscopic focus on the dimensions and characters of each individual bone modification has still failed to overcome equifinality among the various modifying agents acting in prehistory (11).

A new 3D quantitative approach has recently been proposed as capable of capturing "previously unmeasurable diagnostic features of bone surface modifications (e.g., roughness, volume or microscopic differences in depth)" (10, p. 9), and thereby distinguishing among agents of bone modification. This new 3D quantitative method was claimed to accurately classify stone tool cut marks and mammalian carnivore tooth marks 97.5% of the time (10, p. 9). Even at the level of the individual mark, proponents of this method (10) did not include crocodilian modified bone to test the method's efficacy at reliably distinguishing between crocodilian bite marks and cut marks inflicted by stone tools.
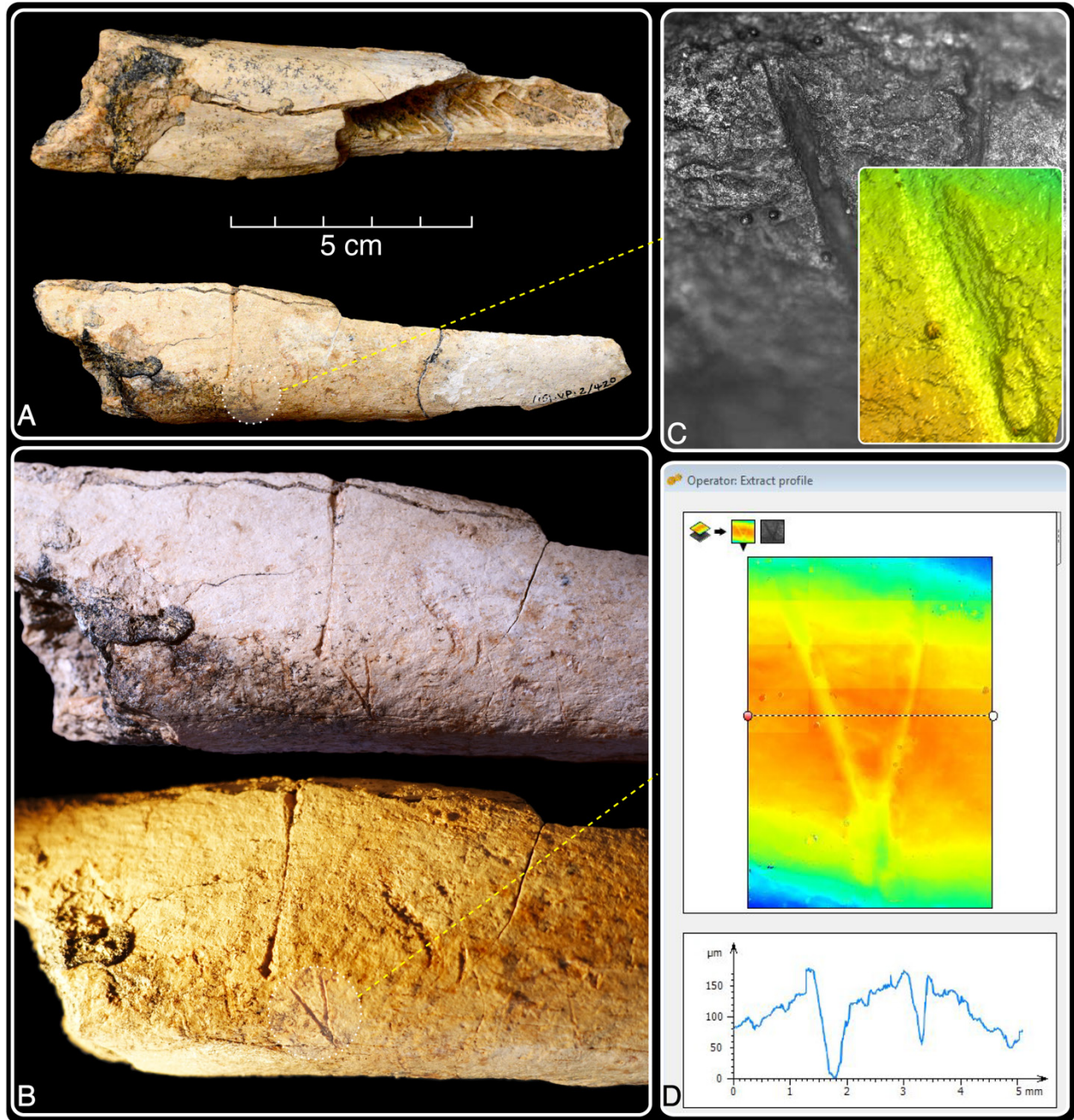
We employed this method to obtain high-resolution 3D quantitative data, and independently appraise the method's diagnostic efficacy (12). Results from our pilot study using a similar instrument and software (including the Contour Analysis module) and following the same procedures detailed in (10) already indicate that the newly proposed 3D quantitative method is not entirely capable of sorting crocodile bite marks with V-shaped cross sections and relatively deep and narrow grooves from similar marks produced by stone tools (Table S1, Fig. S1). Despite the small size of our pilot samples, these already indicate the need for more rigorous testing of such methods using additional experiments. Whereas the approach does appear to standardize measurement, its narrow focus on the morphological attributes of the individual mark limits its ability to reduce equifinality.

We provide additional information on zooarchaeological, depositional, and configurational contexts of individual fossil specimens discussed in the main text in Supporting Information Figs. S1-S13, in which we provide additional illustrations of equifinality among different agents of bone modification, particularly crocodiles.

Fig. S1 Confocal profilometry scan and data from a single mark on the 2.5 Ma bovid tibia from Bouri depicted in the text Fig. 3E. *(A)* 3D model of mark; *(B)* "Studiable" [defined by Mountains(R) software for a stack of confocal scans rendered as an image, surface, or surface image ready to be further analyzed; and as "…a 2-D visual representation of x-y-z coordinates for each measured point" (10)] of mark with form of bone removed; *(C)* 'Volume of a hole' measurements of mark; *(D)* Distance measurements of mark; *(E)* Area of a hole from the profile extracted from the deepest point of the studiable shown in D; *(F)* Contour analysis showing opening angle and floor radius from the portion of the deepest profile that is highlighted on the "area of a hole" studiable shown in *(E)*. Data presented in Table S1 were collected on individual marks using the same software, protocols, and functions, including the contour analysis.

Fig. S2. Modern crocodiles as bone modifiers. *(A)* A modern *Crocodylus niloticus* maxilla and mandible illustrate enormous size and shape variation among the teeth of even a single animal. Posterior teeth *(B)* more often have dull, irregular, worn, or fractured occlusal tips, whereas anterior and recently erupted teeth often retain sharper tips and blade-like crests (carina) mesially and distally (also see text Fig. 2 and Fig. S3 for fossil examples). As a result, even the teeth of a single crocodile are capable of making a wide variety of marks on bones. *(C)* A single modified bone surface that displays variety of marks known to have been produced by biting crocodiles in a controlled feeding experiment. These marks (reproduced with permission from Fig. 1, p. 4 of reference 2) include pseudo cuts with V-shapes as well as irregular pits that mimic stone tool hammerstone percussion pits. Taken in isolation (or on small fragments of limb and/or rib bone shafts), several of these marks would mimic stone tool contact. Encouraging attempts have been made to differentially diagnose the variety of marks already demonstrated to be made by crocodiles by a limited number of experiments (2). Additional experiments under more naturalistic conditions (and particularly with larger living crocodiles) will better circumscribe the range of bone surface modifications produced during crocodile feeding, and will likely expand the equifinality already evident.
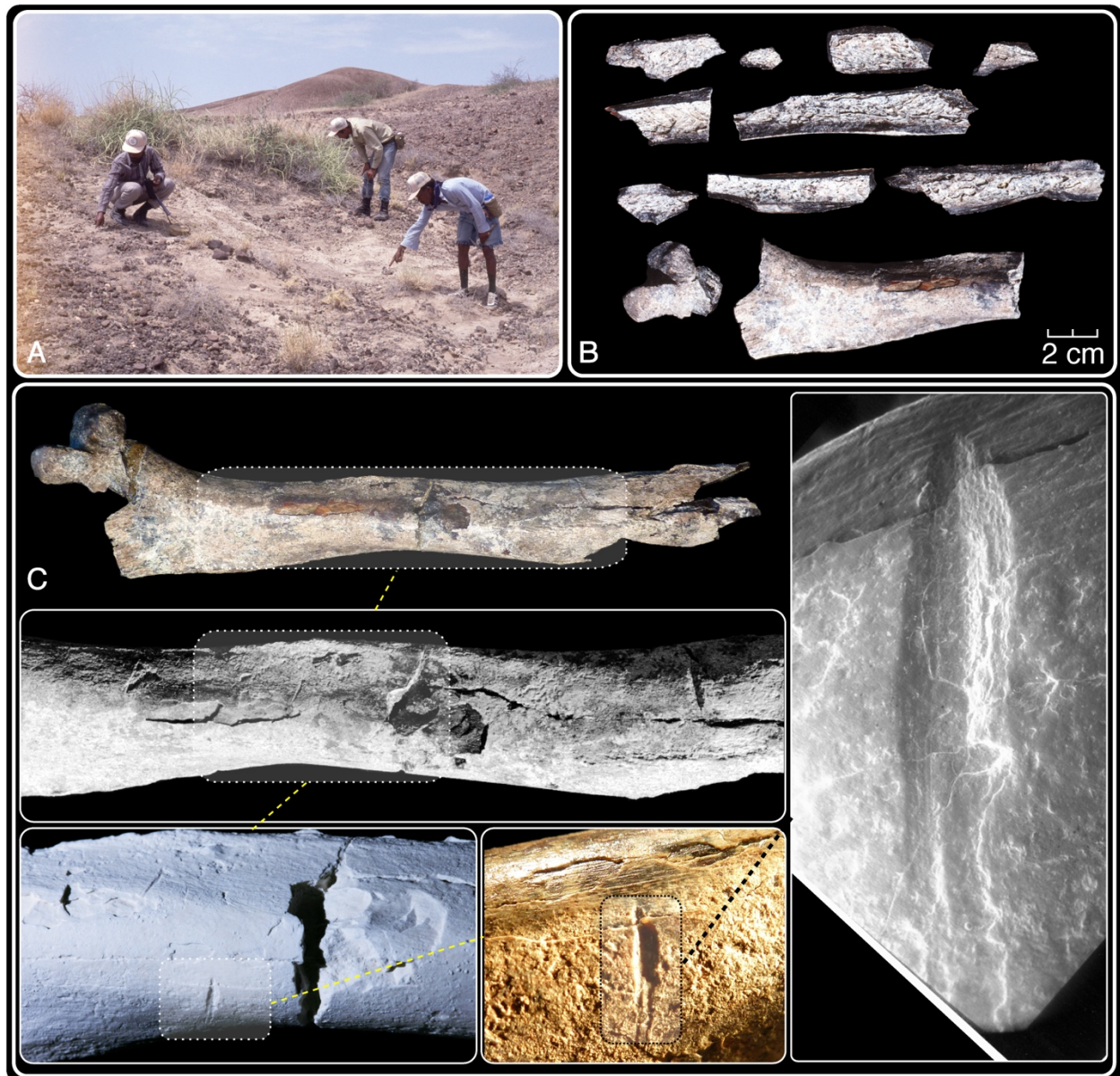
Fig. S3. Bone surface modifications on the 4.2 Ma *Au. anamensis* left humerus (ASI-VP-2/420) from Asa Issie, Middle Awash, Ethiopia. *(A)* Anterior and posterior views of the distal left shaft. Note the ancient fracture and carbonate matrix still adhering to the radial fossa, and an irregular pit on the dorsal surface. *(B)* The dorsal surface of the fossil shows a double-ended drag-snag, several curvilinear, shallow, U-shaped grooves, and two intersecting linear grooves that are straight-sided and V-shaped in profile. Internal striae are present here as they often are in modern and fossil bones modified by crocodiles (text Fig. 2; Figs. S2-3). *(C, D)* Confocal microscopy images and profiles. For this hominid humerus, the variety of adjacent tooth pits, drag-snags, and hook marks provide context that makes an inference of crocodile agency most likely.

Fig. S4. Context and bone surface modification marks on the 3.4 Ma *Au. afarensis* humerus, (MAK-VP-1/12) from Maka, Middle Awash, Ethiopia. *(A)* The 1990 discovery of this specimen showed it to have eroded from the Maka Sand Unit, fracturing and scattering on the surface. The recovery operation resulted in 11 conjoint pieces *(B)* comprising most of the adult bone. Only two of these exhibit more diagnostic tooth pits. *(C)* The restored specimen in anterior view shows several linear marks described and illustrated in text Fig. 1. Here, the overall photograph, the obliquely illuminated high resolution plaster cast, the macro-photograph of the original fossil, and the SEM image show post-fossilization periosteal spalling. Note the microscopic longitudinal linear striae within the macroscopically illustrated linear mark. Had this humeral shaft been recovered without the two distal fragments, such marks might have been interpreted as evidence of Pliocene cannibalism rather than crocodile damage. It is obvious that the more completely preserved the fossil surface, the greater the chance that diagnostic modifications such as tooth punctures above trabecular bone will be captured. Because of equifinality, reliance upon a few marks on small shaft fragments absent a consilience approach to the overall context of the modification is not recommended for determining how bone assemblages are formed.
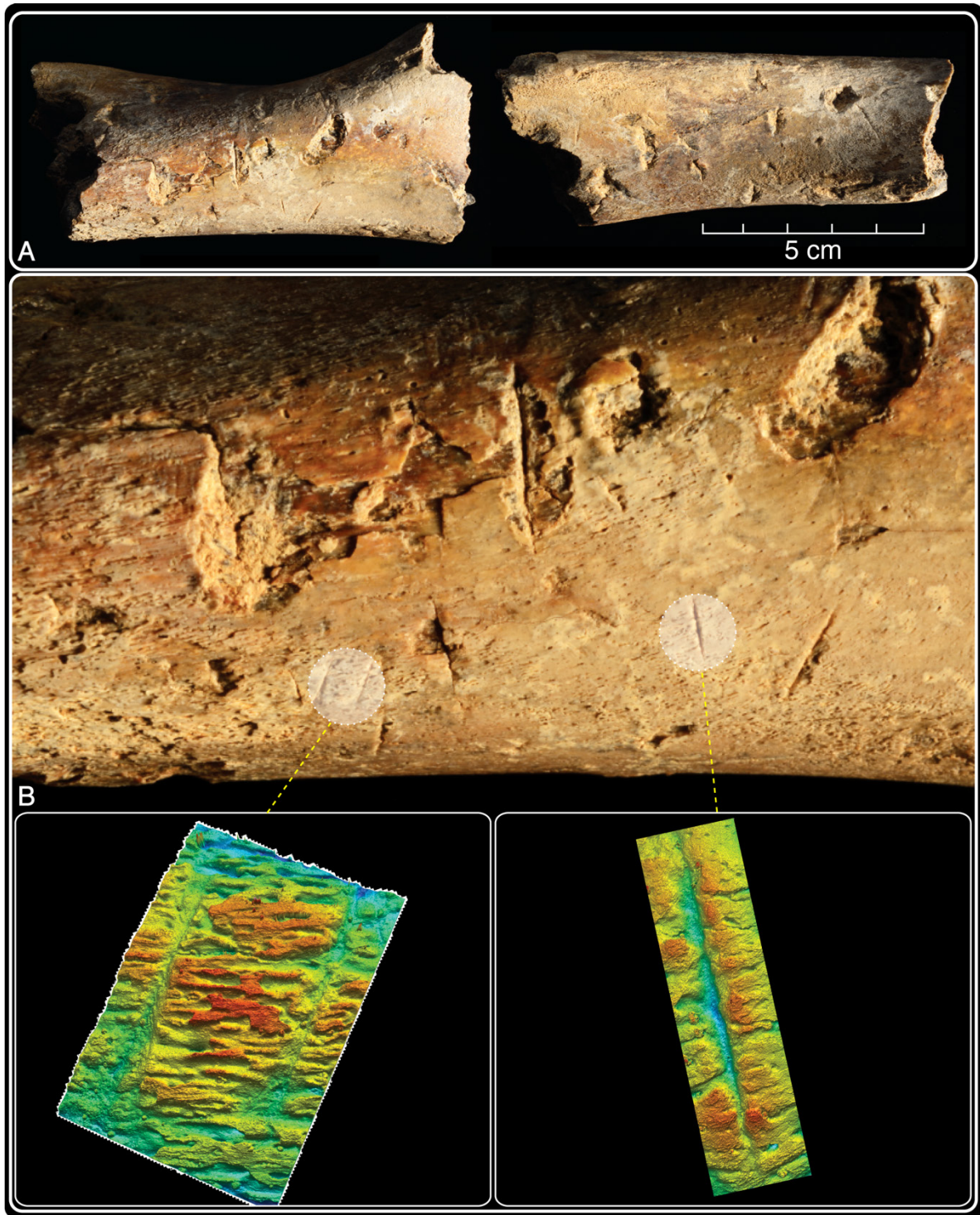
Fig S5. Inferred crocodile damage to a fossil ungulate humerus (MAK-VP-1/754) at the Pliocene MAK-VP-1 locality, Maka, Middle Awash, Ethiopia. *(A)* Bone modifications show the intensity of biting. *(B)* More magnification on the photograph and confocal microscopic images illustrates the wide variety of linear midshaft marks. Several match the marks on the Maka *Au. afarensis* humeral fragment illustrated in text Fig. 1 and Fig. S5, the hominid humerus collected from the same stratum in 1990.

Fig. S6. Context of the BOU-VP-11/14 ungulate tibia and excavated BOU-VP-11/15 equid femur. The Hatayae Member of the Pliocene Bouri Fm. of the Middle Awash (~2.5 Ma) has yielded numerous modified bones. Following the 1997 discovery of *Au. garhi*, extensive archaeological surveys were followed by excavations. None of these excavations recovered stone tools from *in situ*, but yearly visits did encounter freshly eroded artifacts (e.g. the core tool shown in Fig. S13. (A) Highly modified mammal bones *(B, C)* were found on the surface of the BOU-VP-11 locality, ~500 meters SE of the *Au. garhi* cranial holotype (Fig. S9). These occurrences are atop the dated MOVT (Maoleem Vitric Tuff) (8) volcanic ash with indurated upper contact seen in *(A)* as a resistant horizontal band immediately underlying softer sandy sediment that yielded the fossils. *(D-G)* Excavations into this massive sandy horizon produced little additional fish and turtle bone along with a surface-modified equid femur. Some of its modifications were initially interpreted as stone-tool-inflicted percussion and cut marks when published in 1999 (8). Subsequent experimental studies of modifications made by modern crocodiles raise serious concerns about signature-criteria assessment of such individual marks (see text and Fig. S7 for details). The 1998 excavation into a similarly placed stratum at the partial hominid skeleton from BOU-VP-11 lies in the distance at the white vehicle shown in *(G)*.

Fig. S7. Bone surface modifications of the BOU-VP-11/15 equid femur. Recovered *in situ* within an excavation adjacent to the BOU-VP-11/14 bovid tibia surface recovery location (Fig. S6), this nearly intact equid femur *(A)* (distal end at top) exhibits a plethora of bone modifications now known to be made during crocodile feeding activities. The presence of multiple linear scores with internal striations *(D, F)* initially led to the inference that this femur had been processed using stone tools (8). However, subsequent actualistic studies of marks made by crocodile biting demonstrated the production of linear marks with internal striations. These feeding experiments (1, 2, 14) allow a contextual assessment of the overall patterning of marks on the specimen (e.g., compare them with those on the Hadar equid tibia in text Fig. 3). We therefore now infer that many of the marks on the Bouri femur were made by ancient crocodile teeth. These include diagnostic drag-snags *(E)*, as well as round *(B)* and bisected *(C)* tooth punctures through the thin cortex surmounting spongy bone at the metaphyses.

Fig. S8. Bone surface modifications of the BOU-VP-11/14 ungulate tibia illustrate issues of equifinality. *(A)* Four views of the tibial shaft show a diversity of linear and irregular bone markings. Crocodile feeding experiments have so far failed to replicate the deep ecto-cortical conchoidal fracture *(B)* (cast on right**)** and associated deep pits with associated internal striae *(C)* (cast on right**)** seen on the Bouri tibia (see also text Fig. 3 and Fig. S1) and initially interpreted as evidence of forceful stone hammer percussion. However, the equid tibia from Hadar illustrated in text Fig. S2 and the excavated equid femur in Fig. S7 bear similar traces alongside other diagnostically crocodilian damage patterns. Given these cautionary examples and the specimen's lack of metaphyseal ends likely to capture diagnostic traces attributable solely to crocodiles, we conclude that modifications on this Bouri ungulate tibia fall into the zone of equifinality in terms of the agent(s) that made them. See text for details.
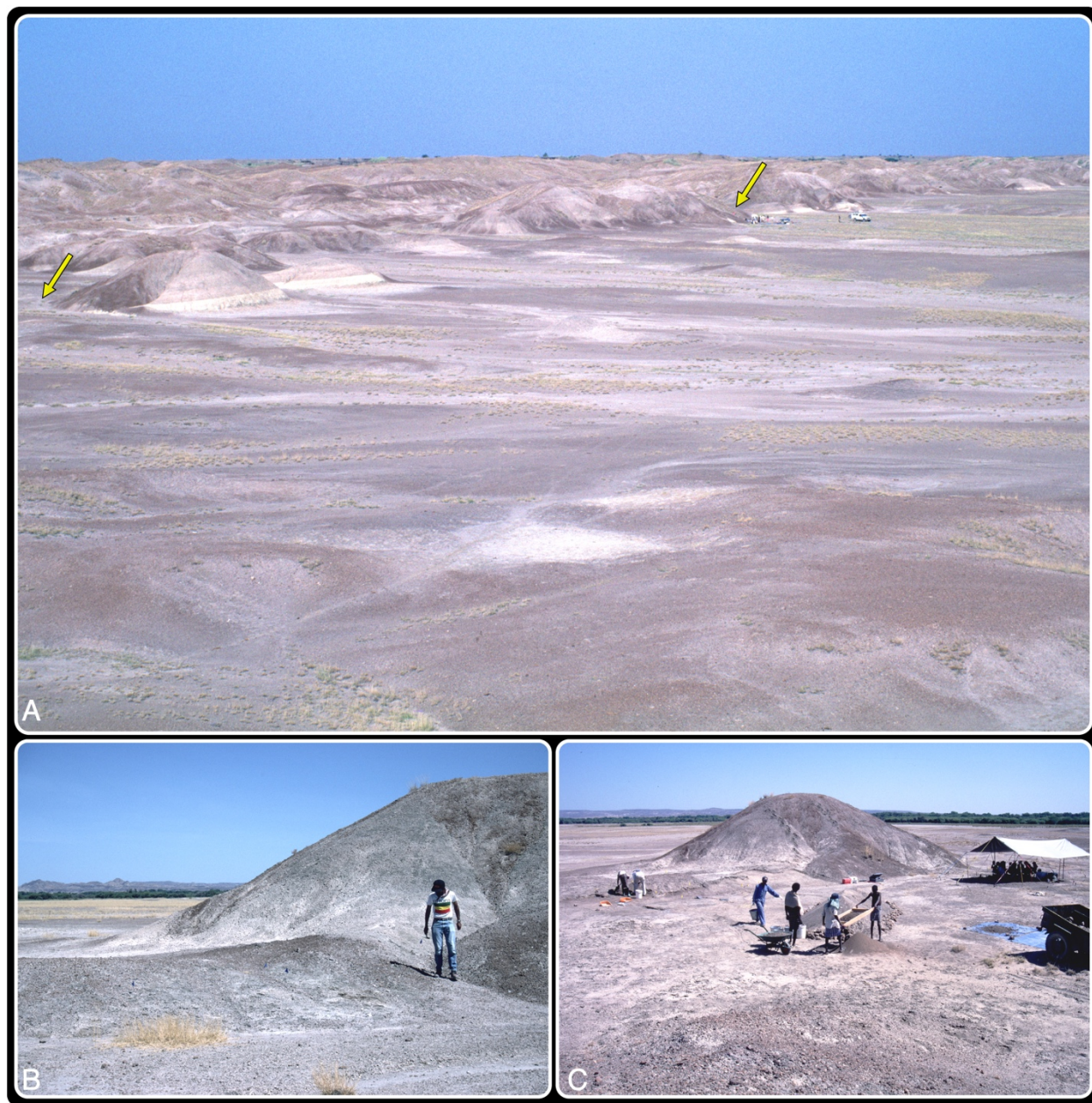
Fig S9. Context of the BOU-A21 hominid and fauna. An overview (view NNW) of the Bouri Formation's Hatayae Member sediments encompasses the holotype *Au. garhi* cranial location (arrow on right) and the BOU-A21 partial hominid skeleton discovery (left arrow) both stratigraphically immediately above the ~2.5 Ma Ar/Ar dated MOVT volcanic marker horizon (the light-colored band dipping to the west). The 1996-97 discovery of associated hominid skeletal parts on the surface (at feet of standing person at lower left) led to comprehensive surface collections of additional hominid and faunal remains, followed by excavations that recovered *in situ* fossils. The most notable excavated finds are *in situ* hominid fossils spatially and stratigraphically associated with modified faunal bones, including an alcelaphine bovid mandible (text Fig. 2; Fig. S10).

Fig. S10. Surface modifications and context of the BOU-VP-12/11 bovid mandible illustrate issues of equifinality. Successive curvilinear scores on the posteromedial parts of this alcelaphine mandible *(A)* were found partially covered by adhering carbonate matrix, and were interpreted as cutmarks made by stone tools (8). Anatomical placement and subparallel disposition of multiple linear striations documented within the long, parallel grooves seen in the SEM images of these marks support this conclusion. Because this fossil and some others from the excavation show fine random striae and polishing sometimes created by trampling of other animals, it is possible that agents besides hominid butchers were responsible for the observed modifications (although marks of such length, with such internal striae have not been documented in actualistic trampling cases; see main text for a more detailed discussion). Surfaces of spatially associated, anciently fractured medium size mammal bones from this horizon *(B, C)* are most often entirely obscured by adhering carbonate matrix, embedded within massive, silty, fine-grained sediments; only one of these fragments *(C)* was macroscopically rounded and edge-polished, showing that in addition to trampling and mammalian carnivore damage, fragments in the bone assemblage were only little subjected to hydraulic and physical abrasion before fossilization. Occurrences in South African cave breccia deposits with minimal integrity and resolution are behaviorally far less useful than such stratified, *in situ* assemblages (15). However, even relatively minimally-disturbed lakeside occurrences such as BOU A21 can also exhibit pre-fossilization modifications resulting from the actions of several biological and physical agents over weeks to years prior to burial. Differential diagnosis of among these modifications requires excellent bone preservation and careful preparation, large assemblages upon which to assess patterns of damage, and thorough actualistic experiments and adequate blind testing. Past events and relative agency (including hominid butchery) will only be accurately illuminated by such a balanced and comprehensive consilience approach. See text for details.

Fig S11. Small bone shaft fragment from the surface of the BOU A21 excavation. This fragment, seen here in SEM *(A, B)* and confocal *(C)* imagery, bears a short but deep, V-shaped *(D)* linear mark that would typically be considered to reflect ancient chopping motion of a sharp edge against fresh bone. Without additional anatomical context, it probably falls into the zone of equifinality between chopping marks left by stone tools and damage by crocodile teeth.

Fig. S12. The ventral surface of a large mammal rib shaft (cf. hippopotamid) found eroding from sediments above the MOVT within the BOU-VP-12 Hatayae Member locality at Bouri. The anatomical dispositions and individual characteristics of these successive marks are strong indicators of butchery with stone tools and contrast with marks left by alternative agents of bone modification.
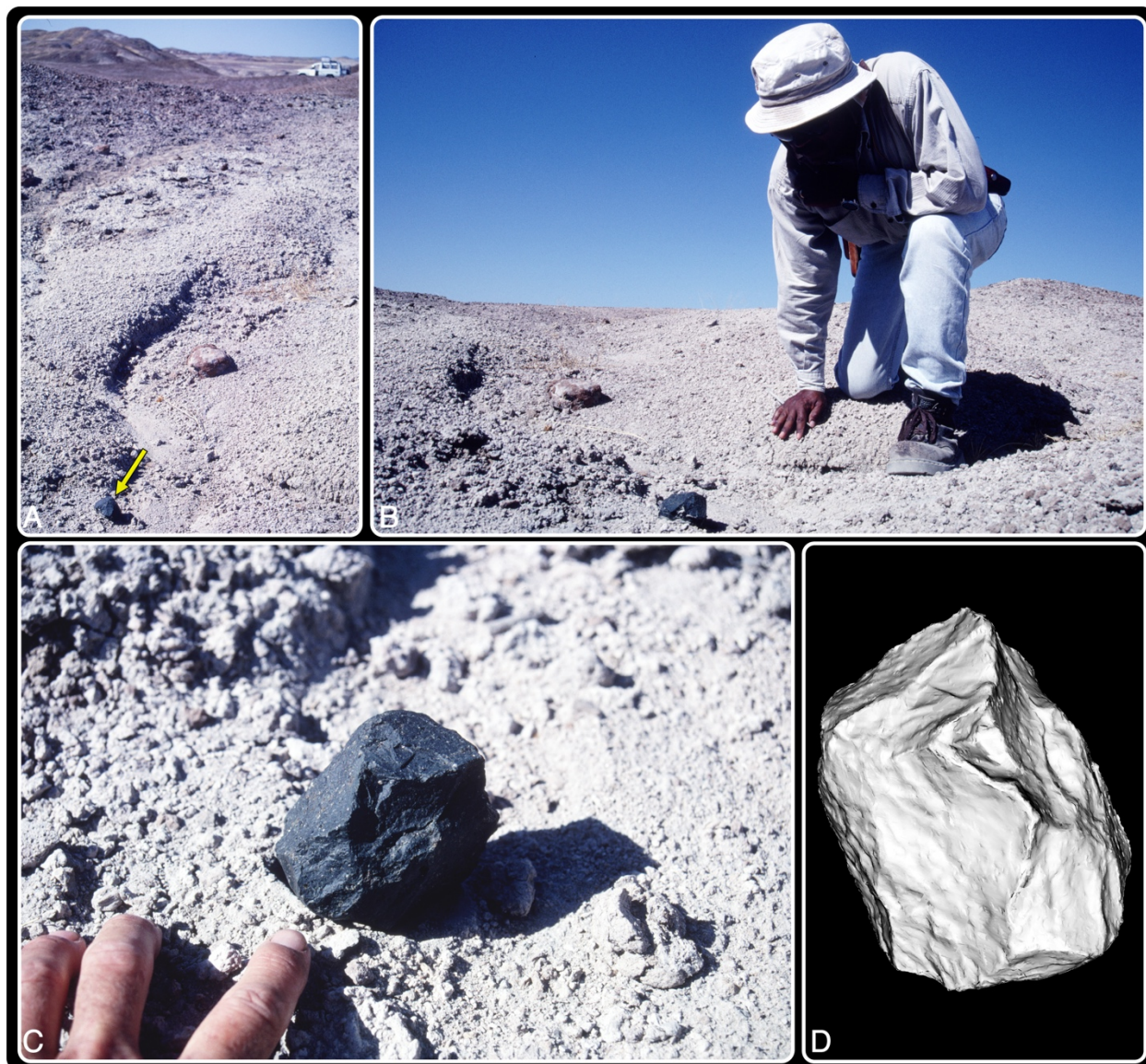
Fig. S13. Surface artifact from BOU-VP-12. This specimen was found upon a resurvey of eroding outcrops ~70m WNW of the BOU-A21 locality and SSW the BOU-VP-12/130 *Au. garhi* holotype discovery location (see Fig. S9). It had freshly weathered from fine grained, near-shore sediments immediately above the MOVT sometime between our December 1998 excavations at BOU-VP-11 and its November 1999 discovery shown here. The unabraded stone tool is a core made on dark, welded volcanic material with phenocrysts. None of the Hatayae Member excavations have so far yielded stone tools *in situ*, probably due to the low artifact density on the seasonally inundated lake margin landscape, the rarity possibly related to the great distances of this location from raw material sources (8).

Table S1. Measurements of variables collected*

	Measurements from 3D studiables				Measurements from deepest profile							
	Surface Area (μm^2)	Volume (μm^3)	Max. Depth (μm)	Mean Depth (μm)	Max. Length (μm)	Max. Width (μm)	Max. Depth (μm)	Area (μm^2)	Max. Width (μm)	Roughness (R_a)	Angle (°)	Radius (μm)
BOU-VP-11/14	4413900	638087007	332.2	144.563	9347.53	837.186	163.05	48441.2	620	5.27	119	503
MAK-VP-1/3	10361400	2723950000	821.594	262.894	12503.8	1242.21	363	346823	1850	17.3	138	1510
ASI-VP-2/420a	1742271.3	68597676.4	204.8	190.3	7853.8	867.2	99.5	296163	611.3	2.97	115	284
ASI-VP-2/420b	212826.45	3.49E+07	103.8	92.2	3540	654	139.6	26784.23	489	4.1	123	398
CrocExpr_VI a	654000	1.93E+07	79.4	29.5	3170	282	77.8	11877	319	1.65	112.1	476.261
CrocExpr_VI b	451000	1.22E+07	75.8	27	1700	308	76.7	19809	450	3.37	123.4	1111
CrocExpr_XI b	353000	4.37E+06	40.8	12.4	2540	86	31.9812	2519.73	160.4	1.94066	131	399.324
CrocExpr_XI c	384628	4.72E+06	43.2804	12.2728	2359.83	376.048	36.0897	3444.21	218.2	1.64252	110.1	412
ButcheryExpr a	1455830	169732027	270.419	116.588	4194.96	390.954	212.078	48743.1	471	3.3	109	421

*Measurements based on Plio-Pleistocene surface-modified fossils from the Middle Awash study area, experimental butchery using unmodified stone flakes, and crocodile bite marks from actualistic experiments; metrics collected on studiables generated by confocal profilometer and using protocols and software described in detail for a new 3D quantitative analysis proposed by Pante and colleagues (10).

SI Appendix

References

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