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S4). The latter ($N = 27$) comprise fallow deer, elephant, and bone fragments assigned to general categories (e.g., artiodactyls, canids, and unidentified mammals). Rodent teeth ($N = 22$) were also recovered, mainly of *Microtus* (table S4). The mammals' spatial distribution reveals no distinct patterns (fig. S4).

Analyses of Level 2 indicate that hominins carried out different activities in two distinct locations. Abundant flint knapping took place in the northwestern area, resulting in a dense concentration of microartifacts (Fig. 1 and fig. S1). Other noteworthy aspects of this activity area include fish exploitation (Fig. 3) and the use of chopping tools (fig. S3).

Greater variation was seen in the activities carried out near the hearth. Although flint knapping around the hearth was less intensive, basalt and limestone knapping was spatially restricted to the hearth (Fig. 1 and fig. S1). The hearth area also served as a focal point for biface modification and for activities involving the use of chopping tools, side scrapers, end scrapers, and awls (fig. S3). The percussors and the pitted stones suggest that nut processing may have involved the use of fire, as recorded for modern hunter-gatherer societies (1, 29). In addition, the differential preservation of fish and crabs, along with their spatial distribution, suggests that they were consumed near the hearth.

The spatial organization of hominin activities in Level 2 thus resulted in discrete patterning of various categories of finds. The evidence from Geshur Benot Ya'aqov suggests that early Middle Pleistocene hominins carried out different activities at discrete locations. The designation of different areas for different activities indicates a formalized conceptualization of living space, often considered to reflect sophisticated cognition and thought to be unique to *Homo sapiens* (3). Modern use of space requires social organization and communication between group mem-

bers, and is thought to involve kinship, gender, age, status, and skill (2).

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Supporting Online Material

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Materials and Methods
Figs. S1 to S4
Tables S1 to S7
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Mozambican Grass Seed Consumption During the Middle Stone Age

Julio Mercader

For my Riposte to this article, see "Stone Age Grain Eating" in my Bond Briefing of January 2011 at www.naturaleater.com.
Click this box for direct link.

The role of starchy plants in early hominin diets and when the culinary processing of starches began have been difficult to track archaeologically. Seed collecting is conventionally perceived to have been an irrelevant activity among the Pleistocene foragers of southern Africa, on the grounds of both technological difficulty in the processing of grains and the belief that roots, fruits, and nuts, not cereals, were the basis for subsistence for the past 100,000 years and further back in time. A large assemblage of starch granules has been retrieved from the surfaces of Middle Stone Age stone tools from Mozambique, showing that early *Homo sapiens* relied on grass seeds starting at least 105,000 years ago, including those of sorghum grasses.

The Mozambican cave site of Ngalue (12°51.517'S, 35°11.902'E) is part of the Niassa Rift (Fig. 1). The cave formed in Proterozoic carbonate rocks (1) located at 1300 m

above sea level. There is a 20-m-long corridor leading into dark chambers, which have the most habitable space, with a useable floor area covering >50 m² and a ceiling height of ~8 m.

The portion of the sequence and the artifacts studied here were deposited throughout the so-called "Middle Beds" (2), a Middle Stone Age clast-supported and time-averaged unit with light yellowish brown sediments that are rich in angular cave spall, lithics, animal bones, and teeth. The deposits span a time range from 105,000 to 42,000 years ago (2). Excavation in 2007 retrieved 555 quartz artifacts.

For this study, I chose 70 stone tools (~12% of the Middle Stone Age assemblage) from all main technotypological types to take into account the broadest range of potential plant uses: scrapers (35%), core tools/grinders (25%), points (15%), flakes (7%), and miscellaneous tools (18%) (Table 1). I selected tools from across the entire industrial scatter across a 13-m transect running along the largest cave chamber. These include

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cobble-sized core implements that have the right size and weight to be used as grinders of vegetable material: Cores and core scrapers make up

more than one-third of the entire assemblage. Special pieces include a rhyolite grinder/core axe, a ground cobble, and a faceted quartz mortar. The

last two implements were flaked on one side to create a dish. All three appear to be covered with red or orange pigments, and in one case there is a patina over the ochre. The lithics have a mean mass of ~85 g (range, <1 to 1000 g) and maximum length of ~50 mm (Table 1). About 20% lack any starch residue ($n = 12$ stone tools), but 80% have some. In all, 2369 granules were identified on these, and each tool on average has 41 granules (range, 1 to 654). The average number of grains on lithics is 270 times larger than that in the site's free-standing sediments. Moreover, the mean number of granule types on stone tools is about 125 times the number of classified morphotypes retrieved from modern topsoils outside the cave. Three-fourths of the starch grains come from scrapers (50.5% of the total) and core/grinding tools (25.5% of the total). About 64% of the total assemblage is well preserved and displays features comparable to those seen in fresh modern specimens. Large depressed circles (Fig. 2F) are noticeable in the center of 639 specimens (27% of the total starch assemblage). Enlarged fissures (Fig. 2G) total 190 (8%). There are 37 instances (~1.5% of the total) in which clumps fused, with gelatinized grains that show flat reliefs, expanded size, and a loss of birefringence. Because the starch-containing artifacts come from dark chambers of the cave, these biogenic polymers cannot derive from in situ, naturally growing plants. Starch preservation over such a long period of time might be due to the formation of a molecular film over the stone surface through adsorption, which, once complete, retards or abolishes the utilization of the adsorbate by microbes (3).

Of the 2369 grains retrieved, 89% ($n = 2112$) are *Sorghum spp.* (Table 1). *Sorghum* shows an extremely variable complex of cultivated, wild, and weedy taxa that defy formal taxonomy (4, 5). All domesticated sorghums derive from *Sorghum bicolor* subsp. *arundinaceum* (5), and they group in three complexes, one of which is restricted to Ethiopia. Modern sorghum grows naturally in the Zambezi-Miombos of the study region, including *Sorghum bicolor* subsp. *bicolor*, race Kafir, and *Sorghum bicolor* subsp. *arundinaceum*, the common wild sorghum. In general, *Sorghum bicolor* makes starches with several shapes, roughly polygonal and rounded, between 5 and 25 μm across (the average for modern sorghum granules is 15 μm) (6). The sorghum grains from the prehistoric assemblage have a mean maximum length of $16.6 \pm 3.6 \mu\text{m}$ ($n = 264$; minimum, 6.5 μm ; maximum, 25.3 μm), which is very close to the modern value. The ancient starch grains display morphologies like those seen in modern *Sorghum bicolor* subsp. *bicolor* (7–9) and in the reference materials from *Sorghum bicolor* subsp. *arundinaceum*. On the basis of granule shapes (7–9), another subset of 427 prehistoric, putative sorghum granules is made up of 43% corneous endosperm (orthogonal subspheres) (Fig. 2, A and B), 39%

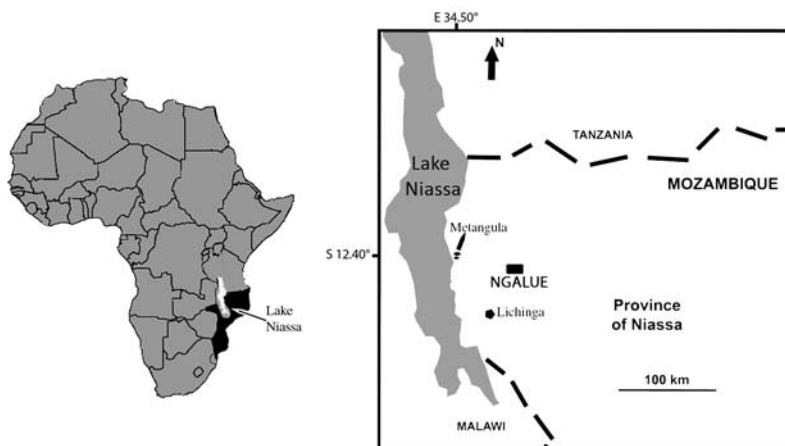


Fig. 1. Study area and site location.

Table 1. Starch and stone tools.

Starch on lithics	Lithics (n)	Granules (n)	Mean (range)
Scrapers ($n = 25$)			
Side scraper	1	6	6
Core scraper	17	1088	64 (0–654)
Convergent scraper	6	103	17 (1–44)
Denticulate scraper	1	1	1
Subtotal		1198	
Average mean		22	
Cores, core tools ($n = 18$)			
Discoidal core	6	46	7 (0–23)
Micro discoidal core	4	12	3 (0–12)
Blade core	1	2	2
Core (other)	3	211	105 (17–211)
Core axe	1	71	71
Polished grinder	2	177	88 (77–100)
Anvil	1	83	83
Subtotal		602	
Average mean		51	
Points ($n = 10$)			
Levallois point	1	38	38
Shouldered point	2	24	12 (3–21)
Point, classic	6	91	26 (4–91)
Point, thick base	1	1	1
Subtotal		154	
Average mean		20	
Flakes, blades ($n = 5$)			
Levallois flake, retouched	2	365	182 (7–358)
Flake	2	2	1
Blade	1	2	2
Subtotal		369	
Average mean		61	
Other tools ($n = 13$)			
Small cleaver	1	1	1
Drill	3	13	4 (0–7)
Small pebble tool	4	32	8 (0–29)
Microlith	2	0	0
Geometric	2	0	0
Subtotal		46	
Average mean		2	

floury endosperm (rounded grains) (Fig. 2C), and 18% from undetermined provenances within the grain (tabular shapes) (Fig. 2D). Six grains have vase shapes (Fig. 2E) like those of sorghum and closely related taxa (9).

The starch on Mozambican lithics shows that woody plants were also exploited during the Middle Stone Age. Lenticular granules with ellipsoid-to-orbicular bodies, lamellae, tenuous centric slits, depressions, pocking, and an

incision along the equatorial plane (Fig. 2H) ($n = 83$) represent 3.5% of all recovered starches. The mean size is $23.5 \pm 6 \mu\text{m}$ (range, 8 to $36.6 \mu\text{m}$). This morphology has been discovered in the seeds, legumes, nuts, and mesocarp from several species in the Fabaceae, Malvaceae, and Apocynaceae (3). Another group of starches includes a pear-shaped body with one tapered end, ellipsoid lamellae, an eccentric cross, sometimes a cuneiform slit, and creases ($n =$

68; Fig. 2L). It represents 3% of the total assemblage. This sample shows a wide range in size: 17 to $67 \mu\text{m}$ (mean, $37.6 \pm 10.8 \mu\text{m}$). The closest match is in the starches from the pith of the Arecaeae; specifically, the trunk of the African wine palm (*Hyphaene petersiana*). An additional starch morphology is pointed ($n = 11$, Fig. 2J). It has a hyperellipsoidal shape (it resembles a rod in three dimensions) with a highly eccentric cross and bent arms. The appearance of this type is restricted to three tools: a grinder, a core axe, and a Levallois flake. Its mean maximum length is $40 \mu\text{m}$ (range, 21 to $68 \mu\text{m}$). It matches starches from the Musaceae, namely, those from the mesocarp and corm tissues of the African false banana (*Ensete ventricosum*). Lastly, I found 12 clusters of compound or fused small granules ($\sim 2 \mu\text{m}$) on a grinder/core axe. The closest equivalent is found in two members of the Hypoxidaceae: *Hypoxis hemerocallidea* (the African potato) and *Hypoxis iridifolia*.

Fifteen stone tools yielded large numbers of altered starch granules. The most frequent damage pattern is documented on stone tool no. 61, which presents 449 instances of flattened granules with an enlarged centric hole and a bulge around the edges (Fig. 2F). Marked transversal fissures appear in at least 70 additional granules from the same stone tool (Fig. 2G). The alterations are associated with other modifications such as loss of birefringence, breakage, surface roughening, and radial fissuring. Several possibilities may account for the observed modifications, including aging and bacterial attack, culinary-induced modifications to the native starch grain (for example, from boiling), and/or hydrolysis during fermentation and/or grinding (10, 11). Establishing the mode of use of starch resources through granule alteration patterns, however, requires a different type of research and additional proof beyond the altered granules alone.

The Mozambican data show that Middle Stone Age groups routinely brought starchy plants

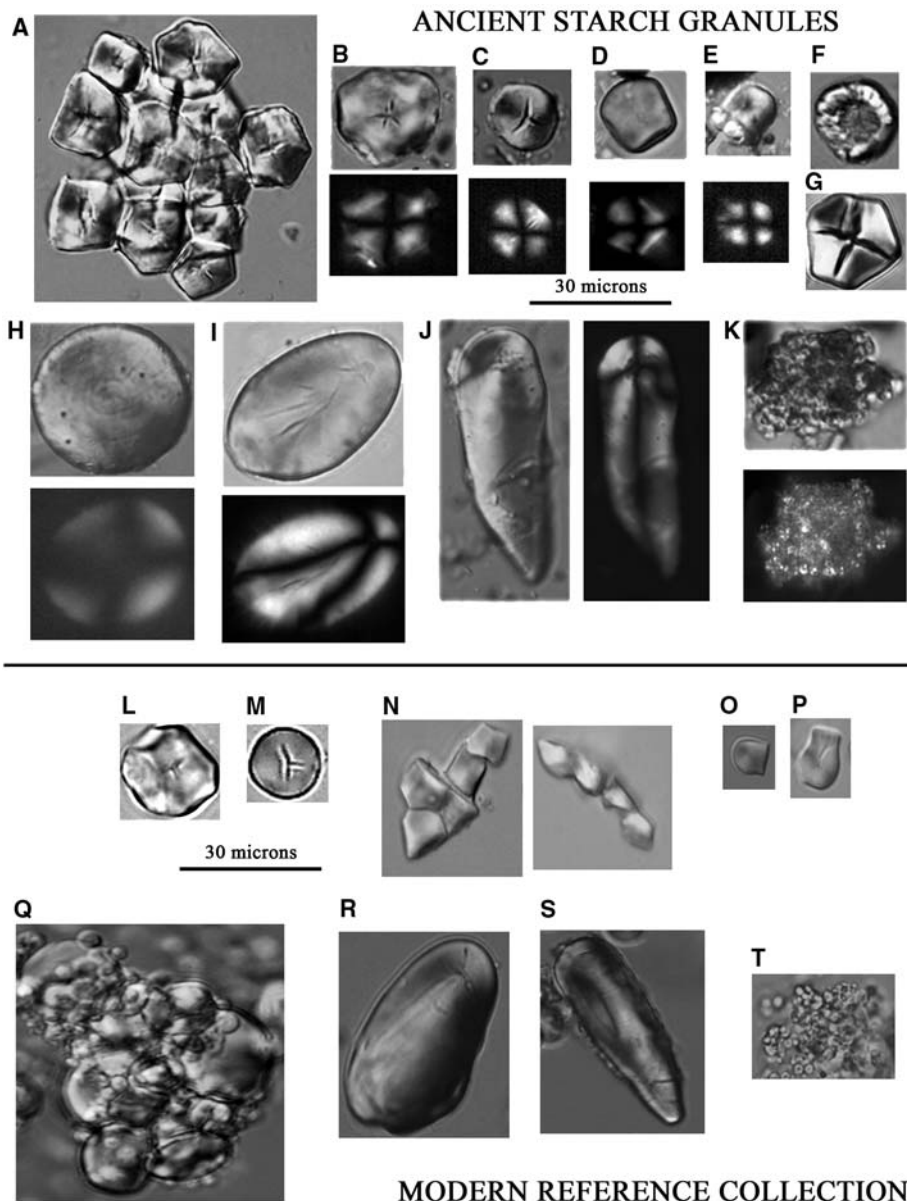


Fig. 2. Selected archaeological granules from *Sorghum* spp. include the following: (A) from stone tool no. 23, (B) from no. 18, (C) from no. 20, (D) from no. 2, (E) from no. 2, (F) from no. 56, and (G) from no. 2; (H) from no. 2, probably a seed type from woody taxa; (I) from no. 66, probably from the trunk of the African wine palm *Hyphaene* spp.; (J) from no. 18; probable source, the African false banana (*Ensete ventricosum*); and (K) from no. 19; likely source, the African “potato” (*Hypoxis* spp.). Selected modern reference material is from the grain endosperm of *Sorghum bicolor* subsp. *arundinaceum* (Poaceae) (L to P). Tabular shapes are shown in (N) (abaxial and side views, respectively). Vase shapes appear in (O) to (P). Lenticular starches from (Q) are from the legume of *Delonix* spp. (Fabaceae). Starch granules from the trunk of *Hyphaene petersiana* (Arecaeae) are exemplified in (R). The starch from the corm of *Ensete ventricosum* (Musaceae) is shown in (S), and the starch from the corm of *Hypoxis hemerocallidea* (Hypoxidaceae) is in (T).



Fig. 3. Examples of high-starch-bearing grinding and pounding implements from Ngalue cave.

to their cave sites and that starch granules got attached to and preserved on stone tools. I cannot prove that starch from all stone tools represents direct tool function (12, 13). Core tools and scrapers were exposed to starches more often than other tool types. Three-quarters of the starch assemblage comes from chipped stone, not ground or polished tools. African Middle Stone Age lithic repertoires do not yield large quantities of dedicated grinders that would demonstrate the processing of seeds. These early grinders are simply modified cobbles and core tools (Fig. 3) (14), with a suspected use that conforms to the technological action known as “diffuse resting percussion” and “pounding” (15), which allow the grinding of plant materials. It is not clear why the tools should be mostly coated with grass starches and not so much with other types of starch. It is possible that high-starch-bearing grass refuse built up

considerably in the cave’s main chamber at times of human occupation, thus coating both tools that were used in the processing of grass seeds and others that were not. These data imply that early *Homo sapiens* from southern Africa consumed not just underground plant staples (16) but above-ground resources too.

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Supporting Online Material

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Universality in Three- and Four-Body Bound States of Ultracold Atoms

Scott E. Pollack,* Daniel Dries, Randall G. Hulet

Under certain circumstances, three or more interacting particles may form bound states. Although the general few-body problem is not analytically solvable, the so-called Efimov trimers appear for a system of three particles with resonant two-body interactions. The binding energies of these trimers are predicted to be universally connected to each other, independent of the microscopic details of the interaction. By exploiting a Feshbach resonance to widely tune the interactions between trapped ultracold lithium atoms, we find evidence for two universally connected Efimov trimers and their associated four-body bound states. A total of 11 precisely determined three- and four-body features are found in the inelastic-loss spectrum. Their relative locations on either side of the resonance agree well with universal theory, whereas a systematic deviation from universality is found when comparing features across the resonance.

One of the most notable few-body phenomena is the universally connected series of three-body bound states first predicted by Efimov (1) in 1970. Efimov showed that three particles can bind in the presence of resonant two-body interactions, even in circumstances where any two of the particles are unable to bind. When the two-body scattering length a is much larger than the range of the interaction potential r_0 , the three-body physics becomes independent of the details of the short-range interaction. Surprisingly, if one three-body bound state exists, then another can be found by increasing a by a universal scaling factor, and so on, resulting in an infinite number of trimer states (2). Universality is expected to persist with the addition of a fourth particle (3–7), with two four-body states associated with each trimer (5, 7). Intimately tied to the three-body state, these tetramers do not require any additional parameters to describe their properties.

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Ultracold atoms are ideal systems for exploring these weakly bound few-body states because of their inherent sensitivity to low-energy phenomena, as well as the ability afforded by Feshbach resonances to continuously tune the interatomic interactions. Pioneering experiments with trapped, ultracold atoms have obtained signatures of individual Efimov states (8–12)—as well as two successive Efimov states (13, 14)—via their effect on inelastic collisions that lead to trap loss. Evidence of tetramer states associated with the trimers has also been found (13, 15). Although the locations of successive features are consistent with the predicted universal scaling, systematic deviations as large as 60% were observed and attributed to nonuniversal short-range physics (13). In the work presented here, we use a Feshbach resonance in ^7Li for which a/r_0 can be tuned over a range spanning three decades (16). This enables the observation of multiple features that are compared to universal theory.

We confine ^7Li in the $|F = 1, m_F = 1\rangle$ (where F is the total spin quantum number and m_F is its projection) hyperfine state in an elongated, cylin-

drically symmetric, hybrid magnetic—plus—optical dipole trap, as described previously (16). A set of Helmholtz coils provides an axially oriented magnetic bias field that we used to tune the two-body scattering length a via a Feshbach resonance located near 737 G (17). For $a > 0$, efficient evaporative cooling is achieved by setting the bias field to 717 G, where $a \sim 200a_0$ (a_0 is the Bohr radius), and reducing the optical-trap intensity. Depending on the final trap depth, we create either an ultracold thermal gas just above the condensation temperature T_C or a Bose-Einstein condensate (BEC) with >90% condensate fraction. For investigations with $a < 0$, we first set the field to 762 G where $a \sim -200a_0$ and proceed with optical-trap evaporation, which is stopped at a temperature T slightly above T_C . In both cases the field is then adiabatically ramped to a final value and held for a variable hold time. The fraction of atoms remaining at each time is measured via in situ polarization phase-contrast imaging (18) for clouds where the density is high, or absorption imaging in the case of lower densities.

Analyzing the time evolution of the number of atoms in the trap determines the three-body loss coefficient L_3 (8, 13, 19), as well as the four-body loss coefficient L_4 (15). Recombination into a dimer is a three-body process because a third atom is needed to conserve both momentum and energy. For $a > 0$, the dimer can be weakly bound with binding energy $\epsilon = \hbar^2/(m a^2)$ (where m is the atomic mass and \hbar is Planck’s constant h divided by 2π), whereas for $a < 0$ there are only deeply bound molecular dimers. The recombination energy released in the collision is sufficient to eject all three atoms from the trap for $a < 0$, as well as for $a > 0$ when $\epsilon \geq U$ (where U is the trap depth). In the case of the BEC data, this latter condition holds for $a \lesssim 5000a_0$. Nonetheless, we assume that all three atoms are lost for any recombination event because, even for a larger than $5000a_0$, we observe rapid three-body