

ARCHAEOLOGY

Emergence of a Neolithic in highland New Guinea by 5000 to 4000 years ago

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The emergence of agriculture was one of the most notable behavioral transformations in human history, driving innovations in technologies and settlement globally, referred to as the Neolithic. Wetland agriculture originated in the New Guinea highlands during the mid-Holocene (8000 to 4000 years ago), yet it is unclear if there was associated behavioral change. Here, we report the earliest figurative stone carving and formally manufactured pestles in Oceania, dating to 5050 to 4200 years ago. These discoveries, at the highland site of Waim, occur with the earliest planilateral axe-adzes in New Guinea, the first evidence for fibercraft, and interisland obsidian transfer. The combination of symbolic social systems, complex technologies, and highland agricultural intensification supports an independent emergence of a Neolithic ~1000 years before the arrival of Neolithic migrants (Lapita) from Southeast Asia.

INTRODUCTION

Wetland agriculture originated in the New Guinea highlands during the mid-Holocene [8 to 4 thousand years (ka) ago], but the lack of evidence for corresponding social changes has placed this region on the periphery of global discussions concerning the emergence of complex societies (Fig. 1) (1). Elsewhere in the world, the development of agriculture is viewed as one of the most notable behavioral innovations in human history, because it is linked to population expansion, village settlement (sedentism), increased territoriality, and pronounced symbolic cultural practices, referred to as the “Neolithic” (fig. S1) (2, 3). The earliest Neolithic in the New Guinea region is associated with agriculturists (Lapita culture) arriving from Southeast Asia in the Late Holocene by 3200 years ago. Our understanding of mid-Holocene New Guinea societies predominantly derives from linguistic, genetic, and paleoecological data, with limited temporal and spatial resolution from existing archaeological records. Only 12 mid-Holocene highland archaeological sites are known, 7 of which are rockshelters with material records indicating use as transient hunting camps (Fig. 2 and table S1) (4–6).

Here, we present multidisciplinary evidence from systematic investigations at the newly discovered highland archaeological site of Waim that sheds light on the nature and timing of social and technological change in New Guinea (Fig. 1). Waim is located at a high elevation in the Jimi valley [1980 m above sea level (asl)], and 54 km north of Kuk swamp (1550 m asl) in the neighboring Wahgi

Valley where the earliest evidence for agriculture has been identified (Fig. 2 and table S1) (1). The Waim archaeological sequence dates from 7350 to 4200 cal yr B.P. (calibrated years before the present). A clear shift in human behavior occurred from 5050 to 4200 cal yr B.P., which overlaps with the intensification and regional expansion of wetland agriculture (1, 7). We report the antiquity of a formally manufactured figurative stone carved face and two stone pestles, previously only known from undated surface finds. In the same context, the earliest components of historically important planilateral axe-adze manufacture, a fibercraft tool with ochre possibly used for coloring string fiber, a fire lighting tool (c.f. strike-a-light), and postholes were also identified. The new evidence from Waim fills a critical gap in our understanding of the social changes and technological innovations that have contributed to the developing cultural diversity in New Guinea. The changes documented here are consistent with social innovations associated with intensive plant food cultivation reported elsewhere in the world and defined as the Neolithic (2).

Site setting, stratigraphy, and chronology

The Waim site is situated on the apex of a prominent steep sided spur on the southern side of the Bismarck Range (Kalam language area, Jimi Valley, Jiwaka Province), within a modern village of the same name (Fig. 3). The spur forms one of the few navigable pathways connecting the tropical lowlands to the subtropical highlands, with the site close to the modern transition from open grasslands to montane rainforest (~2050 to 2100 m asl). Regional paleoclimatic data indicate that temperatures throughout the mid-Holocene were similar to, or even warmer than, the modern day (8). Phytolith analyses of excavated sediment indicate that Waim was in an open grassland setting but was likely to be near the forest margins (Supplementary Materials). Archaeological investigations were initiated following reports of formally manufactured artefacts discovered by local residents during groundworks, comprising stone mortars, pestles, carved faces, and club heads (fig. S2). Excepting stone mortars, these artefact forms had previously been attributed to the mid-Holocene but have not been demonstrated archaeologically through direct dating (9).

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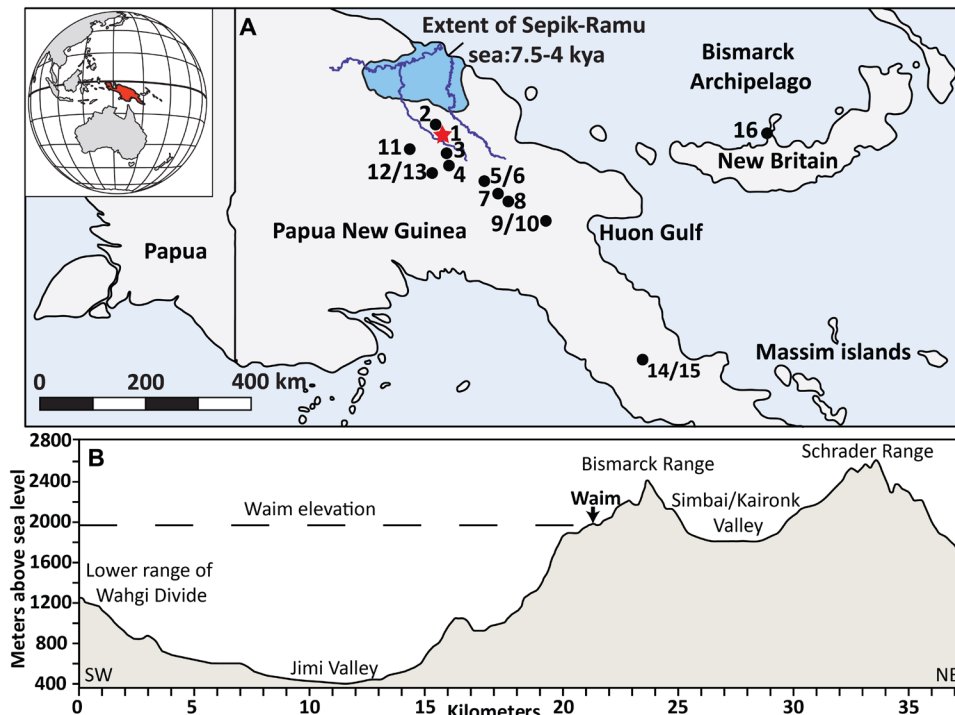


Fig. 1. New Guinea and the location of Waim relative to other mid-Holocene highland sites. (A) Sites mentioned in text and the mid-Holocene extent of the Sepik-Ramu inland sea. 1, Waim; 2, Wanelek; 3, Kuk; 4, Manton; 5, Nombe; 6, Kiowa; 7, Kafiavana; 8, Aibura; 9, NFB, NFX; 10, NGH; 11, Yuku; 12, Manim; 13, Kamapuk; 14, Vilakua; 15, Joes Garden; 16, Kutau obsidian source. (B) Elevation profile [northeast (NE)–southwest (SW)] of Simbai–Jimi Valleys showing the location of Waim. Inset: Global position of New Guinea. Bolded line is equator. Figure credit: Ben Shaw, University of New South Wales (UNSW).

In 2016, a total of 6.5 m² was systematically excavated at the base (squares G and F), on the side (squares A to D), and on top (square E) of the spur apex (Fig. 3), representing an estimated 7 to 8% of the preserved cultural deposit. Fifteen accelerator mass spectrometry (AMS) radiocarbon dates on unidentified wood charcoal collected in situ and in direct association with artefacts/features provide a well-constrained chronology, presented here as calibrated median ages rounded to the nearest 50 years (table S1). Acidic soils (pH range, 3.9 to 4.8) precluded preservation of faunal remains. Four stratigraphic layers were identified on the basis of color and particle size analysis (fig. S3), with two cultural horizons defined on the basis of radiocarbon dating. A date of 9750 cal yr B.P. was obtained from charcoal embedded in the basal clay (layer 4), although an association with human activity is uncertain. The lower cultural horizon (layer 3) represents the earliest unequivocal human presence as evidenced by a small number of lithic artefacts, dating to 7350 to 6350 cal yr B.P. The upper cultural horizon (layers 2a to 2c) included all formally manufactured stone tools and most flaked artefacts (88%), with 12 AMS determinations throughout the layer dating between 5050 and 4200 cal yr B.P. Layer 1 was redeposited clay from modern landscape clearance. The finds discussed below all derive from the upper cultural horizon (layers 2a to 2c).

RESULTS

Stone tool technological innovations from 5050 to 4200 years ago

A large fragment of carved stone depicting the brow ridge of a human or animal face provides the earliest evidence for the figurative ex-

pression of body form in Oceania (Fig. 4A). The carved stone is a gabbro sourced from discrete outcrops 5 to 15 km from Waim and was produced by hammer dressing (fig. S4). A complete stone carving depicting a human face with a bird on top of the head was also recovered by Waim residents before our investigations (Fig. 4B). It was found 20 to 30 cm below the surface while cutting back the hill slope immediately adjacent to where squares B/D were placed. The find location equates to layers 2a and 2b, and therefore securely within the upper cultural horizon.

Figurative stone carvings are part of a regional cultural complex, which spans the highlands and parts of the northern lowlands, as indicated by the distribution of similar objects from undated surface contexts (fig. S5). The distribution of bird carvings is also centered in the highlands where the Waim site is situated, with centers also in the Sepik-Ramu basin and Huon Gulf (Fig. 1). Few isolated bird carvings have been found outside of this range, suggesting that these lowland areas were conduits for interaction with coastal and island populations (9). Many carved stone objects have no recognized function other than having probable social significance, although figurative carvings sometimes feature on stone pestles and mortars. Animal and human forms have been argued to represent spirit figures, consistent with known customary practices in New Guinea and elsewhere in the world (10). Their distribution suggests that they were also part of regionally networked symbolic social system that facilitated communication between a number of dispersed populations. The excavated carved stone described here establishes a minimum antiquity for the symbolic depiction of anthropomorphic/zoomorphic forms in New Guinea.

Two ground stone pestle fragments were recovered in close proximity to each other (adjoining squares C and F) and are the first

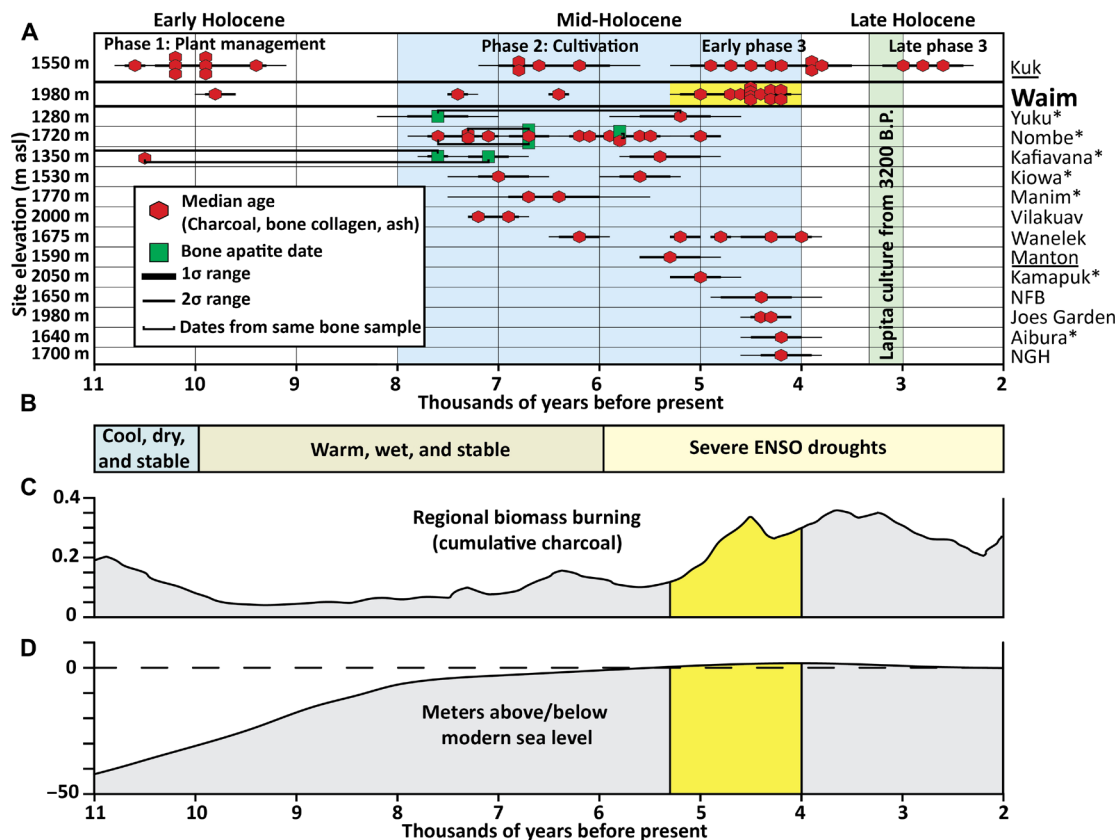


Fig. 2. Chronologies for human settlement in the New Guinea highlands modeled against climate, biomass burning, and relative sea levels. (A) Calibrated AMS charcoal dates from Waim, Kuk agricultural phases 1 to 3, and other mid-Holocene highland sites (>1200 m asl) in New Guinea. (B) General trends in New Guinea climate based on paleocore data (6). (C) Regional biomass burning based on cumulative charcoal records from Papua New Guinea and Indonesia (6). Scale is standardized cumulative charcoal divided by the number of sites from 200-year temporal periods based on age-depth ^{14}C curves. (D) Sea levels in the New Guinea region over time (43). Yellow shading in (A), (C), and (D) indicates major phase of cultural deposition at Waim. Archaeological sites with evidence for cultivation but no contemporary evidence for mid-Holocene domestic occupation are underlined. *Rockshelter sites. Figure credit: Ben Shaw, UNSW.

formally manufactured pestles recovered from a secure archaeological context in Oceania (Fig. 4, C and D). The tools, made from diorite and gabbro-diorite, were manufactured using a combination of hammer dressing and grinding (Supplementary Materials). The pestle fragments were of differing morphologies but similar to numerous undated surface collected examples found in the highlands (e.g., Fig. 4E). The Waim pestles contrast with earlier unmodified cobble pounders (~10 ka ago) and demonstrate a shift in social behaviors associated with food processing (11).

Yam, fruit, and tree nut starches were identified on the distal ground pestle surfaces using the geometric morphometric method (12). Phytoliths associated with tree nut-producing species (e.g., *Castanopsis* and *Flacourtia*) were also present, with tissue fragments supporting the interpretation of soft tissue plant processing (see the Supplementary Materials for starch and phytolith results). Starchy plant taxa included *Dioscorea pentaphylla* (Five leaf yam), *D. alata* (Greater yam), *Pueraria lobata* (Kudzu tuber), *Musa cf. ingens* (Banana), *Castanopsis acuminatissima* (tree nut), *Hydriastele* spp. (palm), and *Saccharum officinarum* (sugar cane). Yam and banana, also identified in the Kuk sequence, are modern staple crops in the highlands, but wild variants are also available (11). *C. acuminatissima*, the most common taxon on both pestles, is an endemic tree species and common throughout the highlands, with small edible starchy nuts available from July to

December (13). Kudzu, also endemic, grows wild and is now considered a famine food perhaps falling into disuse following the introduction of sweet potato ~300 years ago, but has traditional medicinal uses (14, 15). It is uncertain whether yams were harvested locally. However, Waim is near the modern maximum altitudinal growing limit for *D. alata* (2100 m asl) and well above the known limit for *D. pentaphylla* (1550 to 1600 m asl) (16). If mid-Holocene climatic conditions were in the same range or even slightly warmer than the modern day (6), then it is likely that *D. pentaphylla* was harvested at lower elevations and transported up to Waim.

A large ground planilateral axe-adze preform (10 kg) and associated manufacturing debris at Waim indicate a New Guinea highland origin for this technology (Fig. 5A). These finds predate the earliest evidence for planilateral axe-adzes in New Guinea by at least 1000 years, a technology previously thought to have been introduced with agricultural groups (Lapita cultural complex) from Southeast Asia (17, 18). A block of argillite with evidence of sawing is consistent with historically documented techniques of sawing and splitting for axe-adze manufacture (Fig. 5B) (19). A small ground lenticular axe-adze (31 g) was also found, further confirming the mid-Holocene presence of this tool morphology in the highlands (Fig. 6C).

On-site manufacture of ground stone axe-adzes is indicated by preforms and flakes ($n = 10$) exhibiting evidence of hammer dressing

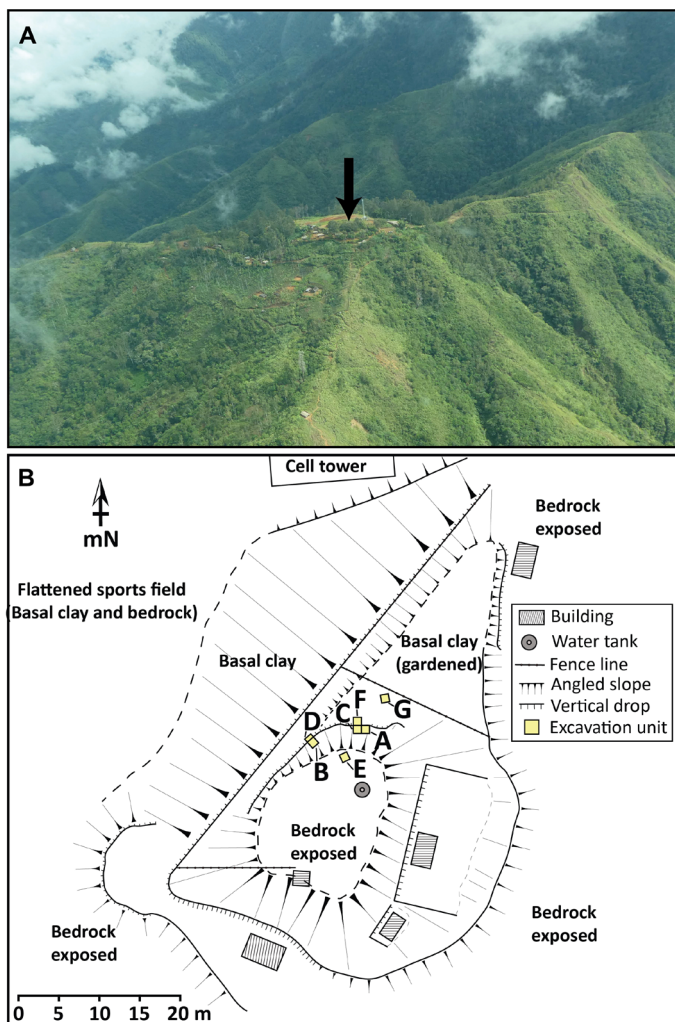


Fig. 3. Setting and plan of Waim. (A) The spur apex where Waim is located; excavated area is indicated by arrow. (B) Location of excavated squares and features of the modern village. Photo credit: Judith Field, UNSW. Figure credit: Ben Shaw, UNSW.

and grinding (Fig. 6, D to F). Both the lenticular axe-adze and the planilateral preform were made of siliceous argillite. The preform is parallelogram in profile, and all surfaces have evidence of grinding, with well-defined asymmetrical bevels at each end. A large lightly ground slab of the same lithology was also found immediately adjacent to the planilateral preform, indicating that they were deliberately cached together (fig. S6). Splitting and sawing is a well-documented method for the manufacture of large planilateral axe-adzes in the highlands, which are recorded as having both functional and ceremonial uses. Known quarries are located in the Jimi and Wahgi valleys where tabloid blocks of raw stone were sourced (Fig. 1) (19). Quarried stone could be readily split along naturally occurring fracture lines and subsequently ground and sawn to produce several axe-adzes (20). Planilateral axe-adze technology in the highlands has therefore been in use for more than four millennia.

Fibercraft and the coloring of string are well-known traditional practices in societies across modern-day New Guinea, and an ochre-stained incised volcanic stone from Waim implies a mid-Holocene antiquity for this technology. The incised stone and a pyroxenite

fragment, both recovered from the upper cultural horizon, were recognized by local informants, the former used to stain organic fibers in the production of woven bags (bilums) and the latter as a fire lighting tool (Fig. 6, A and B). These artefacts were examined for microwear traces to determine function (Supplementary Materials). The incised stone was weathered with ochre residues and had two worked surfaces. Deep grooves had been cut into the surface, probably from sawing, and two are U-shaped in cross section, which is characteristic of wear from pulling soft plant fibers through the cut grooves. The pyroxenite fragment had grinding wear consistent with stone-on-stone use. Pyroxenite has high concentrations of iron-rich minerals, which create sparks for lighting fires (c.f. “strike-a-light”) (21).

The lithic assemblage ($n = 486$) derives from sources no more than 15 km from Waim and includes a range of flakes, angular fragments, and cores, demonstrating on-site reduction and tool manufacture (table S2). Flakes ($n = 214$, 44%) and angular fragments ($n = 181$, 37%), some with retouch and use wear, were the most common artefact classes. Seventeen raw materials were identified, predominated by argillite/siltstone (81.3%), shale (6.2%), and greywacke (6%), with minor contributions of intrusive plutonic and volcanic tuff (fig. S4). Collectively, the lithic assemblage provides evidence for a range of domestic and social activities, specifically complex food processing, axe-adze manufacture, fibercraft, on-site lithic reduction, and symbolic expression.

Obsidian (volcanic glass) transfer to New Guinea

Sourcing analysis of an obsidian core (0.3 g) establishes the first definitive evidence for mid-Holocene transport of obsidian into the highlands from the Bismarck Archipelago, where it has been exploited for 24,000 years (22). It has been attributed to the Kutau source (Willaumez Peninsula) on the island of New Britain using portable x-ray fluorescence spectrometry (pXRF) (fig. S7 and table S3). The Willaumez Peninsula is one of four major chemically distinct obsidian source areas in the wider region, all of which are on islands adjacent to New Guinea (Fig. 1) (22). Waim is one of only three sites in the highlands with obsidian from a mid-Holocene context. Obsidian was present at Nombe rockshelter by 5800 cal yr B.P. and at Kafavana rockshelter no earlier than 5400 cal yr B.P. (18, 23). While these other finds have not been sourced, the Waim obsidian indicates transport from neighboring islands over distances of at least 800 km.

Evidence for village settlement in highland New Guinea

The profiles of five infilled postholes were identified within the same excavation square as the cached preform (figs. S3 and S6). The postholes varied in maximum diameter ($\varnothing = 10$ to 18 cm) and were cut at least 40 cm into layer 4 from layer 2a. The posthole fill dates to 4200 cal yr B.P., consistent in age with the upper cultural horizon (5050 to 4200 cal yr B.P.). It is notable that postholes exhibited spatially discrete clustering and were only identified in adjoining squares A and C. Postholes have been documented at the mid-Holocene open sites of Wanelek, 12 km northwest of Waim, by 4800 cal yr B.P. in association with formally manufactured tanged slate blades. Similar tanged slate blades at Kuk swamp support an agricultural function for these tools (24). At site NFB (Eastern Highlands), postholes are evident from at least 4400 cal yr B.P. (25, 26). Although smaller in diameter (5 to 10 cm), the postholes at these sites have been identified as house posts. The postholes at Waim may therefore have had a similar function, representing a fixed

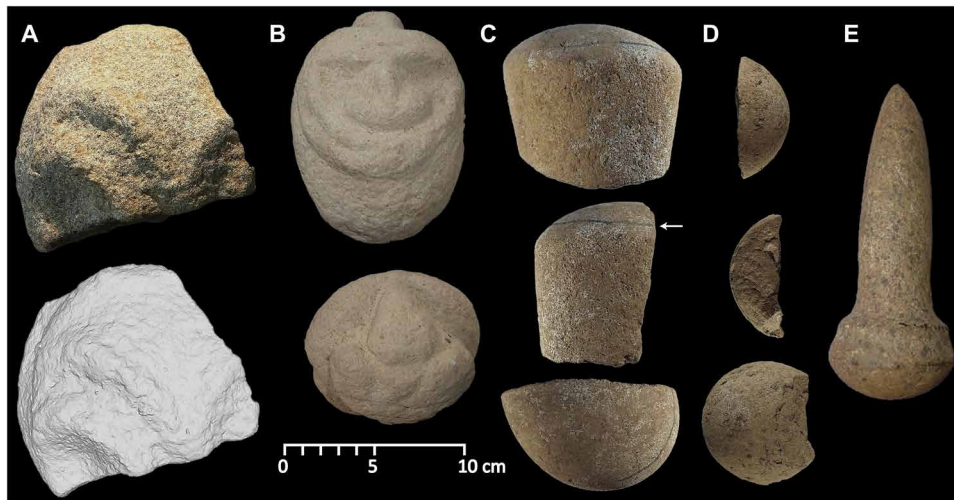


Fig. 4. Formally manufactured stone carvings and pestles from Waim. (A) Excavated fragment of carved stone face with image above and three-dimensional (3D) photogrammetry textured model below showing brow ridges and eye socket. Comparative carvings from undated contexts are provided in fig. S5. (B) Complete carved face with bird above the head showing front and top, found during groundworks in the same location where excavations were undertaken. (C) Large excavated pestle base fragment (pestle 1) with natural mineral lens indicated by arrow. (D) Small excavated pestle base fragment (pestle 2). (E) Complete pestle (local surface find) with similar base morphology as the excavated example (D). Photo and figure credits: Ben Shaw, UNSW.

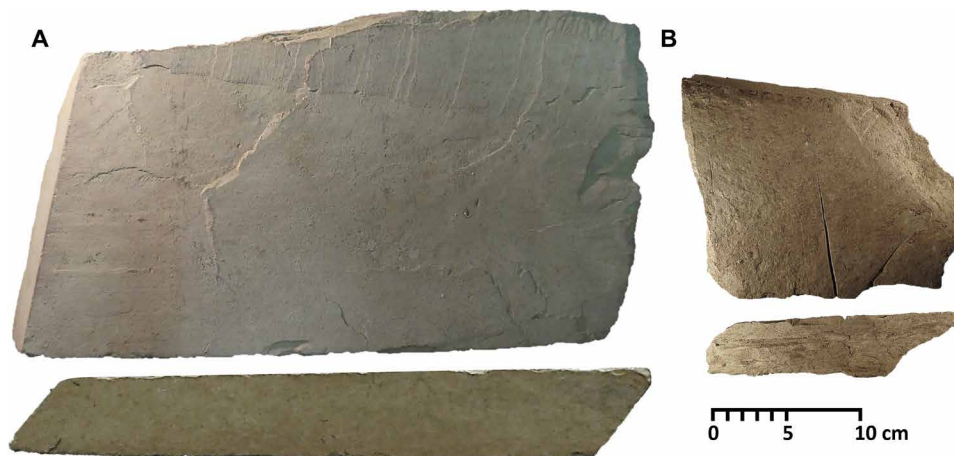


Fig. 5. Components of planilateral axe-adze manufacture from Waim excavations. (A) Large siliceous argillite preform prepared by grinding all surfaces of a naturally occurring tabular slab, with the distal ends heavily ground to obtain an acute angle. (B) Siliceous argillite with deeply incised cut marks, perhaps delineating the distal end of an axe-adze, demonstrating the use of cutting as a manufacturing technique at Waim. Photo credit: Judith Field, UNSW. Figure credit: Ben Shaw, UNSW.

structure. Pleistocene claims for postholes (site NFX) in the highlands are otherwise unconvincing because of their very small size and lack of depth (Fig. 1) (25).

Further evidence for a fixed structure is indicated by the discovery of an unmodified flat rock cut horizontally into the basal clay slope (layer 4), the placement and orientation of which is consistent with a step (fig. S6). It was immediately adjacent to the posthole cluster and near the cached axe-adze preform. Notably, the density of lithic discard here was very low ($n = 107$, 1.45 m^3 ; squares A, C, and F) (figs. S3 and S6). In contrast, a relatively high concentration of lithic artefacts ($n = 307$; 0.85 m^3) recovered from squares B and D reflects differential discard of material refuse down the adjacent slope where it accumulated at the base. Together, the location and patterning of the artefacts and features are suggestive of a maintained domestic space.

DISCUSSION

A Neolithic transition in New Guinea

The emergence of agriculture has long been argued as a catalyst for notable human behavioral innovations (2, 3, 27–29). While the Neolithic was initially applied to Eurasian contexts, it has since been expanded to accommodate a number of regional variations in cultural expression. We have identified substantial commonalities between Eurasian Neolithic cultural packages and the mid-Holocene highland New Guinea sequence (3). Technological and social changes became archaeologically visible at Waim by 5050 to 4200 cal yr B.P., ~2000 years after cultivation of root and fruit crops began and at least 1000 years before the appearance of the Lapita cultural complex (1, 30–32).

Symbolic expression, complex food processing, fibercraft, transformed axe-adze technology, and long-distance offshore obsidian trade

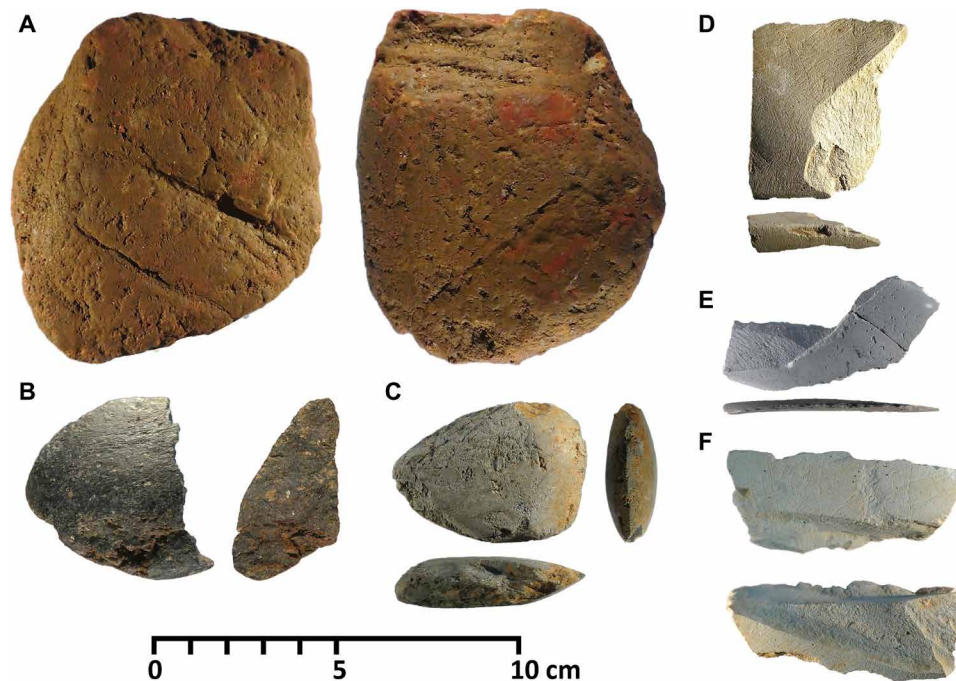


Fig. 6. Ground and cut stone artefacts from Waim excavations. (A) Incised volcanic stone with ochre residue, (B) pyroxenite fragment with striations, (C) siliceous argillite lenticular axe-adze, and (D to F) siliceous argillite tool fragments with ground surfaces. Photo and figure credits: Ben Shaw, UNSW.

represents the independent development of a Neolithic complex in this subtropical highland setting. The newly discovered pestles are contemporary with four putatively dated mortar fragments (Kuk, Nombe, Warrawau, NFB) from other excavated highland contexts, spanning 7000 to 3800 cal yr B.P. (9, 33). Production and use of these stone objects ceased before the introduction of pottery with the Lapita cultural complex. Modern populations have re-used stone mortars and pestles but have no knowledge of their original mode of use (9).

The iconography of stone carvings, expressed as anthropomorphic and zoomorphic forms, suggests that a symbolic social system facilitated communication across language and cultural boundaries in the mid-Holocene (9). The distribution of undated surface finds demonstrates that the components of this cultural complex occur elsewhere in the highlands, with lower densities throughout the lowlands and neighboring island regions (fig. S5) (34). The clustered distribution of these social objects likely relates to major centers of settlement and interaction in the mid-Holocene, with Waim situated within one of these centers. Access between the highlands and lowlands would have improved when a large inland sea on the north coast of New Guinea (Sepik-Ramu basin) reached its maximum extent 7500 to 4000 years ago (Fig. 1) (35). However, the developments identified in the New Guinea highlands were not a sudden innovation but were borne out of long-term incremental technological and social changes originating in the terminal Pleistocene and Early Holocene (36). Ground edge axe-adzes, expedient plant processing tools, wetland plant management, and the genetic differentiation of highland populations all occur before 6000 years ago (1, 4, 24).

The technological changes in the highlands coincide with the intensification and regional spread of agricultural practices. The development of large-scale rectilinear ditch field systems at Kuk (phase 3) from 4500 cal yr B.P. signals a shift to communal organi-

zation of wetland resources and the formation of defined territorial boundaries (1). The divergence of Trans New Guinea languages, closely linked with the spread of agricultural communities, from 6000 to 4000 years further indicates increased territoriality of cultural groups (5). Ancient starch analysis at Waim identified yams and bananas, and while they may represent wild varieties, they are known to have been cultivated at Kuk from 6800 cal yr B.P. It is possible that *D. pentaphylla* was transported to Waim from lower elevations, while other tubers (Kudzu) and tree nuts accessible at higher elevations (montane forest) formed a broad-based subsistence strategy still practiced in the region today (37, 38). There is no evidence for the domestication of endemic fauna (birds, marsupials, and small mammals) in the highlands because their behavior was not conducive to this anthropogenic process. The social innovations identified in the New Guinea highlands show clear parallels with Neolithic processes observed elsewhere in the world, with behavioral adaptations to the unique range of biogeographic settings underlying the remarkable linguistic and cultural diversity that distinguishes this part of the world.

CONCLUSION

The evidence from Waim provides the first in situ evidence for the presence of complex cultural practices in mid-Holocene New Guinea. When considered together with a growing corpus of studies indicating expansion and intensification of agricultural practices, these combined cultural elements represent the development of a regionally distinct Neolithic. Increased population pressure on the uneven distribution of natural resources likely drove this process, further inferred by language and genetic divergence (4–6). The evidence from Waim has now also placed cultural assemblages from less resolved mid-Holocene highland open settlements and rockshelters into a

more secure, and broader, cultural context. Changing settlement patterns, symbolic expression, and technological innovations from at least 4000 to 5000 years ago had a profound influence on New Guinea cultural diversity over succeeding millennia.

MATERIALS AND METHODS

Excavation procedure

Systematic excavation was undertaken by trowel in 1- or 0.5-m² squares by 5-cm spits within apparent stratigraphic layers, with all sediment dry sieved through 5-mm mesh. Inclusive of test pitting, a total of 8.3 m² was excavated. Excavation proceeded until bedrock or culturally sterile clay was encountered. A datum was established before excavation, and all measurements were taken using a dumpy level, stadia rod, and hand tape. Postholes were excavated and labeled individually as features. Feature depth was determined by measuring the horizontal and vertical position in the square where it was first identified and at the deepest point. In situ finds, including charcoal fragments, were bagged individually with context numbers, and their location (*x,y,z*) was recorded. The sieve residues were bagged, weighed, and sorted. Soil samples were collected during excavation, and upon completion of the excavation, all squares were backfilled. The site area was mapped using tape and compass, and site elevation profiles were surveyed with a dumpy level. pH, Munsell soil color, and particle size analysis were subsequently completed at the University of New South Wales.

Radiocarbon dating

All radiocarbon dates were determined from charcoal samples collected in situ and plotted in three dimensions within the excavated squares. Radiocarbon determinations were obtained using AMS at BETA laboratory (Miami, Florida, USA) and the Australian Nuclear and Technology Organisation (Sydney, New South Wales, Australia). All charcoal samples were physically cleaned of sediment adhering to the surface, gently crushed, and then dispersed in deionized water. The samples were pretreated using the acid-base-acid method, by washing the samples with hot HCl acid to eliminate carbonates, and then a wash with NaOH to remove secondary organic acids, followed by a final HCl rinse to neutralize the solution before drying. Pretreated samples were combusted to CO₂ gas by oxidation and then reduced to graphite for analysis. All ¹⁴C determinations were calibrated using the IntCal13 calibration curve and OxCal 4.3 program.

pH and Munsell soil analyses

Soil samples were combined in a 1:5 ratio with distilled water and gently mixed on a shaking table for 1 hour. pH was measured with a digital pH meter, which had been calibrated with solutions of known pH before sample analysis. Sediment color was determined by matching dry samples with a Munsell soil chart (39).

Particle size analysis

Size and modal distribution of the sediment was determined by particle size analysis. Approximately 1 to 3 g of sediment were sieved through 2000- μ m mesh, pretreated with 30% NaOH heated to 80° to 90°C to dissolve the organic component. Reverse osmosis water and several drops of sodium hexametaphosphate [5.5 g/liter; (NaPO₃)₆] were added to the sample as a particle deflocculant 24 hours before analysis. A Malvern mastersizer 2000 laser-diffraction particle size analyzer with a Hydro2000G dispersal unit was used for the analysis.

Three consecutive runs (15 s; 15,000 measurements) were made for each sample, with the average reported. Obscuration was kept within the accepted range of 10 to 20%. Particle size parameters were calculated using GRADISTAT software and the following grain size dimensions: clay, <2 μ m; silt, 2 to 63 μ m; sand, 63 to 2000 μ m.

Stone artefact analysis

All stone recovered from the sieve were assessed to identify the raw material and reduction characteristics, with all natural siltstone discarded onsite. Artefacts were photographed and weighed at the University of New South Wales (UNSW). Artefact density was determined by dividing the number of artefacts by the average spit depth (centimeter), reported for 1 m². Technological analyses were undertaken at Otago University (Dunedin, New Zealand). The following technological categories were used: tool, tool preform, core, flake, angular fragment, and manuport. A tool is any artefact that has been modified through shaping for use and often includes use wear and/or retouch. A tool/preform has been modified into shape, but was discarded before the production process had been completed. A flake is a stone artefact with a defined ventral and dorsal surface and at least one of the following: a platform, bulb of percussion, ripple marks, and distal termination. A core is a parent piece of raw lithic material with negative flake scarring. A used flake/fragment is a flake or fragment with evidence of usewear but no retouch. A core tool is a core that has subsequently been used as a tool. An angular fragment is any piece of stone that has been produced during the flaking process but does not contain the attributes of a flake. A manuport is a stone that is geologically nonlocal and must have been brought to the site by people.

Ancient starch and phytolith analyses

Ancient starch analysis was undertaken on two pestles recovered during excavation and an associated soil sample immediately adjacent to pestle 1. The phytolith assay was undertaken on pestle 1 and the associated soil sample. Each pestle had half of the ground surface placed in an ultrasonic bath in distilled water for 2 min. Because of the high clay content, the samples were deflocculated in 5% (w/v) sodium hexametaphosphate for 48 hours. Samples were rinsed in water with centrifugation, and the starch and phytoliths were extracted using heavy liquid separation with sodium polytungstate (SG. 2.35) and spun at 1000 rpm for 15 min. The supernatant was transferred to a tube and rinsed in water with centrifugation at 3000 rpm for 3 min, three times. Samples were rinsed in acetone and allowed to dry before mounting in 50% glycerol. Soils were prepared using the same method but were sieved using 125- and 53- μ m sieves after the deflocculation step to facilitate the phytolith analysis. The starch analysis involved complete slide scans with a Zeiss Axioskop II transmitted light microscope fitted with Nomarski optics. Images were collected using a Zeiss HRc digital camera and Zeiss Axiovision software. A geometric morphometric analysis of the starch grains was undertaken (12, 40). The comparative reference set was compiled from the Forest Research Institute herbarium and field collections covering both economic and noneconomic starch bearing plant taxa by M. Lovave and J.H.F. For the phytolith study, slides were scanned at \times 400 magnification until 200 phytoliths were recorded. Phytolith identification was based on a large phytolith reference collection for Southeast Asia (41) and augmented by J.H.F. from herbarium specimens (courtesy of the National Herbarium, Canberra, Australian Capital Territory).

Microwear analysis

Five artefacts were selected for further microscopic analysis at the University of Wollongong, Australia. Selected artefacts included the carved face fragment (square B, layer 2b), two stone pestle base fragments (square C, layer 2c; square F, layer 2b), the incised stone (square B, layer 2c), and a fragment of pyroxenite (square D, layer 2b). All artefacts were visually scanned under low magnification ($\times 6.7$ to $\times 45$) using an Olympus SZ61 stereozoom microscope with an external fiber optic, 150-W halogen light source (Olympus LG-PS2). Stereozoom microscope images were captured using an Olympus Infinity 2 camera permitting both color and black and white digital images (recorded as TIF files). The pyroxenite fragment was also examined under higher magnification using an Olympus BX51 metallographic microscope with vertical incident light (bright field and dark field) under high magnification ($\times 50$, $\times 100$, $\times 200$, and $\times 500$). Multifocal images were later stacked using HeliconFocus software. The carved stone fragment and the incised stone were also three-dimensional (3D) scanned using a Rexcan DS3 Silver white light 3D scanner. Scans were processed on Medit EzScan2017 software at ultrahigh resolution and exported as STL files.

pXRF analysis of obsidian

The Waim obsidian piece and 53 obsidian geological samples from all main sources in Papua New Guinea were analyzed using a Bruker Tracer III-SD pXRF at the University of Otago on the following settings: 40 kV, 30 μ A, with a filter (12 mil Al + 1 mil Ti + 6 mil Cu), for a 300-s run time. Before analysis, a pelletized international standard (BHVO-2) was analyzed to confirm the accuracy of the instrument. Calibration to parts per million (ppm) used Bruker's obsidian (OB40) calibration in S1CalProcess (42).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/6/13/eaay4573/DC1>

Fig. S1. World map showing the centers where domestication of at least one plant species has occurred in the Early and Middle Holocene.

Fig. S2. Formally manufactured stone tools found on the surface or recovered during groundworks for gardening and house construction on the Waim spur by local residents before the archaeological investigations.

Fig. S3. Stratigraphic profiles, artefact density, and particle size analysis for the systematically excavated squares at Waim.

Fig. S4. Regional geology of the Simbai-Kaironk-Jimi Valleys showing the location of Waim and likely origins of excavated stone artefacts.

Fig. S5. Map of known stone mortar-pestle distribution and core distribution of stone carved bird iconography in Papua New Guinea and the adjacent islands relative to the location of Waim.

Fig. S6. Structural evidence and artefact distribution at the Waim site.

Fig. S7. Principal components analysis of Waim obsidian flaked piece and obsidian sources.

Fig. S8. Grassland mountains and forested Jimi River Valley landscape below Waim, looking south, with the Jimi-Wahgi divide in the background.

Fig. S9. The Waim site, looking east, situated on a natural hill top within Waim village.

Fig. S10. Excavation of the test pit showing the gabbro pestle fragment and other lithic artefacts exposed in the front (northern) half of the square.

Fig. S11. Partially exposed section that had been previously cut back by Waim residents around the northern edge of the hilltop.

Fig. S12. Square F after excavation showing a possible posthole feature in the lower right hand corner.

Fig. S13. The Waim site with the locations of the systematically excavated squares shown.

Fig. S14. Stone carving from square B, layer 2b.

Fig. S15. Artefact with incised cut/groove marks, from square B, layer 2c.

Fig. S16. Ground-stone fragments and corresponding microwear from various squares of the Waim excavations.

Fig. S17. Comparative reference starch used in this study and not shown in fig. S20.

Fig. S18. Dendrogram for the optimal classifier—a quadratic discriminant—showing the Mahalanobis distance between the means of the species.

Fig. S19. The confusion matrix for the reference species used in the study.

Fig. S20. Archaeological starch and their correlating species identification.

Fig. S21. Phytoliths identified on the Waim pestle and sediment.

Table S1. Radiocarbon determinations from Waim, mid-Holocene New Guinea highland sites, and the Holocene sequence from Kuk swamp (phases 1 to 3).

Table S2. Excavated lithic artefact assemblage from Waim, by square, layer, and artefact type.

Table S3. pXRF elemental concentrations (ppm; Ka1) for the Waim obsidian core and for the obsidian source samples.

Table S4. Numbers of grains identified of each of the comparative reference species.

Table S5. Error range of Bruker Tracer III-SD during analysis, using the U.S. Geological Survey BHVO-2 Geological Standard.

Table S6. Elemental loadings of three components (98% variation) for analyzed obsidian source samples and the Waim obsidian flake.

Text S1. Archaeological investigations at Waim

Text S2. Stratigraphic descriptions of sedimentary layers at Waim

Text S3. Technological and geological characteristics of the Waim lithics

Text S4. Microwear analysis of carved and modified lithic artefacts

Text S5. Geometric morphometric analysis of ancient starch from Waim

Text S6. Phytolith analysis of pestle and sediments from Waim

Text S7. pXRF reference data and principal components analysis of Waim obsidian

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