New Insights into Modern Human Behaviour at Liang Bua (Flores, Indonesia) Based on the Temporal Distribution of Pottery and Mollusks During the Past 5,000 Years

I Made Agus Julianto

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Table of Contents

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List of Tables

List of Figures

Abstract

In addition to preserving a rich archaeological record spanning from ~190 thousand years ago (ka) until the terminal Pleistocene, Liang Bua (Flores, Indonesia) also preserves a rich and relatively complete Holocene stratigraphic sequence with dense accumulations of faunal remains, stone artifacts, and pottery. In this study, the abundances of pottery sherds and various mollusk taxa were examined across nine stratigraphic units to explore temporal variation during the past 5,000 years. This temporal period is important because it is during this time that human populations living in this area shifted from a foraging to a sedentary, agricultural lifestyle. Using data obtained from new archaeological excavations at the site, the first aim of this study was to improve knowledge of when pottery was first introduced as previous research has suggested that this occurred either ~4 ka or ~3 ka. The second aim of this study was to increase understanding about the mollusk assemblage at Liang Bua in terms of its temporal range and taxonomic composition. Particular emphasis was placed on determining whether humans were responsible for accumulating all or part of this large assemblage, which included 3,515 three-dimensionally-plotted specimens and 4,270 specimens recovered from sieved sediments.

The results show that pottery was most likely first introduced to the site ~3.3 ka and used regularly after ~3 ka, likely signaling a shift to increased sedentism or farming in this area. The main shell midden at Liang Bua was deposited between ~4.4 and 3.3 ka and includes mostly freshwater species. Interestingly, 63.1% of *Tarebia granifera* and 66.7% of *Melanoides tuberculata* recovered in Sectors XXXII-XXIX showed signs that they were deliberately cut at their apices. Deliberately cutting the apex of a shell is almost certainly a strategy to obtain the meat of the clam for human consumption. Furthermore, the presence of 12 culturally modified marine shells at Liang Bua suggests that, after ~4.4–4.3 ka, past peoples living around Liang Bua

had strong social and/or symbolic connections to coastal areas either through their own foraging ranges or through trade networks with other peoples living nearer to the ocean.

Introduction

Best known as the type site of *Homo floresiensis*, Liang Bua is a large limestone cave that is located on Flores, an oceanic island in eastern Indonesia (Figure 1) (Brown et al., 2004; Morwood et al., 2004). In addition to preserving a rich archaeological record spanning from ~190 thousand years ago (ka) until the terminal Pleistocene (Sutikna et al., 2016), it also preserves a rich and relatively complete Holocene stratigraphic sequence with dense accumulations of faunal remains, stone artifacts, and pottery (Moore et al., 2009; Morwood et al., 2009; Sutikna et al., 2018, 2020; Veatch et al., 2019, 2020; Julianto et al., 2020; Lin et al., 2020). To date, most analyses of the Holocene fauna from Liang Bua have focused on the mammalian and avian remains (van den Bergh et al., 2009; Meijer et al., 2013, 2017; Veatch, 2014; Sutikna et al., 2018, 2020; Veatch et al., 2019, 2020; Eber et al., 2020; Evans et al., 2020; Alamsyah et al., 2020; Alamsyah, 2021). However, Liang Bua also preserves a relatively large assemblage of shells that is dominated by two freshwater species, *Tarebia granifera* and *Melanoides tuberculata*, both of which are small gastropods from the Thiaridae family (van den Bergh et al., 2009). Other freshwater species documented at the site include *Neritina pulligera*, *Neritodryas cornea*, *Neritodryas dubia*, *Septaria porcellana*, and *Clithon squarrosus*, all of which belong to the Neritidae family, but marine and terrestrial species are also present (van den Bergh et al., 2009).

At Liang Bua, out of 8,846 identified mollusk specimens included in the analysis by Sutikna et al. (2018), only 43 aquatic and 37 terrestrial mollusks were from the Pleistocene deposits. Similarly, previous work also concluded that mollusks were not a focus of hominin activity at Liang Bua during the Pleistocene, either for subsistence or the production of artifacts (van den Bergh et al., 2009). Instead, both studies suggest human exploitation of mollusks occurred during the Holocene, especially after ~5 ka (van den Bergh et al., 2009; Sutikna et al., 2018). Not long after, pottery was introduced to the site either ~4 ka ago (Morwood et al., 2009) or ~3 ka ago (Sutikna et al., 2018). Both of these estimates were based on stratigraphic associations between pottery fragments and radiocarbon-dated charcoal recovered during excavations conducted at the site prior to 2017, in which *in situ* findings were manually plotted using conventional methods (e.g., with plumb bob and string) (Sutikna et al., 2018). From 2017 and onward, however, all excavation details have been digitally recorded using total stations, which provide greater spatial resolution for the acquired archaeological data. Therefore, this study has two main research objectives.

The first aim is to use data deriving from the more recently conducted excavations to more precisely determine when pottery was first introduced at Liang Bua. This is important because pottery likely signals that the human populations in this area were shifting to a more sedentary way of life and, perhaps, the apparent intensive harvesting of freshwater mollusks was also related to this shift (Sutikna et al., 2018). Moreover, the spread of pottery across Island Southeast Asia has long been linked to ideas about the dispersal of Austronesian people and culture (Pawley and Green, 1973; Blust, 1976, 1988; Bellwood, 1988b; Bellwood et al., 1995; Blust, 1999; Bellwood and Renfrew, 2002; Bellwood, 2005; Gray et al., 2009; Spriggs, 2011; Bellwood, 2017). The second aim is to better understand the mollusk assemblage in terms of its age range, species composition, taphonomy, and cultural modification, particularly in their three-dimensional, plotted contexts. Despite dominating the site's faunal assemblage after ~5 ka (van den Bergh et al., 2009; Sutikna et al., 2018), shells were rarely plotted during excavation prior to 2017. Furthermore, previous work interpreted the accumulation of freshwater shell after ~5 ka as the result of human subsistence activities (van den Bergh et al., 2009) but no specific supporting taphonomic evidence was provided. This is not particularly surprising, as most aquatic shell middens are interpreted as such when other evidence of human activity (e.g., stone artifacts) is associated (Szabó, 2017). However, in this study, an emphasis is placed on determining whether there is any taphonomic evidence that humans were responsible for accumulating all or part of the large assemblage of mollusks recovered at Liang Bua and if so, in what ways.

Shellfish, which include crustaceans (e.g., crab, lobster, shrimp, prawn, etc.) and mollusks (e.g., snail, clam, mussel, oyster, scallop, octopus, squid, etc.) provide substantial nutritional benefits as a dietary resource that can often be predictably accessed (Erlandson, 2001; Broadhurst et al., 2002). Shellfish exploitation is usually associated with foraging populations with greater social complexity and reduced mobility (Erlandson, 2001), which together provide a context for stimulating symbolic expression through material culture (Marean et al., 2007). The use of shellfish as a source of food for early modern humans (*Homo sapiens*) and Neandertals is well documented (Marean et al., 2007; Stringer et al., 2008). For instance, modern humans from coastal South Africa consumed at least ten different species of marine shellfish as early as ~164 ka (Marean et al., 2007). Similar evidence from sites in Gibraltar shows that Neandertals also exploited mollusks along with other coastal resources such as seals, dolphins, and fish (Stringer et al., 2008). Shellfish are not only useful as dietary resources but also as raw materials for artifact production. For example, beads made from perforated shells of *Nassarius gibbosulus* (a marine gastropod) represent early evidence for symbolic behavior by modern humans ~135–100 ka at Skhul in western Asia and at Oued Djebbana in North Africa (Vanhaeren et al., 2006). On the Indonesian island of Java, shell tools were used to produce eighteen cut marks on two bovid bones from the fossil-bearing deposit of the Pucangan formation at Sangiran, suggesting that *Homo erectus* recognized shell as a useful raw material as early as ~1.6–1.5 million years ago

(Ma) (Choi and Driwantoro, 2007). In terms of *Homo erectus* potentially collecting and consuming aquatic resources, Joordens et al. (2009) re-analyzed fish bones and shells excavated during the late 19th and early 20th centuries. They found that the aquatic fauna at Trinil included a variety of mollusk species from freshwater, brackish-water, and mudflat habitats, along with catfish and stingray, suggesting that these resources were locally available for exploitation by early hominins (Joordens et al., 2009). However, it remains to be demonstrated if such exploitation by *Homo erectus* actually occurred (Szabó and Amesbury, 2011).

Mollusk exploitation by modern humans in Island Southeast Asia expanded rapidly after ~40 ka (Szabó and Amesbury, 2011). As evidenced at multiple sites across the region, during this time period modern human populations harvested mollusks for food and artifact production from various combinations of saline, brackish, and freshwater conditions mainly around the shores of seas, lakes, and rivers (Szabó and Amesbury, 2011). The exploitation of marine mollusks from coastal areas is well documented on Timor, a large oceanic island east of Flores, at Jerimalai, Lene Hara, Matja Kuru 1, and Matja Kuru 2 (O'Connor et al., 2002; Veth et al., 2005; O'Connor, 2007; Langley and O'Connor, 2016). Marine shells recovered at these sites are dated between ~42 and ~0.2 ka and mostly consist of edible species (e.g., *Nerita* spp., *Strombus* spp., *Trochus* spp., *Turbo* spp., *Lambis* spp., etc.) (O'Connor, 2002, 2007; Langley et al., 2016). Further evidence of the exploitation of marine mollusks by humans for food occurs throughout the region at, for example, Leang Sarru (~35–8 ka on the island of Salibabu) (Ono et al., 2010), Golo Cave (~33–3 ka on the island of Gebe) (Szabó et al., 2007), and Kilu Cave (~29–5 ka on the island of Buka) (Wickler, 2001). Most of these sites as well as others—e.g., Leta Leta Cave and Bubog I in the Philippines (Szabó and Ramirez, 2009; Pawlik et al., 2015), Liang Rundung on Flores (van Heekeren, 1972), Pia Hudale Cave on Rote (Mahirta, 2003; Mahirta et al., 2004)—also preserve culturally modified marine shells. For instance, five shell beads made from *Nautilus pompilius* (~42–4.8 ka) were identified at Jerimalai and beads made from the shells of *Oliva* spp. (mostly *Oliva brettinghami*) (~37–0.2 ka) were identified at Jerimalai (n = 295), Lene Hara (n = 99), Matja Kuru 1 (n = 83), and Matja Kuru 2 (n = 8) (Langley et al., 2016). Many of these *Oliva* beads show modifications for stringing consecutively for personal adornments (e.g., necklaces) (Langley et al., 2016). At Golo Cave, 30 worked shells include shaped operculum artifacts, unretouched flakes, probably retouched pieces, and amorphous fragments (Szabó et al., 2007). In terms of technique, the knapped pieces of *Turbo marmoratus* (~32–28 ka) were shaped by detaching flakes sequentially from the margin in a unidirectional fashion to generate a steeply angled edge, producing more sophisticated artifacts than those made of stone at the site (Szabó et al., 2007). Kilu Cave also preserved various Holocene shell artifacts such as a *Tridacna* shell adze, *Trochus* rings, bivalve scrapers, and shell beads (Wickler, 2001). Clearly, people across Island Southeast Asia have been exploiting marine mollusks for a long time and these animals have played important roles as a dietary resource, raw material for tool manufacture, and for symbolic behaviour of modern human communities in this region (Langley et al., 2016).

Evidence of human exploitation of brackish and freshwater shells occurs throughout Island Southeast Asia (Bellwood, 1988a; Glover, 1981a; Bulbeck et al., 2004; Szabó and Amesbury, 2011; Reynolds et al., 2013; Pawlik et al., 2015; Brumm et al., 2018). For example, at Niah Cave on Borneo, which was part of continental Asia during the Pleistocene at times of low sea levels, between ~50 and 35 ka people harvested brackish (e.g., *Ellobium aurisjudae*, *Polymesoda erosa*) and freshwater species (e.g., *Paludomus everetti*, *Ctenodesma borneensis*) (Reynolds et al., 2013). At Bubog I in the Philippines between ~11–4.2 ka ago, the focus was placed solely on brackish-water taxa (e.g., *Geloina coaxans*, *Terebralia palustris*) (Pawlik et al.,

2015) whereas in western and northeastern Borneo at Gua Sireh (~20 ka ago) and Hagop Bilo (~17–12 ka ago), respectively, an abundance of freshwater shell (*Sulcospira*, *Balanocochlis*, and *Brotia*) dominated by an endemic species, *Brotia pageli*, has been recovered (Bellwood, 1988a; Szabó and Amesbury, 2011). Similarly on Sulawesi, which is located in Wallacea and has never been connected to any other islands in Indonesia or the Asian continent, people harvested freshwater shells for food at Leang Burung 2 between ~31–19 ka (e.g., *Brotia perfecta*) and Leang Sakapao between ~30–25 ka (Glover, 1981a; Bulbeck et al., 2004; Brumm et al., 2018).

Although studies of shell middens have typically focused on aquatic species, land snails can also provide dietary resources for human communities (Rabett et al., 2011). For example, modern humans from Hang Boi cave, in Northern Vietnam, exploited land snails ~12–10 ka (Rabett et al., 2011). Roughly 98% of the shell assemblage at Hang Boi is composed of terrestrial snails, 91% of which belong to *Cyclophorus theodori* and *Cyclophorus unicus*, and many of these shells are burnt suggesting that human activities were responsible for the accumulation (Rabett et al., 2011). Nonetheless, terrestrial snail shells typically form only a small component of shell middens that are the result of human refuse and are generally considered self-introduced into cave deposits (Szabó, 2017).

Materials and Methods

Archaeological excavation

The pottery and mollusk remains examined in this study were recovered during archaeological excavations of multiple Sectors (i.e., specific areas of excavation, typically 2 x 2 m) at Liang Bua (Figure 1). Specifically, assemblages from Sectors XXXII, XXIX, XXVI, XXV, XVI, and VII form the main component of the study sample. In 2018 and 2019, I directly supervised the excavation of Sectors XXIX and XXXII. All *in situ* findings and other important details of the excavations were three-dimensionally plotted using a Nikon Total Station Nivo 5.C. Each Sector was divided into four 1 x 1 m quadrants that were excavated separately in a series of units called lots. Excavation of the first lot proceeded from the cave floor surface until a maximum depth of 15 cm was reached and subsequent lots proceeded until evidence of a new sedimentary layer was exposed or a maximum depth of 10 cm was reached. As new sedimentary layers were exposed within each quadrant, the excavation in that quadrant would temporarily cease until the new layer was also exposed in the other quadrants. Excavated sediments from each lot were dry and wet sieved using 2 mm mesh. Excavation of the other four Sectors occurred prior to 2016 and before total stations were employed at the site. However, the excavation and sieving procedures were similar to those described above (e.g., an initial 15-cm depth interval from the cave floor surface followed by 10-cm depth intervals or until a new sedimentary layer was exposed) except that the entire 2 x 2 m area of each Sector was excavated together and *in situ* findings were plotted manually using conventional methods (e.g., with plumb bob and string) (Sutikna et al., 2018).

Stratigraphic units

The depositional sequence at Liang Bua is divided into eight main stratigraphic units (Units 1–8), based on eight volcanic tephras identified at the site (Sutikna et al., 2018). Holocene sediments comprise Unit 8, which are further divided into three subunits (8A = ~12–5 ka; 8B = ~5–3 ka; 8C = < ~3 ka) (Sutikna et al., 2018). In the present study, all of the pottery and mollusk remains examined derive from Units 8B and 8C. To examine the temporal distribution of these remains, Units 8B and 8C were subdivided further into nine sub-subunits, based on radiocarbon ages obtained from multiple pieces of charcoal from the Sectors under study. Unit 8B was divided into three sub-subunits ($8B_1$ = 5.0–4.3 ka; $8B_2$ = 4.3–3.7 ka; and $8B_3$ = 3.7–3.0 ka) and Unit 8C was divided into six sub-subunits ($8C_1$ = 3.0–2.5 ka; $8C_2$ = 2.5–2.0 ka; $8C_3$ = 2.0–1.5 ka; $8C_4$ = 1.5–1.0 ka; $8C_5$ = 1.0–0.5 ka; $8C_6$ = < 0.5 ka) (Table 1).

All of the radiocarbon dated charcoal samples used in this study were obtained during excavation and have three dimensional (x, y, z) coordinates based on their excavated position (i.e., none were taken from sieved sediments). The charcoal samples obtained from all of these Sectors were sent to DirectAMS Radiocarbon Dating Service in Bothell, Washington, pretreated using acid-base-acid (ABA) procedures, and the ^{14}C content was analyzed using Accelerator Mass Spectrometry (AMS) (Wood, 2015). Using the CALIB 8.2 (Radiocarbon Calibration) program (http://calib.org) (Stuiver et al., 2022), which also includes a revised Southern Hemisphere offset, these ^{14}C ages were calibrated using the IntCal13 calibration dataset for the Southern Hemisphere (SHCal13; Hogg et al., 2013). Thus, the conventional ^{14}C ages in radiocarbon years BP were converted to calendar-year age ranges at the 68% and 95% confidence intervals and only the calibrated ^{14}C ages and their 95% confidence interval ranges are referred to subsequently in this thesis.

Units 8B and 8C in Sectors XXXII-XXIX were subdivided based on six and nine new calibrated radiocarbon ages from charcoal, respectively. These charcoal samples ranged in age between 4,852 and 2,036 years old (representing charcoal recovered nearest to immediately above and below the shell layer) and between 8,425 and 72 years old overall (Table 2). Age models for Sectors XVI-VII and XXVI-XXV were based on 21 (between 12,928 and 1,141 years old) and 14 (between 12,089 and 493 years old) previously calibrated radiocarbon ages from charcoal, respectively (Sutikna et al., 2018).

The mollusk and pottery assemblage

A total of 4,432 mollusk remains recovered from Sectors XXXII-XXIX were identified (number of identified specimens, NISP) to either species or at least genus level (Table 1). Of these, 3,494 specimens have associated x, y, z coordinates while an additional 938 derived from sieving. This sample was supplemented with 3,356 mollusk specimens identified to family level from Sectors XXVI, XXV, and XVI. Of these, 1,432 specimens (only 2 of which were plotted) were recovered from Sectors XXVI (NISP = 489) and XXV (NISP = 956) while 1,921 specimens (only 19 of which were plotted) derived from Sector XVI (Table 1). Taxonomic identifications and nomenclature followed Dharma (2005). Characteristics of cultural modification, casts of shells generated from mineral-rich water that filled the internal cavities, and/or any indication of burning or other anthropogenic signals were also recorded for the remains from Sectors XXXII-XXIX.

A total of 291 pottery sherds were recovered with associated x, y, z coordinates from Sectors XXXII-XXIX (Table 1) (fragments recovered during sieving have not yet been counted). Of these, 234 and 57 derived from Sectors XXXII and XXIX, respectively. Each fragment from Sector XXXII was classified based on its attributes (e.g., characteristics, or features of an entity, and style, or morphology) and variables of interest (e.g., colour, thickness, hardness, and form) (Rice, 2015). Munsell soil colour charts were used to describe the colours of each fragment and digital hand calipers were used to measure each fragment's dimensions (i.e., length, width, and thickness). A total of 2,782 pottery sherds were recovered from Sectors XXVI-XXV (Table 1). Of these, 668 have associated x, y, z coordinates and 2,114 derived from sieving. Sectors XVI-VII had 2,230 sherds with 1,081 recovered from Sector XVI (190 of which were plotted) and

1,149 from Sector VII (excavated by Raden Pandji Soejono in 1980 and details of plotted versus sieved findings were not available) (Table 1).

The abundances of the various mollusk taxa and pottery were calculated for the nine stratigraphic units and the subsequent analyses assumed that all of these elements represent animals/materials that died/were used during the depositional accumulation of the unit from which they were recovered. To examine whether changes in the structure of these assemblages occurred during the past ~5 ka, standard statistical analyses for zooarchaeological data were conducted using PAST, version 4.07 (Hammer et al., 2001). These analyses included chord distance (CD), unweighted pair group with arithmetic mean (UPGMA), evenness, individual rarefaction (Simpson 1/D and richness S), correspondence, and adjusted residuals from contingency tables. Each of these statistical methods is briefly described below but further details are provided in the Appendix.

The degree of change in these assemblages between stratigraphic units was quantified using CD. Assemblages with CD values equal or close to 0 will have identical or very similar compositions whereas those with CD values close or equal to the square root of 2 (i.e., ~1.4) will have very little in common (Ludwig and Reynolds, 1988). To visualize the respective compositions of mollusks and pottery within these stratigraphic units, the unweighted pair group with arithmetic mean (UPGMA) was used for pairwise comparisons of all CD values (Legendre and Legendre, 1998).

Evenness through the stratigraphic sequence was measured using the unbiased Simpson index ($1 - D'$), which here represents the probability that two randomly sampled specimens from a given stratigraphic unit will belong to a different category (i.e., a particular mollusk taxon or pottery fragment), in order to further explore temporal changes in these assemblages. Although this index is sometimes sensitive to changes in richness, it does not vary systematically as a function of sample size (Faith and Du, 2017) and values close to 0 indicate that the assemblage is dominated by a single category. In contrast, values close to 1-1/S (where S is the number of taxa) indicate that all categories in the assemblage are equally abundant. Individual rarefaction (Simpson 1/D and richness S) was also used in order to get the overall trend of increasing or decreasing evenness and richness through the stratigraphic sequence (Hammer et al., 2001).

The abundances of pottery and mollusk taxa within each stratigraphic unit were examined using correspondence analysis, a multivariate statistical technique that examines all units and their respective abundances simultaneously. Adjusted residuals from contingency table analysis were used to evaluate for statistically significant differences between all adjacent stratigraphic units in their abundances (Grayson and Delpech, 2003; Lyman, 2008) and these results facilitate interpreting variation along the axes of the correspondence analysis. If the absolute values of the adjusted residuals were greater than 1.96, then the difference was statistically significant at $\alpha = 0.05$ because adjusted residuals are equivalent to standard normal deviates.

Lastly, Geographic Information Systems enable the exploration and analysis of spatial data (e.g., materials, features, etc.) from archaeological sites in considerable depth and with increased efficiency (Wheatley and Gillings 2002; Gillings and Wheatley 2005). In this study, all of the plotted findings from Sectors XXXII-XXIX have associated x, y, z coordinates that were explored using ArcScene (version 10.8.1), which is a 3D visualization application that allows the excavation data to be explored in three dimensions and from multiple viewpoints.

Results

Sectors XXXII-XXIX

The NISP for pottery sherds and mollusks in Sectors XXXII-XXIX across the nine stratigraphic subunits of Units 8B and 8C are summarized in Table 3 and shown in Figure 2. Pottery was well represented in Units $8B_3$–$8C_6$ but was absent or relatively scarce in Units $8B_1$ (n = 0) and $8B_2$ (n = 3). The classifications of pottery across units are summarized in Table 4. Of these, 59.8% and 8.1% of pottery sherds were part of the body and base, respectively. In terms of size, 16.5 and 5 cm was the largest and the smallest vessel diameter identified. Moreover, two decorative pieces of pottery were found in $8C_4$ from Sector XXXII. In total there were 4,070 complete or relatively complete shells and 362 smaller fragments, with 3,703 and 729 of these recovered in XXXII and XXIX, respectively. Freshwater shell comprised 95.3% of the NISP and was mostly represented by two families, Thiaridae (n = 3,142) and Neritidae (n = 1,064). The two dominant thiarid species present were *Tarebia granifera* (n = 2,656) and *Melanoides tuberculata* (n = 486) while the two dominant neritid species were *Neritina petitii* (n = 658) and *Vittina aquatilis* (n = 265). Thiarids were abundant in Units $8B_2$ (n = 1,768) and $8B_3$ (n = 1,119), whereas neritids were only dominant in Unit $8B_3$ (n = 721). In contrast, terrestrial snails and marine shells were present (although in relatively low numbers compared to freshwater shells) in both Sectors across all stratigraphic subunits except $8C_2$ and $8C_4$, where no shells at all were present.

The total NISP for mollusks in XXXII-XXIX was 4,432, 5.6% of which were completely coated with calcium carbonate, 3.1% showed evidence of direct exposure to fire (burned), and 2.3% showed evidence of indirect exposure to fire (probably burned) (Table 5). Moreover, 14 shells showed clear signs of cultural modification: 12 were made into beads, one appears to have been used as a borer, and one as an adze or scraper (Table 6; Figures 3 and 4). Of the 3,142 thiarid shells recovered, 63.7% were cut at the apex (*Tarebia granifera*, 53.4%; *Melanoides tuberculata*, 10.3%) (Table 5; Figure 5).

The chord distance (CD) values for the pottery and mollusk assemblages in XXXII-XXIX across successive pairs of assigned depositional units are shown in Figure 6. Of all successive pairs, the least amount of change (CD = 0.08) was observed from Units $8C_2$ to $8C_3$ and Units $8C_3$ to $8C_4$, followed by Units $8C_5$ to $8C_6$ (CD = 0.09) and Units $8C_4$ to $8C_5$ (CD = 0.14). More change was observed from Units $8B_2$ to $8B_3$ (CD = 0.40), Units $8B_1$ to $8B_2$ (CD = 0.43) and Units $8B_3$ to $8C_1$ (CD = 0.47) with the largest shift occurring from Units $8C_1$ to $8C_2$ (CD = 1.23). Recall that CD measures differences in relative abundances between units so it is independent of differences in unit assemblage sizes. UPGMA cluster analysis of all pairwise chord distance values between units in XXXII-XXIX resulted in two main clusters, with Units $8B_1$–$8B_3$ and $8C_1$ forming one cluster and Units $8C_2$–$8C_6$ forming the other (Figure 7). Within the first cluster, Unit $8B_1$ was most unlike all of the remaining units while Units $8B_2$ and $8C_1$ were more similar to each other than either was to Unit $8B_3$. Within the second cluster, Units $8C_5$ and $8C_6$ were more similar to each other than either was to any of the other units, while Units $8C_2$ and $8C_4$ were more similar to each other than either was to Unit $8C_3$.

Analysis of pottery and mollusk taxonomy evenness in XXXII-XXIX, using the unbiased Simpson index, indicated some major differences between the assemblages of individual subunits (Figure 8). Marked increases in evenness occurred between Units $8B_2$ and $8B_3$, Units $8C_2$ and $8C_3$, and Units $8C_4$ and $8C_5$, while marked decreases occurred between Units $8B_1$ and $8B_2$, Units $8C_1$ and $8C_2$ and Units $8C_3$ and $8C_4$. There was an overall trend of decreasing evenness observed through the sampled stratigraphic sequence (Spearman's rho (r_s) = 0.72, p =

0.03), however, there was no significant trend in richness (i.e., the number of taxa present in each unit) (r_s = 0.33, p = 0.38).

Axes 1 and 2 of the correspondence analysis explained 79% and 12.8% of the variance in mollusk/pottery abundances from XXXII-XXIX (Figure 9). Units $8B_1$, $8B_2$, and $8B_3$ showed positive scores along axis 1; overall, these deposits were dominated by mollusks (>97.9% of NISP), especially Neritidae and Thiaridae (<37.2% and <79.7% of NISP, respectively), and had low abundances of pottery (<2.1%). Meanwhile, of the other units, Unit $8C_1$ showed the most similarities with Units $8B_1$, $8B_2$, and $8B_3$. It was also dominated by mollusks (82.1% of NISP) but plotted slightly more negatively along axis 1 because pottery significantly increased in proportion from 2.1% to 17.9% of NISP ($8B_3$ to $8C_1$). Units $8C_2$ through $8C_6$ followed a noticeable trend, shifting even further negatively along axis 1. These changes are driven by overall increases in pottery abundance (81.5–100% of NISP) through time, in conjunction with decreasing proportions of mollusks (18.5–0% of NISP) (Table 7) explain a majority of the similarities and differences among stratigraphic units.

Sectors XVI and VII

The NISP for pottery fragments and mollusks from Sectors XVI-VII within the nine stratigraphic subunits of Units 8B and 8C are summarized in Table 8. Pottery was well represented from Units $8B_3$ to $8C_6$ and dominated Units $8C_1$ (n = 561) and $8C_6$ (n = 657). Freshwater shell comprised 86.5% of the NISP and was dominated by two families, Thiaridae (n = 1,209) and Neritidae (n = 444), whereas terrestrial snails and marine shells comprised 10.9% and 2.7% of the NISP, respectively.

The chord distance (CD) values for the pottery and mollusk assemblages across successive pairs of assigned depositional units in XVI-VII are shown in Figure 6. Of all successive pairs, the least amount of change was observed from Units $8C_5$ to $8C_6$ (CD = 0.02), followed by Units $8C_2$ to $8C_3$ (CD = 0.06), $8B_1$ to $8B_2$ (CD = 0.21), Units $8C_3$ to $8C_4$ (CD = 0.37) and Units $8C_4$ to $8C_5$ (CD = 0.39). Meanwhile, more change was observed from Units $8B_2$ to $8B_3$ (CD = 0.56) and Units $8C_1$ to $8C_2$ (CD = 0.72), with the largest shift occurring from Units $8B_3$ to $8C_1$ (CD = 0.78). In the latter, freshwater shell abundance decreased (e.g., Neritidae and Thiaridae decreased from 37.1% to 10.2% and 50.0% to 40.0% of NISP, respectively) whereas pottery significantly increased from 2.2% to 41.1% of NISP. UPGMA cluster analysis of all pairwise chord distance values between units in XVI-VII resulted in two main clusters, with Units $8B_1$, $8B_2$, $8B_3$ forming one cluster and all other units forming the other (Figure 10). Within the first cluster, Units $8B_1$ and $8B_2$ were more similar to each other than either was to Unit $8B_3$. Within the second cluster, $8C_4$ was most unlike all the remaining units, which formed two additional clusters. The first of these only included Unit $8C_1$ while the second included $8C_2$, $8C_3$, $8C_5$ and $8C_6$. Within this cluster, Units $8C_5$ and $8C_6$ were more similar to each other and followed by Units $8C_2$ and $8C_3$ which were also similar to each other.

Analysis of pottery and mollusk taxonomy evenness in XVI-VII, using the unbiased Simpson index, indicated some major differences between the assemblages of individual subunits (Figure 11). Marked increases in evenness occurred between Units $8B_2$ and $8B_3$, and Units $8C_3$ and $8C_4$, while marked decreases occurred between Units $8B_1$ and $8B_2$, Units $8C_1$ and $8C_2$, and Units $8C_4$ and $8C_5$. However, no overall trend of increasing or decreasing evenness was observed through the sampled stratigraphic sequence (Spearman's rho (r_s) = 0.62, p = 0.08) but there was a significant trend in richness (i.e., the number of taxa present in each unit) (r_s = 0.73, p = 0.02).

Axes 1 and 2 of the correspondence analyses explained 72.6% and 17.0% of the variance in mollusk and pottery abundances in XVI-VII (Figure 12). Units $8B_1$, $8B_2$ and $8B_3$ showed positive scores along axis 1; overall these deposits were dominated by mollusks (97.8% to 100% of NISP), especially Neritidae and Thiaridae (<37.1% and <81.7% of NISP, respectively) and had low abundances of pottery (<2.2% of NISP). Meanwhile, of the other units, Unit $8C_1$ showed similarities with Units $8B_1$, $8B_2$, and $8B_3$, but had a relatively less positive score along axis 1 because mollusks made up only 58.9% of NISP while pottery significantly increased from 2.2% to 41.7% ($8B_3$ to $8C_1$). Unit $8C_4$ showed a low negative score, a result of lower mollusk abundance (< 35.5% of NISP) in conjunction with greater numbers of pottery (>64.5% of NISP). Units $8C_2$, $8C_3$, $8C_5$ and $8C_6$ followed this same trend and had even more negative scores along axis 1 than Unit $8C_4$. These changes through time were again driven by greater pottery (>79.7% of NISP) and lower mollusk abundances (<20.3% of NISP) (Table 9) explain a majority of the similarities and differences among stratigraphic units.

Sectors XXVI and XXV

The NISP for pottery fragments and mollusks from Sectors XXVI-XXV are summarized in Table 10. Pottery was recovered from Units $8B_3$ to $8C_6$ and was abundant in Units $8C_2$ (n = 865), $8C_5$ (n = 596), and $8C_6$ (n = 915). Freshwater shell comprised 68.4% of the NISP and was dominated by Thiaridae (n = 921) whereas Neritidae was relatively uncommon (n = 22). Terrestrial snails comprised 30.4% of the NISP and were dominated by Ariophantidae (n=261) and Helicidae (n=65) while in comparison marine shells were present in relatively low numbers (1.2% of NISP).

The chord distance (CD) values for the pottery and mollusk assemblages from XXVI-XXV across successive pairs of assigned depositional units are shown in Figure 6. Of all successive pairs, the least amount of change (CD = 0.06) was observed in Units $8B_2$ to $8B_3$ followed by Units $8C_2$ to $8C_3$ (CD = 0.12), Units $8C_3$ to $8C_4$ (CD = 0.12), and Units $8C_5$ to $8C_6$ (CD = 0.14). In contrast, more change was observed from Units $8C_4$ to $8C_5$ (CD = 0.30), Units $8C_1$ to $8C_2$ (CD = 0.73), and Units $8B_3$ to $8C_1$ (CD = 0.97), with the largest shift occurring from Units $8B_1$ to $8B_2$ (CD = 1.13), where shells were present in low numbers in Unit $8B_1$ (n = 12) but relatively abundant in Unit $8B_2$ (n = 233) as well as no pottery at all in either of these Units. UPGMA cluster analysis of all pairwise chord distance values between units in XXVI-XXV resulted in two main clusters, Units $8B_2$ and $8B_3$ (more similar to each other) forming one cluster and all other Units forming the other (Figure 13). Within the second cluster, Units $8C_1$ and $8B_1$ were more similar to each other and most unlike all the remaining Units, which formed two additional clusters. The first of these clusters, Units $8C_5$ and $8C_6$ were more similar to each other, while the second, Units $8C_2$ and $8C_4$ were more similar to each other than either was to Unit $8C_3$.

Analysis of pottery and mollusk taxonomy evenness in XXVI-XXV, using the unbiased Simpson index, indicated some major differences between the assemblages (Figure 14). Marked increases in evenness occurred between Units $8B_3$ and $8C_1$, while marked decreases occurred between Units $8B_1$ and $8B_2$, Units $8C_1$ and $8C_2$, and Units $8C_5$ and $8C_6$. However, no overall temporal trend of increasing or decreasing evenness was observed through the sampled stratigraphic sequence (Spearman's rho (r_s) = –0.25, p = 0.52) and there was no significant trend in richness either (i.e., the number of taxa present in each unit) (r_s = –0.27, p = 0.49).

Axes 1 and 2 of the correspondence analysis explained 71.6% and 16.1% of the variance in mollusk/pottery abundances (Figure 15). Units $8B_1$, $8B_2$, $8B_3$, and $8C_1$ showed the most positive scores along axis 1; these deposits were dominated by mollusks (76.0% to 100% of NISP), especially Thiaridae (16.7% to 90.9% of NISP) and Ariophantidae (2.6% to 41.7% of

NISP), as well as had sparse recovery of pottery (0.0% to 24.0% of NISP). Meanwhile, of the other units, Units $8C_2$ and $8C_4$ showed the most similarities with Units $8C_3$ but plotted slightly more positively along axis 1 because mollusks in these units comprised 35.2% to 38.8% of NISP, with greater numbers of pottery (>61.2% of NISP). Units $8C_3$, $8C_5$ and $8C_6$ followed a noticeable trend, shifting even further negatively along axis 1. Overall, differences between stratigraphic units were driven by increases in pottery abundances (67.6% to 96.7% of NISP) in conjunction with decreasing abundances of mollusks (32.4% to 3.3% of NISP) (Table 11) explain a majority of the similarities and differences among stratigraphic units.

Sectors XXXII, XXIX, XXVI, XXV, XVI, and VII

The total NISP for pottery fragments and mollusks from all of the Sectors included in this study are summarized in Table 12. Pottery was recovered from Units $8B_2$–$8C_6$ and especially abundant in Units $8C_2$ (n = 1,151), $8C_5$ (n = 1,275), and $8C_6$ (n = 1,228). Freshwater shell comprised 88.2% of the NISP and was mostly represented by two families, Thiaridae (n = 5,272) and Neritidae (n = 1,530). Terrestrial snails comprised 10.5% of the NISP and were dominated by Ariophantidae (n = 521) and Helicidae (n = 79), while in comparison marine shells were present in relatively low numbers (1.4% of NISP).

The chord distance (CD) values for the pottery and mollusk assemblages across successive pairs of assigned depositional units from six adjacent sectors are shown in Figure 6. Of all successive pairs, the least amount of change (CD = 0.06) was observed from Units $8C_5$ to $8C_6$, then followed by Units $8C_2$ to $8C_3$ (CD = 0.11), Units $8C_3$ to $8C_4$ (CD = 0.22) and Units $8C_4$ to $8C_5$ (CD = 0.26). More change was observed in Units $8B_1$ to $8B_2$ (CD = 0.36), Units $8B_2$ to $8B_3$ (CD = 0.37) and Units $8C_1$ to $8C_2$ (CD = 0.63) with the largest shift occurring from Units $8B_3$ to $8C_1$ (CD = 0.66), which is marked as a transition across units (8B to 8C) where the proportions of pottery increased significantly (increased from 2.1% to 36.2 of NISP), in conjunction with decreasing proportions of mollusk (decreased from 97.9% to 63.8 of NISP). UPGMA cluster analysis of all pairwise chord distance values between units from these six adjacent Sectors resulted in two main clusters, Units $8B_1$, $8B_2$, $8B_3$ and $8C_1$ forming one cluster and all other Units forming the other (Figure 16). Within the first cluster, Unit $8C_1$ was most unlike all of the remaining units while Units $8B_1$ and $8B_2$ were more similar to each other than either was to Unit $8B_3$. Within the second cluster, Unit $8C_4$ was most unlike all the remaining units whereas Units $8C_5$ and $8C_6$ were more similar to each other and followed by Units $8C_2$ and $8C_3$ which were also similar to each other.

Analysis of mollusk taxonomy and pottery evenness, using the unbiased Simpson index, indicated some major differences between the assemblages through time (Figure 17). Marked increases in evenness occurred between Units $8B_2$ and $8B_3$, while marked decreases occurred between Units $8B_1$ and $8B_2$, Units $8C_1$ and $8C_2$, Units $8C_4$ and $8C_5$, and Units $8C_5$ and $8C_6$. There was an overall trend of decreasing evenness through time was observed through the sampled stratigraphic sequence (Spearman's rho (r_s) = 0.68, p = 0.04), but there was no significant trend in richness (i.e., the number of taxa present in each unit) (r_s = 0.43, p = 0.24).

Axes 1 and 2 of the correspondence analysis for these six adjacent Sectors explained 81.3% and 10.4% of the variance in mollusk and pottery abundances (Figure 18). Units $8B_1$, $8B_2$, and $8B_3$ showed most positive scores along axis 1; overall, these deposits were dominated by mollusks (>97.9% of NISP), especially Neritidae and Thiaridae (<33.6% and <80.9%, respectively), and had low abundances of pottery (<2.1% of NISP). Meanwhile, of the other units, Unit $8C_1$ showed similarities with Units $8B_1$, $8B_2$, and $8B_3$, but had a relatively less positive score along axis 1 because mollusks made up 63.8% of NISP while pottery significantly increased from 2.1% to 36.2% of NISP ($8B_3$ to $8C_1$). Units $8C_2$ through $8C_6$ followed a noticeable trend, shifting even further negatively along axis 1. Overall increases in pottery abundance (66.3–95.7% of NISP) through time in conjunction with decreasing proportions of mollusks (4.3–33.7% of NISP) (Table 13) explain a majority of the similarities and differences among stratigraphic units.

Discussion

In the Liang Bua stratigraphic sequence representing the past 5,000 years, substantial changes are observed in the mollusk and pottery assemblages. In all six adjacent Sectors, from Unit $8B_3$ to $8C_1$ (~3.7–2.5 ka ago) shell abundance decreased significantly with neritids and thiarids decreasing from 33.6% to 10.2% and 59.7% to 46.3%, respectively. Within the same stratigraphic units, pottery significantly increased through time from 2.1% to 36.2%. However, in Sectors XXXII-XXIX—the only excavations in this study that used total stations—the largest observed change occurred from Unit $8C_1$ to $8C_2$ (CD = 1.23), wherein shell decreased from 71.2% to 0% while pottery increased from 17.9% to 100%. Documenting the timing of the earliest appearance of pottery at the site is of particular interest, and previous studies have suggested that this occurred either ~4 ka (Morwood et al., 2009) or ~3.0 ka, in the uppermost parts of Unit 8B (Sutikna et al., 2018). The better resolution offered by the excavations of Sectors XXXII-XXIX shows that the latter interpretation is probably correct. Almost all of the plotted pottery fragments from these Sectors were recovered stratigraphically above two charcoal samples, dated to 3.25 and 3.29 ka cal. BP, respectively (Figure 2). Although eight pottery fragments were found slightly deeper than this within the stratigraphy, including three from Unit $8B_2$, these may represent younger fragments that became displaced into older sediments. Given the overall distribution of plotted pottery fragments in Sectors XXXII-XXIX as well as mostly sieved pieces from Sectors XVI-VII and XXVI-XXV, it is most reasonable to suggest that pottery was used at the site as early as ~3.3 ka but mostly after ~3 ka and immediately above the dense shell midden (Table 1). After ~3 ka ago (Units $8C_1$–-$8C_6$), pottery comprised 36.2% to 95.7% of NISP whereas during the same temporal interval mollusks comprised only 63.8% to 4.3% -of NISP. The appearance and subsequent regular use of pottery at Liang Bua likely signals a shift to increased sedentism or farming in the area surrounding the cave, and stable isotope analyses of humans and other animals at the site show a sudden shift to more C_4-based foods in their diet after ~2.7 ka (Anderson, 2011; Munizzi, 2013; Tocheri et al., 2020; Alamsyah, 2021).

Prior to 5 ka, mollusks made up 0.2% of the total faunal NISP at Liang Bua (Sutikna et al., 2018). In contrast, they comprised 24.5% and 16.0% of the total faunal NISP in Units 8B and 8C, respectively (Sutikna et al., 2018). In the present study, the mollusk assemblages were particularly abundant (i.e., NISP > 300) in Units $8B_1$–$8C_1$ (~5.0–2.5 ka), especially after 4.4–4.3 ka cal. BP based on the ages of the youngest two charcoal samples recovered at the base of the shell midden (Figure 2). These assemblages were dominated by four species (79.1% of mollusk NISP), *Tarebia granifera* and *Melanoides tuberculata* (both thiarids) as well as *Vittina aquatilis* and *Neritina petitii* (both neritids). One of the main goals of this study was to investigate whether there is any evidence that modern humans were responsible for accumulating all or part of the large assemblage of mollusks recovered at Liang Bua. Interestingly, shells from 1,677 *Tarebia granifera* and 324 *Melanoides tuberculata* (63.1% of 2,656 and 66.7% of 486, respectively) recovered in Sectors XXXII-XXIX showed signs that they were deliberately cut at their apices (Figure 5) whereas none of the *Vittina aquatilis* and *Neritina petitii* from these layers showed any signs of deliberate cutting. Most of these deliberately cut shells (83.4% of 1,667 *Tarebia* *granifera* and 77.5% of 324 *Melanoides tuberculata* with cut apices) were found in Units $8B_2$–$8B_3$ (~4.4–3.7 ka ago) (Figure 19). Deliberately cutting the apex of a shell is almost certainly a strategy to obtain the meat of the clam for human consumption. Indigenous Manggarai people who live around Liang Bua today still collect shells for food (e.g., *Faunus* spp. and *Pila ampullacea*, which have shells that are shaped similarly as thiarids and neritids, respectively), as do many others elsewhere in Indonesia, and will cut the apices to facilitate extraction of the meat when it is necessary (Hamilul, 2020; Zura, 2020; Benyamin Tarus and Stanis Mbembak, personal communication 2021). *Faunus* spp. are brackish-water species that can reach up to 90 mm in length but usually average between ~50–60 mm (Lok et al., 2011) and the small diameter and conical shape of their shells makes it challenging to extract their meat using any kind of implement. Instead, these mollusks are typically processed by cutting the apices prior to boiling the shells in water, which makes it easier to extract the meat by sucking it out from the aperture (Zura, 2020; Benyamin Tarus and Stanis Mbembak, personal communication 2021). In contrast, the neritid shells recovered at the site have relatively larger diameters and more circular shapes. Thus, people at Liang Bua may have processed them similarly to how living Indigenous Manggarai people process *Pila ampullacea*, a freshwater species easily found around rivers and rice fields today (e.g., it is a known agricultural pest because it often lays its eggs in the paddy plant and disturbs the growth of the paddy [Benyamin Tarus and Stanis Mbembak, personal communication 2021]). These shells are typically boiled in water for around 10–15 minutes, then the meat is simply extracted from the shell using a stick or other implement and any cutting of the shell is unnecessary (Hamilul, 2020; Benyamin Tarus and Stanis Mbembak, personal communication 2021).

In the past, to cut the apices of the thiarid shells people at Liang Bua most likely used their teeth, by biting, percussion flaking, where the shell is held stationary and a stone tool is brought down against the apex, or tapping, where the shell apex is forcibly tapped repeatedly on a hard surface (Langley and O'Connor, 2016). Despite the large number of these deliberately cut shells (n = 2,001), only 116 (5.8%) of these also show signs of burning (either direct or indirect). Similarly, only 57 of the 1,064 neritid shells (5.4%) showed any evidence of exposure to fire. If people at Liang Bua consumed these mollusks, then why were so few of these shells burned? Consumption of raw mollusks is possible but risky, as they are a well-known source of trematode parasites (Veeravechsukij et al., 2018). Alternatively, people may have boiled the shells in water. This method is an easy, safe, and effective way to prepare mollusks for human consumption and it allows for large quantities to be processed reasonably quickly and simultaneously. Although pottery could have been used for boiling shells in water, it does not appear in great numbers until after the main shell midden at Liang Bua was deposited. However, Indigenous people in Central Flores have a tradition of cooking rice and other foods in freshly cut pieces of bamboo (Figure 20) and this practice is also common in other places in Indonesia and Southeast Asia. At Mengeruda, a village in Central Flores, this practice involves putting rice along with some spices and sometimes some meat into freshly cut bamboo with enough water (Julianto, 2018). Bamboo has natural joints inside its tubular structure that can hold water or other liquids so pieces of bamboo are cut such that one of these natural joints forms a bottom barrier while food and water are placed inside through the other end that is open. The top (or open end) of the bamboo is then sealed with banana leaves and the bamboo is baked on a charcoal fire until it turns black (Julianto, 2018). As bamboo is plentiful in the area surrounding Liang Bua, this technique or something broadly similar to it was likely used by people to cook mollusks and other foods prior to the regular use of pottery at the site.

Sectors XXXII-XXIX also showed an interesting pattern in terms of the distribution of the thiarid and neritid shells through time (Figure 21). These two families of aquatic shells were concentrated in two main layers: an older (i.e., stratigraphically deeper) layer that was dominated by thiarid species (97.4% of NISP), 82% of which had cut apices, and a younger layer that was dominated by neritid species (60.0% of NISP). In the latter, only 33% of the thiarid shells had cut apices, a marked contrast from that observed in the older layer. This distribution may reflect variation in gathering strategy or perhaps climatic and/or seasonal exploitation as each of these four species vary in their habitat preferences. *Tarebia granifera* is an obligate freshwater dweller with no noted tolerance for even mildly brackish conditions and typically lives in temperatures that range between 6 and 38 °C (Isnaningsih et al., 2017). *Melanoides tuberculata* inhabits a wide range of aquatic environments, either lentic (i.e., still waters, e.g., ponds, basin marshes, ditches, reservoirs, seeps, and lakes) or lotic (i.e., flowing waters, e.g., creeks, streams, runs, rivers, springs, brooks, and channels) at depths between 0.25 and 3.7 m (Vogler et al., 2012). It prefers soft mud, clay, and sand substrates in shallow, slow-flowing bodies of water (Quiroz-Rodriguez et al., 2018) and can tolerate brackish water (Kock and Wolmarans, 2009; Reynolds et al., 2013). Water temperatures below 18 °C or above 32 °C are typically too extreme for *Melanoides tuberculata* and it is usually found in abundance in water temperatures ranging between 21 and 30 °C (Vogler et al., 2012). *Neritina petitii* is associated with freshwater habitats including fast-flowing streams and rivers but as a species within a family dominated by marine taxa, it also has some tolerance for raised saline levels in riverine habitats (Kerr, 2013). Moreover, it is frequently found in waterways that are near to the coast and/or within the reach of strong tides suggesting that it is well suited for and may even prefer, in some cases, brackish-water habitats (Reynolds et al., 2013). Finally, species in the genus *Vittina* are strongly associated with freshwater and brackish-water riparian vegetation such as Nypa palm and mangrove forests but prefer landward rather than seaward habitats (Szabó and Due Awe, 2012).

Although each of these species is typically associated with freshwater, they vary in terms of their ability to survive in brackish water. The Wae Racang, the river that flows immediately north of Liang Bua, originates in the mountains to the south around the modern town of Ruteng. It flows meanderingly toward the northern coast, ultimately draining into the Flores Sea. During the heavy rainfall of the wet season, the Wae Racang is dominated by freshwater but during the dry season, as the ocean tides penetrate inland, salinity levels increase even many kilometers upriver resulting in more brackish water (Hittle et al., 2001; Szabó and Due Awe, 2012). Such a pattern has likely been fairly consistent for the past 6,000 years in this region because annual rainfall has remained relatively stable and similar to present levels based on stable isotopic analyses of a stalagmite from a cave near to Liang Bua (Griffiths et al., 2010). Given that *Tarebia granifera* is the only one of these four species that is an obligate freshwater dweller, it was most likely obtained from the Wae Racang either relatively close to Liang Bua or further upstream because these parts of the river are least likely to ever experience raised salinity levels, even during the dry season. The other three taxa may also have been obtained from these parts of the river but due to their tolerances for brackish conditions, it is also possible that they were obtained from further downstream. In other words, if some of these taxa were obtained from more brackish water, then it is more likely that they were collected in areas north of the cave rather than either near to it or further to the south. Additional research should explore the salinity levels at various points along the Wae Racang during the wet and dry seasons to see if there are patterns that might help better explain the distribution of the thiarid and neritid shells at Liang Bua. Another important possibility to consider is that perhaps the population numbers of the two thiarid species declined within a few centuries after humans began to harvest them for food ~4.4–4.3 ka cal. BP, essentially forcing humans to later shift toward consuming the neritid species instead. Although the current data from the site cannot adequately address such questions, future research should attempt to shed more light on these issues.

What is perhaps more interesting, however, is that prior to ~4 ka, the densities of stone artifacts at the site fluctuated with larger flakes generally underrepresented (Lin et al., 2020). This suggests that people used Liang Bua occasionally and as they exploited resources across the broader landscape, they reprovisioned their toolkit with local raw materials. In contrast, between ~4–3 ka, larger cores were deposited in the cave indicating a lesser degree of flake transport (Lin et al., 2020). The association of the main shell midden and these observed changes in lithic discard frequencies and core sizes suggest that human activities ~4–3 ka at Liang Bua became more focused on the river corridor with increased regularity in the use of the cave and a greater focus on on-site activities (Lin et al., 2020).

Terrestrial snails are generally considered to be intrusive into cave deposits; however, in Malawi, *Lissachatina* (sometimes listed as *Achatina*) that belong to the family Achatinidae were used as a raw material for beads (Miller et al., 2021). At Liang Bua, a total of 12 terrestrial snail taxonomic families have been identified, comprising 10.5% of mollusk NISP. Although dominated by Ariophantidae and Helicidae (63.7% and 9.7% of land snail NISP, respectively), both of which are small animals and unlikely dietary resources for humans, other land snails in the assemblage include Achatinidae, Cyclophoridae, and Dyakiidae (5.2%, 3.9%, and 1.5% of land snail NISP, respectively), all three of which are a potential food source for humans

(Paisantanakij et al., 2018). However, none of the terrestrial shells found in Sectors XXXII-XXIX showed any signs of human modification and because they were not found in any sort of spatial concentration and most were recovered stratigraphically beneath the main shell midden, it seems more likely that they are either intrusive or the result of other natural circumstances. At the very least, it remains unclear whether humans were responsible for the accumulation of terrestrial snails at the site.

In addition to the harvesting of freshwater and possibly brackish-water mollusks for food, shells from multiple marine species (*Nautilus* sp., *Pyrene ocellata*, *Cypraea erosa*, *Strombus mutabilis*, *Trochus* sp., and *Oliva* sp.) show signs of cultural modification, underscoring the significance of these otherwise rare elements in the Liang Bua assemblage (marine taxa represent 1.4% of mollusk NISP). Ornamentation in the form of beads or pendants made from shells is one of the best sources of information regarding social behaviour in early modern human communities (White, 2007; Bar-Yosef Mayer et al., 2009). At Liang Bua, the *Nautilus* specimens represent a large, white and orange-brown patterned species that has been used elsewhere (e.g., Timor and Rote) as a raw material for making beads and pendants (Mahirta, 2003; O'Connor, 2010; Langley et al., 2016). Four of these *Nautilus* shells from Units $8B_2$–$8B_3$ (~4.3–3.0 ka) were fashioned into beads (Table 6). These beads are round in shape with diameters ranging between ~5 to 10 mm with a perforated hole in the middle (presumably for a string) (Figures 3 and 4). Species in the genus *Nautilus* are large in size, reaching around 20 cm in length, and are desirable material for decorative purposes because they have an iridescent nacreous layer in their inner shell (Langley et al., 2016). *Nautilus* species usually inhabit depths around 200–300 m but can also be found in shallow water ~5 m depth with temperatures below 25 °C (Saunders and Ward, 1987; Ward, 1987). Shells of *Nautilus* with evidence of scoring and cutting were previously identified from Sector XI at Liang Bua (van den Bergh et al., 2009) and various kinds of *Nautilus* shell beads have been recovered at sites on the nearby islands of Timor-Leste and Rote (Mahirta, 2003; O'Connor, 2010; Langley et al., 2016).

On Timor-Leste, five *Nautilus* shell beads (~42–4.8 ka) are known from Jerimalai (Langley et al., 2016) and are common at Matja Kuru 1 and 2 (O'Connor, 2010). In terms of shape, the beads from Jerimalai are almost triangular with perforations on one end rather than in the center (perhaps used as pendants) whereas one of the beads (directly dated to ~10.2 ka using AMS) from Matja Kuru 2 has an irregular shape and non-central perforation while the other (directly dated to ~5.1 ka using AMS) is circular in shape with a central perforation (O'Connor, 2010). This latter bead is the most similar to those found in Sector XXXII at Liang Bua. On Rote, *Nautilus* shell ornaments are known from Pia Hudale Cave and Lua Meko (Mahirta, 2003). These include small beads that are round and flat in shape with central perforations (dated to ~13 ka at Pia Hudale Cave and ~6.3–5.6 ka at Lua Meko) as well as an almost triangular shaped pendant (dated to ~13 ka) and a "pointed shell bead" (possibly used as a pendant and dated to ~6.6 ka) with a non-central perforation (Mahirta, 2003:102).

Three other beads from Sector XXXII at Liang Bua in Units $8B_2$ (~4.3–3.7 ka ago) were made from the shells of *Oliva* sp. (Table 6; Figure 3F–H), a species from the family Olividae, which is broadly distributed in the oceans at tropical and subtropical latitudes worldwide (Kantor et al., 2017). These shells usually create distinctive trails by burrowing through sand or mud substrates and are found in intertidal to deep water (Langley and O'Connor, 2016). Species in the genus *Oliva* are carnivorous, typically feeding on bivalves and crustaceans (Short and Potter, 1987; Kantor et al., 2017). These beads are similar to the original shell except that an intentional hole has been produced by removing the apex. Modifying an *Oliva* sp. shell in such a way is easily accomplished by tapping the end against a hard surface and making a hole through which a string can be passed to create a necklace, for example (Langley and O'Connor, 2016). On Timor-Leste, 485 *Oliva* sp. shells with their apices deliberately removed have been identified from the cave sites of Jerimalai, Lene Hara, Matja Kuru 1, and Matja Kuru 2 (Langley and O'Connor, 2016). The oldest of these was found at Jerimalai and was directly dated to ~37 ka ago while a majority were produced ~8.0–4.0 ka (Langley and O'Connor, 2016). Two *Oliva* sp. beads are also known from Niah Cave on Borneo and derive from deposits dated to between ~2.5 and 0.5 ka (Szabó et al., 2013).

Four whole, pierced *Pyrene ocellata* and *Cypraea* spp. were also identified in Units $8B_2$–$8B_3$ (~4.3–3.0 ka ago) from Sector XXXII-XXIX (Table 6; Figure 3B and C; Figure 4D and E). Both of these marine taxa are clearly exotic to the main Liang Bua assemblages. *Pyrene ocellata*, or dove shell, is a marine species in the family Columbellidae that lives in deep, warm water (Lindner, 1977). Its shell is relatively small and ornamented with striking patterns. *Cypraea* spp. are also marine taxa with shells of varied colours and patterns that belong to the family Cypraeidae and live in the warm waters of the intertidal or subtidal reef flat of the Indo-Pacific (Lindner, 1977). These four shells were perforated in the body whorl but the holes in the two *Pyrene ocellata* specimens occurred towards the anterior siphonal canal whereas those in the two *Cypraea* specimens were towards the anterior dorsum. These intentional holes were not drilled but likely pierced with a perforator or sharp point. Indirect percussion was the probable technique used, where the specimens are held and punched in the body whorl using a perforator or sharp point (Szabó, 2008; Vanhaeren et al., 2006). This technique has also been documented in the early manufacture of beads at Skhul (West Asia) and Oued Djebbana (North Africa) (Vanhaeren et al., 2006).

Batissa violacea, a large species of mollusk (typically 120–150 mm in maximum length) (Morton, 1989; Lamprell and Healy, 1998), is the only freshwater bivalve represented in Unit $8B_3$ (~3.7–3.0 ka ago) of Sectors XXXII-XXIX (Table 6). It is an edible mollusk that belongs to the Corbiculidae family (Ledua et al., 1996; Thangavelu et al., 2011) and is typically found in fresh and brackish-water habitats including sandy and muddy beds of rivers as well as running water (Morton, 1989; Ledua et al., 1996; Poutiers, 1998). Two fragments of this taxon show clear evidence of cultural modification (Figure 3). One of these was shaped like a borer "perforator", implying some sort of drilling or piercing function (Figure 3A). However, the other was polished on the end edge suggesting that it was used as a scraper or adze (Figure 3D). In Ilin Island, Philippines, a shell adze was identified at Bubog I and directly dated to ~7.5–7.2 ka (Pawlik et al., 2015). It was made from *Tridacna gigas* by flaking to produce a trapezoidal shape and it was polished on its distal end (Pawlik et al., 2015). In contrast, the Liang Bua shell adze is elongated and semi-circular in shape and was polished on the posterior-ventral end.

Although culturally modified shells were not observed after ~3 ka (Units $8C_1$–$8C_6$) in the Sectors examined in this study, five Nautilus beads were recently recovered from Unit $8C_1$ in the western part of Liang Bua. These beads are associated with three modern human burials that are directly dated to 2.7–2.6 ka cal. BP as well as include pottery and polished adzes as grave goods (Julianto et al., 2020). It is interesting, however, that such beads or other culturally modified shells are not found in the other units where there is a high concentration of pottery sherds. It is possible that as sedentary behaviors increased (i.e., the pottery dominated units), extra-regional exchange and/or the importance of personal adornment with marine shells decreased or disappeared. Although such a scenario may sound counter-intuitive, it is certainly possible that sedentism and food production resulted in decreased mobility and this, in turn, could have led to a decrease in the use of marine shells as personal adornments and/or a decline in extra-regional exchange. Indeed, this appears to be the pattern typically observed at sites across Island Southeast Asia (Wickler, 2001; Mahirta, 2003; Mahirta et al., 2004; Szabó et al., 2007; Szabó and Ramirez, 2009; Ono et al., 2010; Pawlik et al., 2015; Langley et al., 2016; Langley and O'Connor, 2016). Alternatively, it is clear that after ~3 ka the way people are using Liang Bua changes quite dramatically (e.g., intensive mollusk processing ceases completely) and it may simply be that evidence of continued shell processing is situated elsewhere on the landscape surrounding the cave, perhaps closer to sedentary villages or settlements. Further archaeological surveys and excavations are needed in the wider area surrounding Liang Bua to provide the necessary data to answer these interesting questions.

In summary, this study has helped to substantially refine our understanding of human populations living around Liang Bua during the past ~5,000 years. The results show that pottery was first introduced to the site ~3.3 ka cal. BP and used regularly after ~3 ka, likely signaling a shift to increased sedentism or farming. The main shell midden at Liang Bua was deposited between ~4.4 and 3.3 ka cal. BP and includes mostly freshwater species that were harvested for human consumption, almost certainly from the Wae Racang that flows past the cave northward toward its drainage into the Flores Sea. Harvesting these aquatic species was not simply opportunistic gathering because it would have required wading in the river and using the hands and/or feet to intentionally target mollusks (Reynolds et al., 2013). The presence of 12 culturally modified marine shells at Liang Bua is powerful evidence of a symbolic, material culture that shows that people in this area were not only exploiting mollusks for food but also incorporating this material into their social system as social technology. Moreover, marine taxa represent 1.4% of mollusk NISP at the site yet the cave is located ~40 km from either the northern or southern coasts and ~100 km from the western coast (Figure 1B). This marine component of the shell midden coupled with these 'as the crow flies' distances and the difficult, altitudinally variable terrain that lies between the site and the coastal areas suggests that, after ~4.4–4.3 ka cal. BP, past peoples living around Liang Bua had strong social and/or symbolic connections to coastal areas either through their own foraging ranges or through trade networks with other peoples living nearer to the ocean.

TABLE 1. Summary of the Liang Bua assemblages examined in this study. (back to text) (back to discussion)

		NISP[1]							
	Approximate	XXXII and XXIX		XXVI and XXV		XVI and VII		Total	
Unit	Age Range (ka)	Shell	Pottery	Shell	Pottery	Shell	Pottery	Shell	Pottery
$8B_1$	5.0–4.3	44	0	12	0	42	0	98	0
$8B_2$	4.3–3.7	2214	3	233	0	410	1	2857	4
$8B_3$	3.7–3.0	1899	40	249	6	403	9	2551	55
$8C_1$	3.0–2.5	257	56	60	19	805	561	1122	636
$8C_2$	2.5–2.0	0	26	469	865	31	260	500	1,151
$8C_3$	2.0–1.5	4	24	112	236	52	204	168	464
$8C_4$	1.5–1.0	0	60	92	145	157	285	249	490
$8C_5$	1.0–0.5	5	22	173	596	7	657	185	1,275
$8C_6$	0.5–0	9	60	32	915	14	253	55	1,228
	Total NISP	4,432	291	1,432	2,782	1,921	2,230	7,785	5,303

[1]NISP, number of identified specimens.

TABLE 2. New ^{14}C ages for charcoal samples from Liang Bua. (back to text)

Sector	Sample Code	Methods[1]	^{14}C (yr BP)	Age: Median Calibrated (yr cal. BP)	Calibrated Range (ka): 68% CI[3]	Calibrated Range (ka): 95% CI[2]
XXIX	D-AMS-030447	ABA / AMS	127 ± 26	72	0.07–0.02	0.14–0.01
	D-AMS-030446	ABA / AMS	1,771 ± 30	1,639	1.70–1.65	1.71–1.57
	D-AMS-030445	ABA / AMS	1,915 ± 32	1,808	1.84–1.78	1.89–1.73
	D-AMS-030449	ABA / AMS	3,128 ± 31	3,294	3.31–3.25	3.38–3.21
	D-AMS-030444	ABA / AMS	3,642 ± 38	3,911	3.93–3.85	4.00–3.83
	D-AMS-030443	ABA / AMS	4,369 ± 48	4,935	4.89–4.84	5.04–4.83
	D-AMS-030441	ABA / AMS	7,339 ± 42	8,098	8.16–8.05	8.19–8.01
	D-AMS-030442	ABA / AMS	7,289 ± 44	8,071	8.16–8.09	8.17–7.97
	D-AMS-030440	ABA / AMS	7,632 ± 52	8,425	8.43–8.35	8.54–8.31
XXXII	D-AMS-035823	ABA / AMS	2,106 ± 24	2,036	2.06–2.00	2.10–1.99
	D-AMS-035824	ABA / AMS	2,156 ± 24	2,094	2.12–2.05	2.15–2.01
	D-AMS-035825	ABA / AMS	3,084 ± 35	3,247	3.26–3.21	3.36–3.14
	D-AMS-035826	ABA / AMS	3,918 ± 27	4,314	4.30–4.25	4.42–4.23
	D-AMS-035827	ABA / AMS	3,969 ± 28	4,361	4.42–4.35	4.44–4.25
	D-AMS-035828	ABA / AMS	4,327 ± 28	4,852	4.87–4.83	4.96–4.82

[1] Sample pretreatments include acid–base–acid (ABA) and accelerator mass spectrometry (AMS).

[2] CI, confidence intervals.

TABLE 3. Number of identified mollusk and pottery specimens (NISP) from Sectors XXXII-XXIX. (back to text)

Taxon	Stratigraphic Unit									Total
	$8B_1$	$8B_2$	$8B_3$	$8C_1$	$8C_2$	$8C_3$	$8C_4$	$8C_5$	$8C_6$	
Ariophantidae	6	56	30	1	0	0	0	0	0	93
Camaenidae	1	6	0	0	0	1	0	0	0	8
Nautilidae	0	7	4	0	0	0	0	0	0	11
Cerastidae	1	1	0	0	0	0	0	0	0	2
Clausiliidae	0	1	3	1	0	0	0	0	0	5
Columbellidae	0	0	3	0	0	0	0	0	0	3
Cyclophoridae	0	17	4	0	0	0	0	0	0	21
Olividae	1	3	0	0	0	0	0	0	0	4
Cypraeidae	0	3	3	0	0	0	0	0	0	6
Cyrenidae	2	7	7	0	0	0	0	0	1	17
Dyakiidae	8	26	5	0	0	0	0	2	1	42
Neritidae	1	308	721	32	0	1	0	1	0	1,064
Strombidae	0	1	0	0	0	0	0	0	0	1
Thiaridae	22	1,768	1,119	223	0	1	0	2	7	3,142
Trochidae	2	10	0	0	0	1	0	0	0	13
Pottery	0	3	40	56	26	24	60	22	60	291
Total	44	2,217	1,939	313	26	28	60	27	69	4,723

TABLE 4. Pottery sherds from Sector XXXII by anatomy and stratigraphic unit. (back to text)

Anatomy	Units							Total
	$8B_3$	$8C_1$	$8C_2$	$8C_3$	$8C_4$	$8C_5$	$8C_6$	
Base		6	1		2	3	7	19
Body	24	28	10	6	38	6	28	140
Collar	1		1		2	1	2	7
Lip			1		1	1	1	4
Lower Body	1	1			1		1	4
Neck	2	1					1	4
Throat		1						1
Unidentified	5	12	3	3	13	3	16	55
Total	33	49	16	9	57	14	56	234

TABLE 5. Mollusk specimens from Sectors XXXII-XXIX with a cut apex, direct or indirect exposure to fire, and/or coated with calcium carbonate. (back to text)

	NISP[1]					
Taxon	Apex Cut	Direct Exposure to Fire (Burned)	Indirect Exposure to Fire (Probably Burned)	Apex Cut and Burned	Apex Cut and Probably Burned	Coated with Calcium Carbonate
Ariophantidae sp.						1
Cypraea sp.		2				
Neritina petitii		2	41			6
Melanoides tuberculata	324	14	3	7	3	9
Septaria sp.			3			
Tarebia granifera	1,677	119	42	77	29	229
Vittina aquatilis			11			2
Total	2,001	137	100	84	32	246

[1]NISP, number of identified specimens.

TABLE 6. Culturally modified shells from Sectors XXXII-XXIX. (back to text)

Sector	Approximate Age Range (ka)	Stratigraphic Unit	Taxon	Category
XXXII	4.3–3.7	$8B_2$	*Oliva* sp. [1]	Bead
	4.3–3.7	$8B_2$	*Oliva* sp.	Bead
	4.3–3.7	$8B_2$	*Oliva* sp.	Bead
	4.3–3.7	$8B_2$	*Nautilus* sp. [1]	Bead
	4.3–3.7	$8B_2$	*Nautilus* sp.	Bead
	4.3–3.7	$8B_2$	*Nautilus* sp.	Bead
	4.3–3.7	$8B_2$	*Cypraea erosa* [1]	Bead
	3.7–3.0	$8B_3$	*Pyrene ocellata* [1]	Bead
	3.7–3.0	$8B_3$	*Pyrene ocellata*	Bead
	3.7–3.0	$8B_3$	*Batissa violacea* [2]	Adze or Scraper
XXIX	3.7–3.0	$8B_3$	Unidentified	Bead
	3.7–3.0	$8B_3$	*Nautilus* sp.	Bead
	3.7–3.0	$8B_3$	*Cypraea* sp.	Bead
	3.7–3.0	$8B_3$	*Batissa violacea*	Borer / Perforators

[1]Marine species

[2]Freshwater species

TABLE 7. Adjusted residuals (ARs) derived from contingency table analysis of mollusk and pottery abundances in adjacent stratigraphic units from Sectors XXXII-XXIX. ARs to be read as standard normal deviates (values > |1.96| are statistically significant at alpha = 0.05 and are shown in bold). Positive values indicate an increase in abundance relative to the preceding stratigraphic unit whereas negative values indicate a decrease in abundance (e.g., the decline in Thiaridae from Units $8B_2$ to $8B_3$ is indicated by an AR of -15.39). (back to text)

	Stratigraphic Unit							
Taxon	$8B_1$ to $8B_2$	$8B_2$ to $8B_3$	$8B_3$ to $8C_1$	$8C_1$ to $8C_2$	$8C_2$ to $8C_3$	$8C_3$ to $8C_4$	$8C_4$ to $8C_5$	$8C_5$ to $8C_6$
Ariophantidae	**-4.47**	**-2.21**	-1.73	-0.29				
Camaenidae	**-2.37**	**-2.29**			0.97	-1.47		
Nautilidae	0.37	-0.69	-0.80					
Cerastidae	**-4.92**	-0.94						
Clausiliidae	0.14	1.14	0.64	-0.29				
Columbellidae		1.85	-0.70					
Cyclophoridae	**0.58**	**-2.54**	-0.80					
Olividae	**-3.34**	-1.62						
Cypraeidae	0.24	0.16	-0.70					
Cyrenidae	**-4.41**	0.25	-1.06					0.63
Dyakiidae	**-9.18**	**-3.42**	-0.90				**2.13**	-1.51
Neritidae	**2.22**	**17.36**	**-9.38**	-1.71	0.97	-1.47	1.50	-1.61
Strombidae	0.14	-0.94						
Thiaridae	**4.81**	**-15.39**	**4.53**	**-7.36**	0.97	-1.47	**2.13**	0.41
Trochidae	**-3.70**	**-2.96**			0.97	-1.47		
Pottery	0.24	**6.13**	**12.86**	**9.39**	**-2.00**	**3.00**	**-3.43**	0.68

TABLE 8. Number of identified mollusk and pottery specimens (NISP) from Sectors XVI-VII. (back to text)

	Stratigraphic Unit									
Taxon	$8B_1$	$8B_2$	$8B_3$	$8C_1$	$8C_2$	$8C_3$	$8C_4$	$8C_5$	$8C_6$	Total
Arcidae	0	1	0	2	0	0	0	0	0	3
Ariophantidae	6	25	30	70	5	12	10	2	5	165
Buccinidae	0	0	0	1	0	0	0	0	0	1
Cyclophoridae	0	0	0	1	0	3	0	0	0	4
Cypraeidae	0	2	1	1	0	0	0	0	0	4
Ellobiidae	1	0	0	1	1	1	0	1	0	5
Helicidae	0	0	1	2	2	3	4	2	0	14
Nautilidae	0	1	0	0	0	0	1	0	0	2
Neritidae	1	25	153	139	2	4	117	1	2	444
Planorbidae	1	1	2	2	1	0	0	0	0	7
Potamididae	0	0	0	0	0	0	0	0	1	1
Strombidae	0	0	1	0	0	0	0	0	0	1
Succinidae	1	0	0	0	0	0	0	0	0	1
Terebridae	0	0	0	0	0	0	0	0	2	2
Thiaridae	26	336	206	574	19	22	23	1	2	1,209
Veneridae	4	13	5	9	1	4	0	0	2	38
Zonitidae	2	6	4	3	0	3	2	0	0	20
Pottery	0	1	9	561	260	204	285	657	253	2,230
Total	42	411	412	1,366	291	256	442	664	267	4,151

TABLE 9. Adjusted residuals (ARs) derived from contingency table analysis of mollusk and pottery abundances in adjacent stratigraphic units from Sectors XVI-VII. ARs to be read as standard normal deviates (values > |1.96| are statistically significant at alpha = 0.05 and are shown in bold). Positive values indicate an increase in abundance relative to the preceding stratigraphic unit whereas negative values indicate a decrease in abundance. (back to text)

	Stratigraphic Unit							
Taxon	$8B_1$ to $8B_2$	$8B_2$ to $8B_3$	$8B_3$ to $8C_1$	$8C_1$ to $8C_2$	$8C_2$ to $8C_3$	$8C_3$ to $8C_4$	$8C_4$ to $8C_5$	$8C_5$ to $8C_6$
Arcidae	0.32	-1.00	0.78	**-2.58**				
Ariophantidae	**-2.01**	0.69	-1.67	**-2.54**	**2.00**	-1.77	**-3.08**	**2.51**
Buccinidae			0.55	-0.46				
Cyclophoridae			0.55	-0.46	1.85	**-2.28**		
Cypraeidae	0.45	-0.58	-0.90	-0.46				
Ellobiidae	**-3.13**	0.56	0.55	1.21	0.09	-1.31	0.82	-0.63
Helicidae		1.00	-0.42	1.71	0.59	-0.34	-1.34	-0.90
Nautilidae	0.32	-1.00				0.76	-1.23	
Neritidae	0.98	**10.82**	**-12.95**	**-5.27**	0.98	**8.38**	**-13.89**	1.46
Planorbidae	**-1.99**	0.58	-1.27	0.72	-0.94			
Potamididae								1.58
Strombidae		1.00	-1.82					
Succinidae	**-3.13**							
Terebridae								**2.23**
Thiaridae	**3.06**	**-9.60**	**-2.86**	**-11.47**	0.91	-1.76	**-5.65**	1.46
Veneridae	**-2.07**	-1.91	-1.12	-0.63	1.49	**-2.64**		**2.23**
Zonitidae	-1.55	-0.64	-2.13	-0.80	1.85	-1.09	-1.73	
Pottery	0.32	**2.54**	**14.82**	**14.96**	**-3.14**	**-4.23**	**15.80**	**-3.89**

TABLE 10. Number of identified mollusk and pottery specimens (NISP) from Sectors XXVI-XXV. (back to text)

Taxon	Stratigraphic Unit									Total
	$8B_1$	$8B_2$	$8B_3$	$8C_1$	$8C_2$	$8C_3$	$8C_4$	$8C_5$	$8C_6$	
Achatinidae	0	0	0	0	1	1	0	8	2	12
Arcidae	0	0	0	0	2	0	0	0	0	2
Ariophantidae	5	6	11	21	68	24	21	89	16	261
Cyclophoridae	0	0	0	1	2	2	1	1	0	7
Cypraeidae	0	0	0	1	0	0	0	0	0	1
Ellobiidae	1	0	1	3	18	1	2	6	1	33
Helicidae	0	0	0	3	19	11	9	21	2	65
Lymnaeidae	1	10	0	0	5	3	2	7	0	28
Nautilidae	0	0	0	0	1	0	0	0	0	1
Neritidae	0	0	2	9	9	2	0	0	0	22
Olividae	0	1	0	0	0	0	0	0	0	1
Planorbidae	0	0	0	0	5	1	1	1	1	9
Strombidae	0	0	0	0	0	0	1	0	0	1
Subulinidae	0	2	0	4	10	3	0	1	0	20
Thiaridae	2	212	232	17	313	57	53	28	7	921
Veneridae	1	2	2	0	2	1	1	1	1	11
Zonitidae	2	0	1	1	14	6	1	10	2	37
Pottery	0	0	6	19	865	236	145	596	915	2,782
Total	12	233	255	79	1,334	348	237	769	947	4,215

TABLE 11. Adjusted residuals (ARs) derived from contingency table analysis of mollusk and pottery abundances in adjacent stratigraphic units from Sectors XXV-XXV. ARs to be read as standard normal deviates (values > |1.96| are statistically significant at alpha = 0.05 and are shown in bold). Positive values indicate an increase in abundance relative to the preceding stratigraphic unit whereas negative values indicate a decrease in abundance. (back to text)

	Stratigraphic Unit							
Taxon	$8B_1$ to $8B_2$	$8B_2$ to $8B_3$	$8B_3$ to $8C_1$	$8C_1$ to $8C_2$	$8C_2$ to $8C_3$	$8C_3$ to $8C_4$	$8C_4$ to $8C_5$	$8C_5$ to $8C_6$
Achatinidae				0.24	1.02	-0.82	1.58	**-2.24**
Arcidae				0.34	-0.72			
Ariophantidae	**-6.38**	1.05	**5.88**	**-7.64**	1.30	0.89	1.17	**-8.50**
Cyclophoridae			1.80	**-2.09**	1.45	-0.25	-0.88	-1.11
Cypraeidae			1.80	**-4.11**				
Ellobiidae	**-4.42**	0.96	**2.43**	-1.75	-1.67	0.93	-0.10	**-2.18**
Helicidae			**3.13**	-1.66	**2.17**	0.42	-0.84	**-4.51**
Lymnaeidae	-0.66	**-3.34**		0.55	1.17	-0.02	0.09	**-2.94**
Nautilidae				0.24	-0.51			
Neritidae		1.35	**4.62**	**-8.25**	-0.21	-1.17		
Olividae	0.23	-1.05						
Planorbidae				0.55	-0.25	0.28	-0.88	-0.15
Strombidae						1.21	-1.80	
Subuliniidae	0.32	-1.48	**3.61**	**-3.76**	0.21	-1.43	0.56	-1.11
Thiaridae	**7.55**	0.00	**-12.38**	0.40	**-2.86**	1.83	**-9.26**	**-4.23**
Veneridae	**-2.30**	-0.09	-0.79	0.34	0.54	0.28	-0.88	-0.15
Zonitidae	**-6.26**	0.96	0.88	-0.18	1.03	-1.42	1.14	**-2.69**
Pottery		**2.36**	**6.40**	**7.28**	0.97	-1.60	**4.99**	**12.14**

TABLE 12. Number of identified mollusk and pottery specimens (NISP) from Sectors XXXII, XXIX, XXVI, XXV, XVI, and VII. (back to text)

	Stratigraphic Unit									
Taxon	$8B_1$	$8B_2$	$8B_3$	$8C_1$	$8C_2$	$8C_3$	$8C_4$	$8C_5$	$8C_6$	Total
Achatinidae	0	0	0	0	1	1	0	8	2	12
Arcidae	0	1	0	2	2	0	0	0	0	5
Ariophantidae	17	87	71	92	73	36	31	91	21	519
Buccinidae	0	0	0	1	0	0	0	0	0	1
Camaenidae	1	6	0	0	0	1	0	0	0	8
Cerastidae	1	1	0	0	0	0	0	0	0	2
Clausiliidae	0	1	3	1	0	0	0	0	0	5
Columbellidae	0	0	3	0	0	0	0	0	0	3
Cyclophoridae	0	17	4	2	2	5	1	1	0	32
Cypraeidae	0	5	4	2	0	0	0	0	0	11
Cyrenidae	2	7	7	0	0	0	0	0	1	17
Dyakiidae	8	26	5	0	0	0	0	2	1	42
Ellobiidae	2	0	1	4	19	2	2	7	1	38
Helicidae	0	0	1	5	21	14	13	23	2	79
Lymnaeidae	1	10	0	0	5	3	2	7	0	28
Nautilidae	0	8	4	0	1	0	1	0	0	14
Neritidae	2	333	876	180	11	7	117	2	2	1,530
Olividae	1	4	0	0	0	0	0	0	0	5
Planorbidae	1	1	2	2	6	1	1	1	1	16
Potamididae	0	0	0	0	0	0	0	0	1	1
Strombidae	0	1	1	0	0	0	1	0	0	3
Subuliniidae	0	2	0	4	10	3	0	1	0	20
Succinidae	1	0	0	0	0	0	0	0	0	1
Terebridae	0	0	0	0	0	0	0	0	2	2
Thiaridae	50	2,316	1,557	814	332	80	76	31	16	5,272
Trochidae	2	10	0	0	0	1	0	0	0	13
Veneridae	5	15	7	9	3	5	1	1	3	49
Zonitidae	4	6	5	4	14	9	3	10	2	57
Pottery	0	4	55	636	1,151	464	490	1,275	1,228	5,303
Total	98	2,861	2,606	1,758	1,651	632	739	1,460	1,283	13,088

TABLE 13. Adjusted residuals (ARs) derived from contingency table analysis of mollusk and pottery abundances in adjacent stratigraphic units Sectors XXXII, XXIX, XXVI, XXV, XVI and VII. ARs to be read as standard normal deviates (values > |1.96| are statistically significant at alpha = 0.05 and are shown in bold). Positive values indicate an increase in abundance relative to the preceding stratigraphic unit whereas negative values indicate a decrease in abundance. (back to text)

	Stratigraphic Unit							
Taxon	$8B_1$ to $8B_2$	$8B_2$ to $8B_3$	$8B_3$ to $8C_1$	$8C_1$ to $8C_2$	$8C_2$ to $8C_3$	$8C_3$ to $8C_4$	$8C_4$ to $8C_5$	$8C_5$ to $8C_6$
Achatinidae				1.03	0.70	-1.08	**2.02**	-1.70
Arcidae	0.19	-0.95	1.72	0.06	-0.88			
Ariophantidae	**-7.56**	-0.70	**4.29**	-1.10	1.27	-1.28	**1.97**	**-6.07**
Buccinidae			1.22	-0.97				
Camaenidae	-1.62	**-2.34**			1.62	-1.08		
Cerastidae	**-3.69**	-0.95						
Clausiliidae	0.19	1.09	-0.62	-0.97				
Columbellidae		1.82	-1.42					
Cyclophoridae	0.77	**-2.63**	-0.35	0.06	**2.59**	-1.83	-0.49	-0.94
Cypraeidae	0.41	-0.19	-0.35	-1.37				
Cyrenidae	**-3.18**	0.17	**-2.17**					1.07
Dyakiidae	**-6.63**	**-3.53**	-1.84				1.01	-0.47
Ellobiidae	**-7.64**	1.05	1.81	**3.29**	-1.87	-0.16	0.72	-1.95
Helicidae		1.05	**2.15**	**3.31**	1.64	-0.60	-0.32	**-3.90**
Lymnaeidae	-1.07	**-3.02**		**2.31**	0.62	-0.62	0.72	**-2.48**
Nautilidae	0.52	-1.00	-1.64	1.03	-0.62	0.93	-1.41	
Neritidae	**2.95**	**19.55**	**-17.68**	**-12.15**	1.06	**9.48**	**-15.37**	0.13
Olividae	**-2.09**	-1.91						
Planorbidae	**-3.69**	0.66	0.40	1.51	-0.80	-0.11	-0.49	0.09
Potamididae								1.07
Strombidae	0.19	0.07	-0.82			0.93	-1.41	
Subuliniidae	0.26	-1.35	**2.44**	1.73	-0.37	-1.87	0.71	-0.94
Succinidae	**-5.40**							
Terebridae								1.51
Thiaridae	**7.28**	**-17.23**	**-8.74**	**-16.18**	**-4.16**	-1.37	**-8.40**	-1.76
Trochidae	**-2.59**	**-3.02**			1.62	-1.08		
Veneridae	**-5.44**	-1.49	1.30	-1.63	**2.20**	-1.83	-0.49	1.13
Zonitidae	**-6.49**	-0.15	0.25	**2.50**	1.23	**-2.01**	0.81	**-2.09**
Pottery	0.37	**7.04**	**30.24**	**19.59**	1.69	**-2.81**	**11.70**	**7.75**

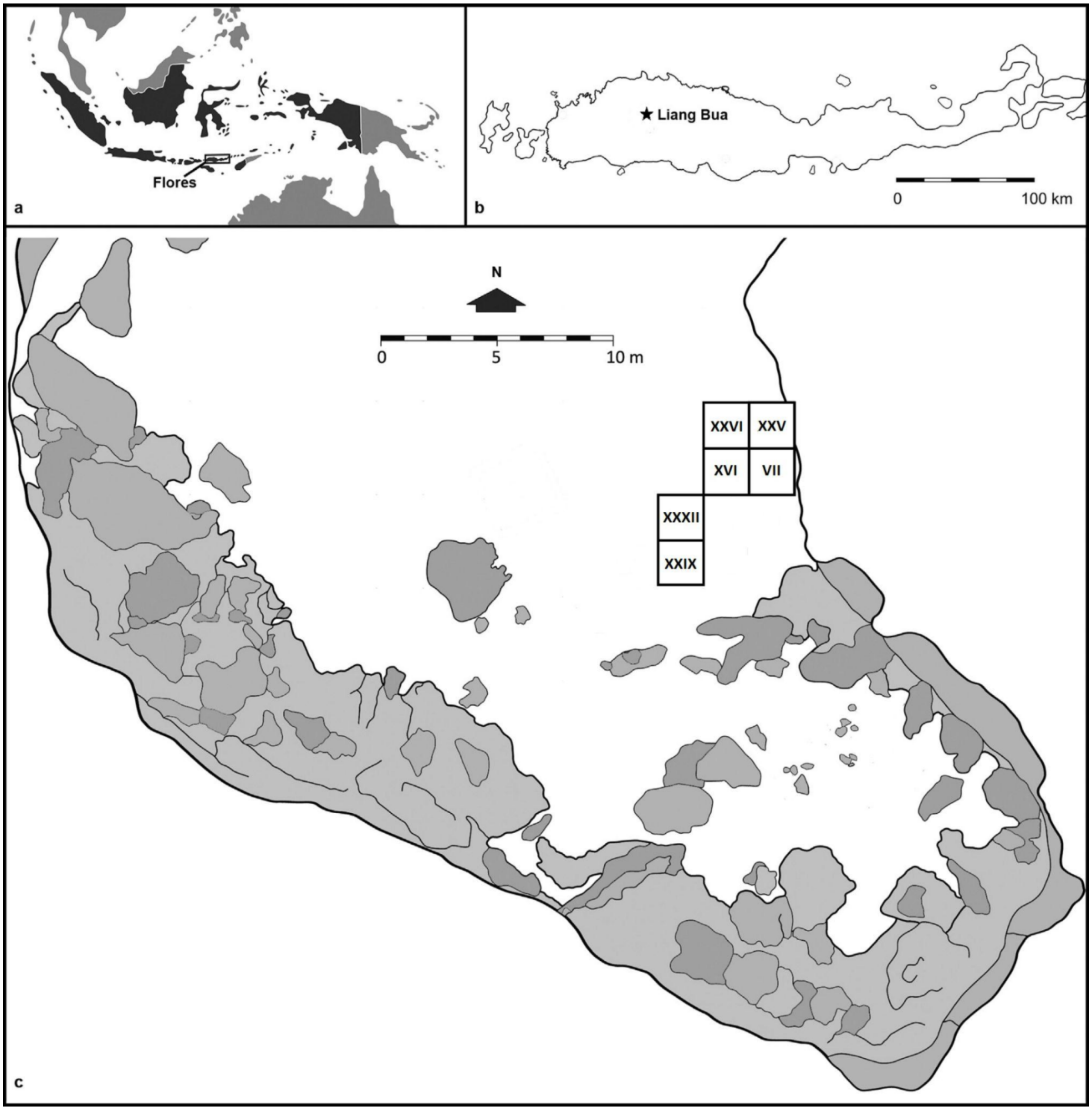


Figure 1. Location and excavation plan of Liang Bua; (a) location of Flores within Indonesia (darker shade); (b) location of Liang Bua on Flores; (c) location of the excavated Sectors discussed in this study (modified from Sutikna et al., 2016). (back to text)

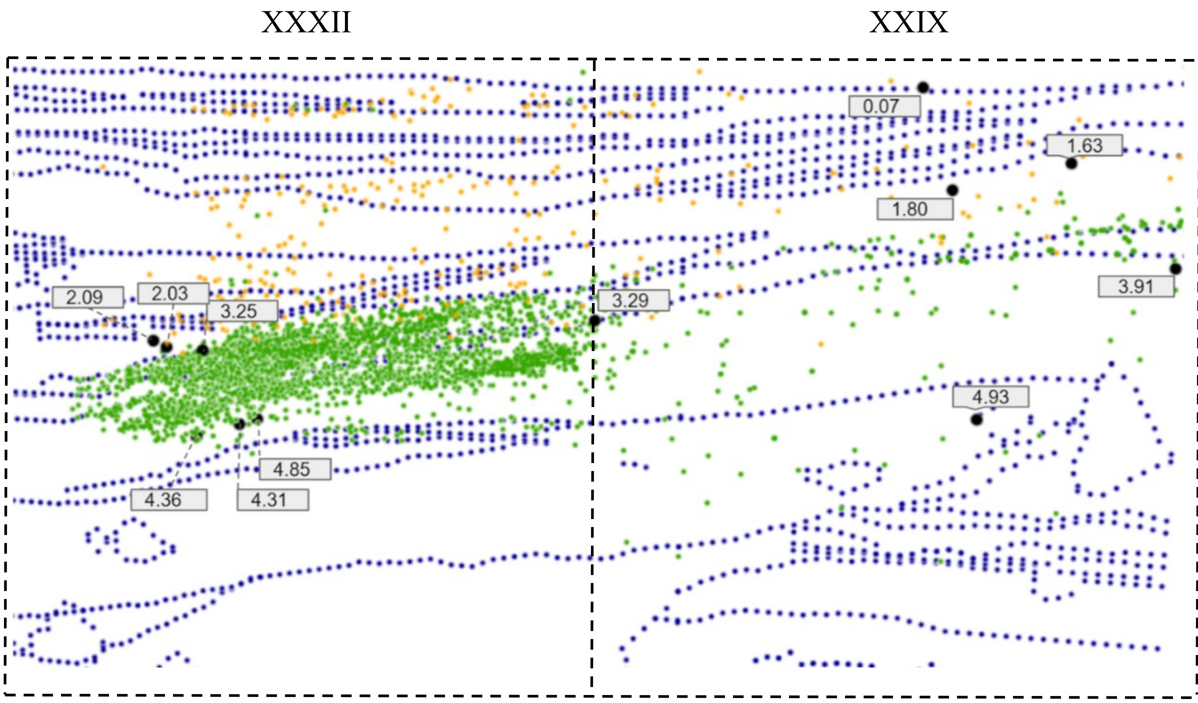
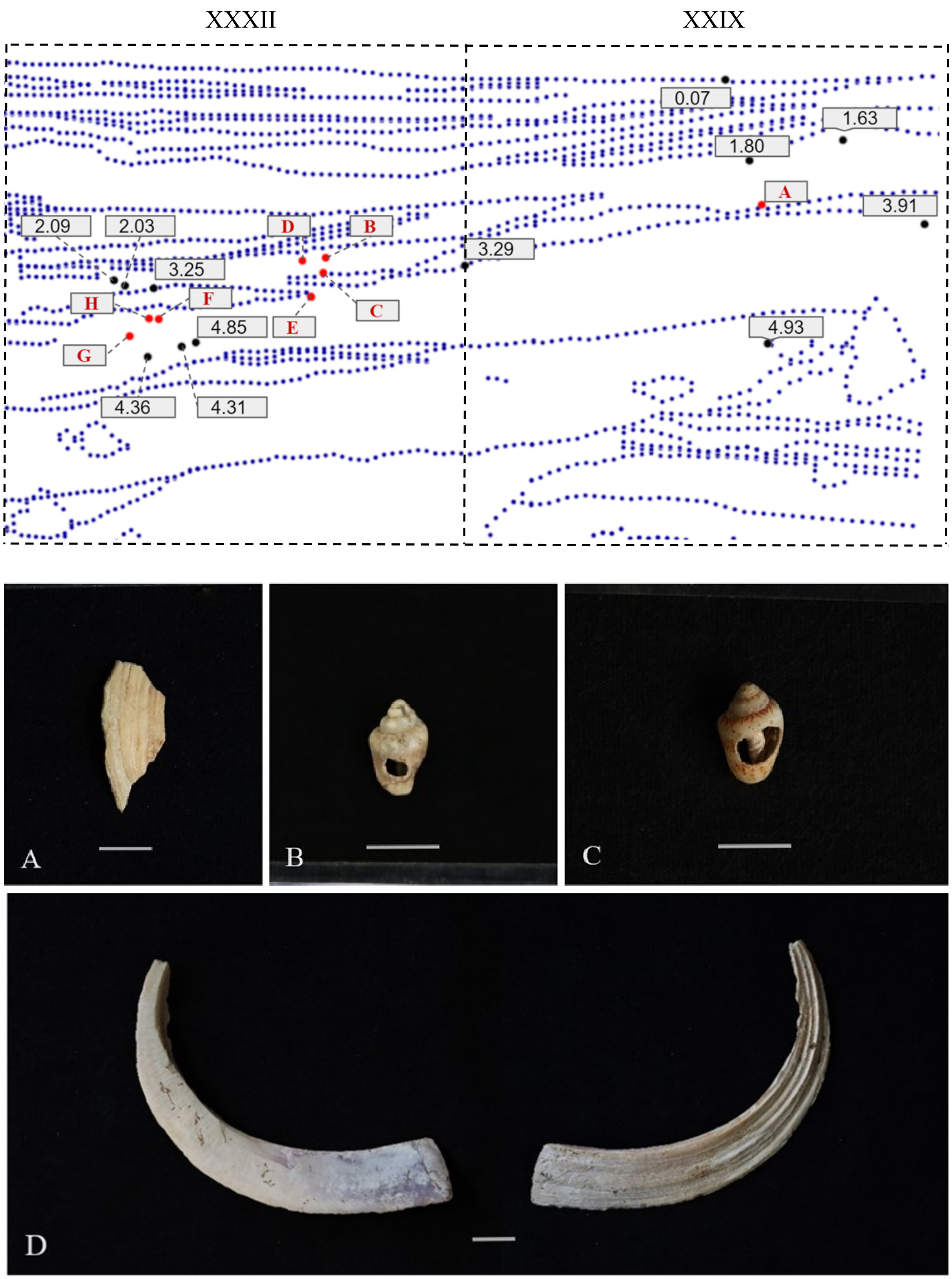


Figure 2. The distribution of radiocarbon-dated charcoal (ka cal. BP) (black circles), pottery fragments (orange circles), and mollusk shells (green circles) as shown projected against the eastern wall (width = 4 m) of the excavation. The blue circles represent the sedimentary layers or features observed in the eastern wall. The present cave floor surface is toward the top of the page and north is toward the left. (back to text)


XXXII
XXIX
0.07
1.63
1.80
A
3.91
2.09
2.03
D
B
3.29
3.25
F
H
C
4.85
E
4.93
G
4.36
4.31
A
B
C
D

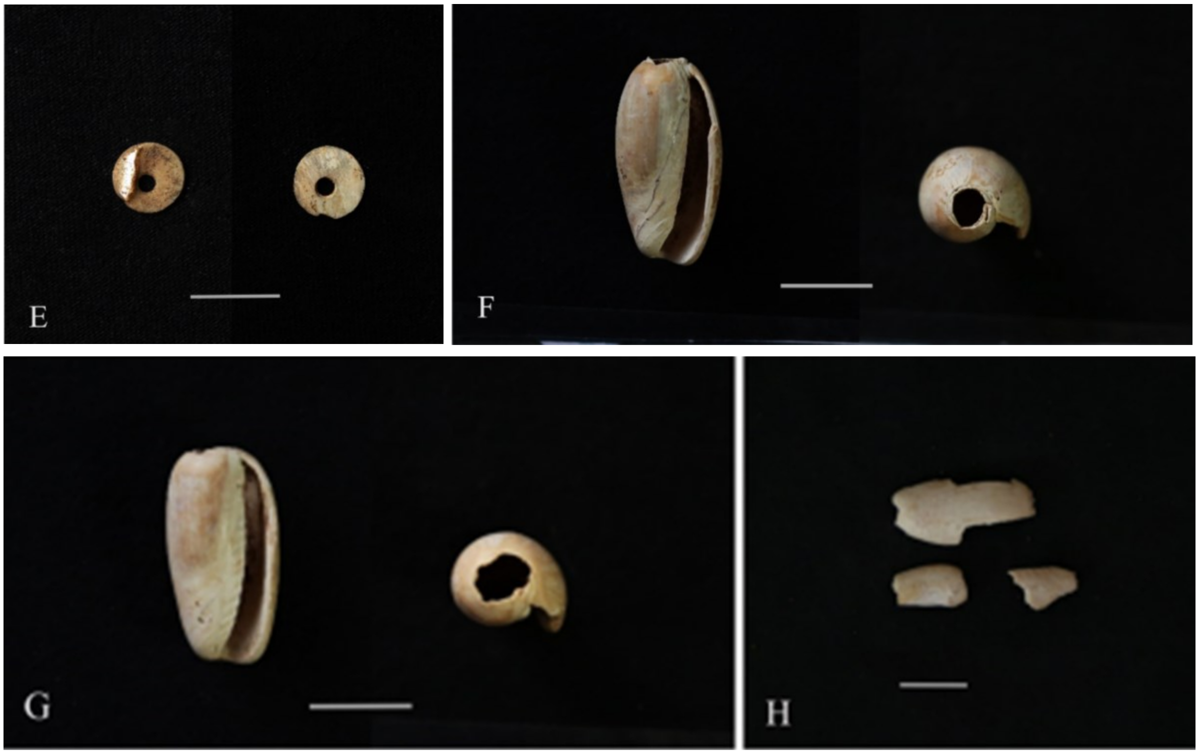


Figure 3. The distribution of radiocarbon-dated charcoal (ka cal. BP) (black circles) and culturally modified shells (red circles) from Sectors XXXII-XXIX. A, borer /perforator; B and C, beads made from *Pyrene ocellata*; D, shell adze or scraper; E, beads made from *Nautilus* sp.; F–H, beads made from *Oliva* sp.). (back to text)

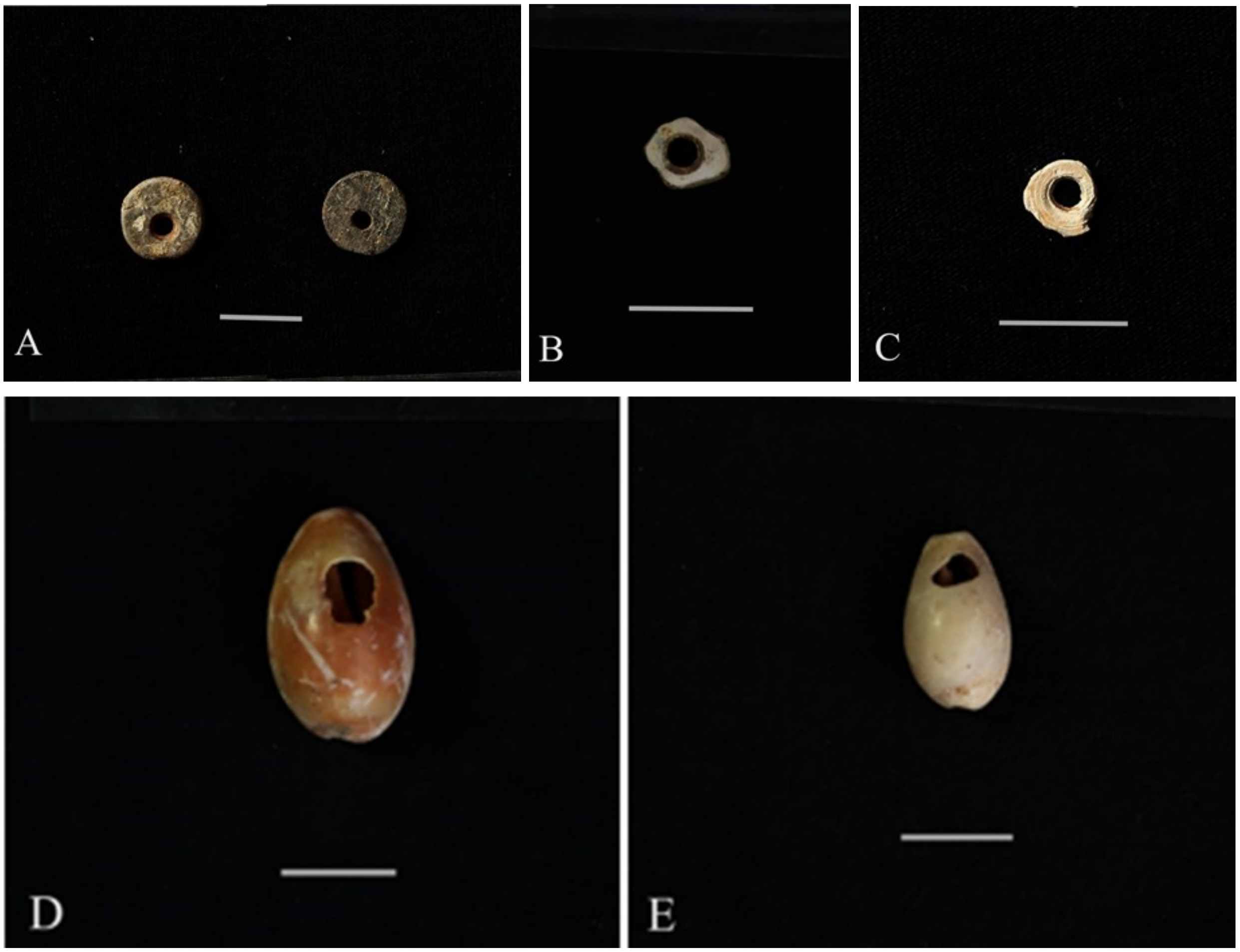


Figure 4. Culturally modified shells recovered from sieved sediments in Sectors XXXII-XXIX. A and B, beads made from *Nautilus* sp.; C, unidentified bead; D and E, beads made from *Cypraea* spp. (back to text)

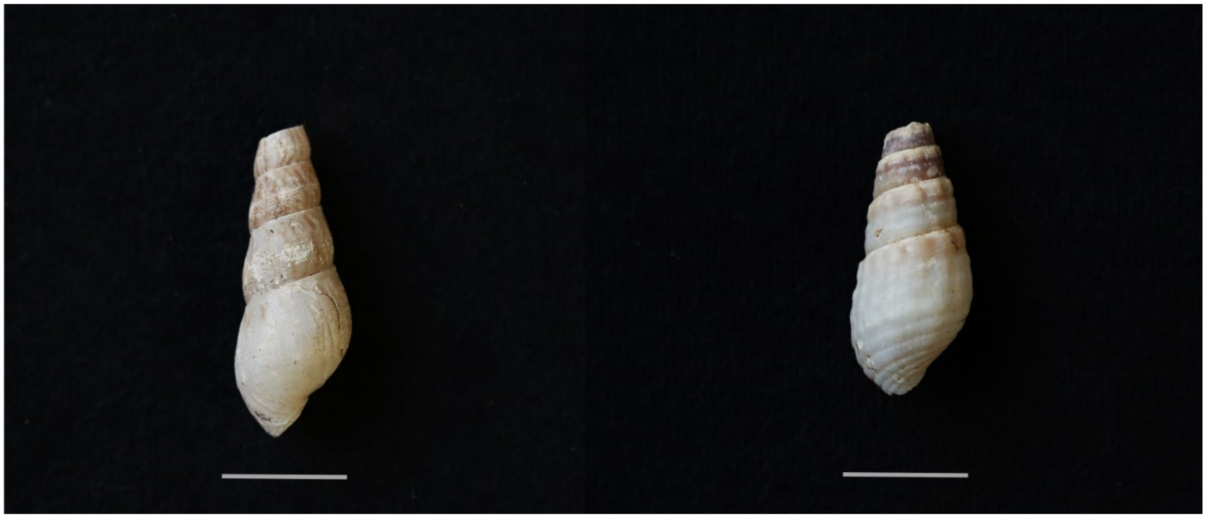


Figure 5. Examples of *Melanoides tuberculata* (left) and *Tarebia granifera* (right) from Sectors XXXII-XXIX that were deliberately cut at the apex. (back to text)

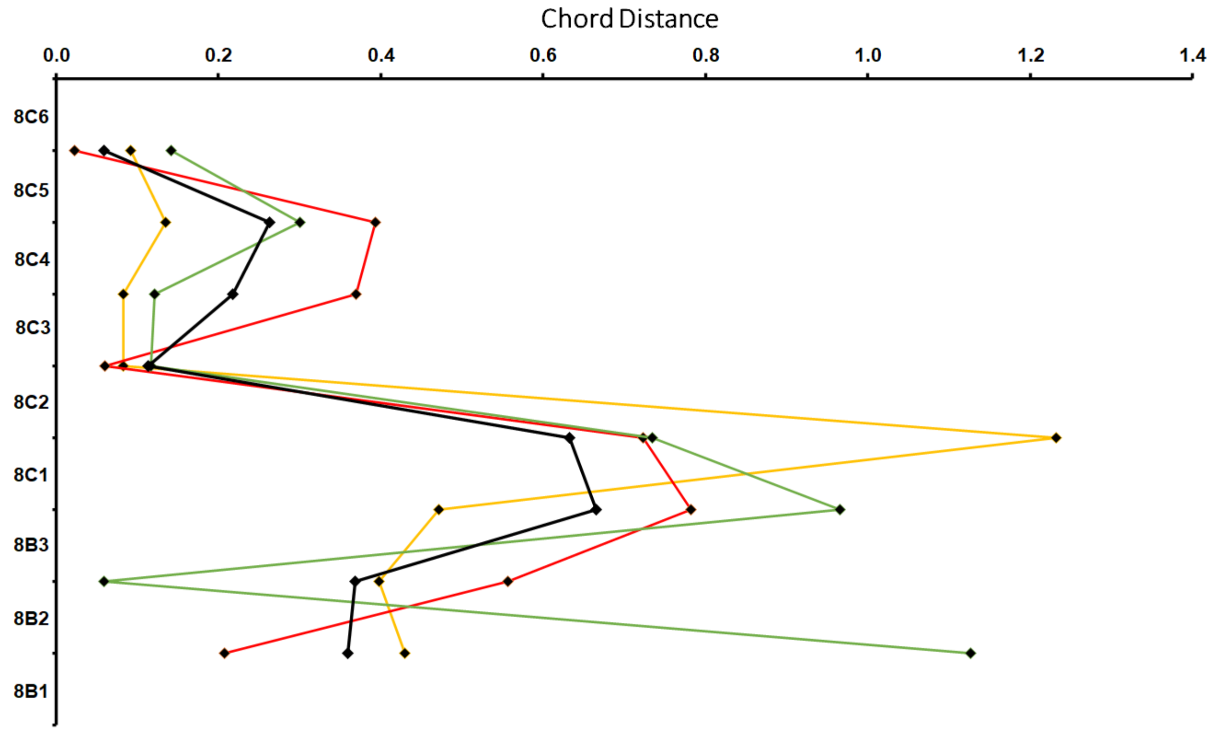


Figure 6. Chord distance (CD) values for shell and pottery abundances across successive pairs of assigned depositional units (Sectors XXXII-XXIX, yellow; Sectors XXVI-XXV, green; Sectors XVI-VII, red; Sectors XXXII-XXIX, XXVI-XXV, and XVI-VII, black. Values close to zero indicate little to no change between units, while more change is indicated by higher values. (back to text)

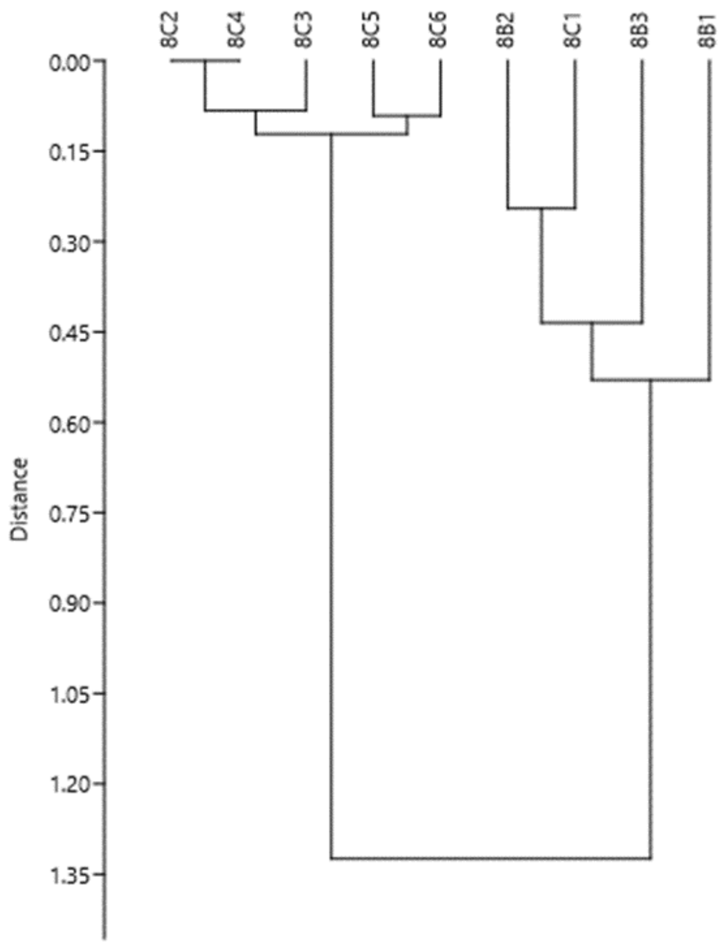


Figure 7. Unweighted pair group method with arithmetic mean (UPGMA) cluster analysis of shell and pottery abundances by stratigraphic units from Sectors XXXII-XXIX. The dendrogram is based on a similarity index (dimensionless) calculated using the matrix of all pairwise chord distances between units. Deeper branches between units indicate less similarity in shell and pottery abundances (e.g., Units $8C_2$–$8C_4$ are more similar to each other than any of them are to Units $8B_1$–$8B_2$). (back to text)

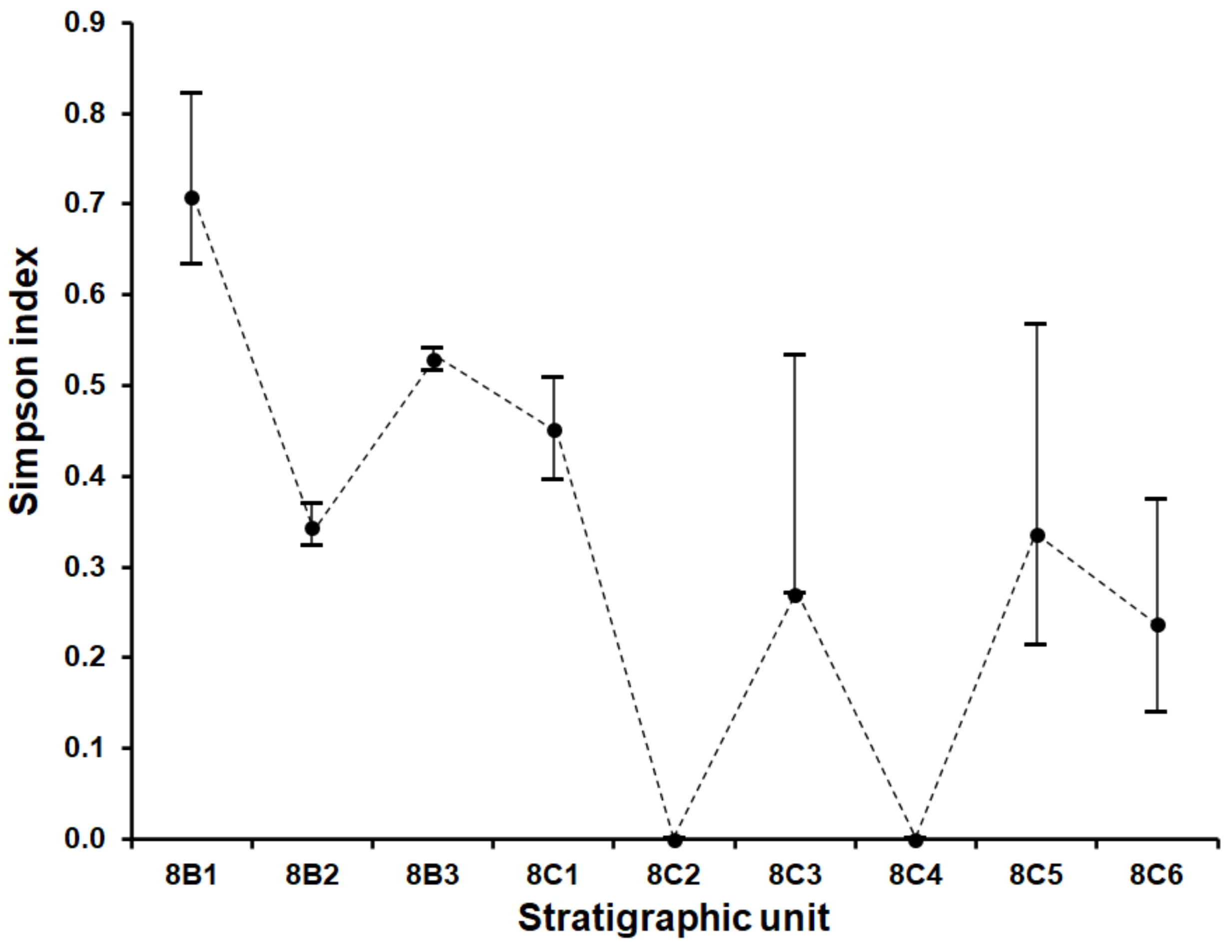


Figure 8. Unbiased Simpson index of shell and pottery evenness throughout the stratigraphic sequence of Sectors XXXII-XXIX. Approximate 95% confidence intervals for the indices of each unit were estimated using the bootstrap procedure (9999 resamples with replacement) provided in PAST, version 4.07 (Hammer et al., 2001). Greater evenness is indicated by higher index values. (back to text)

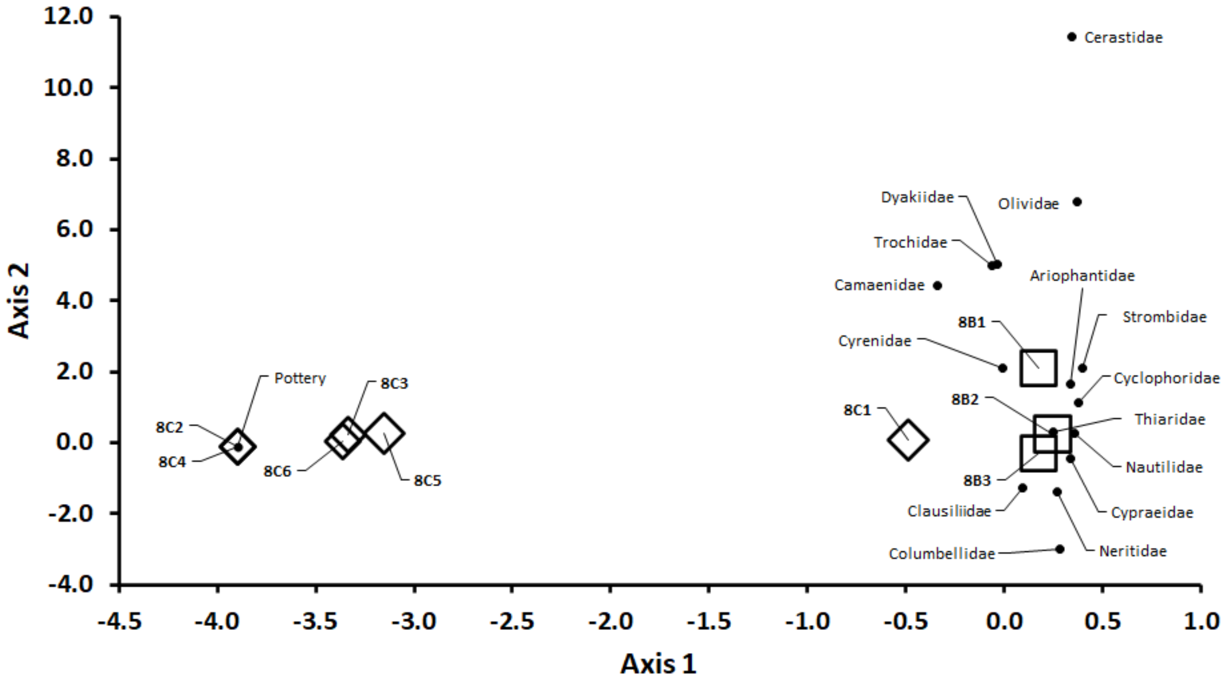


Figure 9. Correspondence analysis of shell and pottery abundances within stratigraphic units from Sectors XXXII-XXIX. Axes 1 and 2 represent 79% and 12.8% of the variance, respectively. Unit symbols: 5 to 3 ka, squares; 3 ka to present, diamonds. (back to text)

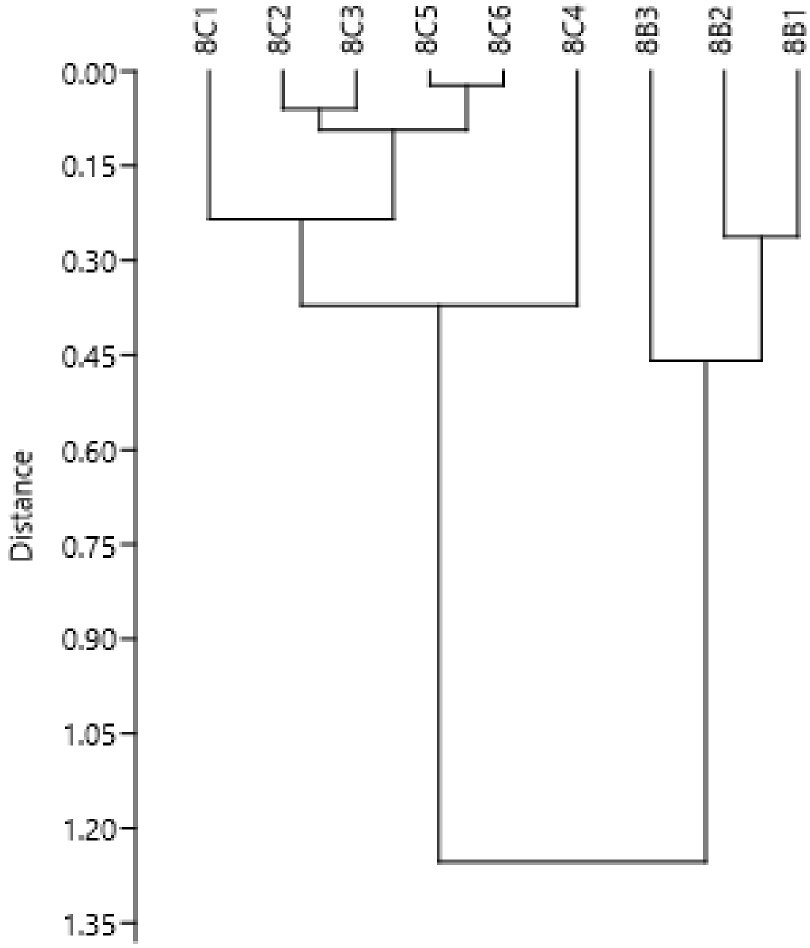


Figure 10. Unweighted pair group method with arithmetic mean (UPGMA) cluster analysis of shell and pottery abundances by stratigraphic units from Sectors XVI-VII. (back to text)

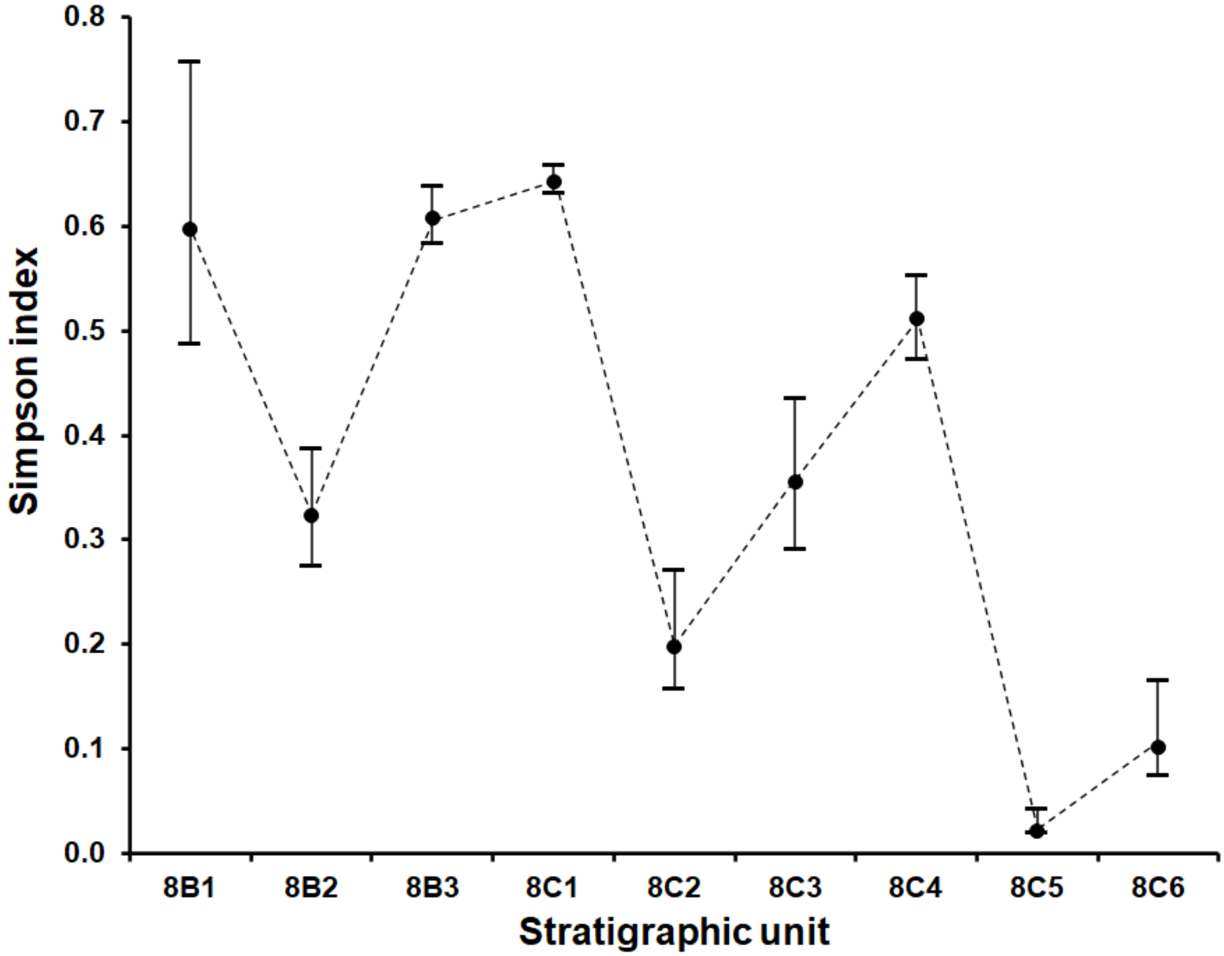


Figure 11. Unbiased Simpson index of shell and pottery evenness throughout the stratigraphic sequence from Sectors XVI-VII. Approximate 95% confidence intervals for the indices of each unit were estimated using the bootstrap procedure (9999 resamples with replacement) provided in PAST version 4.07 (Hammer et al., 2001). Greater evenness is indicated by higher index values. (back to text)

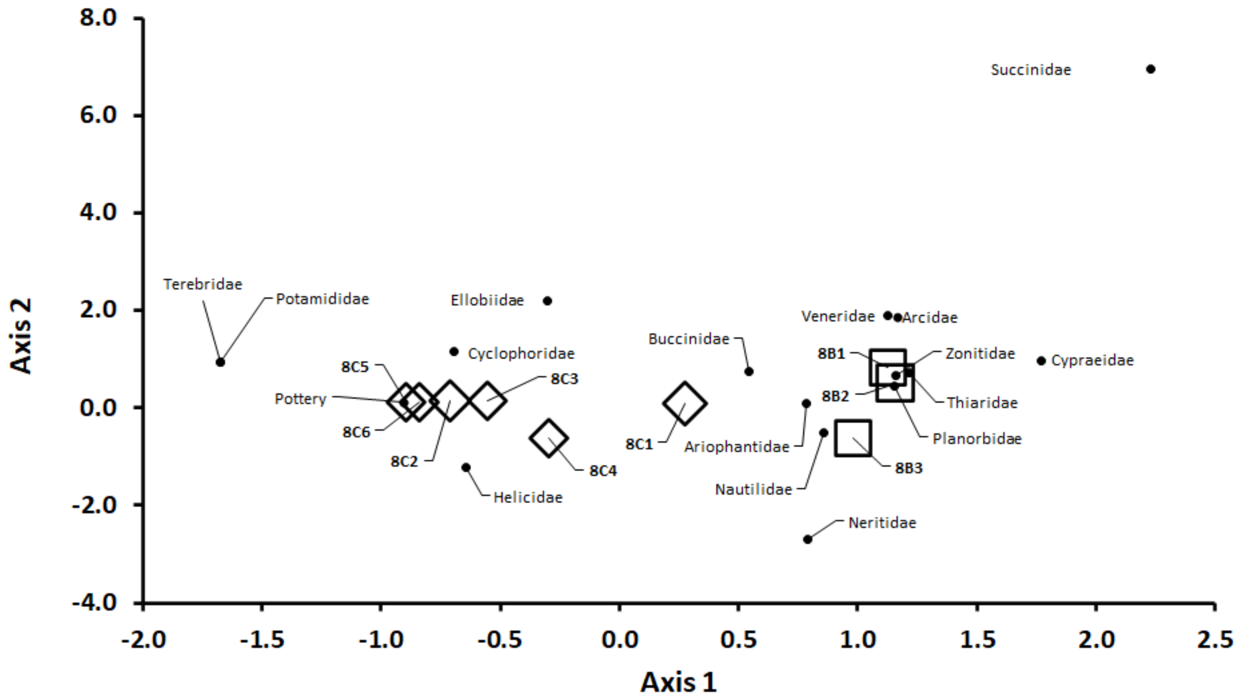


Figure 12. Correspondence analysis of shell and pottery abundances within stratigraphic units from Sectors XVI-VII. Axes 1 and 2 represent 78.7% and 11.7% of the variance, respectively. Unit symbols: 5 to 3 ka, squares; 3 ka to present, diamonds. (back to text)

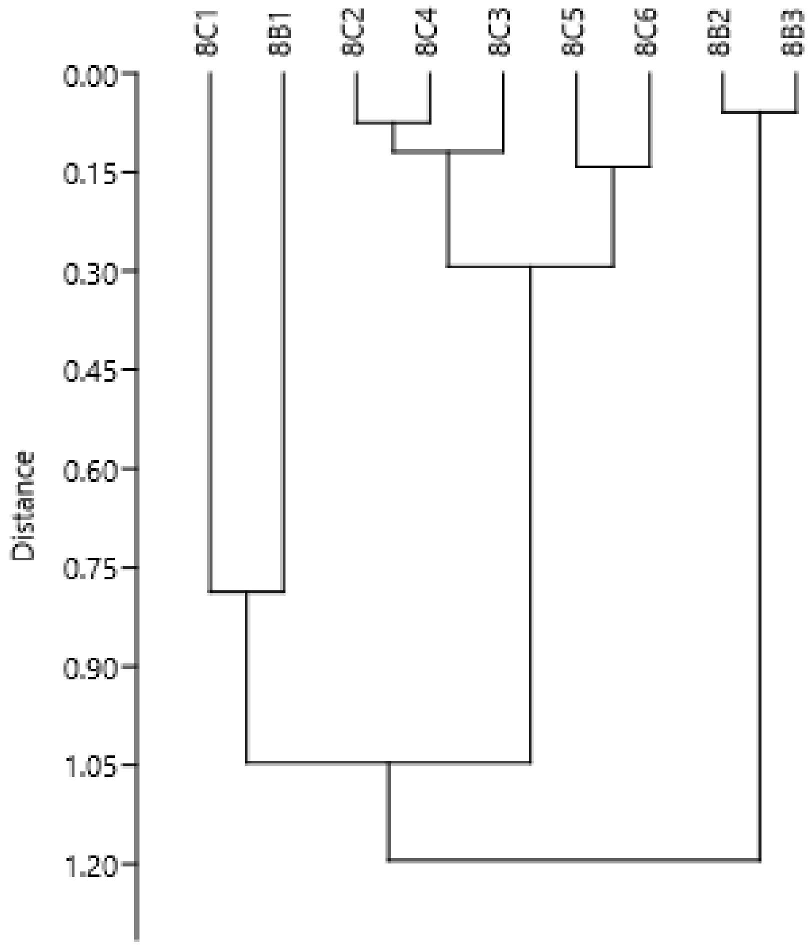


Figure 13. Unweighted pair group method with arithmetic mean (UPGMA) cluster analysis of shell and pottery abundances by stratigraphic units from Sectors XXVI-XXV. (back to text)

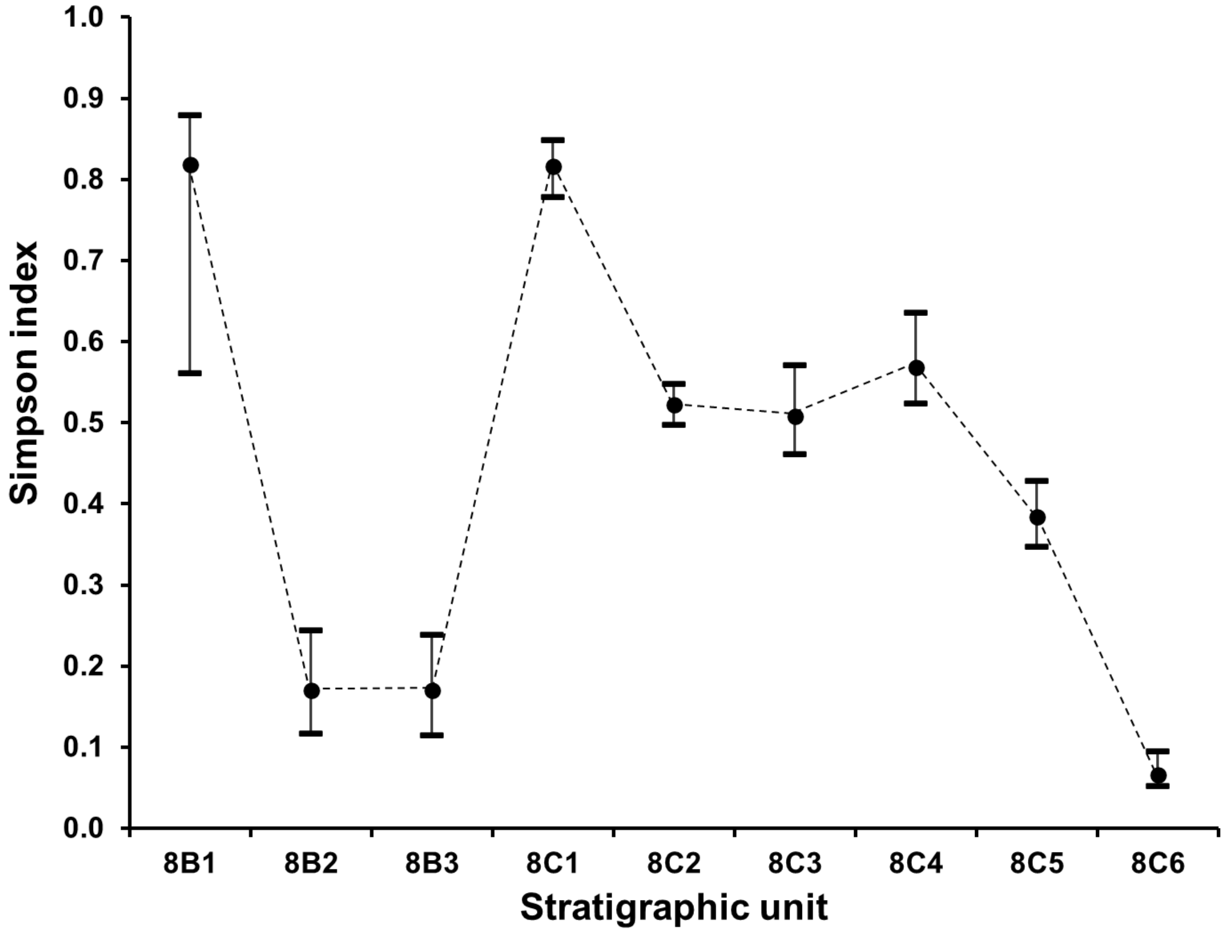


Figure 14. Unbiased Simpson index of shell and pottery evenness throughout the stratigraphic sequence from Sectors XXVI-XXV. Approximate 95% confidence intervals for the indices of each unit were estimated using the bootstrap procedure (9999 resamples with replacement) provided in PAST version 4.07 (Hammer et al., 2001). Greater evenness is indicated by higher index values. (back to text)

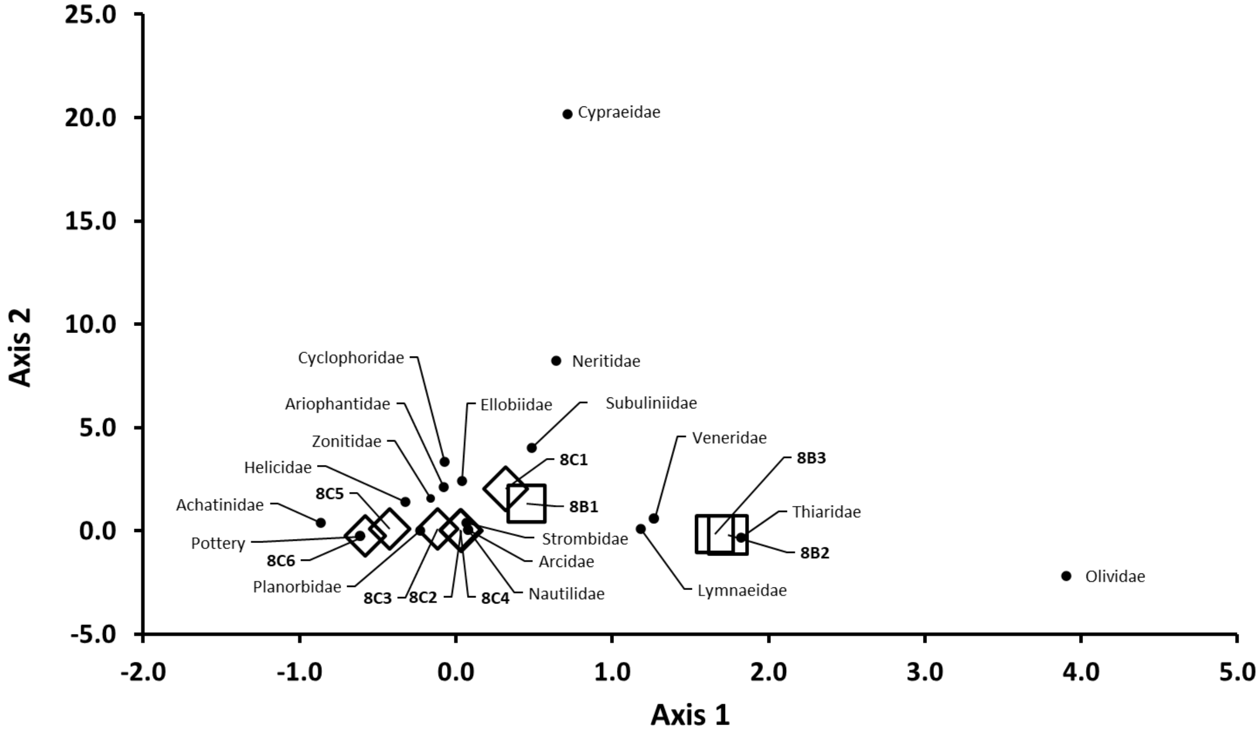


Figure 15. Correspondence analysis of shell and pottery abundances within stratigraphic units from Sector XXVI-XXV. Axes 1 and 2 represent 71.6% and 16.1% of the variance, respectively. Unit symbols: 5 to 3 ka, squares; 3 ka to present, diamonds. (back to text)

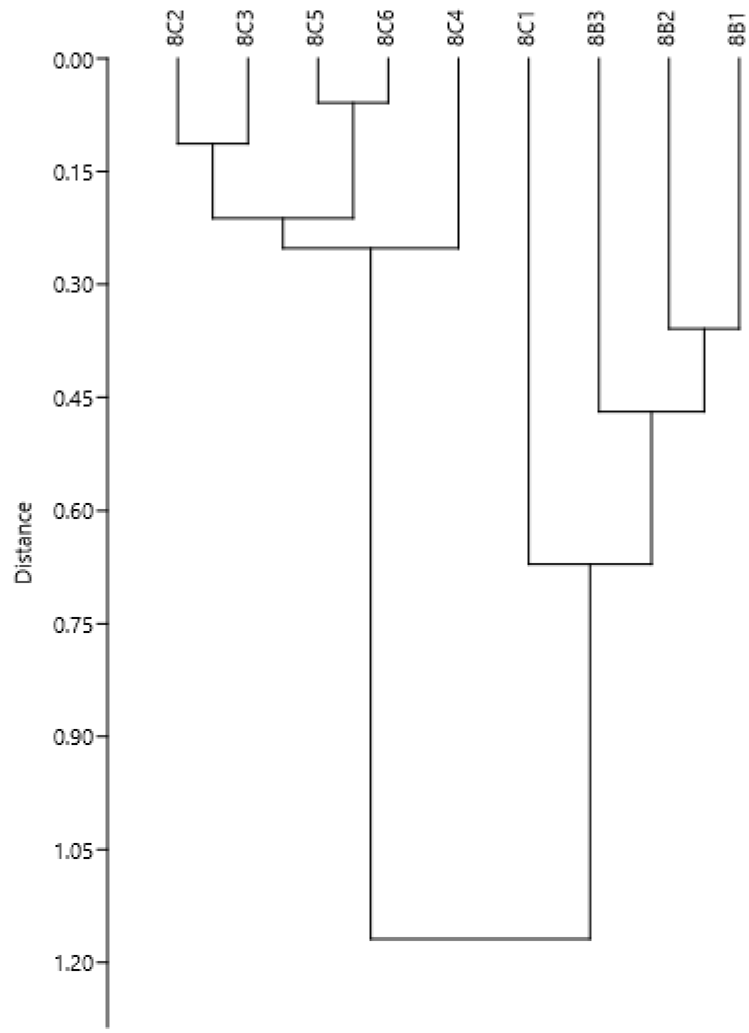


Figure 16. Unweighted pair group method with arithmetic mean (UPGMA) cluster analysis of shell and pottery abundances by stratigraphic units from six adjacent sectors (XXXII, XXIX, XXVI, XXV, XVI and VII). (back to text)

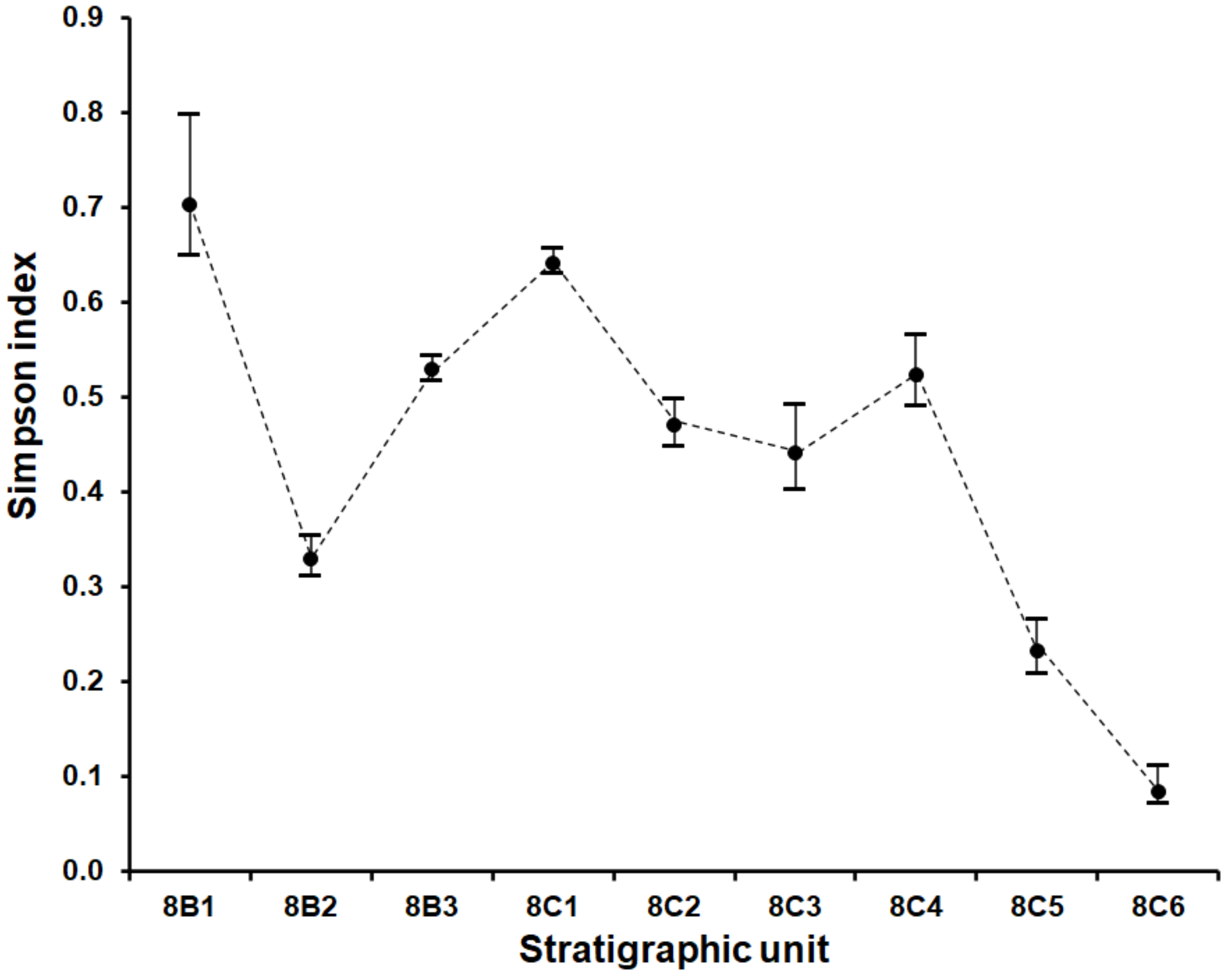


Figure 17. Unbiased Simpson index of shell and pottery evenness throughout the stratigraphic sequence from six adjacent sectors (XXXII, XXIX, XXVI, XXV, XVI, and VII). Approximate 95% confidence intervals for the indices of each unit were estimated using the bootstrap procedure (9999 resamples with replacement) provided in PAST version 4.07 (Hammer et al., 2001). Greater evenness is indicated by higher index values. (back to text)

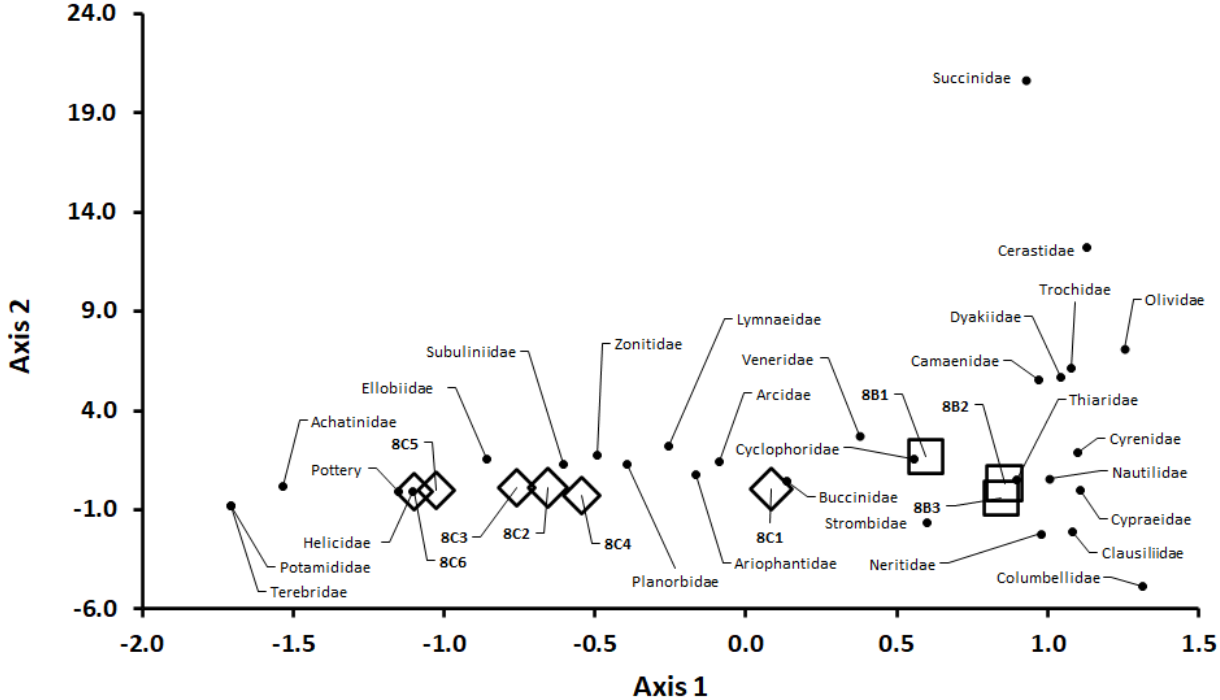


Figure 18. Correspondence analysis of shell and pottery abundances within stratigraphic units from six adjacent Sectors (XXXII, XXIX, XXVI, XXV, XVI and VII). Axes 1 and 2 represent 81.3% and 10.3% of the variance, respectively. Unit symbols: 5 to 3 ka, squares; 3 ka to present, diamonds. (back to text)

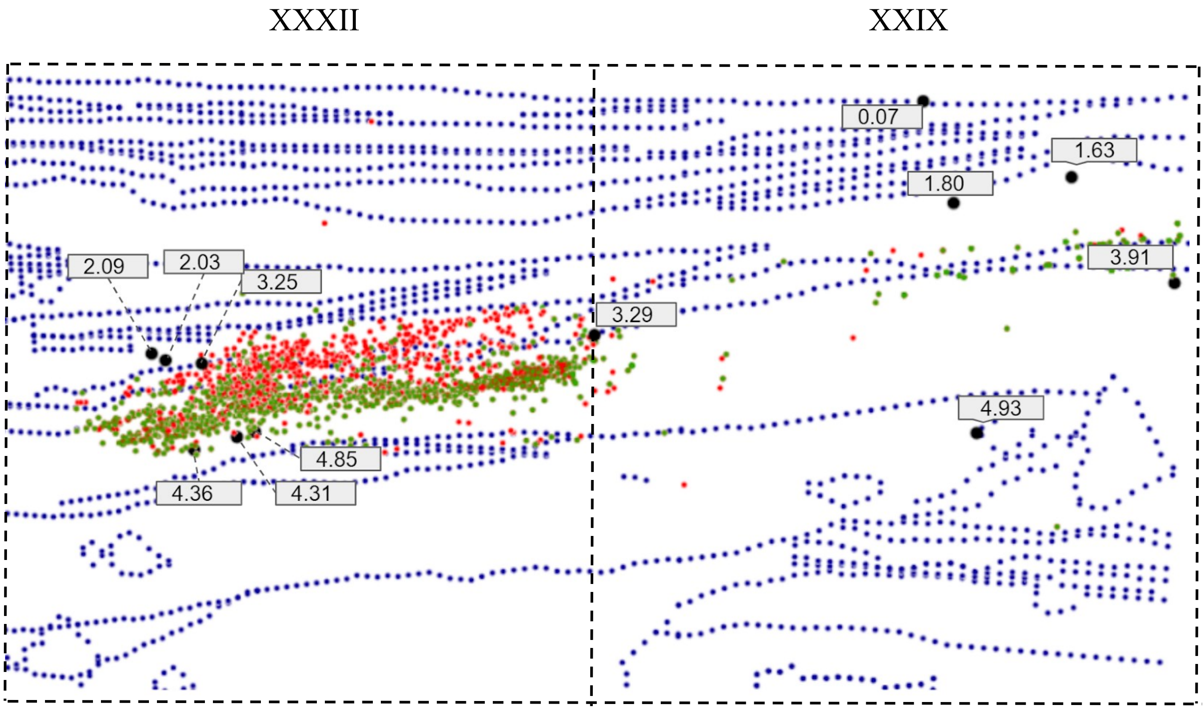


Figure 19. The distribution of radiocarbon-dated charcoal (ka cal. BP) (black circles); thiarid shells (complete, red circles; cut on apex, green circles) as shown projected against the eastern wall (width = 4 m) of the excavation. (back to text)

Figure 20. A tradition of cooking rice in bamboo tubes in Mengeruda, Central Flores. (back to text)

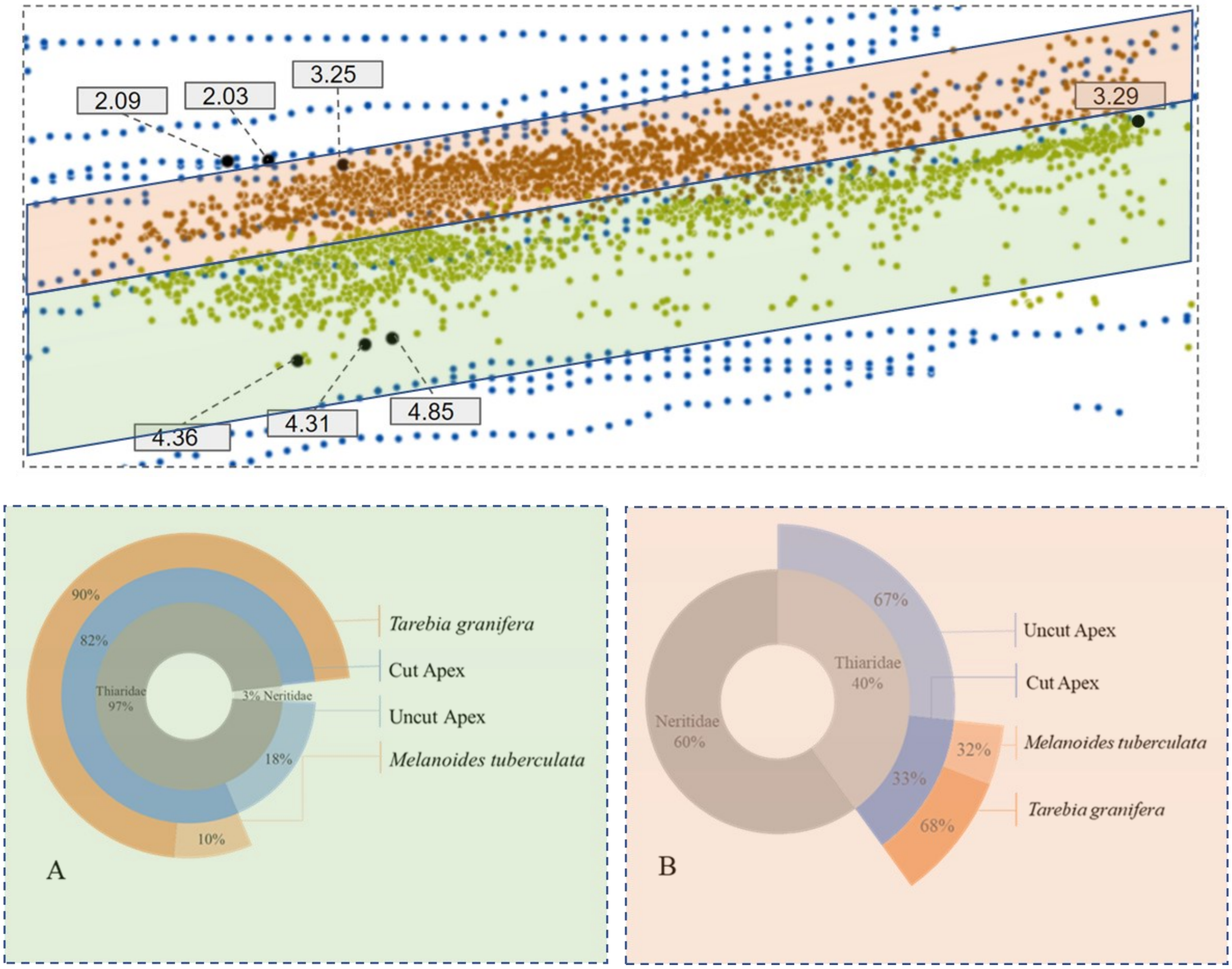


Figure 21. The shell midden at Liang Bua consists of a lower section (A) dominated by thiarids (green circles), 82% of which have their apices cut, and an upper section (B) dominated by neritids (brown circles) and uncut thiarids. (back to text)

Appendix

Chord Distance

Chord distance (CD) is a multivariate statistical distance measure that is frequently used for abundance data (Gavin et al., 2003; Faith, 2013; Sutikna et al., 2018; Veatch et al., 2019; Hammer et al., 2001). In PAST, version 4.07 (Hammer et al., 2001), it is calculated as:

$$d_{jk} = \sqrt{2 - 2\frac{\sum_i x_{ji} x_{ki}}{\sqrt{\sum_i x_{ji}^2 \sum_i x_{ki}^2}}}.$$

As a measure, CD is particularly useful for quantifying how similar (or dissimilar) the taxonomic abundances in different assemblages are from one another. When used together with stratigraphic data, CD provides a measure of how much the abundances have changed across subsequent stratigraphic layers. For example, in this study the following abundances were observed in Sectors XXXII-XXIX:

Taxon	Stratigraphic Unit								
	$8B_1$	$8B_2$	$8B_3$	$8C_1$	$8C_2$	$8C_3$	$8C_4$	$8C_5$	$8C_6$
Ariophantidae	6	56	30	1	0	0	0	0	0
Camaenidae	1	6	0	0	0	1	0	0	0
Nautilidae	0	7	4	0	0	0	0	0	0
Cerastidae	1	1	0	0	0	0	0	0	0
Clausiliidae	0	1	3	1	0	0	0	0	0
Columbellidae	0	0	3	0	0	0	0	0	0
Cyclophoridae	0	17	4	0	0	0	0	0	0
Olividae	1	3	0	0	0	0	0	0	0
Cypraeidae	0	3	3	0	0	0	0	0	0
Cyrenidae	2	7	7	0	0	0	0	0	1
Dyakiidae	8	26	5	0	0	0	0	2	1
Neritidae	1	308	721	32	0	1	0	1	0
Strombidae	0	1	0	0	0	0	0	0	0
Thiaridae	22	1,768	1,119	223	0	1	0	2	7
Trochidae	2	10	0	0	0	1	0	0	0
Pottery	0	3	40	56	26	24	60	22	60

Using the ‘Similarity and distance indices’ option under the ‘Multivariate’ tab in PAST, version 4.07 (Hammer et al., 2001), the CDs between all of these stratigraphic units are calculated as follows:

Units	$8B_2$	$8B_3$	$8C_1$	$8C_2$	$8C_3$	$8C_4$	$8C_5$	$8C_6$
$8B_1$	0.43	0.65	0.51	1.41	1.38	1.41	1.33	1.33
$8B_2$		0.40	0.25	1.41	1.38	1.41	1.34	1.33
$8B_3$			0.47	1.39	1.35	1.39	1.32	1.32
$8C_1$				1.23	1.19	1.23	1.16	1.14
$8C_2$					0.08	0.00	0.14	0.12
$8C_3$						0.08	0.12	0.11
$8C_4$							0.14	0.12
$8C_5$								0.09

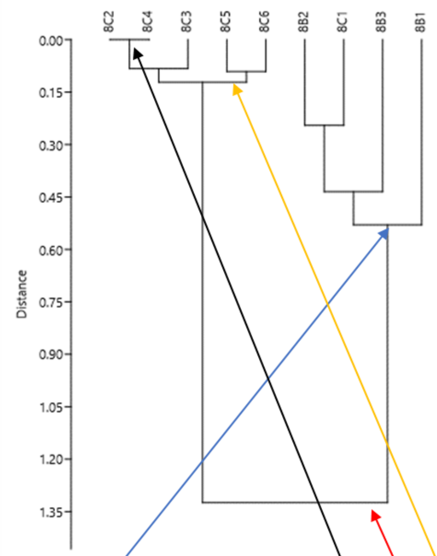
Assemblages with CD values equal or close to 0 have identical or very similar compositions. In this example, Units $8C_2$ and $8C_4$ have a CD value of 0 (shown in the blue rectangle). Examining the abundance data shows that neither of these units contains any mollusks but both contain pottery. In other words, the relative abundances for both are 100%

pottery; thus, they are exactly the same and their CD value is 0. Note that this similarity is independent of assemblage sample size as $8C_2$ has 26 pottery sherds while $8C_4$ has 60. In contrast, CD values close or equal to the square root of 2 (i.e., ~1.4) have nothing, or very little, in common (Ludwig and Reynolds, 1988). For example, Units $8B_1$ and $8B_2$ compared with both $8C_2$ and $8C_4$, results in CD values of 1.41 (shown in the red rectangles). The abundance data show that $8B_1$ and $8B_2$ contain 0% and 0.2% of pottery, respectively; thus, both consist of essentially 100% mollusks. In contrast, Units $8C_2$ and $8C_4$ contain 100% of pottery and 0% of mollusks. Therefore, these particular units are maximally different from each other. Note again the large differences among these four units in assemblage sample size underscoring the fact that CD is calculated from the relative abundances (i.e., the proportions).

Unweighted pair group with arithmetic mean

Unweighted pair group with arithmetic mean (UPGMA) is a form of cluster analysis that produces a dendrogram based on the average statistical distances between groups (Hammer et al., 2001). In this study, UPGMA was used to help visualize the CD values obtained for all pairwise comparisons of the stratigraphic units, as has been done in previous research (Sutikna et al., 2018; Veatch et al., 2019), providing a useful indicator of the similarities/dissimilarities of all units simultaneously.

Using the ‘Clustering’ option under the ‘Multivariate’ tab in PAST, version 4.07 (Hammer et al., 2001), the following dendrogram is produced:



Units	Units								
	$8B_1$	$8B_2$	$8B_3$	$8C_1$	$8C_2$	$8C_3$	$8C_4$	$8C_5$	$8C_6$
$8B_1$	0	0.43	0.65	0.51	1.41	1.38	1.41	1.33	1.33
$8B_2$			0.40	0.25	1.41	1.38	1.41	1.34	1.33
$8B_3$				0.47	1.39	1.35	1.39	1.32	1.32
$8C_1$					1.23	1.19	1.23	1.16	1.14
$8C_2$						0.08	0.00	0.14	0.12
$8C_3$							0.08	0.12	0.11
$8C_4$								0.14	0.12
$8C_5$									0.09

In this example, the average of the CD values in the red rectangle is 1.32, which corresponds to the horizontal line shown in the dendrogram (note the dashed line has been added to highlight the average CD value). This helps show that Units $8C_2$–$8C_6$ are more similar to each other than any of them are to Units $8B_1$–$8C_1$, and vice versa, in terms of their pottery and mollusk compositions. In the blue rectangle, the average of the CD values is 0.53, which shows that Units $8B_2$, $8B_3$, and $8C_1$ are more similar to each other than any of them are to Unit $8B_1$. In the yellow rectangle, the average of the CD values is 0.12, which shows that Units $8C_2$–$8C_4$ are more similar to each other than any of them are to both Units $8C_5$ and $8C_6$. Finally, in the black rectangle, the average of the CD values is 0.00, which shows that Units $8C_2$ and $8C_4$ are identical to one another.

Evenness

The statistical analysis of evenness is commonly used by zooarchaeologists to document change in the faunal composition of assemblages that may reflect how faunal communities have responded to changes in the environment and/or how assemblage accumulators (e.g., carnivores, omnivores) have changed their subsistence patterns (Grayson, 1984; Grayson and Delpech, 2003; Faith and Du, 2017; Sutikna et al., 2018; Veatch et al., 2019). In this study, evenness through the stratigraphic sequence was measured using the unbiased Simpson index ($1 - D'$). In PAST, version 4.07 (Hammer et al., 2001), D' is calculated as:

$$D' = \sum\left(\frac{n_i(n_i-1)}{N(N-1)}\right)$$

where n_i is the abundance of taxon i and N is the total number of individual specimens in the sample.

Using the 'Diversity indices' option under the 'Diversity' tab in PAST, version 4.07 (Hammer et al., 2001), the unbiased Simpson index and its approximate 95% confidence intervals, estimated using the bootstrap procedure (9999 resamples with replacement), for each stratigraphic unit are calculated as follows:

	$8B_1$	$8B_2$	$8B_3$	$8C_1$	$8C_2$	$8C_3$	$8C_4$	$8C_5$	$8C_6$
Upper 95% CI	0.82	0.37	0.54	0.51	0	0.53	0	0.57	0.37
Simpson (1-D')	0.71	0.34	0.53	0.45	0	0.27	0	0.34	0.24
Lower 95% CI	0.63	0.32	0.52	0.40	0	0.27	0	0.21	0.14

The unbiased Simpson index represents the probability that two randomly sampled specimens from a given stratigraphic unit will belong to a different category (i.e., a particular mollusk taxon or pottery fragment). Values close to 0 indicate that the assemblage is dominated by a single category. In this example, Units $8C_2$ and $8C_4$ have unbiased Simpson index values of

0 (shown in the red rectangles). Examination of the abundance data shows that neither of these units contains any mollusks but both contain pottery. In other words, the relative abundances for both are 100% pottery, which means that these units are dominated by a single category. In contrast, values close to 1-(1/S) (where S is the number of taxa) indicate that all categories in the assemblage are equally abundant. Unit $8B_1$ has an unbiased Simpson index value of 0.71 (0.63–0.82 95% CI) (shown in the blue rectangle) and nine taxa recorded (1-[1/9] = 0.89). As 0.71 approaches 0.89, it indicates that all categories in this unit are almost equally abundant from a statistical perspective, and the abundance data confirm this result. In comparison, there are 15 taxa recorded in Unit $8B_2$ (1-[1/15] = 0.93) (shown in the yellow rectangle) and the unbiased Simpson index value is 0.34 (0.32–0.37 95% CI). This result indicates that the assemblage in Unit $8B_2$ is less even than in Unit $8B_1$ and is dominated by one or more taxa. Inspection of the abundance data confirms this result and shows that the assemblage in Unit $8B_2$ is dominated by Thiaridae (n = 1,768) and Nertidae (n = 308) with all other taxa only consisting of 56 specimens or less.

Individual rarefaction

Individual rarefaction is frequently used to compare the number of taxa in samples of different sizes. Using this analysis on large data sets with varying sample sizes, it will produce the number of expected taxa for any smaller sample size (including the smallest sample) (Hammer et al., 2001). In this study, Simpson (1/D) and richness (S) indices were used to test for an overall trend of increasing or decreasing evenness and richness through the stratigraphic sequence.

Using the 'Individual rarefaction' option under the 'Diversity' tab in PAST, version 4.07 (Hammer et al., 2001), the Simpson (1/D) and richness (S) indices are calculated as follows:

Units	Simpson (1/D)	Richness (S)	Rank
$8B_1$	2.81	4.65	9
$8B_2$	1.46	2.46	8
$8B_3$	1.92	2.52	7
$8C_1$	1.70	2.66	6
$8C_2$	1	1	5
$8C_3$	1.33	2.57	4
$8C_4$	1	1	3
$8C_5$	1.44	2.72	2
$8C_6$	1.27	2.04	1

In this study, rank indicates the stratigraphic order of the sequence. Spearman's Rho (r_s) is used to measure the significance of evenness and richness and it is calculated as:

$$r_s = 1 - \frac{6\sum D^2}{n\left(n^2 - 1\right)}$$

Evenness	
N	9
Rho (r_s)	$\boxed{0.72}$
T-statistic	2.74
DF	7
P-value	$\boxed{0.03}$

Richness	
N	9
Rho (r_s)	$\boxed{0.33}$
T-statistic	0.94
DF	7
P-value	$\boxed{0.38}$

The above example for evenness shows that the Spearman's rho (r_s) is 0.72 and its associated p-value is 0.03, meaning that there was an overall trend of decreasing evenness observed through the sampled stratigraphic sequence. In other words, the Simpson (1/D) index values decrease through time and this trend is statistically significant ($p < 0.5$). In contrast, the Spearman's rho (r_s) for richness is 0.33 and its associated p-value is 0.38, meaning that there was no significant trend in richness (i.e., the number of taxa present in each unit) observed through the sampled stratigraphic sequence.

Correspondence analysis

Correspondence analysis (CA) is a multivariate statistical technique that is similar to principal components analysis (PCA), but CA is more appropriate for categorical data whereas PCA is typically used for continuous or other data (Legendre and Lengendre, 1998). In archaeology, CA has gained prominence due to a wide range of applications to archaeological datasets (VanDerwarker, 2010; Hollenbach and Walker, 2010; Sutikna et al., 2018; Veatch et al., 2019). It is particularly useful because it allows for the consideration of multiple cases (e.g., contexts, sites, periods) with multiple variables (VanDerwarker, 2010). In this study, CA is used to examine the abundances of pottery and mollusk taxa within each stratigraphic unit and to provide an overall measure of variation across all units simultaneously.

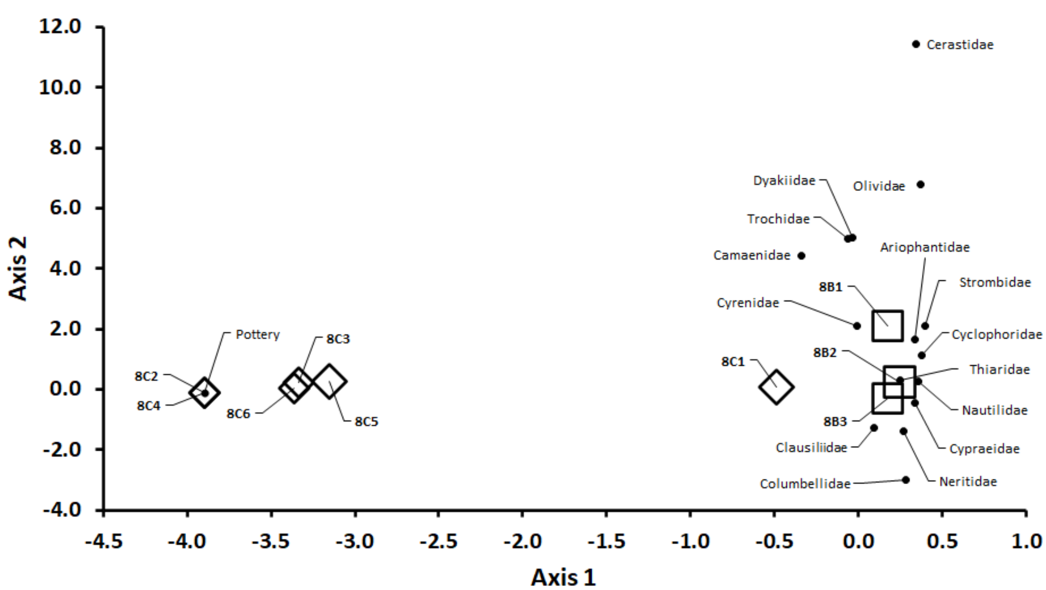
Using the 'Ordination' option under the 'Multivariate' tab in PAST, version 4.07 (Hammer et al., 2001), the eigenvalues and proportions of total variance explained for each CA axis are calculated as follows:

Axis	Eigenvalue	% of total	Cumulative
1	0.62	79	79
2	0.10	12.8	92
3	0.05	6.89	99
4	0.01	0.85	100

As a data reduction technique, the above table shows that the CA has reduced the multivariate data down to two main components, Axes 1 and 2. Together, these axes explain 92% of the total variance in the dataset. By examining how each taxon and each unit plots on these axes, the variation in the abundances of pottery and mollusk taxa within each stratigraphic unit can be visually compared and assessed.

Taxon	Axis 1	Axis 2
Ariophantidae	0.34	1.64
Camaenidae	-0.34	4.44
Nautilidae	0.36	0.24
Cerastidae	0.34	11.44
Clausiliidae	0.09	-1.27
Columbellidae	0.28	-3.01
Cyclophoridae	0.38	1.13
Olividae	0.37	6.77
Cypraeidae	0.34	-0.45
Cyrenidae	0.00	2.10
Dyakiidae	-0.03	5.04
Neritidae	0.27	-1.39
Strombidae	0.40	2.10
Thiaridae	0.25	0.30
Trochidae	-0.06	4.98
Pottery	-3.90	-0.10

Units	Axis 1	Axis 2
$8B_1$	0.18	2.10
$8B_2$	0.25	0.21
$8B_3$	0.18	-0.30
$8C_1$	-0.49	0.06
$8C_2$	-3.90	-0.10
$8C_3$	-3.34	0.21
$8C_4$	-3.90	-0.10
$8C_5$	-3.15	0.26
$8C_6$	-3.36	0.05



In this example above, axes 1 and 2 of the CA illustrate how the compositions of mollusk taxa and pottery vary across all stratigraphic units. Pottery is most strongly associated with Units $8C_2$–$8C_6$, while mollusks are most strongly associated with Units $8B_1$–$8C_1$. Similarly, how individual mollusk taxa influence the distribution of Units $8B_1$–$8C_1$ along mostly axis 2 is also observed. For example, Unit $8B_1$ is not dominated by Thiaridae and/or Neritidae like Units $8B_2$–$8C_1$ are, and thus it shows a higher positive score along axis 2.

Adjusted residuals from contingency table analysis

In this study, adjusted residuals from contingency table analysis were used to facilitate the interpretation of the variation observed along the axes of the CA. Adjusted residuals account for variation that is due to differences in sample size and enable an evaluation of whether differences in abundances between adjacent stratigraphic units are statistically significant (Grayson and Delpech, 2003; Lyman, 2008; Sutikna et al., 2018; Veatch et al., 2019). The adjusted residuals were calculated as follows:

$$d_{ij} = \frac{O_{ij} - E_{ij}}{\sqrt{E_{ij}\left(1 - \frac{n_{i.}}{N}\right)\left(1 - \frac{n_{.j}}{N}\right)}}$$

where $n_{i.}$ is the total frequency for row i, $n_{.j}$ is the total frequency for column j, and N is the overall total frequency (Bewick et al., 2004). The following data example illustrates how adjusted residuals were used in this study. In the data below, the top red rectangle shows the number of Ariophantidae specimens present in Units $8B_1$ and $8B_2$ along with the total number specimens in those units that are not Ariophantidae. These data result in an adjusted residual of -4.47 (shown by the red rectangles), which means that there is a decline in Ariophantidae from Unit $8B_1$ (6/44 = 13.6%) to $8B_2$ (56/2217 = 2.5%). As the absolute value of this adjusted residual is greater than 1.96, the difference is statistically significant at $\alpha = 0.05$ because adjusted residuals are equivalent to standard normal deviates. In contrast, a statistically significant increase in Neritidae is observed from Unit $8B_2$ to $8B_3$ based on an adjusted residual of 17.36 (shown by the blue rectangles).

Units	Ariophantidae	Not Ariophantidae	Total
$8B_1$	6	38	44
$8B_2$	56	2161	2217
$8B_3$	30	1909	1939
$8C_1$	1	312	313
$8C_2$	0	26	26
$8C_3$	0	28	28
$8C_4$	0	60	60
$8C_5$	0	27	27
$8C_6$	0	69	69

Units	Neritidae	Not Neritidae	Total
$8B_1$	1	43	44
$8B_2$	308	1909	2217
$8B_3$	721	1218	1939
$8C_1$	32	281	313
$8C_2$	0	26	26
$8C_3$	1	27	28
$8C_4$	0	60	60
$8C_5$	1	26	27
$8C_6$	0	69	69

	Stratigraphic Unit							
Taxon	$8B_1$ to $8B_2$	$8B_2$ to $8B_3$	$8B_3$ to $8C_1$	$8C_1$ to $8C_2$	$8C_2$ to $8C_3$	$8C_3$ to $8C_4$	$8C_4$ to $8C_5$	$8C_5$ to $8C_6$
Ariophantidae	**-4.47**	**-2.21**	-1.73	-0.29				
Camaenidae	**-2.37**	**-2.29**			0.97	-1.47		
Nautilidae	0.37	-0.69	-0.80					
Cerastidae	**-4.92**	-0.94						
Clausiliidae	0.14	1.14	0.64	-0.29				
Columbellidae		1.85	-0.70					
Cyclophoridae	**0.58**	**-2.54**	-0.80					
Olividae	**-3.34**	-1.62						
Cypraeidae	0.24	0.16	-0.70					
Cyrenidae	**-4.41**	0.25	-1.06					0.63
Dyakiidae	**-9.18**	**-3.42**	-0.90				**2.13**	-1.51
Neritidae	**2.22**	**17.36**	**-9.38**	-1.71	0.97	-1.47	1.50	-1.61
Strombidae	0.14	-0.94						
Thiaridae	**4.81**	**-15.39**	**4.53**	**-7.36**	0.97	-1.47	**2.13**	0.41
Trochidae	**-3.70**	**-2.96**			0.97	-1.47		
Pottery	0.24	**6.13**	**12.86**	**9.39**	**-2.00**	**3.00**	**-3.43**	0.68

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