Mainland-coastal interactions in East Borneo: Inter-site comparison and Bayesian chronological models of two Late Pleistocene–Holocene sequences (Liang Abu and Kimanis rock shelters)

Sébastien Plutniak, Asftolfo Araujo, Bambang Sugiyanto, Adhi Agus Oktaviana, Jean-Michel Chazine, François-Xavier Ricaut

Mainland-coastal interactions in East Borneo: inter-site comparison and Bayesian chronological models of two Late Pleistocene-Holocene sequences (Liang Abu and Kimanis rock shelters)

Sébastien Plutniak[1] Asftolfo Araujo[2] Bambang Sugiyanto[3]
Adhi Agus Oktaviana[4] Jean-Michel Chazine[5]
François-Xavier Ricaut[6]

[1] *Laboratoire Travaux et Recherches Archéologiques sur les Cultures, les Espaces et les Sociétés* (TRACES, UMR 5608), Université Toulouse Jean Jaurès, Maison de la Recherche, 5, allées Antonio Machado, 31058, Toulouse, France.
[2] *Museu de Arqueologia e Etnologia*, Universidade de São Paulo, Avenida Professor Almeida Prado, 1466, 05508-070 São Paulo, SP, Brazil.
[3] *Laboratoire Centre de Recherche et de Documentation sur l'Océanie* (CREDO, UMR 7308), Aix Marseille Université, CNRS, EHESS, 13331 Marseille, France.
[4] *Pusat Penelitian Arkeologi Nasional* (*Arkenas*), Balitbang Kemendikbud, Jakarta, Indonesia.
[5] *Balai Arkeologi Maluku*, Jl. Namalatu - Latuhalat, Latuhalat, Nusaniwe, Latuhalat, Nusaniwe, Kota Ambon, Maluku 98117, Indonesia.
[6] *Laboratoire Évolution et Diversité Biologique* (EDB, UMR5174), Université de Toulouse Midi-Pyrénées, CNRS, IRD, UPS,118 route de Narbonne, Bat 4R1, 31062 Toulouse, France.

[Preprint of: Sébastien Plutniak et al. [2022], "Mainland-coastal Interactions in East Borneo: Inter-site Comparison and Bayesian Chronological Models of two Late Pleistocene-Holocene Sequences (Liang Abu and Kimanis rock shelters)," *The Journal of Island and Coastal Archaeology*, DOI: 10.1080/15564894.2022.2108947.]

Contents

Abstract

In recent decades, East Borneo has become an increasingly important archaeological "hot-spot" in Island Southeast Asia as a result of early dates for rock art ca. 38,000 BP and the greater number of excavated sites that support a much longer period of human occupation. However, the chronology of settlement and adaptation to environmental changes during the Pleistocene–Holocene transition is still poorly known. Here we report on an excavation at the Liang Abu rock shelter which has contexts dating from the Late Pleistocene (12,660 ± 58 uncal. BP) to the present day, indicating a *terminus ante quem* (TAQ) for human occupation at 23,790 BP. We present the results of an attempt to systematically integrate and compare data from Liang Abu and Kimanis, a geographically close site with a previously published sequence. Particular attention is paid to post-depositional issues in tropical settings and to data compatibility, reuse, and reproducibility, relying on open-source software for data processing (R scripts) and Bayesian chronological modeling. Two Bayesian models are built and compared using the *ChronoModel* software, which can handle outliers and uncertainty (e.g., freshwater reservoir effect). This first inter-site comparison for Borneo results in a new chronology of human settlement and mainland–coastal interactions in East Borneo and paves the way for future regional synthesis.

Keywords: Island Southeast Asia; excavation; coastal adaptation; post-depositional processes; Austronesian studies

Introduction: Archaeology in East Borneo

Archaeological investigations in East Borneo have been carried out since the early 1990s not long after the first rock art was identified (Chazine 1995). A recent study dated this rock art to about 38,000 BP (Aubert et al. 2018), placing it among the earliest traces of figurative art worldwide. However, our archaeological knowledge about the surrounding region is still very limited. Surveys and excavations have only taken place at a few dozen sites scattered over a vast territory spanning ca. 750,000 km², which limits the possibility for local and regional syntheses. In North Borneo, a recent restudy of the Niah caves has made significant progress, but was limited to a small area (Barker 2013, Barker and Farr 2016). In Kalimantan (the part of Borneo under Indonesian administration), archaeological knowledge still suffers from a general lack of investigation.

Luckily, the situation has improved over the last decade as a result of investigations conducted in Central Borneo (Kusmartono et al. 2017) and, in particular, the eastern part of the island. Research carried out in the upper Birang River by Karina Arifin (Arifin 2004, Arifin 2017) and 100 km south along the Lesan River by the MAFBO project (2011–2016)[1] following previous Franco–Indonesian surveys and test-pit campaigns from 2003 to 2009, now compare well-documented sites for the first time. In this paper, we compare two major sites in East Borneo: the Liang Abu rock shelter (excavated in 2009 and 2012) and Kimanis cave, the most well-documented site in the upper Birang region which was excavated in 1998. Both sites are located at equivalent distances from the sea and radiocarbon dates suggest that they were occupied since the late Pleistocene. However, whereas Kimanis has relatively easy access to the northern coast through the Birang River, Liang Abu is separated from the sea by a karstic mountain range creating two possible, but longer routes to the sea. By collating and reprocessing unpublished (Liang Abu) and published (Kimanis) data, we provide a useful comparison of these two sites that helps to contextualize the region's chronology and relationships between inland sites and the coast across two different types of topography.

In addition to the scarcity of archaeological sites in Borneo, research in this area is challenged by two other issues: a lack of taphonomic information in archaeological reports and difficulty in comparing data generated by different research teams. Concerning the former, analyzing potsherd relationships at Agop atas (Sabah), Bellwood stated that "Southeast Asian cave archaeology has in the past suffered because of the scant attention paid" to horizontal and vertical disturbances (Bellwood 1988, p. 118). Thirty years later, geoarchaeological methods in Southeast Asian archaeology are still rarely used. Morley identified only five excavations where these methods were applied (Morley 2017) and only one excavation was in Borneo (Niah caves). In this paper we focus on the issues in restudying the Liang Abu data.

In terms of the second issue, the comparison of data from the two sites is a crucial step in advancing archaeological knowledge in the region. This comparison required us to critically evaluate data generated by different research teams using different methods, and to conduct a literature review with otherwise limited availability (e.g., unpublished data or limited-distribution site reports) or information. Although the emphasis of this paper is on Liang Abu material, data from Kimanis will also be treated in depth. We integrate the Liang Abu and Kimanis data —when possible, into a single comparative space— using common statistical procedures and Bayesian chronological modeling, grounded on the principle that data availability and analysis reproducibility are essential to consolidate archaeological knowledge and future studies (Marwick 2017, see Supplementals 1 and 2 for the R code used for this paper).

[1] MAFBO: *Mission Archéologique Française à Bornéo*, `https://kaltim.hypotheses.org`.

This paper addresses these two issues and aims to: (1) report on the data generated at Liang Abu during the 2009 and 2012 excavations, paying particular attention to the taphonomic aspects; and (2) integrate Liang Abu and Kimanis data to present a consolidated archaeological synthesis for the chronology of human settlement and mainland–coastal interaction in East Borneo. We first present the Liang Abu site, the excavation procedures, and the sequence. We then address perturbation and post-depositional processes and present the archaeological material recovered during the excavation and discuss it in reference to the results from Kimanis. Finally, we report the chronometric results and summarize the results of the comparison between Liang Abu and Kimanis. We hope that this first attempt to compare data from Bornean sites excavated by different research teams will give a basis for future and extended regional synthesis, paying similar attention to reproducibility.

1 Excavation at the Liang Abu rock shelter

1.1 Site location

The Liang Abu shelter is located in the tropical rainforest of East Borneo, 80 km from the western coast of the Celebes Sea and 95 km northwest of the Makassar Strait (latitude/longitude (lat/lon): 1.468306, 117.287861, Figure 1). It is located at the border between two major Oligocene–Miocene geological formations: the sedimentary Maau formation[2] and the Lebak karstic formation, which consists of limestone breccia, sandstone, and an intercalation of limestone and marl. The site of Liang Abu is included in the Kelai River catchment (Figure 2). In addition, although being separated from the sea by the karstic formation, the rock shelter is located near to an indirect southward pathway to the sea, namely the Karangan River. However, the closest river to the shelter is the Lesan (or Lasan) River, a tributary of the Kelai leading only to the north.

The Liang Abu area is currently included in the Berau district of the Indonesian province of East Kalimantan. The village of Merabu (lat/lon: 1.505861, 117.2745), on the Lesan River, is the closest current human settlement, approximately 5 km away from the site. Liang Abu is a vast and dry west-facing rock shelter with a rock wall slanted at an acute angle. The current ground level is about 8 m away and 2.5 m above a swamp (Figure 3). The dimensions of the shelter are about 25 m long and between 5 and 8 m in width (Figure 4). There are a number of adjacent cavities and crevices above the main part of the rock shelter which are included in an active karstic system. Remains of relatively recent funerary practices have been found in these upper cavities, including human bones, remains of wood and rattan coffins, and pottery sherds. Below, we compare Liang Abu with the Kimanis site, a cave with a rock shelter covering about 22 x 8 m, located near the Birang River, a tributary of the Malinau River. The site is located in the "Birang" Tertiary and Oligocene formation, whose upper part is characterized by alternating marl, limestone, and tuff deposits. Several test pits have been excavated, but all the dated samples come from the "C_4" 1 x 2 m trench which reached 3 m in depth (Arifin 2017).

1.2 Research history

Liang Abu was first located and surveyed by French and Indonesian speleologists in 2006 as part of an archaeological program conducted beginning in the early 1990s by J.-M. Chazine, who discovered significant examples of rock art in East Borneo (Chazine 1999, Chazine

[2]The Maau formation is about 1800 m thick. Its lower part consists of interbedded breccia, conglomerate, sandstone, limestone, marl, shale, and tuff. The upper part consists of interbedded clay-stone, siltstone, sandstone, and calcite veinlets (Sukardi et al. 1995).

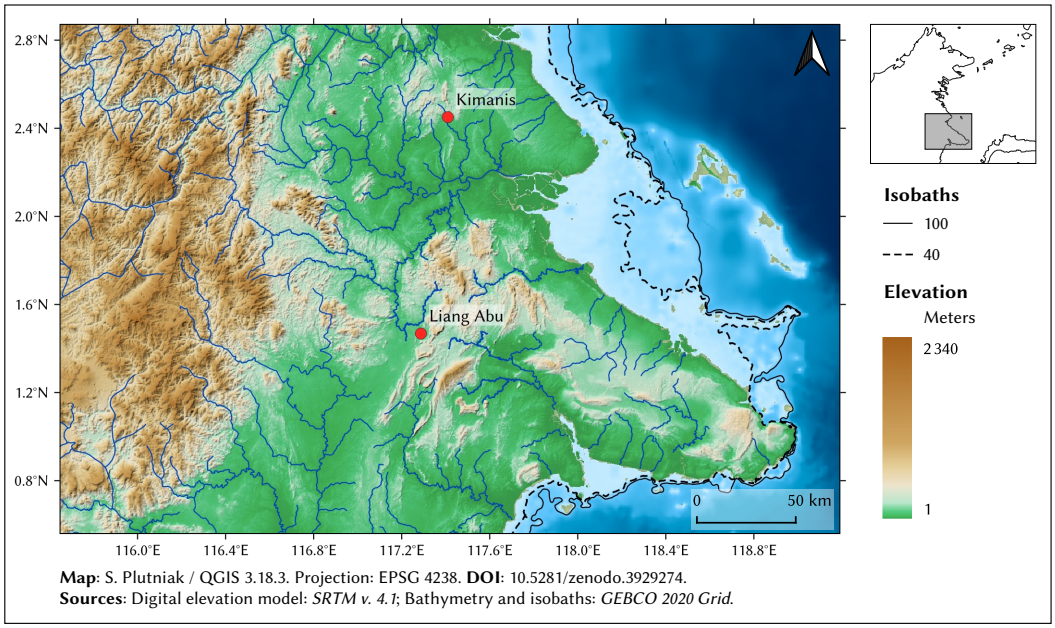

Figure 1: Study area with the location of the Liang Abu and Kimanis sites. The 100 m and 40 m isobaths are represented, indicating ancient coastlines at ca. 15,000 BP and ca. 11,000 BP, respectively.

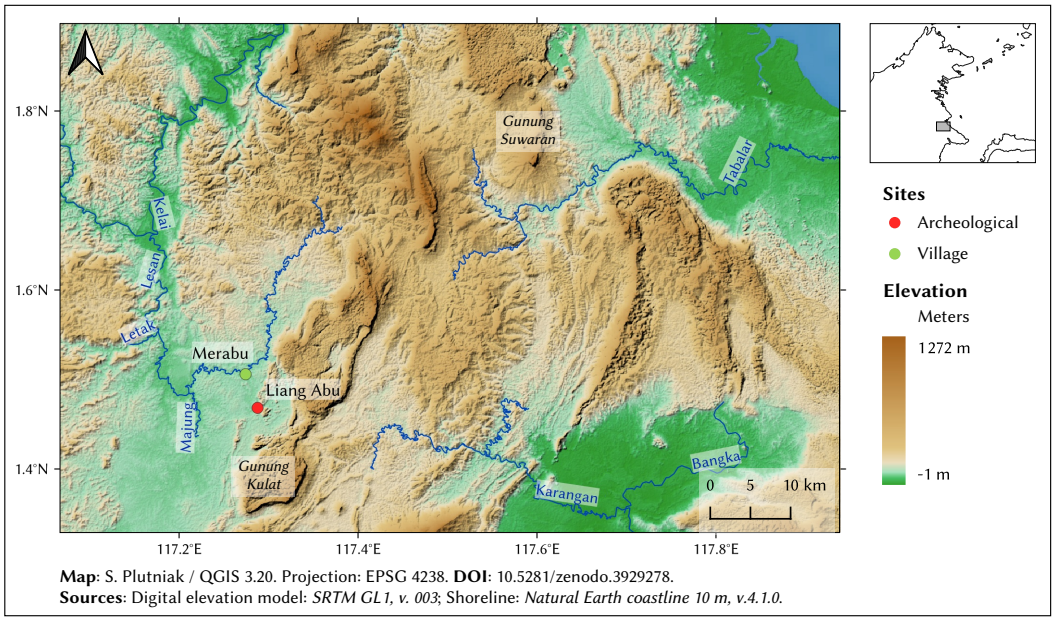

Figure 2: Location of Liang Abu in the Mangkalihat karstic area, 80 km from the mangrove shallow shores of the Celebes Sea.

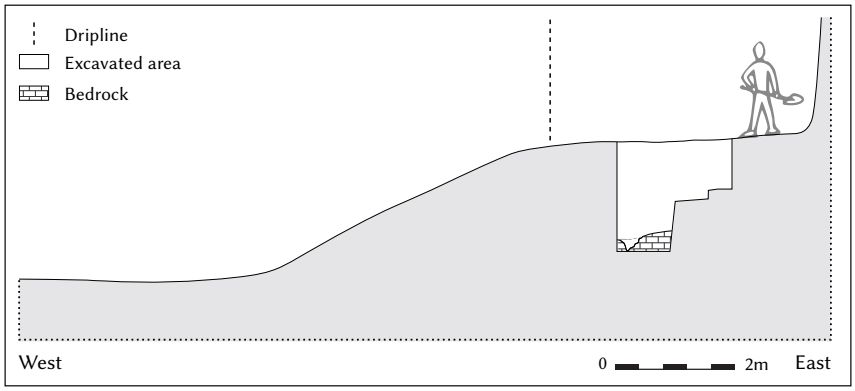

Figure 3: East–west section of the Liang Abu rock shelter along the 11th axis of the grid (visible on the left part of Supplemental 1, Figure 1). Drawing: S. Plutniak, from Plutniak et al. 2016, edited.

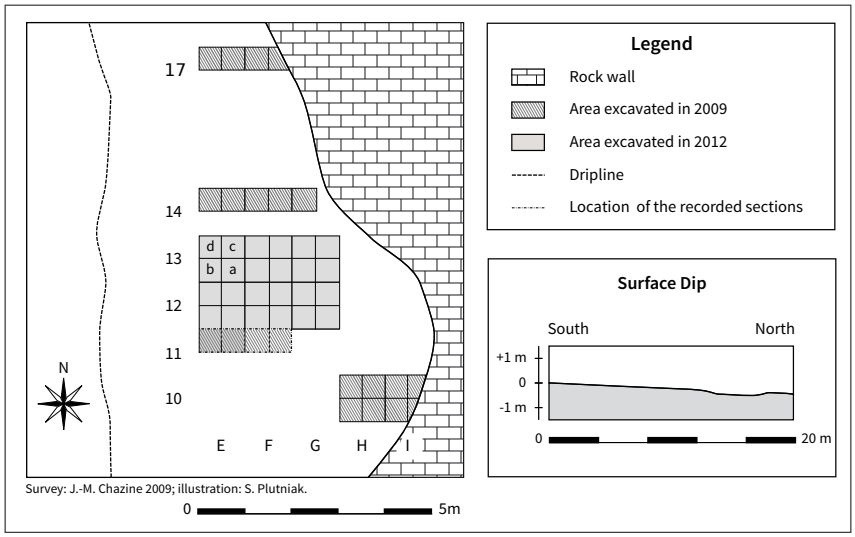

Figure 4: Plan of the excavated area in the Liang Abu rock shelter. Map: S. Plutniak.

2005). The Liang Abu site was first excavated in 2009 in the framework of the MAFBO, a French–Indonesian archaeological program. In 2012, a new excavation campaign was undertaken by a team led by F.-X. Ricaut (Ricaut et al. 2012). During the two campaigns the base camp was established in a nearby shelter, Liang Beloyot (lat/lon: 117.289389, 1.472556), where upper cavities contain rock art.

Archaeological material recovered during these excavations is stored at the *Dinas Pemuda, Olahraga dan Pariwisata* (Department of Tourism, Youth and Sport, Sangata, East Kutai, Indonesia) and at the *Pusat Penelitian dan Pengembangan Arkeologi Nasional* (National Research Center for Archaeology, Jakarta, Indonesia). Access to this material is under the authority of the *Direktorat Pelestarian Cagar Budaya dan Permuseuman* (BPCB, Directorate of Cultural Heritage and Museums), Samarinda, Indonesia. Preliminary analysis of these materials is reported in the yearly scientific reports of the project.[3]

1.3 Excavation procedures and data

In 2009, four trenches were opened perpendicular to the shelter opening and excavated to a depth of around 1 m using both dry and wet sieving (Figure 4), Trench 1 corresponds to rows 17Ec-d and 17Fc-d, Trench 2 to rows 14Ec-d, 14Fc-d and 14Gd, Trench 3 to rows 11Ec-d and 11Fc-d, and Trench 4 to rows 10H and 10I. In 2012, a grid system was established, in which the 2009 test pits were included. Each grid square measures 1 x 1 m, and was divided into four 0.5 m sub-squares coded a, b, c, and d.

In 2012, excavations were extended north of Trench 3 (Squares 12E, 12F, 12G, 13E, 13F, and 13G) for a total surface of 6 m², and deepened for four sub-squares (12Ea, 12Eb, 12Fa, 12Fb, 1 m² in total). Possible substrate was reached at a depth of 150–160 cm from the current ground level (Figure 5 and, for the Harris diagrams, Supplemental 1, Figure 2). The sediments were dry sieved through a 2 mm sieve and sorted in the field[4], except for the sediments from Sub-square 12Eb. In this case, a specific procedure was applied to study the micro-fraction remains. Micro-remains and artifacts were defined as remains smaller than 2 mm. The relevance of their study for understanding transportation and post-depositional disturbance was demonstrated long ago (Dunnell and Stein 1989, Fladmark 1982, Stein and Teltser 1989). The materials from Sub-square 12Eb were wet sieved through a 5 mm sieve and then through a 2 mm sieve. Results from Layers 2 and 3 were briefly mentioned in Plutniak et al. 2016 and are more closely examined in this paper. Materials from the deeper layers (4, 5, 6, 8, 9, 13, 15, 16) have yet to be analyzed.

Most of the Liang Abu archaeological deposit is formed by a powdery, light gray to dark brownish silt-sized sediment. In the absence of composition analysis which must be conducted in a future study, we can only hypothesize that this accumulation of ash is the result of intense human activity. This feature is not a "normal" outcome of human occupation in rock shelters, much less in humid tropical settings, where limestone walls provide a minimum amount of clastic input into the sediment, compared with sandstone (Araujo et al. 2008). In addition, this feature is recalled by the toponym "Liang Abu," which means "Ash shelter" in Indonesian. Besides Bornean rock shelters, those with similar anthropogenic sediments have also been described at the Yuku rock shelter in New Guinea (Horrocks et al. 2008). At Liang Abu, the only layers which do not feature ashy deposits are Layer 18, which is formed by a harder (indurated) silt deposit, Layer 16 formed by a more compact clay-silt sediment, and Layer 2 which contains fine gravel.[5]

[3] See Chazine et al. 2009, Chazine et al. 2010, Ricaut et al. 2011, Ricaut et al. 2012, Ricaut et al. 2013, Ricaut et al. 2014.

[4] In 2009, the sediments were dry sieved through a 5 mm sieve.

[5] For a detailed description of the excavation procedure and layers, see Supplemental 1, Section 1.

Table 1: Radiocarbon AMS dating from Liang Abu. In the "Laboratory" column, "UBA" refers to the 14 Chrono Center in Belfast and "GifA" refers to the *Laboratoire des Sciences du Climat et de l'Environnement* in Gif-sur-Yvette, France. Units: $F^{14}C$ refers to Fraction modern with ^{13}C fractionation and background corrections, $\delta^{13}C$ gives the AMS isotope fractionation.

Lab.	Id	Square	Layer	Spit	Depth	Material	Age BP	sd	$F^{14}C$	$F^{14}C\pm$	avgRo	uAC	$\delta^{13}C$ (‰)
UBA	20840	12Gd	2	–	79	charcoal	1524	22	0.8272	0.0023	831.01	12.2	-41.2
GifA	11358	11Fc	2	–	80	charcoal	8110	50	–	–	–	–	–
UBA	20839	12Ec	2	–	83	charcoal	1672	21	0.8121	0.0021	830.58	12.6	-32.5
UBA	26297	12E	3	–	91	charcoal	5966	33	0.4758	0.0019	–	–	-27.3
UBA	–		7	–	–	bone	failed	–	–	–	–	–	–
GifA	11357	11Ec	8 (top)	–	91–107	charcoal	8165	45	–	–	–	–	–
UBA	20841	12Fb	10 (top)	–	165	charcoal	10222	38	0.2801	0.0013	291.21	13.5	-27.8
UBA	–	11Ed	10	–	146–166	bone	failed	–	–	–	–	–	–
GifA	11356	11Ed	10	–	165	charcoal	11590	60	–	–	–	–	–
UBA	27060	11Ec	12 (top)	8	180	shell	14902	72	0.1564	0.0014	–	–	–
UBA	20842	12Eb	12	–	185	bone	12660	58	0.2068	0.0015	234.67	31.2	-20.7
UBA	20838	11Ed	13 (top)	5	197	charcoal	34206	730	0.0142	0.0012	19.91	22.1	-21.0
UBA	27059	12Eb	13	6	200	shell	16166	107	0.1337	0.0018	–	–	–
UBA	26299	12E	13	6	200	shell	19761	87	0.0854	0.0009	–	–	-21
UBA	27058	12Eb	15	7	–	tooth	failed	–	–	–	–	–	–
UBA	26303	12E	16	8	–	tooth	failed	–	–	–	–	–	–

Fifteen samples were submitted for radiocarbon dating; four were sampled in the 2009 excavation and 11 in the 2012 excavation (Table 1). When possible, they were sampled in the top and bottom parts of the layers. No sample was associated with a specific archaeological structure except a charcoal fragment from Layer 2, located in a zone with a higher quantity of faunal, pottery, and lithic remains in Sub-square 12Ec (UBA-20839) (Supplemental 1, Figure 24). Samples from teeth and long bone shaft fragments of unidentified large mammals (potentially Suidae or Cervidae) failed due to the absence of collagen, apart from a bone sampled in Layer 12 (UBA-20842). In 2009, a charcoal fragment was sampled at the bottom of the excavation (GifA-11356), corresponding to Layer 10, and in 2012, a second charcoal fragment was sampled at the top of this layer (UBA-20841).

2 Post-depositional processes in tropical rainforest

Several methods to estimate post-depositional perturbation are presented in this section. Considering the horizontal dimension, we can only address perturbation in Layer 2 with the available data: spatial densities and pottery refitting are used. Vertical perturbation is studied throughout the sequence using pottery refitting, examination of bioturbations, and radiocarbon dating anomalies.

2.1 Horizontal distribution of remains in Liang Abu Layer 2

Layer 2 was the layer excavated on the largest surface (see the Harris diagrams in Supplemental 1, Figure 2) and, consequently, it was the only layer for which a horizontal analysis was possible. This layer also has the highest density of remains (Figures 8 and 9). Since object counts are only available for lithic (Grenet and Sarel 2022), mollusk shell (Plutniak and Ricaut 2022), and pottery remains (Plutniak 2022b), we limited the study of these objects to Squares 12E, 12F, and 12G. Objects were randomly located within their sub-squares, and a two-dimensional (2D) kernel density estimation was computed from

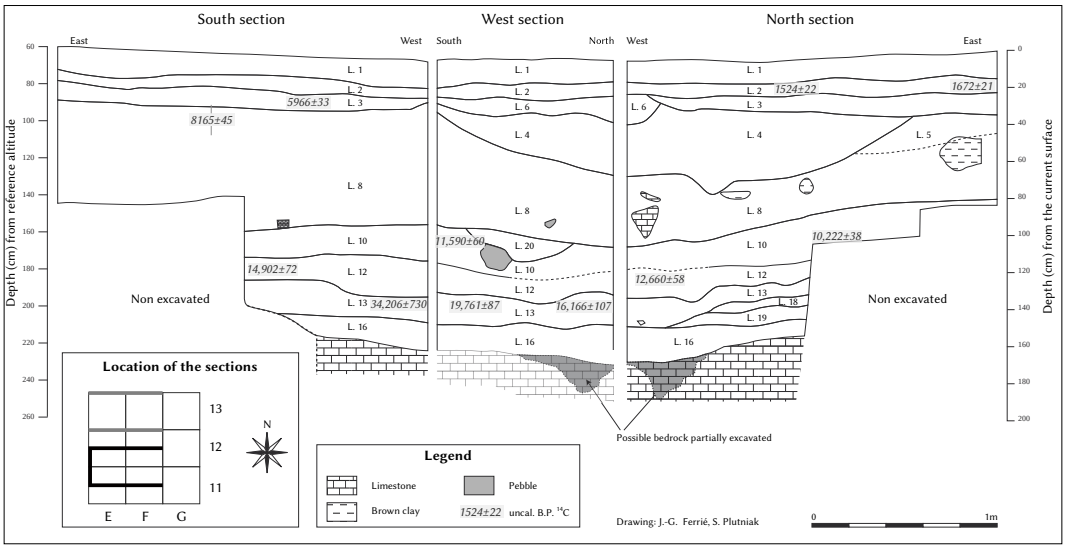

Figure 5: Stratigraphy synthesised from the observation of sections of Squares 11{EF}, 12{EF}, and 13{EF}. For the north section, Layers 1, 2, and 3 were determined from the sections highlighted in light gray in the plan at the bottom left of the figure (these layers were excavated in Squares 13E, 13F, 12E{cd}, 12F{cd}). The labels of the ^{14}C ages indicate the approximate projected location of the samples. Note that the Arabic layer designations are not in numerical order and that different scales are used for x and y axes. Drawing: J.-G. Ferrié and S. Plutniak.

the resulting set of (x, y) coordinates.[6]. The spatial distribution of their cumulated density (Figure 6) reveals a higher density in Square 12G, close to the shelter's wall. Examining the densities of each class of remains shows a higher concentration of pottery in Square 12G, closer to the shelter's wall. The spatial distribution of lithic artifacts is bimodal, with the highest density also in 12G and a second concentration in 12E, close to the shelter opening. Shell remains, on the contrary, are concentrated in Square 12F.

Pottery sherds and lithic artifacts are concentrated closer to the shelter wall, whereas mollusk shell density is higher in the area closer to the outside of the shelter. Interpretation of this spatial distribution on a 3 m2 surface is limited, and we cannot state whether this reflects human activities in the shelter. Simplistic hypotheses, such as assuming that production activities were carried out in the most protected part of the shelter, and cooking and discarding of shells made toward the outside part, are not supported, notably by the distribution of shell remains. The observed distributions most likely reflect the effect of alteration processes, assuming that the outer part of the shelter is potentially more exposed to water washing and to sediment movement due to local topography (Figure 3).

2.2 Spatial distribution and refitting of pottery sherds

Refitting relationships between archaeological fragments have long been used to address post-depositional processes and disturbances (Cahen and Moeyersons 1977, Villa 1982). At Liang Abu, refitting relationships were only studied from the pottery material (n = 1104 sherds). This material has been studied in a previous publication (Plutniak et al. 2016), but little attention was paid to refitting. When looking for pottery sherds which

[6]Two-Dimensional Kernel Density Estimation (Venables and Ripley 2002) implemented in the MASS 7.3-45 package for R. As demonstrated by our tests, the random spatial assignation of the objects has no effect on the general features of their distribution pattern.

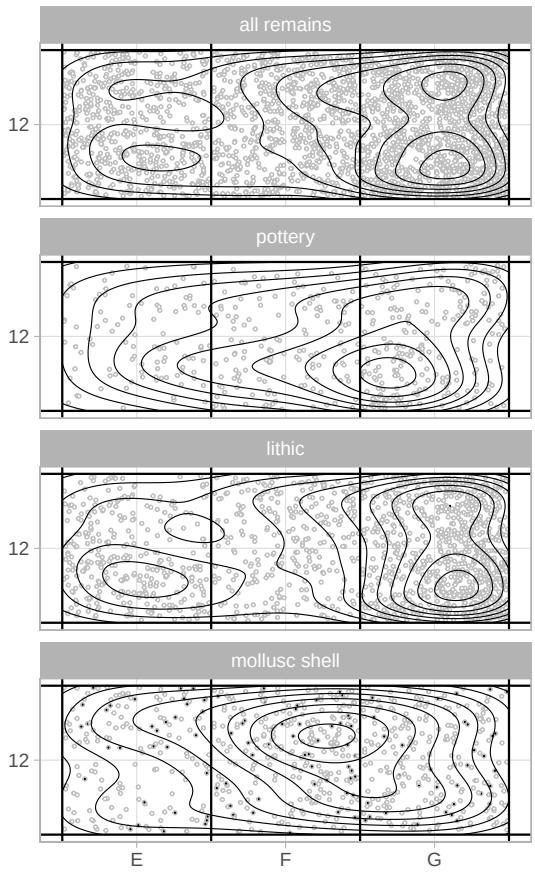

Figure 6: Liang Abu, Layer 2. Cumulated spatial density and density of lithic artifacts, pottery, and mollusk shell remains, by class of remains. Shell remains with broken apexes are distinguished by black dots.

belonged to the same original object, two types of relationships were defined: connection relationships (proper refitting) and similarity relationships (when similarities in motif or material obviously show that two sherds came from the same object, excluding all ambiguous cases). Connection relationships are rare and more difficult to identify, but they are also far more reliable and less subjective than similarity relationships. Equal time was devoted to searching for relationships between the different squares of the site. In total, 56 connection relationships and 484 similarity relationships were identified between three vertical units (surface, Layer 1, and Layer 2).

2.2.1 Movement of pottery sherds in Layer 2

These data are firstly analyzed from a spatial perspective. Structural geology methods, such as "fabric analysis," have already been applied to archaeological sequences (Bertran and Texier 1995, Enloe 2006, Lenoble and Bertran 2004). These methods, which have been previously applied to lithic refitting (Bordes 2000), are used here for the spatial analysis of pottery sherds from the same original object.

In Layer 2, 31 connection and 181 similarity relationships were determined and located by square (Figure 7, left). Relationships within the same square include six connection relationships and 111 similarity relationships, for which azimuth and distance were computed (Figure 7, right). Maximal distance is about 3 m between connecting sherds and about 6 m between similar sherds, suggesting significant dispersion of the material in this layer. Study of the azimuths shows the presence of multiple orientations, dominated by a general north–south orientation. The studied area is a rectangle with a north–south orientation, which might overestimate this orientation of the relationships between sherds. However, a Mann-Whitney-Wilcoxon test reveals no significant difference between the azimuth of similarity and connection relationships, the former being only short-distance relationships. The short-distance movement of sherds might result from sediment and fluvial movement along the north–south dip (see plan in Figure 4) and/or animal action such as digging (Wood and Johnson 1982) and trampling (Villa and Courtin 1983). In contrast, long-distance relationships (e.g., between Squares 11 and 17) are more likely to result from pre- or post-depositional human or animal action.

Assuming that the matching sherds were deposited at the same time and in the same location, these results give evidence for depositional disturbances, which are very common in stratified archaeological sites and must not be disregarded when analyzing data. Results also suggest that other classes of objects (including lithics, bones, etc.) from other layers also potentially moved horizontally in the sediment.

2.2.2 Refitting and layer cohesion

Analysis of the relationships between sherds can assess the relevance of the vertical divisions between layers of the sequence as already noted for Liang Abu in Plutniak et al. 2016. However, the method has been improved and developed such as the "topological study of archaeological refitting" (TSAR) method which is described in detail by Plutniak 2021c and implemented in the *archeofrag* package for R (Plutniak 2021a). At Liang Abu, similarity and connection relationships were observed between the sherds from the surface ("Layer 0"), Layer 1, and Layer 2 (Table 2). Updated results using the Liang Abu pottery refitting dataset (Plutniak 2021b) are presented here, using additional analyses for similarity relationships and the TSAR method for connection relationships.

Similarity relations Given a square table x with the number of similarity relationships within and between layers (Table 2), the statistical distance between the layers (i, j) are

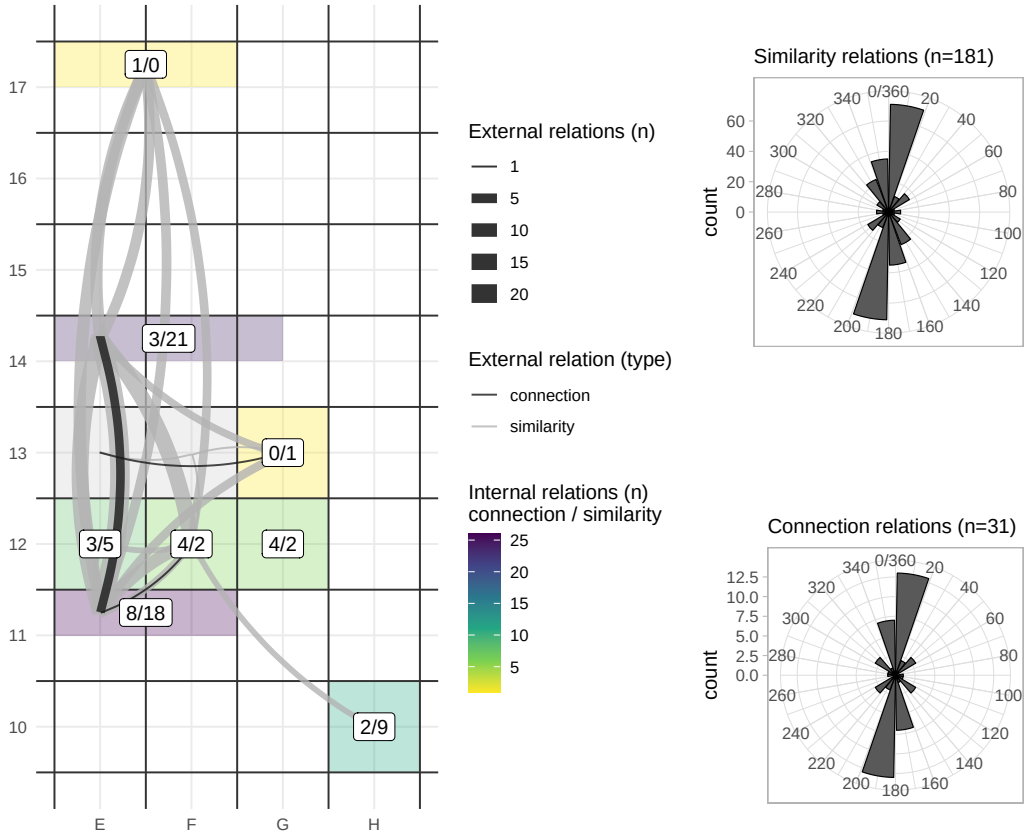

Figure 7: Relationships between pottery sherds. Left: count and type of internal and external relationships between squares (internal relationships are represented by the squares' labels and color; external relationships are represented by edges). Right: azimuths of the connection and similarity relationships.

Table 2: Liang Abu: distribution of the connection (bold font) and similarity relationships within and between the three layers.

	0	1	2
0	4 / **15**		
1	0 / **0**	18 / **234**	
2	0 / **1**	3 / **61**	31 / **173**

computed as the difference between the maximal number of relationships observed in the table and the number of relationships between layers i and j:

$$dist(x_i, x_j) = max(x) - x_{ij}$$

Assuming that adjacent and close layers in the sequence must have lower statistical distances than distant layers, it is expected that the result of a hierarchical clustering computed on this distance table would reflect the order of the layers. Applying this method to Liang Abu Layers 0, 1, and 2 confirmed this expectation, demonstrating an absence of significant admixture.[7]

However, similarity relationships have a logical limitation due to their transitive nature (if fragments A and B are similar, and fragments B and C are also similar, then fragments A and C are also similar). All fragments are connected to each other, resulting in multiplying the number of relations without validating them by an observation (two fragments have necessarily one relation, the fragments: three relations, four fragments: six relations, five fragments: 10 relations, 10 fragments: 45 relations, etc.). A solution to this problem is to consider connection relationships only, which are also more certain and which enables consideration of topological aspects. More detailed analyses were therefore conducted by applying the TSAR method.

Connection relations and topological approach The principle of the TSAR approach is to consider not only the number of connection relationships, but also their relative position on the original object (their "topology" or "structure"; e.g., fragment A was adjacent and connected to fragments B and C, fragment D was also connected to fragments B and C but not to fragment A). For this, connection relationships between sherds are modeled by graphs ("networks"). Nodes represent sherds and edges represent connection relationships, which are weighted as a function of the topological properties of the nodes they connect. Layers are studied by pair (as in a Harris matrix). Cohesion values are computed for each layer to measure their relevance (or "self-adherence") (see Plutniak 2021cfor mathematical details). Results for cohesion measurements range between [0;1], with values toward 0 for low cohesion and 1 for high cohesion and their sum never being superior to 1 for a pair of layers. In addition, an admixture value can be computed for each pair of layers, summarizing the relationship between their respective cohesion values. The admixture of two layers is computed as: 1 − (cohesion $_{layer1}$ + cohesion $_{layer2}$) and ranges between [0;1], with high values reflecting very mixed layers.

Count of data, cohesion, and admixture measurements are reported in Table 3. The cohesion values show that Layer 1 is much more cohesive than Layer 0 (surface), and that Layer 2 is only slightly more cohesive than Layer 1. This suggests that the pottery sherds found on the surface reflect a different period of activity; this could be the case if pottery was recently broken and spread at the surface, as suggested by our local informants. In contrast, Layers 1 and 2 appear as distinct and consistent spatial units, with a low level of admixture. In addition, as demonstrated in Plutniak 2021c, comparing the empirical refitting data from Liang Abu to simulated models of layer formation supports the distinction between Layers 1 and 2. Refitting analyses were limited to the layers containing pottery, demonstrating and quantifying the existence of low perturbations. However, evidence of bioturbation was observed all along the sequence.

2.3 Bioturbations

Geological processes and bioturbation (both faunal and vegetal) are often underrated by archaeologists in the absence of geoarchaeological analysis, but they must nevertheless

[7] See Supplemental 1, Section 5.2.

Table 3: The maximal number of unique objects the pottery sherds come from, number of sherds, number of connection and similarity relationships, cohesion, and admixture values for each pair of spatial units (0 and 1, 1 and 2).

	Layers 0 & 1	Layers 1 & 2
Objects	10	28
Fragments	29	72
Connection relations	22	52
Similarity relations	249	468
Cohesion layer 0	0.09	–
Cohesion layer 1	0.91	0.4
Cohesion layer 2	–	0.59
Admixture	0.00	0.01

be distinguished (Johnson 1990). Chemical and geomicrobiological alteration along with bioturbations, including the action of termites, wasps, burrowing land snails, earthworms, robber wasps, snake nests, and penetrating roots are some of the numerous factors interacting with depositional processes in humid tropical settings (Stephens et al. 2017, Morley 2017, Araujo and Piló 2017). During the excavations of Liang Abu, evidence of intense faunal and vegetal activity was observed all along the sequence. These observations were not systematically recorded; therefore, this section is limited to general remarks, which are nevertheless important to corroborate with the results presented.

Layer 1 was directly under the current level of surface circulation. It was approximately 12 cm thick with yellow-brown and very powdery sediment. This layer was compressed in its upper part and perturbed by bioturbation and trampling. In contrast, Layer 2 was well-defined in stratigraphy, consisting of dark brown and powdery sediment mixed with a large amount of fine gravel and pieces of charcoal. Layer 3 was directly below Layer 2 and also contained light brown, powdery sediment and charcoal, but no gravel. Both anthropogenic and natural processes could potentially explain these stratigraphic differences.

In tropical settings, the actions of insects, worms, and termites can produce sediment sorting and generate gravel lines such as the one observed in Layer 2 (Wood and Johnson 1982). Multiple holes and tunnels were observed in the sequence, downwards from the surface toward the insect cocoons located in Layer 1 (Supplemental 1, Figure 18). Some would have resulted from wasp activities; insect pupae were observed in the majority of the layers, with a higher frequency in the upper two-thirds of the stratigraphy (Supplemental 1, Figure 17). These insects were not sampled and, consequently, not identified, but informal observations suggest they are Hymenoptera.[8] Digging activities in these galleries can move light objects, such as charcoal fragments. In addition to bioturbation due to insect activity, bioturbation due to plant roots was clearly observed in the east part of the excavation area, in particular in the lower third of the stratigraphy.

In the absence of relevant evidence supporting an anthropogenic or a geological explanation, more field investigations are needed to clarify the formation process of the layers. More generally, we consider an absence of major perturbations in the Liang Abu sequence, while stressing that bioturbations cannot be excluded when discussing the anomalies observed, including radiocarbon dating outliers in particular.

[8]We thank Jean-Bernard Huchet for his attempt to identify these insects.

2.4 Radiocarbon outliers

The four major reasons for biased radiocarbon dates are summarized in Ramsey 2009: (1) error in the measurement procedure; (2) difference between the radiocarbon isotope ratio of the sample and the ratio of the calibration curve at the associated age; (3) systematic offset between the measurements made for the calibration curve and those for the sample due to reservoir effects; and (4) erroneous association between measurements and the events of interest, generally due to post-depositional perturbation. In particular, issues 3 and 4 were encountered at Liang Abu.

2.4.1 Freshwater reservoir effect

Dating results from freshwater shells are expected to be excessively older, due to the freshwater reservoir effect (FRE, or "hard water effect") (Philippsen 2013). Regarding Southeast Asian archaeology, the uncertainty in determining the magnitude of FRE was already emphasized and observed offsets up to 1500 years were noted (Spriggs 1989, p. 598). The range of FRE can be estimated by comparing several paired dates from shell and charcoal with clear archaeological association; thus, correcting the offset by applying a ΔR, as is done for the correction of marine samples (Cook et al. 2015). A systematic study showed FRE can be highly variable even in the same region (Schulting et al. 2015). However, concerning Southeast Asia and 30 years after Spriggs' review, no further systematic inquiries or correction references have been conducted (contrary to marine reservoir corrections).

In East Borneo, FRE measurements are limited by an insufficient number of ages and lack of contextual information about the samples. This is the case at Kimanis, where an offset of about 3000 years was suggested by comparing uncalibrated ages from charcoal and freshwater shell from stratigraphic Unit 3 (ANU-11150 and ANU-11258) (Arifin 2017, p. 100). Note that, once calibrated, the offset between the upper bound of the HDP regions of the two dates is equal to 4725 years and to 5523 years for the lower bound (Table 7). Similarly, an offset of about 8500 years was observed at Lubang Payau (a shelter close to Kimanis), Square C3, Spit 6, comparing a date from charcoal (4610 ± 110 uncal. BP, ANU-11152) and a date from a freshwater shell (13,100 ± 140 uncal. BP, ANU-11260) (Arifin 2004, p. 104). This is also true at Liang Abu, where Layers 12 and 13 are the only ones for which two dated samples are available for comparison. However, it must be stressed that these samples were found in different squares and not in direct relation within a site showing evidence of post-depositional disturbances. In Layer 12 the samples include a freshwater shell (UBA-27060, 14,902 ± 72 uncal. BP) and a bone (UBA-20842, 12,660 ± 58 uncal. BP, Table 1). Once calibrated, the two dates present an offset of about 3000 years: the offset between the HDP regions of the two dates is equal to 3020 years for the upper bound and to 3101 years for the lower bound. The bone comes from an undetermined large mammal, such as a Suidae or a Cervidae. This is supported by the measured value for the stable carbon 13 isotope (-20.7‰), suggesting a terrestrial diet (Katzenberg 2008). Consequently, it can be assumed that the bone was not affected by FRE. Nevertheless, caution is needed in the absence of precise taxonomic identification and the direct association of shell and bone samples. However, the ordering of the dates is coherent, since a piece of charcoal from Layer 10 (directly above Layer 12) gave a result at 11,590 ± 60 uncal. BP (GifA-11356). Accordingly, the conditions to rigorously obtain a valid FRE value from this pair of samples are not entirely satisfied.

From Layer 13, we obtained two ages from freshwater shells (UBA-27059, 16,166 ± 107 and UBA-26299, 19,761 ± 87 uncal. BP), and the third one from a piece of charcoal (UBA-20838, 34,206 ± 730 uncal. BP). Again, FRE cannot be approximated since the result obtained from the charcoal is clearly too old, being two times older than the result from the

shells.

In summary, FRE is likely to have affected the shell samples from Liang Abu. However, considering the available data, there is no way to determine its magnitude and no evidence to support any arbitrary FRE correction value from the offsets observed in Kimanis (about 5500 years) and Liang Abu (about 3100 years).

2.4.2 Post-depositional migrations of dated samples

Two cases of movement must be discussed for Layers 2 and 13. Sample GifA-11358 was collected in 2009 in the middle of the pottery layer (Layer 2). However, its dating is too old (8110 ± 50 uncal. BP) and older than the sample from Layer 3 situated below (5966 ± 33 uncal. BP). This sample likely moved from a deeper layer and its dating result is interpreted as an outlier, giving additional evidence of perturbations at the site.

Concerning Layer 13, results from the samples on shells are coherent (16,166 ± 107 and 19,761 ± 87 uncal. BP). This suggests that the piece of charcoal, which gave an older age (UBA-20838, 34,206 ± 730 uncal. BP), moved from a different place, whether from a layer below (potentially Layer 16, or even deeper) or was naturally deposited from outside the shelter by washing or movement in a colluvium. For this reason, this dating cannot be used as a *terminus post quem* (TPQ) for human occupation at Liang Abu although, as shown previously, recent dates of rock art in the area exceed 30,000 years BP. Consequently, the dating of the older occupation remains uncertain and only a *terminus ante quem* (TAQ) for human occupation can be determined from a mollusk shell age (19,761 ± 87 uncal. BP) with possible FRE effect.

Currently, Liang Abu is the archaeological sequence from East Borneo with the largest number of ages, and this creates an opportunity for this site to be compared with available regional data. Kimanis is the closest and most well-studied Pleistocene–Holocene site that has been investigated by a different research team. The chronometric results from Liang Abu and Kimanis have some similarities. Both yielded relatively robust dates around 15,000 BP, as well as much older dates, but with unclear stratigraphic locations (34,206 ± 730 uncal. BP (36,950–36,275 cal. BP) on charcoal from Liang Abu and 23,630 ± 480 uncal. BP (28,877–27,036 cal. BP) on freshwater shells from Kimanis). These latter ages suggest that human occupation at these sites could be older. But without new excavations to confirm or refute this hypothesis, the chronometric anomalies observed at Liang Abu must be addressed by analyzing the distribution of other archaeological remains.

3 Cultural and environmental changes in Liang Abu and Kimanis-C4 sequences

This section aims to identify variation in the archaeological artifacts throughout the sequence to determine the changes in human activities at Liang Abu and Kimanis. First, the vertical distribution of archaeological remains and micro-remains at Liang Abu is studied to detect changes in the intensity of the occupation. Second, data from Liang Abu and Kimanis are compared, including: (1) a preliminary analysis of archaeozoological data; and (2) a discussion of stone age industries. Note that these results are preliminary, based on available published and unpublished data.

3.1 Vertical distribution of remains

At Liang Abu, only Sub-squares 12Ea and 12Eb were excavated all the way to the bottom (Supplemental 1, Figure 2). To enable a more extensive analysis of the vertical distribution

of remains, we enlarged the dataset by including the remains from the 10 upper layers from Sub-squares 12Fa and 12Fb. Due to the different volumes excavated, the layers were compared in terms of the density of remains.

Density was computed using two methods: first, as the weight of remains by cubic meter (Figure 8) and, second, when the information was available, as the number of remains by cubic meter (only for shells and stone artifacts) (except for stone artefacts, Figure 9). Results converge and show that Layers 2 and 12 have the highest density of remains. The distribution of faunal (in terms of kg/m³) and shell (remains/m³ and kg/m³) densities is clearly bimodal, with peaks in Layers 2 and 12 and with very low densities in the other layers. Similarly, stone artifacts are denser in Layers 2 (remains/m³), with equally low densities in the other layers. The difference between the two density measures for stone artifacts means that Layers 10 and 12 contain a similar number of remains, but with heavier pieces in Layer 10. Accordingly, Layer 10 does not reflect more intense stone tool activities. In summary, the layers can be grouped into four sets:

1. Layers 16–13: low intensity of human occupation and significant shell consumption, no charcoal.

2. Layer 12: first episode of intense occupation, characterized by high densities of fauna and shells in particular.

3. Layers 10–3: low intensity of occupation with charcoal production and shell consumption only in Layer 10.

4. Layer 2: second episode of intense occupation, characterized by high densities of fauna (including shells), stone tool activity, the presence of pottery, and high density of charcoal.

For Kimanis, the intensity of the occupations can be approximated from the number of lithic and faunal remains reported in Arifin 2004 and Arifin 2017. However, due to the unavailability of data on the excavated volumes, it is not possible to compute densities and, consequently, rigorously compare the different units between them and with the Liang Abu sequence.

3.2 Micro-remains

At Liang Abu, the boundary between Layers 2 and 3 is of particular interest: it corresponds to the TPQ for pottery layers and is included in a large chronological hiatus (Table 1). Micro-fraction remains from Sub-square 12Eb were used to compare Layers 2 and 3. Each bag of sediment was sampled (25% for Layer 2 and 50% for Layer 3) and the micro-remains were sorted and counted for fragments of mollusk shell, bone, rock, and concretions. Rock fragment refers to rock-wall fragments and materials from outside the shelter, such as sandstone, granite, and flint. Concretions refer to concretions of undetermined composition: either natural aggregates of grains or small fragments of ceramics. A density index (number of remains by liter) was computed to normalize the count before comparison.

Without considering the mesh size (2 mm and 5 mm), there is a significant difference between the content density of the two layers, as validated by the chi-squared test[9] (Supplemental 1, Figures 20 and 21). In particular, the standardised residuals show that the densities of charcoal and shell are significantly higher in Layer 2 than in Layer 3. The residuals suggest a difference in concretions, but the density of concretions is similar in

[9] χ^2=44.824, p-value=1e-05.

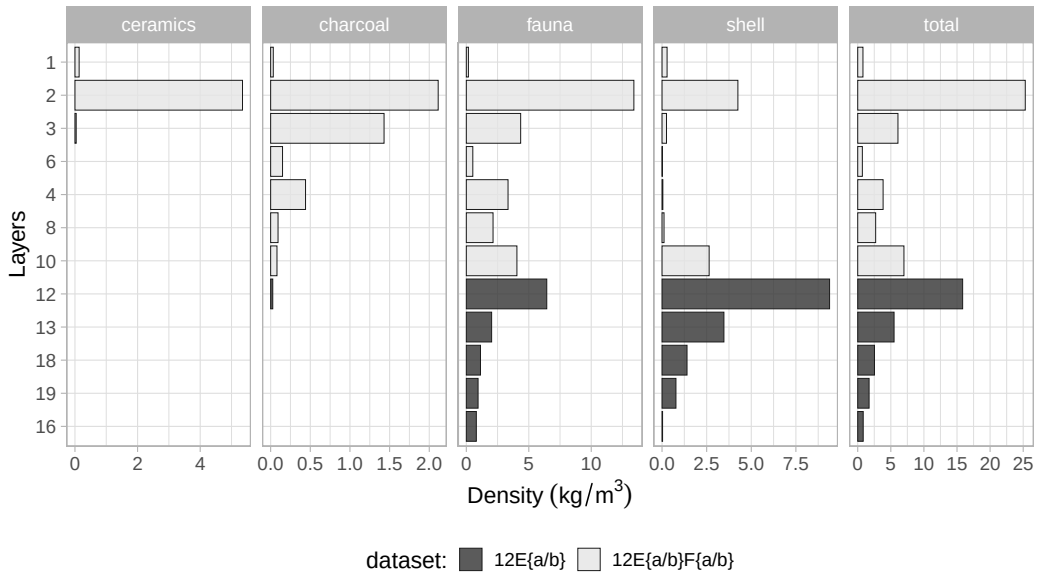

Figure 8: Density by class of remains by layer (kg/m³), squares (12E{ab}) and (12E{ab} and 12F{ab}). Lithic remains are not included, due to missing data on weight. Note that the x-axes have different scales.

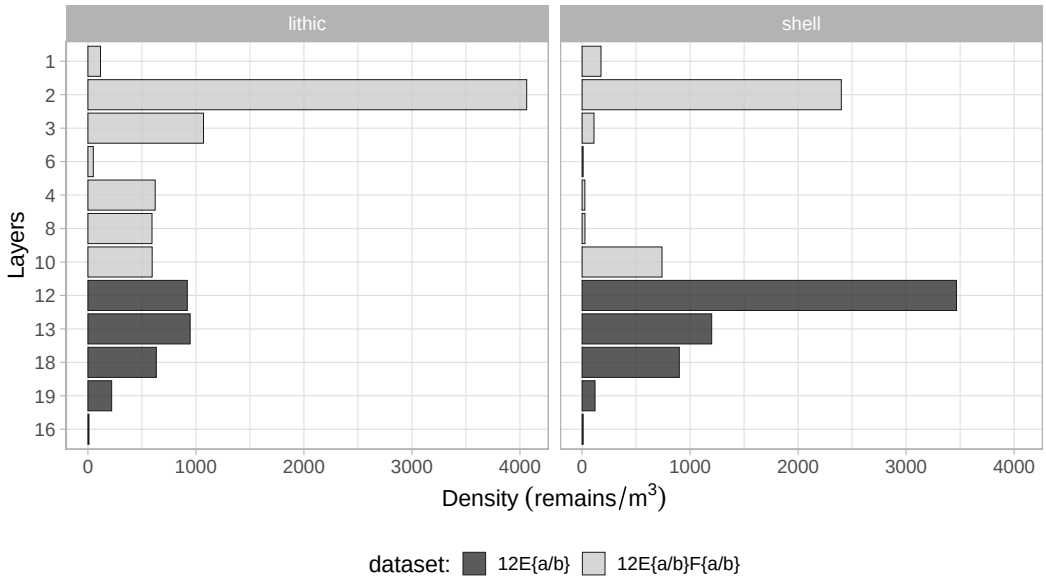

Figure 9: Liang Abu: density (number of objects/m³) of stone artifacts and shells by layers in square (12E{ab}) and (12E{ab} and 12F{ab}) and Layers 1–16.

the two layers. Comparisons as a function of mesh size give similar results,[10] except that residuals do not suggest a difference in shell density (Supplemental 1, Figure 21). Note that concretions were small in size, as the majority were retrieved by the 2 mm mesh, and that gravels of Layer 2 were also detected (higher density of rock fragments >5 mm).

In conclusion, the analysis of micro-fractions from Sub-square 12Eb demonstrates that there is a significant difference in the density of charcoal and shell between Layers 2 and 3, but there is no difference in the density of rock fragments, bones, and concretions. This supports the hypothesis that Layer 2 did not result from bioturbation processes because these processes would not have differentially sorted the types of remains across the two layers.

3.3 Faunal remains

Preliminary results for vertebrate remains are based on a sample from Sub-squares 12Eb, 11Ec, and 11Ed, from which 2.3 kg of remains were recovered (data: Ferrié and Plutniak 2022). In total, 649 remains were identified at least to the level of the taxonomic class (about 17% of the total weight). The material is highly fragmented and numerous fragments are burned, especially in the indeterminate fraction of the assemblage. Cut marks and gnawing marks are very rare, contrary to shell breaking. However, an in-depth study of the fauna needs to be conducted to determine the part of the remains related to food consumption, and that related to non-anthropogenic introduction (bats and shells in particular). Taxonomic composition is presented by class (Figure 10), by order (Supplemental 1, Figure 22), and by family (Supplemental 1, Figure 23). Proportion is used because different volumes were excavated in the three sub-squares.

3.3.1 Vertebrates: An increasing presence of reptiles in more recent times

Regarding taxonomic classes, mammals and reptiles are the most numerous classes in each level. Mammals are the only class identified in the deepest layer (Layer 16) and their proportions decrease from the bottom to the top of the sequence, whereas the proportion of reptiles increases from Layer 13 to Layer 2. Fishes (Actinopterygii) are only present in the upper layers (from Layer 10 to 2). Among the mammals, primates and even-toed ungulates (Artiodactyla) are dominant in each layer. Layer 16, the deepest layer, contained few bone remains, but has a different composition with more primates and rodents (Rodentia). A human tooth was found in Layer 3 and three orangutan (Pongo pygmaeus) teeth were found in Layer 13 and 16.

At Kimanis, the trend in the ratio between mammals and reptiles is similar (Arifin 2017, p. 102): reptile remains are concentrated in the upper part of the sequence (Units 1, 2, 3; only 18 fragments were found in Units 4 and 5), while mammal remains are present from Units 1 to 5. Note an exception: turtles are also present in Units 4 and 5. However, at Kimanis, Unit 3 contains 75% of all the mammal and reptile remains, while at Liang Abu mammals are less concentrated. There is a similarity between the two sites: bats are only present in the upper layers, although in different proportions. Chiroptera is the most represented order at Kimanis but is rarer at Liang Abu. Kimanis rock shelter is the opening to a larger cave, implying natural Chiroptera deposition, contrary to Liang Abu rock shelter which is only associated with a few upper cavities, making natural deposition less probable.

[10] For 5 mm mesh size: χ^2=28.628, p-value=2e-05; for 2 mm mesh size: χ^2=19.512, p-value=0.00036.

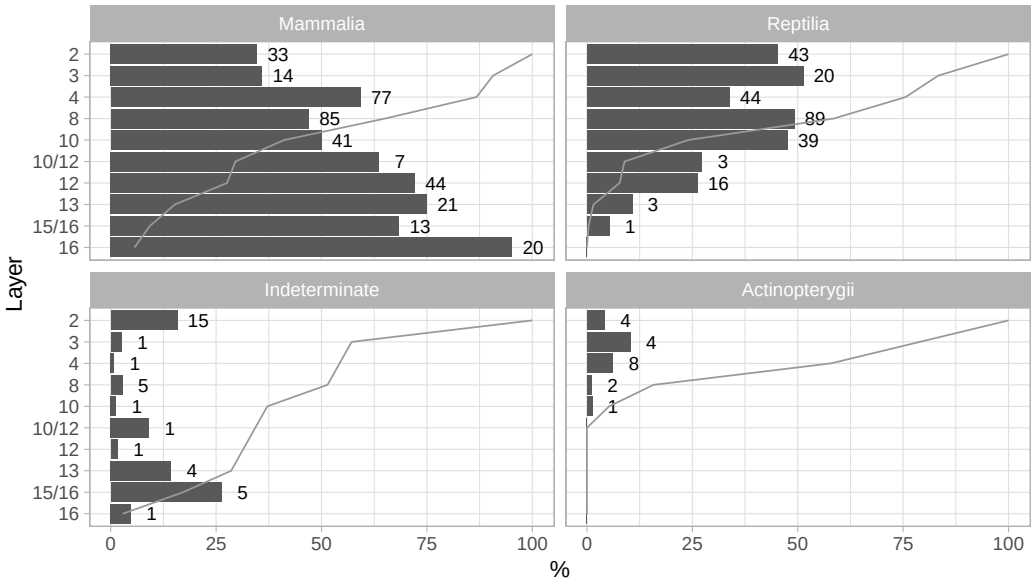

Figure 10: Liang Abu, fauna: proportion by class and layer (Sub-squares 11E{c, d}, 12E{a, b}, and 12F{a, b}). Object counts are given on the top of each bar. Data recorded for the boundaries between layers during the excavation are reported, e.g., Layer "12/10" refers to a sample located in Layer 10 or 12. Rather than randomly attributing these samples to one of the layers, these categories are reported and the reading is smoothed by using cumulative curves of remain counts.

3.3.2 Mollusks: Clear changes and evidence of coastal contact

At Liang Abu, the following information was recorded for each mollusk shell: taxonomic family, presence/absence of burn traces, and broken/intact apex, assuming that a broken apex demonstrates anthropogenic consumption (data: Plutniak and Ricaut 2022). Due to differences in the volumes excavated in the different parts of the site, we only present results for Sub-squares 11E{c, d}, 12E{a, b}, and 12F{a, b} for which equal volumes were collected (see Harris diagrams, Supplemental 1, Figure 2). Four families of mollusks were distinguished,[11], Lymnaeidae and Thiaridae (freshwater snails), flat shells identified as Helicarionidae or Cyclophoridae (land snails), and Cypraeidae, marine shells commonly referred to as cowries (Figure 11). These gastropods were concentrated in Layers 2, 10, 12, and 13. Most Thiaridae had their apex broken, and only less than half of them had traces of burning. No difference in burning is observed throughout the sequence. Cypraeidae and Helicarionidae/Cyclophoridae are only present from Layers 8 to 2. Most of the Cypraeidae had their apex broken and some were burned (no quantification available).

At Kimanis, the highest concentrations of shells were in Units 3 and 4 (Arifin 2017, p. 101). Cowries were mostly found in Units 1 and 2. However, 95% of the mollusks recovered from the sequence were freshwater snails *Brotia* spp., with their apex removed. A tenuous presence of marine shells was recorded in Units 3 (two individuals) and 2 (one individual), but with uncertain identification (Arifin 2017, p. 111).

[11]These identifications must be considered cautiously, since they were not made by a qualified malacologist, but by using the standard taxonomic categories used in the regional archaeological literature.

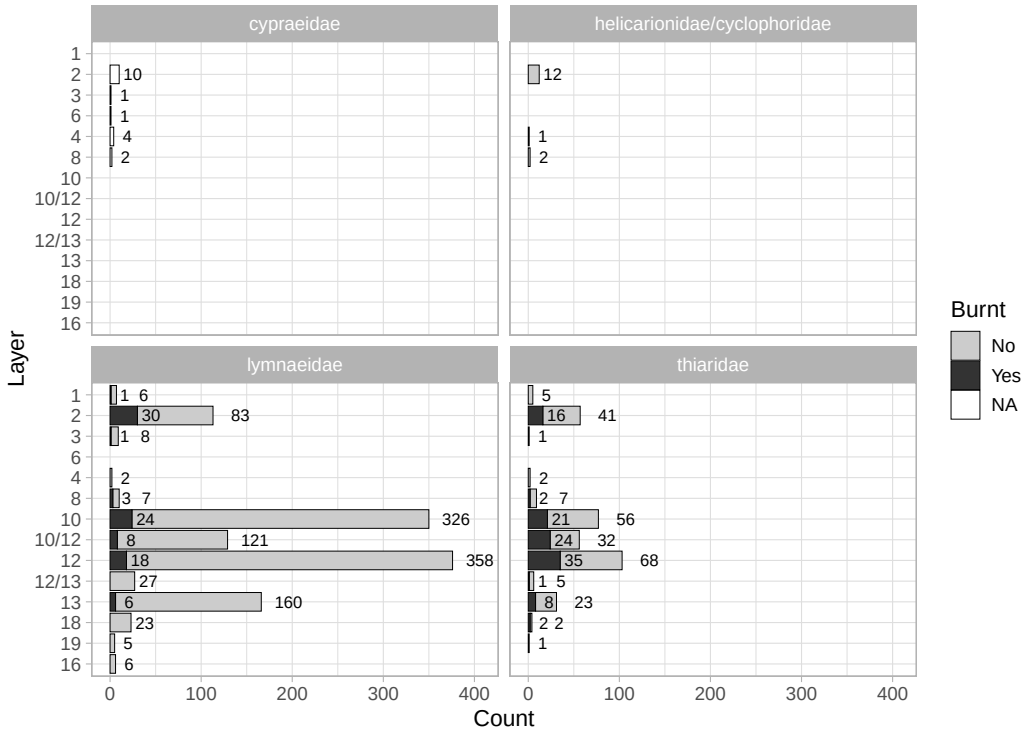

Figure 11: Liang Abu, fauna: shells from Sub-squares 11E{c, d} and 12E{a, b}. Uncertain layer attribution was noted with a slash. "NA" stands for "not available data".

3.4 Artifacts

3.4.1 Bone

A bone working industry was also present at Liang Abu: the four test pits from 2009 identified 22 artifacts distributed throughout the layers. These were small (1–3 cm) and made from the long bones of smaller mammals with traces of longitudinal scraping (study by J.-G. Ferrié in Ricaut et al. 2011, p. 32). However, this material has not yet been analyzed to complement the conclusions from other bone industry sites, notably in Southeast Asia (Rabett 2005), Borneo (Bujeng and Chia 2012), and the upper Birang sites. The Birang sites presented a small sample of worked bone: seven remains at Kimanis in the aceramic layers, and five remains at Lubang Payau from the ceramic and aceramic layers (Arifin 2017, p. 109).

3.4.2 Stone

Previous studies of stone artifacts from Liang Abu (Forestier et al. 2017, pp. 27-34, Grenet et al. 2016, pp. 136-142) and the upper Birang sites (Arifin 2004, pp. 169-234, Arifin 2017, pp. 112-116) showed that there was no temporal variation in the composition of these assemblages. Here, we present a reprocessing of data to compare the Liang Abu (data: Grenet and Sarel 2022) and Kimanis assemblages (Supplemental 1, Sections 11, 12, and 13). Examination of raw material, artifact classes, and flake size confirm a few major internal changes in each sequence, and a few major differences between the two assemblages.

Raw material at Liang Abu and Kimanis were determined by direct macroscopic observation (by Josette Sarel and Karina Arifin, respectively), using different geological categories. To enable comparison, we defined matched categories and used only the objects

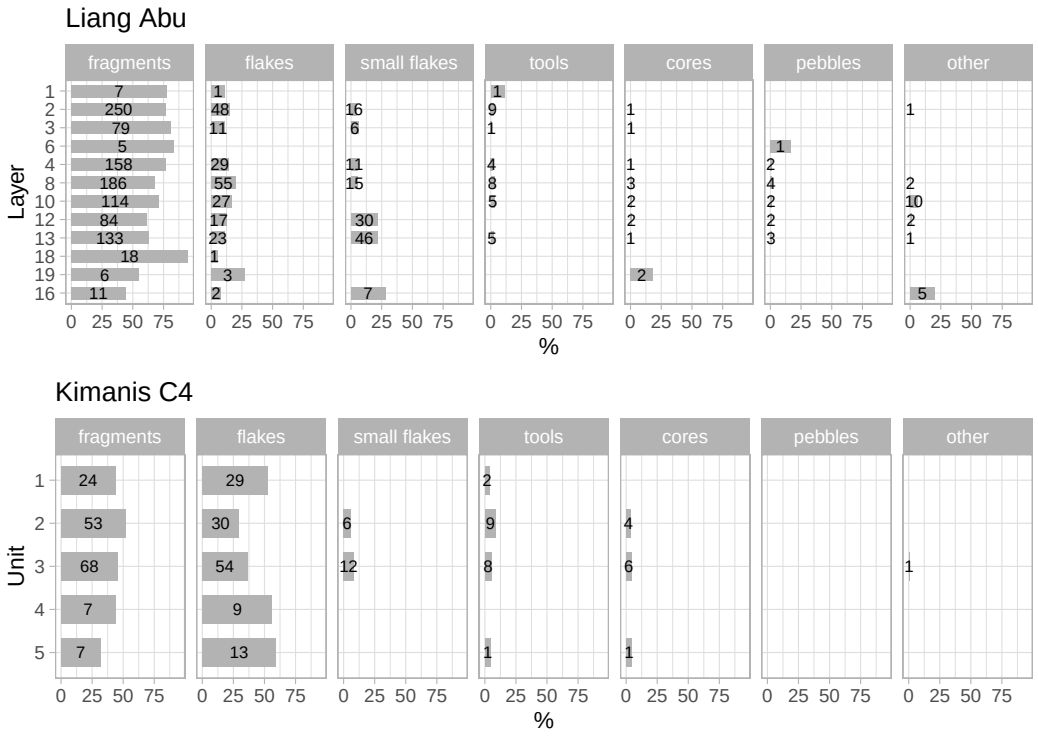

Figure 12: Stone artifacts: proportions (bars) and count (labels) of stone artifact classes by level at Liang Abu (11E and 12E) and Kimanis/C4 (from Arifin 2004, p. 183).

from Kimanis with lengths >2 mm (Table 4). Raw material profiles of the two sites are very different. Except for volcanic rocks, all the other geological categories show statistically significant differences: flint is present at Liang Abu and absent at Kimanis, quartz and quartzite are abundant at Kimanis and very rare at Liang Abu, calcareous sandstone and sedimentary rocks are absent at Liang Abu and well represented at Kimanis. In addition, internal variation was observed at Kimanis, with the presence of milky quartz limited to the upper units (2 and 1) and remnant cortex was observed on some pieces, suggesting the use of river pebbles (Arifin 2017, p. 112). Origins of the raw materials at Liang Abu included primary location material (flint from the near karstic area) and secondary location material (metamorphic rocks moved by rivers, neocortex), but an in-depth analysis is required to obtain more accurate results.

Different lithic taxonomies were used in the previous studies of the two assemblages. Consequently, we defined a new classification to match the assemblages together (Table 5). At Kimanis, there were significantly more flakes, more tools, and less fragments, than in Liang Abu (Figure 12). However, tools were concentrated in the upper levels at both sites. The only notable technological features highlighted by previous authors include bipolar flaking at Kimanis, only observed in Units 2 and 1 (Arifin 2017, p. 112), and converging edge tools at Liang Abu, also in the upper layers (10–2) (Grenet et al. 2016, p. 140).

Comparing the size (cm) of the flakes at Liang Abu (Squares 11E and 12E) and Kimanis (C4) revealed no statistically significant difference.[12] Similarly, the proportion of small flakes does not differ at the two sites, although they were found all along the sequence at Liang Abu and, on the contrary, concentrated in Units 2 and 3 at Kimanis (Figure 12).

[12]Wilcoxon test, W = 9050, p-value = 0.4518, see Supplemental 1, Section 13.

Table 4: Comparison of the count and proportion of lithic artifact raw material at Liang Abu (left) and Kimanis (right). To make the comparison possible, the concepts used for each site were matched (central column) and objects with length <2 mm were removed from the original Kimanis counts ("n" column) before computing the proportion ("%" columns). Bold values in the "%" columns indicate significant statistical differences determined from the residuals of a χ^2 test performed on the count of objects by matched concepts, except the "other" class (χ^2=529.73, p-value<2.2^{-16}, see Supplemental 1, Section 12). Liang Abu data: Ricaut et al. 2012, Table 3, p. 50, including all the material from Squares 11E, 12E, 12F, 12G, 13E, 13F, and 13G, except chips and flakes <2 mm. Kimanis data: Arifin 2004, Table 9.76, p. 223, completed by Tables 9.9, p. 177, 9.21.2, p. 188–189, 9.34, p. 199.

	Liang Abu			Matched concepts	Kimanis			
	n	Raw material	%	Raw material	%	Raw material	n	n'
	87	Chert	**46**	Chert	**37**	Chert	278	325
	318	gray-green chert				–	–	–
	184	Flint	**21**	Flint	**0**	–	–	–
	155	Andesite				–	–	–
	–	–	18	Volcanic rocks	24	Microgranodiorite	30	35
	–	–				Volcanic rocks	150	183
	10	Quartzose flint				–	–	–
	–	–				Crystalline quartz	11	56
	–	–	**1**	Quartz(ite)	**10**	Milky quartz	16	55
	–	–				Quartzite	51	63
	–	–	**0**	Calcareous sandstone	**19**	Calcareous sandstone	146	146
	–	–				Unident. sedimentary rock	38	43
	–	–	**0**	Sedimentary rocks	**8**	Sandstone	8	8
	–	–				Calcareous siltstone	11	20
	114	Limestone	**13**	Limestone	**2**	Limestone	16	16
	–	–				Crystalline limestone	2	2
	5	Calcite	1	Other	0	–	–	–
	1	Fossil wood				–	–	–
Σ	874		100		100		757	952

Table 5: Count and proportion by lithic artefact class in Liang Abu (left) and Kimanis/C4 (right). The concepts used for each site were matched (central column) and proportions were computed by matched classes ("%" columns). Bold values in the "%" columns indicate significant statistical differences determined from the residuals of a χ^2 test performed on the count of objects by matched classes (χ^2=147.69, p-value<2.2^{-16}, see Supplemental 1, Section 11). Liang Abu data: Ricaut et al. 2012, Table 4, p. 51, material from Squares 11E and 12E. Kimanis/C4 data: Arifin 2004, Table 9.17, p. 183.

Liang Abu			Matched concept	Kimanis/C4		
Count	Class	%	Class	%	Class	Count
14	pebble	1	pebble	0	–	–
13	core				–	–
0	–	1	core	3	bipolar core	5
0	–				unidirectional core	2
0	–				multidirectional core	4
217	flake	**15**	flake	**40**	flake	132
0	–				bipolar flake	5
130	flake <20 m	9	small flake	5	flake <20 mm	14
0	–				bipolar flake <20 mm	4
6	blade & bladelet				retouched flake	2
27	tool				utilised and retouched flake	10
0	–	2	tool	**6**	utilised flake	4
0	–				hammer stone & grindstone	1
0	–				grindstone fragment	1
0	–				hammerstone fragment	2
835	splinter				core fragment	3
216	chunk				flake fragment	45
0	–	71	fragment	**46**	flake shatter	33
0	–				heat shatter	16
0	–				shatter	63
21	limestone tablet				–	–
1	other	1	other	0	–	–
0	–				manuport	1
Σ 1480	–	100		100		347

Table 6: Summary of the upper and lower parts of the sequences at Liang Abu and Kimanis/C4. The "+" symbol indicates the noteworthy presence of a feature; "(+)" indicates the insignificant presence of a feature, and "++" indicates its highest occurrence(s). "Particular lithic technology" refers to the presence of bipolar flaking (at Kimanis) and converging edge tools (at Liang Abu).

Site	Layer	Pottery	Reptiles	Remains density	Shells	Small flakes	Particular lithic technology	Coastal contact	Time range (cal. BP)
L. Abu	2	++	+	++	++	+	+	+	
	3	(+)	++			+	+	+	
	4		+			+	+	+	
	8		++			+	+	+	
	10		++		+		+		13,585–13,320
	12		+	++	++	++			15,284–14,914
	13		(+)		+	++			
	16								
Kms/C4	1	+	+	+	(+)		+	+	
	2		++	+	(+)	+	+	+	
	3		++	+	++	+			13,580–10,790
	4		(+)		++				
	5		(+)		+				

3.4.3 Pottery: Reconsidering red-slipped pottery

At Liang Abu, ceramic material was found on the surface in Layers 1 (n =300 sherds) and 2 (n =759) and, probably due to site perturbations, in Layer 3 (n = 17) (data: Plutniak 2022b). The distribution, technology, pottery fabrics, morphology, and motifs of this material have been extensively presented and discussed in Plutniak et al. 2016. Comparison with Kimanis/C4 is limited because only 58 sherds were found at this site in Unit 1, which contains a charcoal fragment dated to 1270 ± 240 uncal. BP (Table 7). Only six sherds were decorated with "carved paddle impressed with ribbed motifs" similar to Liang Abu motifs. Shape reconstruction suggested globular pots at both sites. However, contrary to Liang Abu, no red-slipped exterior was observed at Kimanis. Based on this absence, Arifin stressed the difference between East Borneo and North Borneo (Sabah) (Arifin 2017, p. 116). However, this statement must now be reconsidered, since a previous analysis demonstrated that red-slipped pottery was also introduced in East Borneo (Liang Abu, Liang Jon, see: Plutniak et al. 2014), although it is not attested in all the known sites.

4 Chronological modeling and discussion

4.1 Summary of inter-site comparison

Results from the comparative analysis of Liang Abu and Kimanis enable a new archaeological synthesis for this region of East Borneo, focusing on the relationships between coastal and mainland areas. The comparison between the main distinctive features at the two sites is summarized in Table 6.

Both sequences can be divided into a lower and an upper part, although different features distinguish each sequence. At Liang Abu, Layer 10 is transitional between the lower part (Layers 16, 13, 12) and the upper part (Layers 8, 4, 3, 2) of the sequence. Layer 10 separates Layer 12, characterized by evidence of intense occupation (remains density, shells, lithic), and the subsequent period characterized by a higher frequency of reptile remains,

the absence of shell, converging edge tools, and evidence of coastal contact. At Kimanis, Unit 3 is transitional between the lower part of the sequence (Units 4 and 5), is characterized by ephemeral occupation, the virtual absence of reptiles (number of individuals = 1), and low density of remains. The upper part (Units 1 and 2) is characterized by a higher density of remains, the presence of bipolar flaking, an increase in reptile remains, and evidence of coastal contacts.

At both sites, evidence of coastal contacts was found above the transitional layers. At Liang Abu, Layers 8, 3, and 2 contain cowries. Layer 2 also features red-slipped pottery, considered in the literature to be evidence of migration from continental Asia (Bellwood 2017, pp. 276-281, Plutniak et al. 2014). At Kimanis cowries were found in Units 1 and 2 (in C4 and C8) (Arifin 2004, p. 246). All the tools made from marine shells come from Units 1 and 2 (Arifin 2004, p. 247), and the deeper marine shell excavated in C4 was in Unit 2, Spit 20 (Arifin 2004, p. 136, Arifin 2017, p. 111). In addition, a single cowrie was recovered in Unit 3, Spit 24, Square C4. Such a small object is likely to have been transported after deposition and is thus weak evidence of coastal contact in Unit 3.

An additional distinction can be made in the upper part of the two sites, related to the presence of pottery material: in Layers 2 and 1 at Liang Abu, and in Unit 1 at Kimanis.

Given the scarcity of available dating and the problem raised by dating from shells, Bayesian modeling was used to calibrate the ages and to obtain chronometric estimations for three major anthropic changes: (1) the transitional periods, associated with significant changes in the two sequences and predating coastal contact; (2) the earliest traces of coastal contact at both sites; and (3) the introduction of pottery at both sites.

4.2 Bayesian models

4.2.1 The *ChronoModel* approach

Bayesian modeling is becoming an increasingly used tool in the context of Island South East Asian and Pacific archaeology. For example, Rieth and Athens 2019 and Cochrane et al. 2021 recently used the *Oxcal* software on the chronology of the Late Holocene expansion in Oceania and the Neolithic dispersal in Island Southeast Asia, respectively. Our analysis of East Bornean sites is a case-study to use a different software, called *ChronoModel* 2.0.18 (Lanos and Dufresne 2019), presenting distinctive features when compared with *OxCal* and *Bcal* (Lanos and Philippe 2017, Lanos and Philippe 2018):

1. *ChronoModel* is an open source software,
2. the treatment of outliers does not need *a priori* weighting;
3. the "event" concept is an intermediate solution between the combination of dates and the grouping of dates in a bounded phase as in *Oxcal*; and
4. the flexibility to define "phases," which can include one or multiple events, an event being possibly included in different phases, allowing the phases to overlap.

Consequently, model construction in *ChronoModel* is twofold, distinguishing between an "event" model and a "phase" model, both being processed together using hierarchical Bayesian analysis. In addition to calibrating the individual ages, constraints can be integrated into a Bayesian model, used to generate more accurate dating of the events and to approximate the time interval between the dates of these events. Generally speaking, a single sample does not date a period, but a single event. Due to depositional and post-depositional processes, it is unlikely that the dated events correspond exactly to the beginning and end of the layers. *ChronoModel* reports results as highest posterior density

(HDP) regions with a 95% confidence for different time concepts, including: the Phase time range (period of time containing both the beginning and end of a phase) and the Gap range (the period of time excluding the end of the first phase and the beginning of the second phase). The latter can be used to bracket the period of time in which the historical process we associate with the second phase might have started. Note that, hereafter, the term "phase" specifically refers to the meaning of this concept in *ChronoModel*.

4.2.2 Liang Abu–Kimanis models

A "conservative" and a "restricted" model were built and their results were compared (Plutniak 2022a). The "conservative" model strictly observes the Bayesian approach and the distinction between prior and posterior information. In this model, all the ages presented in Tables 1 (Liang Abu) and 7 (Kimanis) were included, including possible outliers and ages from shell (FRE corrections were applied to the latter). In addition to this main model, a "restricted" model was created for comparison. In the "restricted" model, possible outliers were excluded from the event and phase models, thus breaking the principles of Bayesian reasoning, and no FRE correction was applied. Exclusion of dates requires additional assumptions on the first hand and adds confusion between prior and posterior information (since considering a sample as an outlier implies use of the result of the dating as prior information). Considering the available data, layers are associated with one, two, or at maximum three dated samples. All calibrations were made using the Northern Hemisphere curve (IntCal20 curve, Reimer et al. 2020) given that Borneo is within the intertropical convergence zone.

The "conservative" model includes both Liang Abu and Kimanis data in its "event" model and 10 related phases in its "phase" model. Events and phases are related by temporal order constraints (Figure 13). The exact magnitude of the FRE effect, potentially making the dates of the shell samples older, is unknown. However, as discussed above, an offset of 3100 years was determined at Liang Abu and also suggested in the literature. Assuming that the magnitude of the FRE can range from 0 to 3100 years, this range of uncertainty is implemented in the Bayesian Model for ages on shells using the "wiggle matching" procedure offered by *ChronoModel*, which is suitable for introducing uncertainty ranges.

Some choices in the model construction must be emphasized. Concerning Layer 2 at Liang Abu, an ordering constraint was applied between the possible outlier age (GifA-11358) and the two other ages from samples found above and below. Regarding Layer 12, since the shell sample (UBA-27060) was found at the top of the layer, we introduced an ordering constraint on the bone sample (UBA-20842) found below (assuming that no FRE affected the bone sample). For Layer 13, ordering constraints were introduced between the possible outlier date derived from charcoal (UBA-20838) and the two ages from two shell samples found a few centimeters deeper (UBA-27059 and UBA-26299). The wiggle matching procedure handles the possible FRE effect of these two ages, providing a TAQ for Liang Abu occupation.

Six phases were thus defined to date the three anthropic changes previously mentioned:

1. a phase for the TAQ of Liang Abu occupation;
2. an "intense occupation" phase, corresponding to Layer 12;
3. a "transition" phase, corresponding to Layer 10 (including two samples from charcoal and bone, related by an ordering constraint);
4. a phase corresponding to the first evidence of "coastal contact" observed in Layer 8;

Table 7: AMS Radiocarbon dating from Kimanis/C4 (source: Arifin 2017, p. 101). New unmodeled calibrations (at 2σ) in years BP were made using the Intcal 2020 curve (Reimer et al. 2020). Note the offset between ANU-11150 and ANU-11258.

Lab.	Id	Square	Layer	Unit	Spit	Depth	Material	Age BP	±	From	To
ANU	11311	C4	C	1	8	35-40	charcoal	1270	240	1695	724
ANU	11148	C4	D	2	11	50-55	charcoal	4650	90	5586	5051
ANU	11149	C4	D	2	20	98	charcoal	8840	250	10,582	9321
ANU	11150	C4	D	3, top	24	105-110	charcoal	10,030	260	12,608	10,790
ANU	11258	C4	D	3, top	24	105-110	shell	13,860	180	17,333	16,313
ANU	11151	C4	F	3, bottom	34	155-160	charcoal	11,270	220	13,580	12,758
ANU	11259	C4	J	5	59	280-285	shell	23,630	480	28,979	27,115

5. a phase for the pre-pottery Layer 3;

6. and a "pottery" phase including the two relevant dates from Layer 2.

For Kimanis, all the dates presented in Table 7 were calibrated. We rely on the association between dates and "units" given by the author, although some of these associations are ambiguous. In particular, the samples from Spit 24 are attributed to Unit 3, although the drawing of the sequence shows them at the bottom of Layer D, which is attributed to Unit 2 (Arifin 2017, fig. 6.2 p. 102). More generally, the relationships between stratigraphic layers and "units" are difficult to understand. An ordering constraint was applied to the date from shell (ANU-11259) from Unit 5 and the dated charcoal at the bottom of Unit 3 (ANU-11151). On the contrary, the date from shell (ANU-11258) from Unit 3 was excluded from the "phase" model and no ordering constraint was applied, because in the absence of a sufficient number of dated samples, the model cannot interpret this shell date as an outlier. Four phases were defined in the "phase" model.

1. A phase for the TAQ of Kimanis occupation, corresponding to Unit 5.

2. The "transition" phase corresponds to Unit 3: the two dates from charcoal pieces sampled at the bottom (ANU-11151) and the top of this unit (ANU-11150), respectively, can approximate the beginning and the end of this phase.

3. Recording coastal contact evidence at Kimanis raises multiple issues: identification of the shell species is uncertain and the relative location of shells with respect to the dated samples in Units 2 and 3 is unclear. Consequently, the "coastal contact" phase in the phase model corresponds to Unit 2, where most of the cowries were found.

4. The "pottery" phase corresponds to Unit 1.

The "restricted" model was built by removing the wiggle matching correction for FRE, dates from the "conservative" model (Liang Abu: GifA-11358, UBA-27060, UBA-20838; Kimanis: ANU-11258), and the TAQ phases of each site (see Supplemental 1, Figure 25).

4.3 Results and discussion

From the examination of post-depositional processes and the result of the Bayesian model, we can now propose a new local synthesis for the Holocene, after the Last Glacial Maximum (LGM, corresponding to ca. 26,500–19,000 BP) (Clark et al. 2009). After discussing the TAQ for occupation at Liang Abu and Kimanis, we present the results for the three

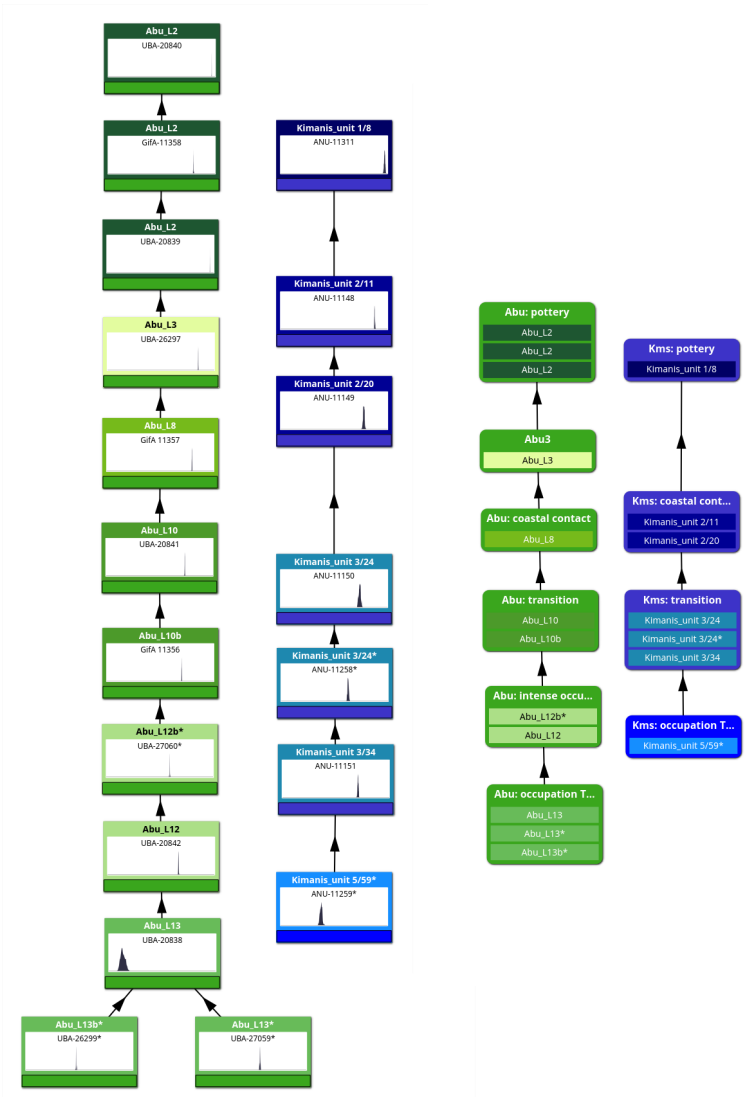

Figure 13: “Conservative” Bayesian model defined in *ChronoModel* for Liang Abu (green) and Kimanis (blue). In the “Event model” (left side), the dates are grouped into events. In the “Phase model” (right side) the events are grouped in phases. Arrows represent temporal order constraints. The dates from shell samples are marked with an asterisk.

anthropic changes:[13] (1) the transition phases (summarized in Table 6, at Liang Abu this transition occurred after an intense occupation phase); (2) evidence of earliest coastal contact; and (3) the introduction of pottery. The discussion is grounded in the "conservative" model results. Results from the "restricted" model are mentioned to illustrate the discrepancies between the two models and the benefits of *ChronoModel*'s features.

4.3.1 Occupation TAQ at Liang Abu and Kimanis

Results from the conservative Bayesian model give a large TAQ for occupation at Liang Abu, from 23,793 to 15,236 BP (phase time range), and a narrower and older time range for Kimanis: from 28,955 to 23,716 BP (phase time range). The limits and uncertainty of the data used to determine these TAQ were discussed above, and must be kept in mind when considering these results. It must be stressed that they do not date occupation at Liang Abu and Kimanis, but give state-of-the-art TAQ, calling for further and more precise investigation. However, these are interesting results, since the "restricted" model does not permit the computation of the TAQ.

4.3.2 "Intense occupation" phase

High remains density, significant freshwater shellfish consumption, and production of small lithic flakes determined an intensive post-LGM occupation at Liang Abu, dated by the "conservative" model from 16,196 to 14,106 BP (phase range). The end of the phase falls in the gap range between the "intense occupation" and "transition" phases, from between 14,314 and 13,819 BP. This period corresponds to the end of the Pleistocene and the beginning of an acceleration of sea level rise (Figure 14). Results from the "restricted" model give a narrower phase range, from 15,509 to 14,613 BP.

Increases in cave frequentation have also been reported at other sites in Borneo. However, these were associated with a later period and were potentially explained by population movements inland from the coast due to marine transgression (Piper and Rabett 2014). Interestingly, at Liang Abu, evidence of intense occupation is earlier and not associated with evidence of coastal contact. This could be due to the lack of data and sampling effects or explained by an indirect effect of sea level rise, whereby the movement of coastal populations pushed mainland populations even further inland. In all cases, this stresses the importance of detailed comparisons between sites. At the Niah caves, in North Borneo, intensification of cave frequentation is observed from ca. 11,500 BP (Rabett et al. 2013, p. 252). At Kimanis, this process has also been associated with the same period (Arifin 2017, pp. 117-118). However, evidence for coastal contact in this period is missing at Kimanis. Accordingly, we process and discuss the related chronometric data in relation to the "transition" phase.

4.3.3 Transition phases

Transition phases at the two sites distinguish between the lower and the upper part of the sequences (Table 6). The dates for these transition phases are similar at the two sites. At Liang Abu, the "transition" phase started between 14,314 and 13,819 BP (gap range between the "intense occupation" and "transition" phases), and ended between 11,579 and 9471 BP (gap range with the "coastal contact" phase). At Kimanis, the dated samples are interpreted as boundaries of the "transition" phase, which started ca. 17,214 and ended ca. 9988 BP (phase time range). This phase overlaps with the period of acceleration in sea level rise (from ca. 14,000 to ca. 9000 BP). Evidence of coastal contact at Kimanis and

[13] See Supplemental 1 and supplementary data for the numerical results.

Liang Abu are dated after this period. Interestingly, the end of the "transition" phases corresponds approximately to the Late Holocene Period identified at the Niah caves, from ca. 11,500 BP (Rabett et al. 2013). These correspondences are better observed in the "restricted" model, which returns a narrower phase range for the "transition" phase, from 14,006 to 10,279 BP (see Supplemental 1, Figure 26). This is the major difference in the results of the two models.

4.3.4 First coastal contact phases

At Liang Abu, evidence of first coastal contact was found in Layer 8, which is dated with a single sample located at the top of the layer. This *phase time range* gives a TAQ for the "first coastal contact" between 9467 and 8767 BP. Determining this date range is much more complicated at Kimanis due to the issues mentioned above. The "first coastal contact" phase in the model, cautiously defined from samples at the top and bottom of Unit 2, gives a phase time range of 10,941–4725 BP. This time range is too large to efficiently fuel the discussion.

The dating of evidence of "first coastal contact" can be discussed in relation to sea level rising (see Figures 1 and 14). The distance from the sites to the coast over time is examined, assuming that transport occurred preferentially along rivers. In general, the effect of sea level elevation was less significant on the eastern coast of Borneo than on the Sunda shelf on the western coast (or in North Borneo, as in the Niah caves Rabett et al. 2013, pp. 217-222). Concerning Kimanis, sea level rise did not shorten the southern access to the sea through the Birang River (about 130 km away) and had little effect on the northern access to the coast, via the Binai River (about 70 km away). On the contrary, sea level rise had significant consequences for coastal access from Liang Abu, as demonstrated by comparing the distance to the coast during the "intense occupation" phase and the "transition" phase. During the "intense occupation" phase, the sea was about 170 km away using the northern access through the Tabalar River, whereas the shortest pathway (about 130 km away) was through a southern route through the Karangan River (with a long terrestrial trek before reaching the Karangan). At the end of the "transition" phase, due to sea level rise, the sea was at similar distance using both pathways (about 130 km). The change was more dramatic at Niah between the two dates: the distance to the coast decreased from 120 km to 50 km (and 20 km today). Consequently, as discussed by Rabett et al. 2013, this environmental change is likely to have induced changes in human behavior.

4.3.5 Pre-pottery Early Holocene inter-phases

From ca. 9000 BP the rise in sea level slowed down before stabilizing around 2500 BP. This period was characterized by two major phenomena. First, a dramatic decrease in human occupation, leading Bellwood to suggest a virtual absence of human occupation in Borneo between 8000 and 3500 BP (Bellwood 2017, p. 149). corresponds to the possible date of genetic admixture between populations due to migrations from the Philippines to Borneo: using data from North (Brunei) and East Borneo (Mangkalihat peninsula, the location of Liang Abu) the admixture between the Bornean population and the Kankanaey (Philippines) population has been dated to 3431 BP (standard error: 588 years) (Hudjashov et al. 2017, Figure 5 and Table S6A). Second, this period was characterized by environmental change that led to drier conditions. Data from the Bau Bau cave (260 km south of Liang Abu) provide evidence for a dryer episode between ca. 7700 to 6300 BP (Wurster et al. 2017). The authors suggested that this episode was related to climatic changes (increased grasses or replacement of rainforest with seasonal or deciduous forest) or to an opening of the canopy due to human-induced fire.

At Liang Abu, the beginning of these two phenomena (gray shading in Figure 14) is posterior to the TAQ for the first evidence of coastal contact. In addition, the drier period exactly overlaps with the phase range of Layer 3 (7024–6570 BP), which is included in the upper part of the sequence characterized by a low-intensity occupation and evidence of coastal contact. This is consistent with Bellwood's earlier statement. On the contrary, at Kimanis, evidence of more intense occupation was observed in Units 3 and 2, the latter being associated with a charcoal sample dated to 5586–5051 BP (Table 7), which is within Bellwood's period of virtual absence of human occupation.

It is hypothesized that this absence is a consequence of the lack of excavated sites and of an increase in dispersal and mobility between inland areas and the coast, as supported by the permanence of coastal contact material evidence in the upper part of the Liang Abu and Kimanis sequences. In addition, from the end of the dryer event (about 6300 BP), the use of the current shortest route from Liang Abu to the coast, through the Karangan River (about 90 km), was even more probable.

4.3.6 Pottery phases

At Liang Abu, the large gap between the "Layer 3" phase and the "pottery" phase does not give us much information about the introduction of pottery. Considering the strong association of dated samples with pottery sherds in Layer 2, the dates from this layer are considered to date the pottery and give a TAQ for its introduction, which occurred before 1976–1076 BP (Layer 2 phase time range). Results from the "restricted" model give a slightly narrower phase range for Liang Abu, from 1754 to 1243 BP. At Kimanis, due to the location of the dated sample, the end of the "first coastal contact" phase gives a TPQ for pottery introduction: it occurred during the large time gap between the "first coastal contact" phase and the "pottery" phase, i.e., between 4677 and 2129 BP (gap range). In addition, Arifin also reported a TPQ for pottery introduction at Lubang Payau (4610 ± 110, 5585–5030 cal. BP, ANU-11152, recalibrated, Arifin 2017, p. 101).

As already pointed out by several authors, reliably dated "Neolithic" evidence is rare in Borneo (Bellwood 2017, pp. 269-274, Cochrane et al. 2021) but available data can nevertheless be compared with our results. Bellwood et al. stressed the importance of the direct dating of a rice grain embedded in a pottery sherd from Gua Sireh (3850 ± 260, CAMS-725, Bellwood et al. 1992). Based on this date, he discussed the introduction of rice, pottery, and possible Austronesian-speakers to Borneo from about 2500 BCE (i.e., 4250 BP) (Bellwood 2017, p. 273). As stressed by Bellwood, this result must be considered cautiously due to the potential bias related to the dating methods used in the 1990s. Recalibration of this date gives a range of 4883–3568 BP, which is much earlier than the possible earlier dated evidence of pottery in the Niah caves: in the West Mouth, pottery is associated with burial B159, which is dated to 3143–2927 BP (Lloyd-Smith et al. 2013, pp. 266-267). A recent study, based on a Bayesian chronological model that argues that neither the "Out of Taiwan" nor the "Western Route Migration" hypotheses are particularly supported by the results, dates the introduction of pottery in North Borneo to 4560–2460 BP (Cochrane et al. 2021). This interval, although large and imprecise, corresponds to our results from Liang Abu and Kimanis.

5 Conclusions

In recent decades, East Borneo has become a new archaeological "hot-spot" in Island Southeast Asia due to the increasing number of excavated sites and the discovery of rock art, revealed by recent dating to be one of the earliest instances of human artistic ex-

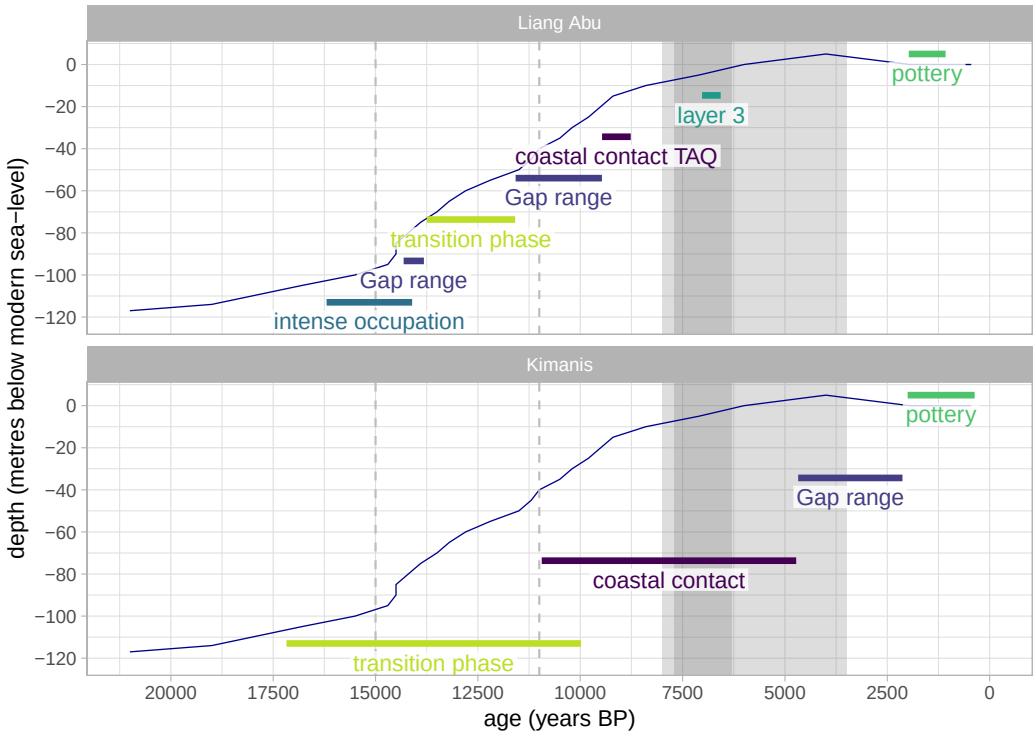

Figure 14: Results of the "conservative" chronological Bayesian model for Liang Abu and Kimanis. Horizontal lines correspond to the phase time ranges (σ=95%) generated by *ChronoModel* for the thematic phases (note that their vertical placement has no particular meaning). The curve shows the sea level change, drawn using data from Sathiamurthy and Voris 2006. Vertical gray shadings indicate: the virtual absence of human occupation in Borneo according to Bellwood 2017 (light gray) and the dryer climatic episode detected in East Borneo (dark gray). The dotted vertical lines indicate the isobaths (at -40 and -100 m) plotted on the map in Figure 1.

pression worldwide. In this chapter, we have reported on Liang Abu, currently the most thoroughly documented archaeological sequence in the region, by comparing it to data from Kimanis, the closest previously published site. This comparison was also the first methodological attempt in Borneo to integrate data generated at different sites and by different research teams into the same analytical framework. The study demonstrated the difficulty of re-using archaeological data due to: (1) the use of unmatching and different description standards; and (2) information deficiencies linked to insufficiently detailed reports. These issues can be resolved with the faster publication of data (raw tables) and analytical procedures (software and code) accessible to the research community.

Contributing to overcoming these difficulties, the use of a Bayesian chronological model helped to integrate Liang Abu and Kimanis results within a single analytical framework. A new chronology of human settlement and mainland–coastal interactions in East Borneo was presented, focusing on three major anthropic changes: "transitional periods" associated with responses to the dramatic environmental changes of the Early Holocene, earliest traces of coastal contact, and the introduction of pottery. Similarities and discrepancies in the timing of these changes at Liang Abu, Kimanis, and the Niah caves demonstrate the importance of robust empirical comparisons (as claimed by Bulbeck 2008). The files containing the data and the specifications of the Bayesian chronological models are provided, as well as the data and codes used to compare data in this paper, ensuring the control and reproducibility of the results. This will allow other researchers to draw on and update this archaeologically based model of human settlement in East Borneo by integrating new information from future studies.

6 Data and material

Supplemental 1

Supplementals can be downloaded on the editor's webpage at https://doi.org/10.1080/15564894.2022.2108947.

- Excavation and layers description
- Data and R Packages
- Figure 6: Spatial density of lithic, pottery, and shell remains, layer
- Figure 7: Orientation and number of relationships
- Pottery refitting: cohesion and admixture of layers
- Figure 8: Density by class of remains
- Figure 9: Density of stone artefacts and shells
- Figure 10: Fauna by class
- Figure 11: Fauna, shells
- Figure 12: Stone artefacts
- Stone artefacts: chi-test on classes in Liang Abu and Kimanis
- Stone artefacts: chi-test on raw material classes in Liang Abu and Kimanis
- Stone artefacts: lengths of flakes from Liang Abu and Kimanis

- Figure 14: Results of the "conservative" chronological Bayesian model
- Supplementary Figure 16: View of the shelter
- Supplementary Figure 17: Insect holes in the north section
- Supplementary Figure 18: Insect pupa
- Supplementary Figure 19: Roots in sub-square 11Ed
- Supplementary Figure 20: Comparison of the density of micro-remains
- Supplementary Figure 21: Comparison of the density of micro-remains (2 mesh sizes)
- Supplementary Figure 22: Fauna by order
- Supplementary Figure 23: Fauna by family
- Supplementary Figure 24: View of layer 2 during excavation, sub-square 12Ec
- Supplementary Figure 25: Diagram of the "restricted" Bayesian model
- Supplementary Figure 26: Results of the "restricted" Bayesian model

Supplementary data

- The Liang Abu's pottery data: 10.5281/zenodo.3929562.
- Liang Abu lithic data: 10.5281/zenodo.6774519.
- Liang Abu fauna data: 10.5281/zenodo.6774530
- The Bayesian models and the results are available at: 10.5281/zenodo.3929615.
- The sea level dataset from Sathiamurthy and Voris 2006 is available at: 10.5281/zenodo.3929568.

Acknowledgements

We thank former participants in the MAFBO project (https://kaltim.hypotheses.org): Jean-Georges Ferrié, Bénédicte Voeltzel, Michel Grenet, and Josette Sarel; Jean-Bernard Huchet for insect classification, Tim Thomas for his suggestions, and Philippe Lanos and Philippe Dufresne for their support on chronological modeling. We also acknowledge support from the LabEx TULIP, France and thank the Kabupaten Kutai Timur authorities, the *Direktorat Pelestarian Cagar Budaya dan Permuseuman* (BPCB, Samarinda), the *Pusat Penelitian dan Pengembangan Arkeologi Nasional* (National Research Center for Archaeology, Jakarta), the *Kemenristekdikti* for the Foreign Research Permit, the *Balai Arkeologi Banjarmasin* (Banjar Baru, Kalimantan Selatan), and the Merabu people for their help and support. Finally, we thank the reviewers and editors of *The Journal of Island and Coastal Archaeology* for their comments and support.

Authors' contributions

Sébastien Plutniak: Conceptualization, Methodology, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization. **François-Xavier Ricaut**: Investigation, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Astolfo Araujo**: Investigation, Writing - Review & Editing. **Jean-Michel Chazine**: Writing - Review & Editing. **Bambang Sugiyanto**: Investigation. **Adhi Agus Oktaviana**: Investigation, Project administration.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This research was supported by French ANR grant number ANR-14-CE31-0013-01 (grant OceoAdapto to F.-X. R.), the French Ministry of Foreign and European Affairs (*Mission archéologique française à Bornéo* to F.-X. R.), and the French Embassy in Indonesia through its Cultural and Cooperation Services (*Institut Français en Indonésie*).

Ethical declaration

All samples used for dating (remains, charcoal, shell) were obtained after discussions with stakeholders and people of the Merabu community village. The study was approved by the Pusat Penelitian Arkeologi Nasional (ARKENAS), Jakarta, Indonesia (n^r 1420 / P4 / Kemendikbud / 2013). Permission to conduct research in Indonesia was granted by the State Ministry of Research and Technology (RISTEK) to F.-X. Ricaut (Permit number: 2C13JD0571-L).

References

Araujo, Astolfo, James K. Feathers, Manuel Arroyo-Kalin, and Michelle M. Tizuka [2008], "Lapa das Boleiras Rockshelter: Stratigraphy and Formation Processes at a Paleoamerican Site in Central Brazil," *Journal of Archaeological Science*, 35, 12, pp. 3186-3202, DOI: 10.1016/j.jas.2008.07.007.

Araujo, Astolfo and Luís Beethoven Piló [2017], "Towards the Development of a Tropical Geoarchaeology: Lagoa Santa as an Emblematic Case Study," in *Archaeological and Paleontological Research in Lagoa Santa. The Quest for the First Americans*, ed. by Pedro Da-Gloria, Walter A. Neves, and Mark Hubbe, trans. by Martin Charles Nicholl, Cham: Springer, pp. 373-391, DOI: 10.1007/978-3-319-57466-0_17.

Arifin, Karina [2004], *Early Human Occupation of the East Kalimantan Rainforest (the Upper Birang River Region, Berau)*, PhD thesis, Australian National University, Canberra, DOI: 10.25911/5d78db8273824.

Arifin, Karina [2017], "Terminal Pleistocene and Early Holocene Human Occupation in the Rainforests of East Kalimantan," in *New Perspectives in Southeast Asian and Pacific Prehistory*, ed. by Philip J. Piper, Hirofumi Matsumura, and David Bulbeck, terra australis, 45, Acton: ANU Press, pp. 97-124.

Aubert, Maxime, Pindi Setiawan, Adhi Agus Oktaviana, A. Brumm, P. H. Sulistyarto, E. W. Saptomo, B. Istiaw, T. A. Ma'rifat, V. N. Wahyuono, F. T. Atmoko, J.-X. Zhao, J. Huntley, Paul S. C. Taçon, D. L. Howard, and H. E. A. Brand [2018], "Palaeolithic Cave Art in Borneo," *Nature*, 564, pp. 254-257, DOI: 10.1038/s41586-018-0679-9.

Barker, Graeme (ed.) [2013], *Rainforest Foraging and Farming in Island Southeast Asia. The Archaeology of the Niah Caves, Sarawak. Volume 1*, McDonald Institute Monographs, Cambridge: McDonald Institute for Archaeological Research, 410 pp.

Barker, Graeme and Lucy Farr (eds.) [2016], *Archaeological Investigations in the Niah Caves, Sarawak, 1954–2004. The Archaeology of the Niah Caves, Sarawak. Volume 2*, McDonald Institute Monographs, Cambridge: McDonald Institute for Archaeological Research, 592 pp.

Bellwood, Peter [1988], *Archaeological Research in South-Eastern Sabah*, Sabah Museum Monographs, 2, Kota Kinabalu: Sabah Museum and State Archives, viii–282 p.

Bellwood, Peter [2017], *First Islanders. Prehistory and Human Migration in Island Southeast Asia*, Hoboken (N.J.): Willey Blackwell, xvi–360.

Bellwood, Peter, Richard Gillespie, Gill B. Thompson, John S. Vogel, I. Wayan Ardika, and Ipoi Datan [1992], "New Dates for Prehistoric Asian Rice," *Asian perspectives*, 31, 2, pp. 161-170.

Bertran, Pascal and Jean-Pierre Texier [1995], "Fabric Analysis: Application to Palaeolithic Sites," *Journal of Archaeological Science*, 22, 4, pp. 521-535, DOI: 10.1006/jasc.1995.0050.

Bordes, Jean-Guillaume [2000], "La séquence aurignacienne de Caminade revisitée : l'apport des raccords d'intérêt stratigraphique," *Paléo. Revue d'archéologie préhistorique*, 12, 1, pp. 387-407, DOI: 10.3406/pal.2000.1611.

Bujeng, Velat and Stephen Chia [2012], "Bone and Shell Artifacts from Bukit Sarang, Buntulu and Gua Kain Hitam B, Niah, Sarawak," in *Crossing Borders. Selected Papers from the 13th International Conference of the European Association of Southeast Asian Archaeologists*, ed. by Mai Lin Tjoa-Bonatz, Andreas Reinecke, and Dominik Bonatz, NUS Press, Singapore, pp. 35-50, DOI: 10.2307/j.ctv1nthm4.9.

Bulbeck, David [2008], "An Integrated Perspective on the Austronesian Diaspora: the Switch from Cereal Agriculture to Maritime Foraging in the Colonisation of Island Southeast Asia," *Australian Archaeology*, 67, 1, pp. 31-51.

Cahen, Daniel and Jan Moeyersons [1977], "Subsurface Movements of Stone Artefacts and their Implications for the Prehistory of Central Africa," *Nature*, 266, 5605, pp. 812-815, DOI: 10.1038/266812a0.

Chazine, Jean-Michel [1995], "Et pour quelques grottes de plus… Découvertes spéléologiques et archéologiques à Kalimantan," *Les Nouvelles de l'archéologie*, 61, pp. 30-32.

Chazine, Jean-Michel [1999], "Unraveling and Reading the Past in Borneo: an Archaeological Outline of Kalimantan," in *Le Pacifique de 5000 à 2000 avant le présent : suppléments à l'histoire d'une colonisation / The Pacific from 5000 to 2000 BP: colonisation and transformations*, Vanuatu, July 31-Aug. 6, 1996, ed. by Jean-Christophe Galipaud and Ian Lilley, Colloques et Séminaires, Paris: Éditions de l'IRD, pp. 213-225.

Chazine, Jean-Michel [2005], "Rock Art, Burials, and Habitations: Caves in East Kalimantan," *Asian Perspectives*, 44, 1, pp. 219-230, DOI: 10.1353/asi.2005.0006.

Chazine, Jean-Michel, Jean-Georges Ferrié, Michel Grenet, Sébastien Plutniak, and Bénédicte Voetzel [2009], *Rapport de mission franco-indonésienne, Nord-ouest Papua et Est Bornéo*, Rapport de mission, Ministère des affaires étrangères et européennes, 88 pp.

Chazine, Jean-Michel, François-Xavier Ricaut, Antonio Guerreiro, Sébastien Plutniak, Josette Sarel, and Bénédicte Voetzel [2010], *Mission archéologique à Bornéo. Programme de coopération franco-indonésien*, Rapport de mission, Ministère des affaires étrangères et européennes, 88 pp.

Clark, Peter U., Arthur S. Dyke, Jeremy D. Shakun, Anders E. Carlson, Jorie Clark, Barbara Wohlfarth, Jerry X. Mitrovica, Steven W. Hostetler, and A. Marshall McCabe [2009], "The Last Glacial Maximum," *Science*, 325, 5941, pp. 710-714, DOI: 10.1126/science.1172873.

Cochrane, Ethan E., Timothy M. Rieth, and Darby Filimoehala [2021], "The First Quantitative Assessment of Radiocarbon Chronologies for Initial Pottery in Island Southeast Asia supports Multi-directional Neolithic Dispersal," *Plos One*, 16, 6, pp. 1-17, DOI: 10.1371/journal.pone.0251407.

Cook, Gordon T., Philippa L. Ascough, Clive Bonsall, W. Derek Hamilton, Nicola Russell, Kerry L. Sayle, E. Marian Scott, and Jessica M. Bownes [2015], "Best Practice Methodology for 14C Calibration of Marine and Mixed Terrestrial/Marine Samples," *Quaternary Geochronology*, 27, pp. 164-171, DOI: 10.1016/j.quageo.2015.02.024.

Dunnell, Robert C. and Julie K. Stein [1989], "Theoretical Issues in the Interpretation of Microartifacts," *Geoarchaeology*, 4, 1, pp. 31-41, DOI: 10.1002/gea.3340040103.
Enloe, James G. [2006], "Geological Processes and Site Structure: Assessing Integrity at a Late Paleolithic Open-air Site in Northern France," *Geoarchaeology*, 21, 6, pp. 523-540, DOI: 10.1002/gea.20122.
Ferrié, Jean-Georges and Sébastien Plutniak [2022], *Data set for the fauna material excavated at the Liang Abu site (East Kalimantan, Indonesia)*, Zenodo, DOI: 10.5281/zenodo.6774530.
Fladmark, Knut R. [1982], "Microdebitage Analysis: Initial Considerations," *Journal of Archaeological Science*, 9, 2, pp. 205-220, DOI: 10.1016/0305-4403(82)90050-4.
Forestier, Hubert, Michel Grenet, Antony Borel, and Vincenzo Celiberti [2017], "Les productions lithiques de l'Archipel indonésien," *Journal of Lithic Studies*, 4, 2: *La notion de "chaîne opératoire" dans le monde : 50 ans d'études technologiques en Préhistoire*, pp. 231-303, DOI: 10.2218/jls.v4i2.2544.
Grenet, Michel and Josette Sarel [2022], *Data set for the lithic material excavated at the Liang Abu site (East Kalimantan, Indonesia)*, Zenodo, DOI: 10.5281/zenodo.6774519.
Grenet, Michel, Josette Sarel, Ruly Fauzy, Adhi Agus Oktaviana, Bambang Sugiyanto, Jean-Michel Chazine, and François-Xavier Ricaut [2016], "New Insights on the Late Pleistocene–Holocene Lithic Industry in East Kalimantan (Borneo): the Contribution of three Rock Shelter Sites in the Karstic Area of the Mangkalihat Peninsula," *Quaternary International*, 416: *Southeast Asia: human evolution, dispersals and adaptation*, pp. 126-150, DOI: 10.1016/j.quaint.2015.11.044.
Horrocks, Mark, Susan Bulmer, and Rhodri O. Gardner [2008], "Plant Microfossils in Prehistoric Archaeological Deposits from Yuku Rock shelter, Western Highlands, Papua New Guinea," *Journal of Archaeological Science*, 35, 2, pp. 290-301, DOI: 10.1016/j.jas.2007.03.005.
Hudjashov, Georgi, Tatiana M. Karafet, Daniel J. Lawson, Sean Downey, Olga Savina, Herawati Sudoyo, J. Stephen Lansing, Michael F. Hammer, and Murray P. Cox [2017], "Complex Patterns of Admixture across the Indonesian Archipelago," *Molecular Biology and Evolution*, 34, 10, pp. 2439-2452, DOI: 10.1093/molbev/msx196.
Johnson, Donald Lee [1990], "Biomantle Evolution and the Redistribution of Earth Materials and Artifacts," *Soil Science*, 149, 2, pp. 84-102.
Katzenberg, M. Anne [2008], "Stable Isotope Analysis: a Tool for Studying Past Diet, Demography, and Life History," in *Biological Anthropology of the Human Skeleton*, ed. by M. Anne Katzenberg and Anne L. Grauer, 3rd ed., Hoboken (N.J.): John Wiley & Sons, vol. 2, pp. 469-504.
Kusmartono, Vida, Imam Hindarto, and Eko Herwanto [2017], "Late Pleistocene to Recent: Human Activities in the Deep Interior Equatorial Rainforest of Kalimantan, Indonesian Borneo," *Quaternary International*, 448, Supplement C, pp. 82-94, DOI: 10.1016/j.quaint.2016.09.025.
Lanos, Philippe and Philippe Dufresne [2019], *Chronomodel version 2.0: Software for Chronological Modelling of Archaeological Data using Bayesian Statistics*, http://www.chronomodel.com.
Lanos, Philippe and Anne Philippe [2017], "Hierarchical Bayesian Modeling for Combining Dates in Archaeological Context," *Journal de la Société Française de Statistique*, 158, 2: *Humanités et Statistiques*, pp. 72-88.
Lanos, Philippe and Anne Philippe [2018], "Event Date Model: a Robust Bayesian Tool for Chronology Building," *Communications for Statistical Applications and Methods*, 25, 2, pp. 131-157, DOI: 10.29220/CSAM.2018.25.2.131.
Lenoble, Arnaud and Pascal Bertran [2004], "Fabric of Palaeolithic Levels: Methods and Implications for Site Formation Processes," *Journal of Archaeological Science*, 31, 4, pp. 457-469, DOI: 10.1016/j.jas.2003.09.013.
Lloyd-Smith, Lindsay, Graeme Barker, Huw Barton, Judith Cameron, Franca Cole, Patrick Daly, Chris Doherty, Chris Hunt, John Krigbaum, Helen Lewis, Jessica Manser, Victor Paz, Philip J. Piper, Ryan J. Rabett, Garry Rushworth, and Katherine Szabó [2013], "'Neolithic' Societies c. 4000-2000 Years Ago: Austronesian Farmers?" In *Rainforest Foraging and Farming in Island Southeast Asia. The Archaeology of the Niah Caves, Sarawak. Volume 1*, ed. by Graeme Barker, McDonald Institute monographs, Cambridge: McDonald Institute for Archaeological Research, pp. 255-298.

Marwick, Ben [2017], "Computational Reproducibility in Archaeological Research: Basic Principles and a Case Study of their Implementation," *Journal of Archaeological Method and Theory*, 24, 2, pp. 1-27, DOI: 10.1007/s10816-015-9272-9.

Morley, Mike W. [2017], "The Geoarchaeology of Hominin Dispersals to and from Tropical Southeast Asia: A Review and Prognosis," *Journal of Archaeological Science*, 77, pp. 78-93, DOI: 10.1016/j.jas.2016.07.009.

Philippsen, Bente [2013], "The Freshwater Reservoir Effect in Radiocarbon Dating," *Heritage Science*, 1, 1, p. 24, DOI: 10.1186/2050-7445-1-24.

Piper, Philip J. and Ryan J. Rabett [2014], "Late Pleistocene Subsistence Strategies in Southeast Asia and their Implications for Understanding the Development of Modern Human Behaviour," in *Southern Asia, Australasia and the Search for Modern Human Origins*, ed. by Robin Dennell and Martin M. Porr, Cambridge: Cambridge University Press, pp. 118-134.

Plutniak, Sébastien [2021a], *Archeofrag: an R package for Refitting and Spatial Analysis in Archaeology*, DOI: 10.5281/zenodo.4720392, https://CRAN.R-project.org/package=archeofrag.

Plutniak, Sébastien [2021b], *Refitting Pottery Fragments from the Liang Abu Rockshelter, Borneo*, Zenodo, DOI: 10.5281/zenodo.4719577.

Plutniak, Sébastien [2021c], "The Strength of Parthood Ties. Modelling Spatial Units and Fragmented Objects with the TSAR Method – Topological Study of Archaeological Refitting," *Journal of Archaeological Science*, 136, p. 105501, DOI: 10.1016/j.jas.2021.105501.

Plutniak, Sébastien [2022a], *"ChronoModel" Bayesian Chronological Models for East Borneo, based on data from the Liang Abu and Kimanis Sites*, Zenodo, DOI: 10.5281/zenodo.3929614.

Plutniak, Sébastien [2022b], *Data set for the pottery material excavated at the Liang Abu site (East Kalimantan, Indonesia)*, Zenodo, DOI: 10.5281/zenodo.3929562.

Plutniak, Sébastien, Astolfo Araujo, Simon Puaud, Jean-Georges Ferrié, Adhi Agus Oktaviana, Bambang Sugiyanto, Jean-Michel Chazine, and François-Xavier Ricaut [2016], "Borneo as a Half Empty Pot: Pottery Assemblage from Liang Abu, East Kalimantan," *Quaternary International*, 416: *Southeast Asia: Human Evolution, Dispersals and Adaptation*, pp. 228-242, DOI: 10.1016/j.quaint.2015.11.080.

Plutniak, Sébastien, Adhi Agus Oktaviana, Bambang Sugiyanto, Jean-Michel Chazine, and François-Xavier Ricaut [2014], "New Ceramic Data from East Kalimantan: the Cord-marked and Red-slipped Sherds of Liang Abu's layer 2 and Kalimantan's Pottery Chronology," *Journal of Pacific Archaeology*, 5, 1, pp. 90-99, DOI: 10.5281/zenodo.1165930, https://pacificarchaeology.org/index.php/journal/article/view/126.

Plutniak, Sébastien and François-Xavier Ricaut [2022], *Data set for the shells excavated at the Liang Abu site (East Kalimantan, Indonesia)*, Zenodo, DOI: 10.5281/zenodo.6774534.

Rabett, Ryan J. [2005], "The Early Exploitation of Southeast Asian Mangroves: Bone Technology from Caves and Open Sites," *Asian perspectives*, 44, 1, pp. 154-179.

Rabett, Ryan J., Graeme Barker, Huw Barton, Chris Hunt, Lindsay Lloyd-Smith, Victor Paz, Philip J. Piper, Rasmathiri Premathilake, Garry Rushworth, Mark Stephens, and Katherine Szabó [2013], "Landscape Transformations and Human Responses, c. 11,500–c. 4500 years ago. The Archaeology of the Niah Caves, Sarawak. Volume 1," in *Rainforest Foraging and Farming in Island Southeast Asia*, ed. by Graeme Barker, McDonald Institute monographs, Cambridge: McDonald Institute for Archaeological Research, pp. 217-254.

Ramsey, Christopher Bronk [2009], "Dealing with Outliers and Offsets in Radiocarbon Dating," *Radiocarbon*, 51, 3, pp. 1023-1045, DOI: 10.1017/S0033822200034093.

Reimer, Paula J., William E. N. Austin, Edouard Bard, Alex Bayliss, Paul G. Blackwell, Christopher Bronk Ramsey, Martin Butzin, Hai Cheng, R. Lawrence Edwards, Michael Friedrich, Pieter M. Grootes, Thomas P. Guilderson, Irka Hajdas, Timothy J. Hogg Heaton, Alan G., Konrad A. Hughen, Bernd Kromer, Sturt W. Manning, Raimund Muscheler, Jonathan G. Palmer, Charlotte Pearson, Johannes van der Plicht, Ron W. Reimer, David A. Richards, E. Marian Scott, John R. Southon, Christian S. M. Turney, Lukas Wacker, Florian Adolphi, Ulf Büntgen, Manuela Capano, Simon M. Fahrni, Alexandra Fogtmann-Schulz, Ronny Friedrich, Peter Köhler, Sabrina Kudsk, Fusa Miyake, Jesper Olsen, Frederick Reinig, and Minoru and Sakamoto [2020], "The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP)," *Radiocarbon*, 62: *IntCal20: Calibration Issue*, pp. 725-757, DOI: 10.1017/RDC.2020.41.

Ricaut, François-Xavier, Jean-Michel Chazine, Jean-Georges Ferrié, Antonio Guerreiro, and Josette Sarel [2011], *Mission archéologique à Bornéo. Programme de coopération franco-indonésien*, Rapport de mission, Ministère des affaires étrangères et européennes, 111 pp.

Ricaut, François-Xavier, Ruli Fauzi, Michel Grenet, Antonio Guerreiro, and Sébastien Plutniak [2013], *Mission archéologique à Bornéo. Programme de coopération franco-indonésien*, Rapport de mission, Ministère des affaires étrangères et européennes, 97 pp.

Ricaut, François-Xavier, Jean-Georges Ferrié, Antonio Guerreiro, Sébastien Plutniak, and Josette Sarel [2012], *Mission archéologique à Bornéo. Programme de coopération franco-indonésien*, Rapport de mission, Ministère des affaires étrangères et européennes, 145 pp.

Ricaut, François-Xavier, Adhi Agus Oktaviana, Jean-Georges Ferrié, Antonio Guerreiro, Michel Grenet, and Sébastien Plutniak [2014], *Mission archéologique à Bornéo. Programme de coopération franco-indonésien*, Rapport de mission, Ministère des affaires étrangères et européennes, 125 pp.

Rieth, Timothy M. and J. Stephen Athens [2019], "Late Holocene Human Expansion into Near and Remote Oceania: A Bayesian Model of the Chronologies of the Mariana Islands and Bismarck Archipelago," *The Journal of Island and Coastal Archaeology*, 14, 1, pp. 5-16, DOI: 10.1080/15564894.2017.1331939.

Sathiamurthy, Edlic and Harold K. Voris [2006], "Maps of Holocene Sea Level Transgression and Submerged Lakes on the Sunda Shelf," *Tropical Natural History Supplement*, 2, pp. 1-44.

Schulting, Rick J., Christopher Bronk Ramsey, Vladimir I. Bazaliiskii, and Andrzej Weber [2015], "Highly Variable Freshwater Reservoir Offsets found along the Upper Lena Watershed, Cis-Baikal, Southeast Siberia," *Radiocarbon*, 57, 4, pp. 581-593, DOI: 10.2458/azu_rc.57.18458.

Spriggs, Matthew [1989], "The Dating of the Island Southeast Asian Neolithic: an Attempt at Chronometric Hygiene and Linguistic Correlation," *Antiquity*, 63, 240, pp. 587-613, DOI: 10.1017/S0003598X00076560.

Stein, Julie K. and Patrice A. Teltser [1989], "Size Distributions of Artifact Classes: Combining Macro- and Micro-Fractions," *Geoarchaeology*, 4, 1, pp. 1-30.

Stephens, Mark, J. Rose, and David D. Gilbertson [2017], "Post-depositional Alteration of Humid Tropical Cave Sediments: Micromorphological Research in the Great Cave of Niah, Sarawak, Borneo," *Journal of Archaeological Science*, 77: *Geoarchaeology in the Humid Tropics: Practice, Problems, Prospects*, pp. 109-124, DOI: 10.1016/j.jas.2016.01.015.

Sukardi, B. Djamal, S. Supriatna, and S. Santosa [1995], *Peta geologi lembar Muaralasan, Kalimantan / Geological Map of the Muaralasan Quadrangle, Kalimantan*, Bandung.

Venables, William N. and Brian D. Ripley [2002], *Modern Applied Statistics with S*, 4th ed., New York: Springer, xi–495 p.

Villa, Paola [1982], "Conjoinable Pieces and Site Formation Processes," *American Antiquity*, 47, 2, pp. 276-290, DOI: 10.2307/279901.

Villa, Paola and Jean Courtin [1983], "The Interpretation of Stratified Sites: A View from Underground," *Journal of Archaeological Science*, 10, 3, pp. 267-281, DOI: 10.1016/0305-4403(83)90011-0.

Wood, W. Raymond and Donald Lee Johnson [1982], "A Survey of Disturbance Processes in Archaeological Site Formation," in *Advances in Archaeological Method and Theory. Selections for Students from Volumes 1–4*, ed. by Michael B. Schiffer, New York: Academic Press, pp. 539-605, DOI: 10.1016/B978-0-12-624180-8.50016-0.

Wurster, Christopher M., Hamdi Rifai, Jordahna Haig, Jupiri Titin, Geraldine Jacobsen, and Michael Bird [2017], "Stable Isotope Composition of Cave Guano from Eastern Borneo reveals Tropical Environments over the Past 15,000 cal yr BP," *Palaeogeography, palaeoclimatology, palaeoecology*, 473, pp. 73-81, DOI: 10.1016/j.palaeo.2017.02.029.