Initial micromorphological results from Liang Bua, Flores (Indonesia): site formation processes and hominin activities at the type locality of *Homo floresiensis*

Mike W. Morley¹, Paul Goldberg^{1,2}, Thomas Sutikna^{1,3}, Matthew W. Tocheri^{4,5}, Linda C. Prinsloo¹, Jatmiko^{3,1}, E. Wahyu Saptomo^{3,1}, Sri Wasisto³, Richard G. Roberts¹

¹ Centre for Archaeological Science, School of Earth and Environmental Sciences, University of Wollongong, Wollongong, NSW 2522, Australia;

² Institut für Naturwissenschaftliche Archäologie, Eberhard-Karls-Universität Tübingen, Rümelinstrasse 23, 72070 Tübingen, Germany;

³ Pusat Penelitian Arkeologi Nasional, Jakarta 12510, Indonesia;

⁴ Department of Anthropology, Lakehead University, Thunder Bay, Ontario P7B 5E1, Canada;

⁵ Human Origins Program, Department of Anthropology, National Museum of Natural History, Smithsonian Institution, Washington DC 20013, USA.

Abstract

Liang Bua, a karstic cave located on the island of Flores in eastern Indonesia, is best known for yielding the holotype of the diminutive hominin Homo floresiensis from Late Pleistocene sediments. Modern human remains have also been recovered from the Holocene deposits, and abundant archaeological and faunal remains occur throughout the sequence. The cave, the catchment in which it is located and the gross aggradational phases of the sediment sequence have all been subject to a great deal of scientific scrutiny since the discovery of the holotype of H. floresiensis in 2003. A recent program of geoarchaeological research has extended analyses of the site's deposits to the microstratigraphic (micromorphological) level. The stratigraphic sequence in the cave is well defined but complex, comprising interstratified sediments of diverse lithologies and polygenetic origins, including volcanic tephra, fine-grained colluvium, coarse autogenic limestone gravels, speleothems and anthropogenic sediments, such as combustion features. The sedimentological and chemical heterogeneity suggest that processes of site formation and diagenesis varied markedly through time, both laterally and vertically. We present initial results from samples collected in 2014 from an excavation area near the rear of the cave, which yielded radiocarbon ages from charcoal that fill an important temporal gap in the chrono-stratigraphic sequence of previously excavated areas of the site. The results indicate marked changes in site environment and hominin activity during the Late Pleistocene, relating primarily to the degree to which the cave was connected to the hydrogeological system and to the varying intensities of use of the cave by hominins. Importantly, we identify anthropogenic signs of fire use at the site between 41 and 25 thousand years ago, most likely related to the presence of modern humans.

1. Introduction

Flores is a tectonically active, oceanic island situated in the central sector of the Indonesian Archipelago and forms part of the Banda Volcanic Arc (Westaway et al., 2009a, b) (Figure 1a). Liang Bua is a large karstic cave situated in the central western part of the island (Figure 1b,c) and formed in the base of the northern

slopes of a low mountain of Miocene limestone (Figure 2a,b). It probably developed originally as a sub-surface dissolution chamber, or doline, which subsequently collapsed and was exposed sub-aerially as the adjacent river—the Wae Racang—cut laterally and vertically into its floodplain (Westaway et al., 2009a). The 2001–2004 excavations at Liang Bua recovered the remains of a previously unknown hominin species, *Homo floresiensis*, and this discovery has raised many interesting questions about the evolutionary history of this enigmatic species and past patterns of hominin dispersals and interactions between Africa and Island Southeast Asia (Brown et al., 2004; Morwood et al., 2004, 2005; Dennell and Petraglia, 2012; Boivin et al., 2013; Cooper and Stringer, 2013; Bellwood, 2014; Dennell et al., 2014; Groucutt et al., 2015; Reyes-Centeno et al., 2015; Sutikna et al., 2016).

Figure 1: (a,b) Location of Liang Bua on the island of Flores in Island Southeast Asia; (c) plan of the site with the area of focus for the present study denoted by the red rectangle, and the location of the stratigraphic column on the western profile (Figure 4) indicated by the red arrow (modified from Sutikna et al., 2016).

Ongoing excavations at Liang Bua are revealing a deep and spatially complex series of interstratified clastic sediments and chemical precipitates (Figure 2c–e), the deposition of which most likely correlates with marked changes in depositional environment at the site over the last two hundred millennia (Westaway et al., 2009b; Sutikna et al., 2016). A robust understanding of the formation, preservation and degradation of the site is essential to draw meaningful inferences about the rich assemblages of stone artefacts and hominin and other faunal remains recovered from the deposits. This need has become even more apparent following the recently revised interpretation of the stratigraphy and chronology of the Liang Bua deposits

and the *H. floresiensis* remains found within them (Sutikna et al., 2016). This new evidence suggests that all skeletal remains of *H. floresiensis* and artefacts attributed to this species are between about 100–60 and 190–50 thousand years (ka) old, respectively (Sutikna et al., 2016), and do not extend until ~17 or 13–11 thousand calibrated radiocarbon (^{14}C) years before present (ka cal. BP) as suggested previously (Morwood et al., 2004, 2005, 2009; Roberts et al., 2009).

Figure 2: (A) Geomorphological context of Liang Bua (blue arrow), situated at the base of a low hill, and (B) view of the interior of the cave taken from near the rear wall; (C) view from the central rear of the cave looking northeast, showing Sector XXIV (the focus of this study) in the foreground and indicated in green; in the background are excavated sectors near the eastern wall (see Figure 1c); (D) lower part of sequence exposed in west profile of Sector XXIV, with combustion feature (red arrow, Unit 5), iron-stained layer with flowstones (upper black arrow, Unit 4), flowstone separating Units 2 and 3 (lower black arrow), and truncation horizon at Unit 1–2 interface shown by dashed line, scale is 10 cm (yellow bar in bottom right corner); (E) upper flowstone separating Units 8 and 9 with manganese oxide horizon beneath, scale in bottom right corner is 10 cm). Photographs in (A) and (B) by Djuna Ivereigh (IndonesiaWild.com).

Figure 3: Stratigraphic schemes compiled from multiple exposures of the sequence across Liang Bua (at left, modified from Sutikna et al., 2016) and of Sector XXIV (at right), the focus of this study. The thicknesses of the sediment columns are only approximate and are not to scale, representing roughly 15 m and 4 m of vertical sequence, respectively. This disparity in thicknesses is related to the relatively shallow depth of deposits at the rear of the cave. Cross-correlation between the sequences is possible using a flowstone and tephra T3, with possible correlation between lower flowstones indicated. The 46–20 ka gap in the sequence reported by Sutikna et al. (2016) is mostly filled by the new sequence dated in the rear of the cave. The new ^{14}C ages (in ka cal. BP) are shown in red; ages in blue are from Sutikna et al. (2016).

Deposits dated to between ~46 and 20 ka cal. BP are conspicuously missing from the main areas excavated previously and this hiatus in the stratigraphic record covers a crucial time period of potential hominin prehistory on Flores (Sutikna et al., 2016) (Figure 3). Currently, the earliest evidence for modern humans on Flores comes from the Holocene sequence at Liang Bua and suggests a relatively continuous presence at the site after ~11 ka cal. BP (Morwood et al., 2004, 2005, 2009; Moore et al., 2009). In contrast, archaeological evidence suggests modern humans were on Timor by ~42 ka cal. BP (O'Connor et al., 2011; O'Connor, 2007, 2015) and had reached Australia by ~50 ka ago (Roberts et al., 1990, 1994; Turney et al., 2001; Bowler et al., 2003; Allen and O'Connell, 2014; Clarkson et al., 2015; Hiscock, 2015; O'Connell and Allen, 2015). The discovery and documentation of ~46–20 ka deposits at Liang Bua or elsewhere on Flores would potentially provide critical details for addressing questions regarding potentially late-surviving populations of *H. floresiensis* and/or an earlier presence of modern humans on the island.

In 2011, an area of 1 m by 2 m (Sector XXIV) was excavated in the middle rear of the cave (Figures 1c and 2c). The primary goal of this excavation was to document the possible southernmost extent of tephra T3 (~50–47 ka), one of eight tephras (T1–T8) identified in the stratigraphic sequence at Liang Bua (Sutikna et al., 2016). T3 is a key stratigraphic layer that overlies all known *H. floresiensis* remains. In 2014, a charcoal sample from 152 cm depth (below the present surface of the cave floor) in Sector XXIV returned an unexpectedly early age of 34.5–33.9 ka cal. BP (95% confidence interval). This result was 15 millennia older than any of the ¹⁴C ages obtained previously from Liang Bua (Roberts et al., 2009) and raised the possibility that much of the unexplored rear of the cave could preserve deposits within the 46–20 ka cal. BP interval, thus providing a more complete picture of site formation and hominin activities over the last ~190 ka. Thus, a 1 m by 2 m area (Sector XXVII) immediately adjacent to the north wall of Sector XXIV was excavated (Figure 1c) in 2014 and additional charcoal samples were obtained for radiocarbon dating.

In an earlier geomorphological study of Liang Bua, Westaway et al. (2009a, b) divided the cave into a rear and front chamber, with coarse conglomeritic and fine colluvial sediments deposited at the rear, and a deep, well-stratified sequence at the front. They reconstructed diachronic changes in depositional environments by employing broad-scale sedimentological and geomorphological observations from several exposures across the site, using luminescence, electron-spin resonance, uranium-series and ¹⁴C chronologies (Roberts et al., 2009). They identified a number of processes driving sediment accumulation and degradation, including fluvial (riverine sediments), colluvial (slopewash), chemical precipitation (flowstone formation), volcanic (aeolian tephra) and post-depositional processes (subsidence and slumping). However, they did not attempt to reconstruct in fine detail the depositional and post-depositional environments at the site.

To develop high-resolution models of depositional and post-depositional change at Liang Bua, a program of multi-scalar geoarchaeological research was initiated in

2014, focussing initially on Sector XXIV because of its potential to provide new information regarding the history of the site during this previously undocumented period. We targeted the western wall of this sector to improve our understanding of the formation and preservation of sediments located in the rear of the cave, and their association with those recorded at the southern edge of the front chamber. The wider goals of this geoarchaeological research are to analyse the site and stratigraphy at varying scales, from the macro to the micro, using a suite of field and analytical techniques, including landscape geomorphological survey, sedimentology, micromorphology, and vibrational spectroscopy (i.e., Fourier-transform infrared [FTIR] and Raman spectroscopy). Here we report initial results from the micro-scale component of the study. Our specific aims were to investigate and clarify the environmental conditions during deposition of each lithological layer, identify the diagenetic processes that have occurred (e.g., any modification of the sediments or the material contained within them) and to explore possible signals of hominin behaviour preserved within the deposits potentially spanning the chronological gap from ~46 to 20 ka ago. Together, these data provide critical and much needed context for interpreting the environmental history of the site and its rich archaeological and palaeontological record.

2. Methods

Backfill was removed from the previously excavated 1 m by 2 m portion of Sector XXIV. Detailed macro- and micro-stratigraphic descriptions of the ~4 m depth of deposits exposed along the western wall of the Sector were undertaken in the field, and ten lithological units were identified (referred to here as Units 1–10). Six samples for micromorphological analysis (MM4–MM9) were collected to characterise the major stratigraphic units and microfacies (Figure 4, Tables 1 and 2); samples MM1–MM3 were collected from Sector XII to target specific tephra layers that do not occur in Sector XXIV and were not included in this study.

Micromorphology samples were collected as oriented blocks using plaster bandages to retain their integrity. Once extracted, these samples were shipped to the University of Wollongong (Geoarchaeology Laboratory in the Centre for Archaeological Science), where they were partially unwrapped and oven-dried at 40°C for five days or until dry. Each block was impregnated with crystic resin (Dalchem) diluted with styrene at a ratio of 9:4 and catalysed with methyl ethyl ketone peroxide (MEKP) to yield 12.5 ml per litre of resin/styrene mixture. After curing for seven days, the samples were returned overnight to the drying oven at 50°C. They were then trimmed with a circular saw fitted with a diamond encrusted masonry saw blade into 50 mm by 75 mm ‘wafers’ that were sent to Spectrum Petrographics (Vancouver, WA, USA) for manufacture of the final thin sections.

Thin sections were observed with stereo and petrographic microscopes at magnifications ranging from 8x to 200x under plane-polarised light (PPL) and cross-polarised light (XPL). In addition, thin sections were scanned on a flatbed scanner at

1 2400 dpi, both in reflection mode and without the flatbed cover (Goldberg and
2 Aldeias, submitted); the latter produces an image similar to dark field illumination
3 and highlights highly reflective areas, such as those rich in carbonate and iron. Thin
4 section terminology follows that of Stoops (2003).

5
6 A total of nine charcoal samples from Sector XXIV and the immediately adjacent
7 Sector XXVII were sent to DirectAMS (Seattle, WA, USA) for ^{14}C dating, where they
8 were pretreated using acid–base–acid procedures (Table 3). The ^{14}C content was
9 then measured using accelerator mass spectrometry and the conventional ^{14}C ages
10 were converted to calendar-year age ranges at the 68% and 95% confidence
11 intervals using the SHCal13 southern hemisphere calibration data set (Hogg et al.
12 2013) and CALIB 7.1 (Stuiver et al., 2016; <http://calib.qub.ac.uk/calib/>).

13
14 FTIR spectra were recorded in the mid-infrared region ($600\text{--}4000\text{ cm}^{-1}$) using a
15 Lumos infrared microscope from Bruker. The spectra were measured directly on the
16 thin sections MM4B and MM6B. All spectra were recorded in absorbance mode
17 using an attenuated total reflectance (ATR) objective fitted with a germanium ATR
18 crystal. The spectral resolution was 4 cm^{-1} and 64 individual scans were combined
19 to obtain each spectrum. In cases where the FTIR spectrum of the resin also
20 appeared in the spectra, a spectrum recorded on a piece of the same resin was
21 subtracted using the interactive subtraction option in the OPUS software from
22 Bruker.

23
24 A WITec 3000 Alpha spectrometer was used to obtain the Raman spectra. A 532 nm
25 solid state laser (WITec Focus Innovation) was used as the excitation source and a
26 long distance 50x Zeiss objective focussed the laser on the samples, resulting in a
27 spot size of $\sim 2\text{ }\mu\text{m}^2$. The number of acquisitions and acquisition time depended on
28 the crystallinity of the material, but typically 10 acquisitions, each of 6 s duration,
29 were made at a spectral resolution of 2 cm^{-1} .

1 **Table 1:** Summary characteristics of the lithological units under examination for this study, using field-data collected in 2014 and 2015. The ages are
2 based on the new radiocarbon chronology presented in this study (see Table 3), except: (*) U-Th ages measured previously on calcite flowstones
3 (Westaway et al., 2007a; Sutikna et al., 2016); (¹) broad age ranges estimated by the dating of associated units in this study and Sutikna et al. (2016).

Unit no.	Description (sedimentology)/ Nature of interface with underlying unit	Field interpretation	Archaeo-material	Thin section	Age
10	Firm to compact, silts and silty clays. Homogeneous with very weak bedding. Becomes looser towards the modern ground surface. Organic rich	Recent to sub-recent cave floor sedimentation – multiple origins including colluvial, aeolian and bedrock attrition	Possible Neolithic hearth?	—	—
9	Clay silt with frequent sand-sized inclusions of calcium carbonate and occasional fine sand	Possibly wetter conditions, causing post-depositional alteration of underlying flowstone	—	—	—
—	FLOWSTONE Laminar calcite speleothem overlying manganese-stained and cemented sediment	Fine-grained colluviation in humid conditions Humid conditions, laminar sheetflow. Post-depositional diagenetic transformation of carbonate flowstone	—	MM4	—
8	Variably compact sands with frequent poorly-sorted limestone gravels. A thick (~5 cm) bed of carbonate-cemented sediment is present within this unit. Occasional charcoal fragments and flecks recorded in the lower region	Coarse, autogenic limestone gravel originating from the physical breakdown of the walls and roof. Presence of water attested by carbonate-bonded sediments? Generally dry?	Occasional combustion bi-products	MM4	25.0–24.4
7	Partially indurated sand with occasional to moderate frequencies of limestone gravel. Distinct lenses and beds of ash and fine charcoal interspersed in the matrix	Abundant evidence of reworked combustion bi-products, but without intact combustion features. Layers of indurated sediment within this unit suggest periods of standing water within otherwise dry period	Frequent combustion bi-products	MM5	31.1–34.5
6	Moderately compact silts with frequent small limestone gravel and calcareous granular inclusions. Very occasional anthropogenic inputs, including fine charcoal flecks and fragments	Reworking of eroded parent bedrock by colluviation and spalling of material from walls and roof. Sporadic use of cave by hominins	Combustion bi-products	MM6	33.3
5	Loose, limestone gravel in a sandy matrix, fining upwards to medium to small gravels in clay silt matrix. Occasional charcoal fragments and/or finely divided charcoal powder interspersed within the sediment matrix. Localised lenticular burnt feature present in upper part of this unit containing abundant ash and charcoal	Coarse autogenic material originating from the physical breakdown of the parent limestone intermixed with coarse colluvium. Shift to drier conditions? Anthropogenic burning activity	Combustion feature, hearth	MM6	38.3–40.9
4	FLOWSTONE AND IRON PAN Thin upper and lower flowstones (~ 1 – 2 cm), seal a compact Fe-stained sediment	Surface stabilisation, humid, wetting-drying? Iron-panning	—	—	46.6*
3	Firm and homogeneous, clay-rich silts with very occasional fine gravel inclusions. This unit has affinities with Unit 2, but	Re-activation of colluvial sedimentation	—	MM7	~50–47 ¹

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with a higher clay content. The distal end of tephra T3 is present within this unit where it banks up against and pinches out on the angled lower surface					
—	FLOWSTONE	Surface stabilisation, laminar sheetflow	—	—	49.9*
2	Firm, weakly stratified and sub-horizontally bedded, clay silts with sand-sized and fine gravel inclusions. Blocky structure. Pale and calcareous towards upper contact. Fine white laminae of calcium carbonate increase in uppermost 0.10 m directly beneath flowstone	Colluvial sediments accumulating on angled slope of cave floor topography. Calcareous laminae may foreshadow formation of overlying flowstone?	—	MM8 MM9	~190–50 ¹
1	Firm to compact, horizontally bedded, fine to medium, interbedded sands, silts and clay. Layers exhibit various bedform morphologies including ripples with clay drapes and iron-stained foresets	Fluvial, in-channel, channel-marginal and slackwater sediments	—	MM9	~190–50 ¹

1 **Table 2:** Summary micromorphological characteristics of the units as observed in the thin sections, including interpreted process and inferred
2 depositional environment.

Thin section	Unit no.	Micromorphological characteristics	Process	Depositional environment
MM4A	9	Very loose and porous structure, with abundant clay aggregates, frequently slaked. Common clay coatings on mineral grains and within void spaces. Heavily bioturbated. Frequent vughs and channel voids	Colluviation (wet)	Sub-recent (mid to late Holocene) colluvial accretion of sediments across cave floor environment
MM4B	9	Same as MM4A		
	8	Severely phosphatised mineral layer overlying manganese-stained sediments, most likely due to the presence of phosphate above the flowstone (subsequently eroded). Authigenic phosphates present below, and local decalcification immediately below modified flowstone. Secondary carbonate precipitation observed in void spaces and in lower portion of thin section	Colluviation (dry) Mineral precipitation Diagenesis (guano deposition?)	Humid environment with persistent ingress of groundwater resulting in carbonate flowstone production. Subsequent dissolution and phosphatisation of flowstone, and localised decalcification of underlying calcareous sediments by acid-loaded percolating water
MM5A	7	Loosely-packed and porous silty sand with frequent coarse angular limestone and speleothem fragments. Poorly sorted, with localised patches of finer-grained clays and silts. Intensive bioturbation, with silt coatings common. Fine charcoal dispersed throughout matrix in low to medium quantities. Clay aggregates often mechanically fractured	Roof spall Colluviation (dry)	Coarse sediments accumulated due to physical attrition of the walls and roof of the cave, with some minor input of colluvium (cracked clay clasts). High porosity with relatively large interstitial void spaces. Generally dry environment with sporadic groundwater throughput
MM5B	7	Same as MM5A, but with localised Fe-staining and higher concentration of fine charcoal fragments and flecks		
MM6A	6	Loosely- to moderately-packed silts and sands with coarse, angular limestone fragments. Localised patches of finer-grained clays and silts towards upper portion. Infrequent charcoal flecks and fragments. Vughs occasionally contain re-precipitated calcium carbonate. Occasional Fe-staining of silt coatings	Roof spall Colluviation (dry) Hominin use of fire	Very similar to Unit 7, with evidence of sporadic water throughput evidenced by the increase in fine silts and clays Combustion feature is <i>in-situ</i> fireplace related to hominin activity in this rear area of the site
MM6B	6	In general, the sediments have close affinities with Unit 6 in MM6A. The exception is a micro-stratified combustion feature with very high occurrences of charcoal and ash (the latter being partly dissolved and re-crystallised). High frequencies of thermally-modified (cracked and baked) clay aggregates, with basal rubified zone. Sediments below feature are highly calcareous, with finer-grained sediments above		
	5	Same as Unit 6 in MM6B, but highly calcareous and lower concentrations of fines	Roof spall Colluviation (dry)	Coarse autogenic sediments derived from the walls and roof of the cave with minor addition of colluvium under dry conditions

MM7	3	Fine silts and clays, including clay aggregates and fine clay matrix. Coarse components dominated by rounded clay aggregates and low frequencies of poorly sorted mineral grains (primarily quartz). Occasional small vughs and channel voids. Bioturbation evident above ash, and thin lens of secondarily deposited ash intermixed with silts and clays.	Colluviation Volcanism	Colluviation under slopewash and gravitational conditions Deposition of windborne volcanic ash (tephra), banked up against angled surface. Possible thermal reaction with underlying sediment and shrinkage of fines Air-borne volcanic ash deposition (Tephra T3). Acid environment, promotion of mineral dissolution Sheetwash/slopewash sedimentation. Localised diagenesis due to acid dissolution of mobile minerals (calcite)
		Volcanic ash is very finely laminated with fining-up sequence and occasional vesicular pumice grains. Planar void present immediately beneath thin volcanic ash, where it is also locally decalcified		
MM8	2 (upper)	Very similar to Unit 3 but with a higher porosity. Vughs and planar voids, occasionally coated with silt. Larger clay and silt rip-up clasts in upper half. In upper third very finely laminated calcium carbonate and occasional thicker bands of calcite with plant cellular structure	Colluviation Mineral precipitation	Continuing water ingress to site and slopewash colluviation of fines under wet conditions, with small-scale erosion of clays from surface and rear of cave. Increasingly persistent surface flow causing calcite precipitation at and below the surface, decreasing porosity. Stability of cave floor causes reduction of colluvial input. Biologically-mediated incipient flowstone formation
MM9	2 (lower)	Calcareous silt and clay with small quantities of fine sand (poorly sorted). Abundant clay clasts generally intact. Highly calcareous in localised areas. Becomes increasingly Fe-stained away from contact with Unit 1	Colluviation	Newly formed, steep-angled relief initiates slopewash sedimentation. Active erosion and re-mobilisation of sediments downslope from rear of site, coincident with activation of hydrological system connected by fissures in bedrock. Calcite present as fine, reworked limestone/calcite grains
	1-2 transition		Erosion	River migration away from cave, lowered base level
	1	Interbedded calcite sands, silts and clays. Localised Fe-staining occurring within b-fabric of clays and silts, and infilling void spaces. Deformation features at upper contact and occasional small burrows with silt coatings	Fluvial sedimentation	River inundation of cave system. Variable energy fluvial sedimentation, including deposition of calcareous channel sand, and fine-grained slackwater deposits.

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Table 3: New ^{14}C ages for charcoal from Sectors XXIV and XXVII

Sample code	Depth (cm)/ Unit	Methods ¹	$\delta^{13}\text{C}$ (‰)	^{14}C (yr BP)	Age		
					Median Calibrated yr cal. BP	Calibrated Range (ka cal. BP)	
						68% CI ²	95% CI ²
D-AMS-007550	143/7	ABA / AMS	-26.3	27,954 ± 125	31,605	31.75–31.42	32.03–31.29
D-AMS-005947	152/7	ABA / AMS	-28.1	30,168 ± 158	34,161	34.32–33.98	34.52–33.85
D-AMS-007546	153/7	ABA / AMS	-28.0	27,466 ± 120	31,263	31.36–31.16	31.46–31.07
D-AMS-007547	154/7	ABA / AMS	-23.7	27,587 ± 107	31,328	31.43–31.27	31.53–31.13
D-AMS-007549	201/6	ABA / AMS	-33.2	29,074 ± 153	33,258	33.49–33.04	33.66–32.82
D-AMS-007555	137/8	ABA / AMS	-22.1	20,516 ± 58	24,616	24.77–24.45	24.95–24.36
D-AMS-007551	237/5	ABA / AMS	-21.7	36,323 ± 259	40,930	41.25–40.64	41.48–40.31
D-AMS-007552	239/5	ABA / AMS	-27.1	33,817 ± 173	38,284	38.54–38.07	38.70–37.67
D-AMS-007553	250/5	ABA / AMS	-20.4	22,288 ± 94	26,463	26.61–26.28	26.85–26.14

¹ABA, acid-base-acid pretreatment; AMS, accelerator mass spectrometry measurement technique;

²CI, confidence intervals

3. Radiocarbon dating

The ^{14}C dating results for the charcoal samples from Sectors XXIV and XXVII are shown in Table 3 and Figure 4. The 95% confidence interval age range of the studied sequence is between ~41.5 and 24.4 ka cal. BP, confirming that this rear area of the cave preserves deposits that are missing only a few metres further to the north in all previously excavated areas of the cave. One of the nine samples (D-AMS-007553) returned a stratigraphically inconsistent age (26.9–26.1 ka cal. BP at the 95% confidence interval) for Unit 5. Given the relatively large interstitial void spaces between gravel clasts in this layer, it is possible that this anomalously young age (relative to two other ages from Unit 5 that accord with the ages from Units 6–8) relates to charcoal that has infiltrated from higher up in the sequence.

1
2 **Figure 4:** Stratigraphy of western profile of Sector XXIV. Units (encircled numbers),
3 micromorphological samples (rectangles), calibrated radiocarbon ages (in ka cal. BP, black numerals)
4 and previously reported U-series ages (in ka, blue numerals; Westaway et al., 2007a; Sutikna et al.,
5 2016) are indicated.

4. Macro-stratigraphy and micromorphology

Thin section MM9 (Units 1 and 2; Figures 4 and 5)

Units 1 and 2 occur stratigraphically below tephra T3 and the flowstone that underlies it (Figure 4). Although the ages of these two units at this exact location are yet to be determined, they are interpreted here to be between ~190 and 50 ka, based on their stratigraphic relationships with the rear conglomerate wall and T3, respectively (Sutikna et al., 2016). Three distinct lithological facies are apparent in thin section MM9, with the two lowermost corresponding to Unit 1 and the upper correlating with Unit 2 (Figure 5a). The upper part of Unit 1 exhibits an erosional contact that dips towards the mouth of the cave at an angle of ~45–55°. The basal sediments of Unit 1 comprise horizontally-bedded sediments of calcareous, iron-stained sand, grading upwards into laminated fine sands and silts (Figure 5b,c), the latter exhibiting deformation structures at the upper interface (e.g., shear and contortions). The sediments from Unit 2 that rest unconformably on Unit 1 consist of rounded clay aggregates derived from sediments similar to those just beneath the contact, and are cemented by micrite and in some cases by sparite.

Figure 5: Thin section MM9 from Units 1 and 2. **(a)** Macroscan (dark field view) showing the sharp erosional contact (arrows) between Units 1 and 2. Unit 1, below the contact, comprises horizontally-bedded calcareous sands overlain by orange silts and clays. Unit 2 is looser and more calcareous, being secondarily cemented. Rectangle refers to enlarged view in (b) and (c); **(b)** interbedded silt and clay with localised iron staining and mottling. The vertical crack microstructure is due to the clayey nature of the sediment and relates to post-excavation drying and shrinking. Some bioturbation is evident by the mm-sized circular void at centre-left filled with loose material (PPL); **(c)** lowermost zone showing calcareous sand that is locally cemented by sparry calcite (XPL).

Thin section MM8 (Unit 2; Figures 4 and 6)

This sample was taken from the upper part of Unit 2, directly beneath a laterally extensive flowstone (~2–4 cm thick) (Figures 4 and 6a). The sediments consist of poorly sorted, sand-sized clay aggregates in a clayey, calcitic matrix. In addition, occasional fragments and flecks of charcoal, fragments of flowstone and bone, and highly weathered rip-up clasts of silt and clay are present in the matrix. In the upper part of the thin section, layers of finely laminated calcite occur within the matrix (Figure 6d,e), becoming increasingly well-developed towards the top, immediately below the base of the flowstone. The increase in these calcite laminae, which exhibit an organic cell structure (Figure 6d), parallels an increase in carbonate cementation.

Figure 6: Thin section MM8 from Unit 2. **(a)** Macroscan (dark field) shows calcitic laminae representing incipient flowstone formation. The brown, rounded clay aggregates are similar in composition to the bedded silts and clays in Unit 1 **(b)** lower region of thin section shows clay-rich aggregates (with quartz and limestone sand inclusions) that have been compressed and plastically deformed (XPL); **(c)** same as (b), in PPL; **(d)** flowstone showing finely laminated structure with biological crusts, again indicating flowstone formation partly driven by algae and/or moss growth, as can be seen at the rear of the cave today. **(e)** detailed view of flowstone at base exhibiting a laminar cellular structure suggesting biologically-mediated calcite precipitation. Rounded clay grain in upper right has a similar composition as clays in Unit 1 (PPL);

Thin section MM7 (Unit 3; Figures 4 and 7)

Thin section MM7 (Unit 3; Figure 7a) is separated from Unit 2 by the flowstone referred to above. Unit 3 bears affinities to Unit 2, being clay-rich, densely packed, and poorly sorted (Figure 7b,c). A discrete volcanic tephra with vesicular pyroclasts, which pinches out to the south towards the rear of the cave, represents the southernmost extent of T3 (~50–47 ka) at Liang Bua. A large planar void separates the tephra from the underlying decalcified sediment (Figure 7a), which exhibits weakly developed fissures aligned perpendicular to the tephra. Internally, the

tephra exhibits a uniform fining-up texture (Figure 7c,d). Above the primary tephra band there is evidence for secondary tephra deposition in the form of a thin laminated band, possibly relating to the reworking of the primary tephra by sheetwash. Such laminations are absent in the primary tephra band, precluding deposition by water of this volcanic ash. In the uppermost 1–2 cm of MM7 (Figure 7a), the sediments become looser and more porous, with local occurrences of grain aggregates (~3 mm in diameter).

Figure 7: Thin section MM7 from Unit 3. **(a)** Macroscan with distal end of tephra T3 evident. Sediments in the upper 1–2 cm are heavily bioturbated; **(b)** matrix in upper region of thin section showing limestone clast at right (itself containing volcanic grains) and dense, partially aggregated clay-rich matrix with inclusions of volcanic grains (PPL); **(c)** clay-rich matrix with heterogeneous array of coarser components reminiscent of a colluvial diamict (PPL); **(d,e)** detail of tephra showing clear fining-up sequence (XPL and PPL).

Thin sections MM6A and MM6B (Units 5 and 6; Figures 4 and 8)

Units 5 and 6 are between ~41.5 and 32.8 ka cal. BP in age, based on the dated charcoal samples from these units (Table 3). Sample MM6 includes sediments that indicate a major shift in depositional environment. Two thin sections were made from this sample, with MM6A (Figure 8a,b) and MM6B (Figure 8f) corresponding to the upper half (Unit 6) and lower half (Units 5 and 6) of the sample, respectively.

In the field, Unit 5 heralds a marked increase in coarse limestone gravel that continues up to and includes Unit 8 (Figure 4), allied with a highly calcareous matrix. At the top of Unit 5 is a lenticular combustion feature that measures ~0.4 m across (Figure 2d), as observed in profile (Figures 3 and 7a,b). This feature has a distinct internal structure, comprising three micro-horizons, which are from bottom to top (Figure 8a):

1. *Reddened substrate* formed in a fine-grained, calcareous sand and silt, with inclusions of bright red, heat-cracked clay aggregates;
2. *Dark, organic-rich layer* containing charcoal, ash aggregates, some burnt bone and fine sand-sized aggregates of red and organic-rich clay; and
3. *Upper calcareous layer* of mostly intact micritic ashes (Figure 8c,d); in some areas the calcite has been dissolved and reprecipitated as micrite cement.

Figure 8: Thin sections MM6B and MM6A from Units 5 and 6. **(a)** Macroscan of MM6B. The vertical tripartite structure of the combustion feature is shown, with basal reddened substrate (1), dark organic-rich layer (2), and an upper calcareous ash layer (3), indicating that this feature is intact and in primary position; **(b)** note the bright calcareous area in the lower part of the dark field scan,

1 associated with calcareous environment adjacent to flowstone; **(c)** remains of rodent bones held
2 within a disintegrating raptor pellet (PPL); **(d)** bedded ashes in the upper part of the combustion
3 feature (PPL); **(e)** Raman (left) and FTIR spectra recorded from a selected area of MM6B—see box in
4 (a)—showing the distribution of calcite and calcite-phosphate mixtures, as well as the iron oxides
5 colouring the clay yellow (goethite) and red (hematite); **(f)** dark field macroscan of MM6A showing
6 heterogeneous nature of the deposit, including angular clasts of limestone and speleothem (roof fall),
7 some of which show localised laminated calcareous coatings (arrows). Also note the contrast
8 between these sediments and the fine-grained colluvium from the base of the sequence, where coarse
9 autogenic material is a major component of the inclusions; **(g)** isotropic, phosphatised area in the
10 centre (XPL); **(h)** detail of laminated calcite coating on speleothem fragment. This stalactitic tufa
11 formed on the limestone before it was detached from the ceiling (XPL); **(i)** lower left-hand quadrant
12 of MM6A. Note the partially decalcified nature of the matrix in the lower right-hand side of the
13 photomicrograph. Mineral grain is hornblende (PPL).

14
15
16 Raman and FTIR spectroscopy (Figure 8e) reveal clay and calcite are present
17 throughout thin section MM6B, with the exception of the calcareous ash layer,
18 where FTIR spectra of calcite and calcite mixed with phosphate were recorded. The
19 position of the strongest band in the calcite spectra varied between 1410 and 1390
20 cm^{-1} , possibly due to the varying amount of phosphate present in the structure,
21 thereby illustrating the heterogeneous process of diagenesis (Figure 8g–i). The
22 pigment colouring the clay yellow was identified as goethite, $\text{FeO}(\text{OH})$, which was
23 oxidised to hematite (Fe_2O_3) when baked by the fire.

24
25 Unit 6 occurs in the upper part of thin section MM6B and throughout thin section
26 MM6A (Figure 4). Its composition is very similar to Unit 5, but with an increase in
27 void space (Figure 8f). The key characteristics of Unit 6 are high frequencies of
28 coarse autogenic material comprising speleothem fragments and limestone spalls
29 (500 μm to 10 mm in maximum dimension; Figure 8f) originating from the cave
30 walls and roof. We observe a significant decrease in fines (clays and fine silts) and a
31 marked increase in anthropogenic and biogenic components (e.g., charcoal, bone,
32 owl pellet; Figure 8c). Most of these inclusions are fractured and broken; for
33 example, no intact features can be seen at the top of thin section MM6A.

34 35 ***Thin sections MM5A and MM5B (Unit 7; Figures 4 and 9)***

36 Unit 7 is ~34.5–31.1 ka cal. BP in age, based on the dated charcoal samples (Table
37 3). The coarse components of this lithological facies are similar to those in the
38 underlying Unit 6, containing frequent, large and angular autogenic limestone and
39 speleothem fragments, as well as mechanically fractured clay intraclasts/fragments
40 (Figure 9a–c). Fine charcoal fragments and ash are also scattered throughout the
41 matrix (Figure 9d,e). Two thin sections were made from sample MM5, the upper half
42 of Unit 7 represented by MM5A (Figure 9a) and the lower half by MM5B (not
43 shown).

44
45 The upper part of sample MM5 is noteworthy for its granular porosity and
46 abundance of loosely aggregated, angular clay clasts (Figure 9a). The matrix in the

lower part of MM5A is calcareous, consisting of calcite-cemented, sand-sized limestone particles and micritic ash (Figure 9d,e). By contrast, the upper part of MM5A contains only isolated patches of micritic groundmass, which appear to be partially dissolved. Similarly, we noted the presence of etched limestone with increased porosity, and dissolved ash and decalcified bone fragments. These features show two cycles of diagenesis: an initial phase represented by calcite cementation of the ashes and limestone sand, followed by a phase of patchy calcite dissolution. Furthermore, these observations suggest that decalcification probably took place from the top down, which is consistent with phosphatisation of the overlying deposit (thin section MM4B, described below). Some of the calcite within the matrix is derived from loose, unbedded aggregates of ash, which point to reworking of former combustion features. Bioturbation increases in the upper part of MM5A (Figure 9a), as does porosity, and is specifically exemplified by a large elliptical void (~35 mm across) in the middle of sample MM5A; the void is partially infilled with silt and clay containing inclusions of limestone and clay clasts.

Figure 9: Thin section of MM5A from Unit 7. **(a)** Dark field macroscale showing predominantly angular aggregate grains of orange clay, some of which are fractured, reworked from the back of the cave by water ingress occurring during a generally drier period. The elliptical void in the centre is lined with poorly sorted silt and clay that also contains sand-sized aggregates of clay. Note the presence of black flecks of charcoal scattered throughout the slide, indicative of anthropogenic inputs. Arrow points to a localised concentration of calcareous ash, shown in detail in (b-e); **(b,c)** rounded clay grain at right exhibits a desiccation crack filled with secondary calcite that is coeval with that in the matrix. Note the partially decalcified domain at left that is isotropic in (c) (XPL). These images demonstrate that the sediments were deposited, cemented and then partially decalcified; the latter process is likely tied to the phosphatisation visible in the overlying sample MM4 from Units 8 and 9; **(d,e)** detail showing partially cemented calcitic ashes, with arrows pointing to individual ash rhombs in (d). At right is a fragment of bone with recrystallised ash in the voids (PPL and XPL, respectively).

Figure 10: Thin section of MM4B from Units 8 and 9. Macroscans in normal (a) and dark field (b) view. The lighter, centre part consists of a cm-thick band of flowstone, which has been decalcified (shown by dissolution voids) and also phosphatised. The dark staining beneath is secondary manganese oxide. Both phosphate and Mn oxides are common diagenetic bi-products associated with leaching and the presence of bat guano. The upper part is composed of loose aggregates of angular clay clasts and rests on the phosphatic zone with a sharp, erosional contact; it is extensively bioturbated. The clay aggregates are similar in composition to the sediments at the bottom of the slide, although the latter are calcareous and contain some limestone fragments. The dark field scan highlights the light-coloured, calcareous deposits at the base, which contain limestone grains and have been bioturbated. Note the lack of reflection of the decalcified flowstone that is now phosphatic; (c, d) shows vugs that attest to dissolution of the carbonate and subsequent coating of slightly iron-rich, yellow-brown calcareous silt (PPL and XPL, respectively); (e) Raman (left) and FTIR spectra showing the distribution of clay, phosphate and manganese oxide throughout the sample; (f) phosphatised flowstone (PPL); (g) phosphatic zone showing ghosts of the original calcite grains that now have low-order birefringence of apatite (XPL).

Thin sections MM4A and MM4B (Units 8 and 9; Figures 4 and 10)

Unit 8 is dated to 25.0–24.4 ka cal. BP, based on a single dated charcoal sample (D-AMS-007555 in Table 3). Two thin sections were made from sample MM4, which spans Units 8 (MM4B; Figure 10a,b) and 9 (MM4A; not shown). These reveal a distinct change in depositional environment, with a switch to wetter environmental conditions indicated by repeated calcite precipitation and dissolution cycles (Figure 10a–d). Thin section MM4B captures the transition from lithological Units 8 to 9, while MM4A corresponds exclusively to Unit 9. In general, these sediments are richer in clay than those in Unit 7, and the overall aggregate size is much smaller than in the underlying units. The clay is identified as kaolinite by the typical OH stretching vibrations at 3696 and 3620 cm^{-1} in the FTIR spectrum (Figure 10e). Capping Unit 8, observed in thin section MM4B, is a laterally continuous, ~20 mm-thick flowstone. This flowstone has been diagenetically altered by phosphatisation throughout, along with the precipitation of Mn oxides below the top of the crust (Figure 10a,b,f,g). This Mn oxide is identified as MnO_2 , with a broad Raman band at 580 cm^{-1} (Figure 10e). Manganese oxides are sensitive to laser power; although this was kept quite low, MnO_2 was oxidised to Mn_3O_4 (655 cm^{-1}) by laser heating (Buciuman et al., 1998). A representative FTIR spectrum of the phosphate crust shows that the most intense peak, attributed to the asymmetric stretch vibration (ν_3) of the phosphate group, appears at 1024 cm^{-1} . This is a 17 cm^{-1} wavenumber shift from 1041 cm^{-1} reported for dahlite, which is the main component of similar crusts found in prehistoric caves such as Kebara and Hayonim (Weiner et al., 2002). The shift to lower wavenumbers also occurs in some Raman spectra, where the position of the symmetric stretch vibration (ν_1) of the phosphate group has shifted from ~962 cm^{-1} for dahlite to ~950 cm^{-1} attributed to amorphous calcium phosphate (Sauer et al., 1994). A possible explanation is that the humid tropical environment of Liang Bua inhibits crystallisation, but further work is necessary to verify this interpretation.

Directly overlying this weathered speleothem, with a sharp bounding interface, is a layer of finely aggregated angular clay fragments. This uppermost part of the profile contains very loose and porous sediments, as well as reworked aggregates that have very different compositions.

5. Discussion

5.1 Depositional and diagenetic environments inferred from the micromorphology

The results of the micromorphological analyses allow for a refined reconstruction of the depositional and diagenetic history of Liang Bua between ~190 and 20 ka ago (Figure 11).

Figure 11: Schematic illustration depicting the changing depositional environments at Liang Bua as observed in the micromorphological record, supplemented with data from Westaway et al. (2009b). Age estimates are as shown in Figure 3.

Unit 1, thin section MM9: fluvial sedimentation and incision (~190–120 ka)

Exposed at the base of the stratigraphic column, we record cross-bedded fluvial sands (Unit 1; corresponds with Unit 2 of Westaway et al., 2009b) that are consistent with deposition in a fluvial, channel-marginal environment, probably

1 sometime between ~190 and 120 ka ago when the Wae Racang still flowed within
2 the cave (Roberts et al., 2009; Sutikna et al., 2016). Variations in flow velocity
3 associated with this channel-marginal interaction deposited interstratified beds of
4 iron-stained, channel sands (small bars, medium-energy environment) and ripple
5 bedforms on which clay and silt drapes were deposited in a very low-energy
6 environment (Figure 5a). As the river migrated away from the site, downcutting into
7 its floodplain, the upper part of this alluvium was truncated, creating a steep-angled
8 surface susceptible to small-scale slumping, and on to which successive sediments
9 were deposited (Figure 2d).

10 ***Unit 2, thin sections MM9 and MM8: colluviation and flowstone formation***
11 ***(~190–120 to 50 ka)***

12
13 Following the retreat of the river from the cave, slopewash colluviation was initiated
14 under humid conditions. The water that mobilised these sediments entered the cave
15 via fissures at the rear, consistent with previous observations (Westaway et al.,
16 2009b). This accords with our observations of downslope movement of poorly
17 sorted sediments containing high frequencies of rounded clay and silt aggregates,
18 including reworked material scoured from Unit 1 beneath. The high frequency of
19 void spaces and the overall porous character of these sediments suggest intensive
20 bioturbation (probably by burrowing insects) in the damp environment at the rear
21 of the cave. As only a small amount of charcoal is present and it has been reworked,
22 we cannot ascertain whether it has a natural or anthropogenic origin.

23
24 A gradual switch in the hydrology of the cave is marked by the increasingly frequent
25 calcitic micro-laminae recorded in the sediment directly beneath the well-developed
26 flowstone that immediately overlies Unit 2. These calcitic micro-laminae features
27 show signs of biological structures, suggesting they were probably formed partly
28 through the presence of algae and/or mosses. Hydrologically, these incipient
29 flowstones record the early stages of persistent ingress of CaCO₃-charged spring
30 flow, precipitating calcite into the upper surface of the fine-grained sediment and/or
31 within patches of vegetation growing at the rear of the cave. This reorganisation of
32 the cave hydrology may reflect changes in the monsoonal cycle and concomitant
33 fluctuations in precipitation (Westaway et al., 2007b, 2009a).

34 ***Unit 3, thin section MM7: colluviation and volcanic activity (~50–47 ka)***

35
36 Above the flowstone that caps Unit 2, we detect a return to colluvial sedimentation.
37 Poorly sorted sediments again indicate downslope colluviation of both fine clays
38 (travelling partially in suspension) and coarser clay aggregates, which have been
39 reworked from older deposits further to the rear of the cave, many of which are in
40 the process of disaggregating (slaking). The aggregates are more densely packed in
41 the lower half of the thin section than in the upper half, above a layer of volcanic ash,
42 which is the distal expression of tephra T3. This tephra is thickest (~75 cm) from
43 the cave centre to the eastern wall, where it fills a basin-like depression in the relict
44 cave floor topography (Sutikna et al., 2016).

1
2 In Sector XXIV, the main (macroscopic) tephra band (~5 mm in thickness) is clean
3 and homogeneous, and displays a linear fining-up composition indicating burial in
4 primary position (see, for example, Morley and Woodward, 2011). This observation
5 is supported by a series of planar voids parallel and perpendicular to the base of the
6 tephra, consistent with thermal shrinking of the semi-saturated clays beneath. A
7 series of impure tephra laminations are recognised in the sediment matrix
8 immediately above the primary fallout, indicative of remobilisation of tephra
9 sourced from elsewhere in the cave or from outside via infiltration.

10 ***Units 5–8, thin sections MM6, MM5 and MM4: switch to drier conditions, hominin***
11 ***fire use (~41–24 ka)***

12
13 We observe macro- and micro-stratigraphic features in Units 5–8 that include *in situ*
14 combustion features and reworked combustion bi-products. This evidence clearly
15 indicates controlled use of fire by hominins between ~41 and 24 ka cal. BP. An
16 intact combustion feature interstratified between Units 5 and 6 presents a very
17 well-defined suite of features characteristic of an *in situ* fireplace. In Unit 7, we
18 identify disassembled combustion bi-products concentrated in discrete bands and
19 lenses, interspersed within the sediment matrix. These are indicative of the
20 reworking of combustion material, either by anthropogenic ‘housekeeping’ practices
21 (e.g., Goldberg et al., 2009; Miller et al., 2009) or by colluviation.

22
23 This fire use by hominins at the site took place against a backdrop of generally drier
24 conditions occurring from midway through Marine Isotope Stage 3 to a time broadly
25 equating to the Last Glacial Maximum (LGM) (Clark et al., 2009). Sediments with a
26 calcareous and calcite-cemented matrix, and a general reduction in fine clays and
27 silts, support decreased sheetwash and a reduction, or cessation, of water ingress to
28 Sector XXIV. Furthermore, there is evidence for increased physical and mechanical
29 attrition of the cave walls and roof, with high frequencies of coarse, autogenic
30 limestone spalls and speleothem fragments that commonly exhibit an angular
31 morphology. Aggregated clay grains—introduced into the sediment matrix by
32 weathering and dry colluviation—are commonly mechanically fractured, in contrast
33 to the clay aggregates undergoing slaking in Units 2 and 3. Lastly, we note enhanced
34 physical weathering of inclusions, which is suggestive of sub-aerial weathering in a
35 dry substrate without trampling.

36 ***Units 8 and 9, thin section MM4: return to humid conditions, accelerated***
37 ***dissolution processes (~24 ka to present)***

38
39 A flowstone that formed directly on top of Unit 8 marks a return to more humid
40 conditions at the site, with the initiation of laminar sheetflow from the rear of the
41 cave. The laterally extensive flowstone covers an area of at least 8 m² where
42 observed in Sectors XXIV and XXVII. It appears intact at the macroscopic scale, but
43 micromorphological analysis shows severe diagenesis of this speleothem, with
44 calcite replacement by phosphate throughout. Phosphatisation of this flowstone is

1 also associated with precipitation of manganese oxide directly beneath. These
2 phosphate crusts (Figure 9c,d) are similar to those found in prehistoric caves
3 elsewhere, such as Kebara and Hayonim (Weiner et al., 1995), where their
4 formation has been tied to the presence of bat guano (Karkanis et al., 2002;
5 Karkanis and Goldberg, 2010). Furthermore, it is likely that percolating water
6 associated with this diagenesis is responsible for the decalcification of Unit 7 seen in
7 sample MM5. This water may have formed a perched water-table or occluded layer
8 that was previously responsible for cementation of part of Unit 8, as seen at the base
9 of thin section MM4B.

11 Colluvial slopewash (Unit 9; also Unit 10 that was not sampled for this study)
12 signifies a strengthening of humid conditions, with an increase in clay and clay intra-
13 clasts. Many of the grain aggregates are angular in shape and appear to have a
14 variety of compositions, characteristic of reworking of weathered material that had
15 accumulated in the fissures and across the rear of the cave during the preceding dry
16 period; these deposits would have been mobilised when reconnected with the karst
17 hydrogeological system. It is clear from the sedimentary record and the slope of the
18 bounding surfaces that fluctuations in water ingress through fissures in the bedrock
19 at the rear of the cave were instrumental in changes in the depositional
20 environment at Liang Bua.

21 ***5.2 Key processes and other factors governing sediment deposition and*** 22 ***diagenesis at Liang Bua***

23 The results of this study refine our understanding of the processes, mechanisms and
24 other factors influencing sediment deposition and diagenesis at Liang Bua, building
25 on those identified previously (Westaway et al., 2009b). We discuss each of these, in
26 turn, below.

27 ***Colluviation***

29 This is the dominant mode of sedimentation observed in the rear of Liang Bua. As
30 originally recognised by Westaway et al. (2009b), colluviation at this site is
31 associated with slopewash processes that are driven by the hydrological dynamics
32 of the karst system. Our micro-scale study has revealed high frequencies of clay and
33 fine-silt aggregates that were reworked by the erosive action of surface water flow.
34 These clay aggregates are clearly derived from different sources, and a range of
35 processes are likely to be responsible for their transportation, including slopewash,
36 gravity and occasional small-scale mudflow events. Where we observe different
37 types of aggregates in thin section, future research will aim to isolate the relative
38 contributions of different source materials. We note that other materials can also
39 contribute to the composition of the colluvium, including weathered limestone and
40 speleothem fragments, occasional tephra shards and anthropogenic inclusions such
41 as charcoal, burnt bone fragments and stone artefacts.

1 It should be borne in mind that, for colluviation to occur, there has to be relief
2 within the cave system and this relief was most likely initiated by a phase of incision
3 by the Wae Racang followed by slumping and subsidence of the newly exposed and
4 truncated deposits. Periods of stabilisation, perhaps marked by flowstone
5 formation, could indicate intervals when relief was reduced due to the infilling of the
6 front chamber depo-centre, possibly linked to reorganisation of the fluvial system or
7 internal karst hydrology, or due to blocking of the entrance by landslides and/or
8 roof collapse near the cave entrance.

9
10 Alternation between colluviation and flowstone precipitation has been recognised at
11 other tropical cave sites in Southeast Asia and Australasia. At the site of Selminum
12 Tem in western New Guinea, Gillieson (1986) recorded a recurring sequence of
13 deposits, initially with a mass movement, followed by slopewash sedimentation and,
14 finally, by flowstone formation. Postulating the driver of this sequence, he asked if
15 “this sequence reflects events in small catchments feeding the phreatic passage, then
16 hillslope erosion is largely accomplished by periodic phases of instability, resulting
17 in pulses of sediment moving out of the catchment” (1986: 542). This explanation
18 may explain the depositional sequence observed thus far at Liang Bua (or at least in
19 part). Given the variety in fabric of small clayey clasts recorded in the colluvium,
20 pulses of sediment slumping and washing through the fissures and chambers at the
21 rear of the site may have occurred during periods of instability. In this scenario,
22 capping flowstones form when stability is achieved and sediment availability is
23 reduced, which could be linked to decreased monsoon frequency and/or intensity, a
24 reduction in sediment accommodation space at the site, or some combination of
25 these factors.

26 ***Speleothem formation***

27
28 Speleothems are a common occurrence among the deposits at Liang Bua. These
29 include dense clusters of stalactites precipitated over much of the ceiling of the cave,
30 buried tabular flowstones that conform to the buried cave floor topography, and
31 large, localised stalagmitic masses growing on the cave floor. The configuration and
32 alignment of stalactites on the ceiling of the cave has been discussed previously
33 (Westaway et al., 2009a). Positive phototropism is cited as the mechanism
34 responsible for the growing angle of the stalactites formed near the entrance since
35 the site was first exposed to sunlight. Whether uranium-series ages can be obtained
36 from these speleothems to further constrain the timing of the opening of the cave to
37 the sub-aerial environment requires further investigation.

38
39 The formation of tabular flowstones on top of Units 2, 3, 4 and 8 may be driven by a
40 number of processes, including an increase in CaCO₃-charged flowing water, a
41 reduction in porosity of the surface and sub-surface sediments, or a change in the
42 topography of the cave floor. Gillieson (1986) linked the inception of flowstone
43 formation in caves in the New Guinea highlands to time gaps in sediment deposition,
44 which may similarly play a part in flowstone formation at Liang Bua.

Recent work has shown that flowstone formation can be influenced by biological processes (see, for example, Northup and Lavoie, 2001; Taborosi, 2006). Formation of the calcareous laminae observed in MM8 is likely to have been biologically mediated, given their affinities to the ‘encrusted’ stalactites recorded in cave environments in southern Thailand (Taborosi et al., 2005). At present, however, we do not have thin sections of other calcareous, non-phosphatised flowstones at Liang Bua. Further sampling should assess the role of organisms (e.g., algae and mosses) in their formation, as well as their palaeoenvironmental ramifications. The presence of biological carbonate structures in sample MM7 suggests that the front brow of the cave was open at this time, allowing light into the rear of the cave. Once a flowstone is sufficiently well-developed vertically and laterally to form an impermeable barrier to sub-surface flow, it could act to concentrate and accelerate surface water flow to lower-lying areas of the cave and increase the potential to erode unconsolidated sediments. This may have implications, therefore, for the erosion of other strata nearer to the front of the cave. The presence of fine plant filaments on the surface of bedrock or existing flowstones, which would trap water flowing slowly across its surface, explains the propensity of flowstones at Liang Bua to form on steeply angled surfaces.

A massive stalagmite that exists on the present cave floor just to the east of Sector XXIV is a substantial carbonate accretion that resembles a stromatolitic stalagmite—the so-called ‘lobsters’ or ‘craybacks’ discussed in Taborosi (2006). The growth of these structures is linked to the photosynthetic activity of cyanobacteria, again suggesting the possibility of obtaining—via uranium-series dating—a minimum age for the opening of the cave.

Diagenesis and other post-depositional modifications

Diagenetic features recorded in thin sections were identified chiefly in the upper third of Sector XXIV’s stratigraphic sequence. The heavily phosphatised flowstone capping Unit 8 is associated with manganese oxide precipitation (e.g., López-González et al., 2006; Karkanas et al., 2008; White et al., 2009; Karkanas and Goldberg, 2010) and is most likely related to guano accumulation on the flowstone surface after it formed (e.g., Ford and Williams, 2007; Karkanas and Goldberg, 2010). It is not only the flowstone that has been subject to dissolution in this acidic environment—dissolution of limestone blocks in the sediments immediately beneath and above this flowstone (i.e., the upper part of Unit 8 and lower part of Unit 9) has resulted in the formation of ‘ghosts’ of these clasts (Figure 10g). In addition, we observed decalcification of the matrix in the sediments immediately beneath the flowstone. We also observed a laminar void situated between the upper surface of this flowstone and the immediately overlying, fine-grained colluvial sediments, possibly indicating erosion of the guano by water flowing across this hard surface. Why this type of diagenesis occurs only in the upper part of the sequence—at least in this part of the cave—is as yet unknown. However, it may relate to a shift in environmental conditions in the cave that catalysed an acidic environment in association with the addition of bat guano. Bats are regular

inhabitants of the cave today and their skeletal remains have been recovered consistently throughout the depositional sequence, including multiple species of fruit and insectivorous bats (van den Bergh et al., 2009).

Combustion features and fire-use

Micromorphological evidence of fire-use by hominins is restricted to Units 5–8 (the isolated occurrences of charcoal in Unit 2 cannot unequivocally be associated with hominin activity), which represent a temporal interval (~41–24 ka) that is characterised by drier palaeoenvironmental conditions (Westaway et al., 2009a). The intact combustion feature sampled between Units 5 and 6 exhibits a tripartite sequence highly diagnostic of an *in situ* fireplace. Interestingly, this feature contains very low frequencies of burnt or calcined bone compared to similar features found in some other caves (e.g., Goldberg et al., 2009; Berna et al., 2012; Miller et al., 2013). Elsewhere in Southeast Asia, evidence for fire-use has been recognised at sites on Borneo and the Philippines (Stephens et al., 2005, 2016, this volume; Mijares and Lewis, 2009), although this has been limited to individual diagnostic—but disassociated—components (e.g., baked sediment, ash and charcoal fragments).

Higher up the sequence, in Unit 7, we recorded dense concentrations of disaggregated combustion material that likely relate to fireplace cleaning, surface trampling or colluviation. Hominin activity in the rear of the cave is perhaps unsurprising as it would have formed elevated ground, high and dry above lower-lying areas around the cave mouth and eastern wall, where pools of standing water and/or muddy conditions unfavourable to subsistence activities might have existed. Such high ground would also have served well as a vantage point from which to survey the fringes of the valley, allowing for the early warning of approaching prey or possibly komodo dragons, the only known large predator on Flores and nearby islands during the Quaternary (Hocknull et al., 2009).

These combustion features represent the oldest unequivocal evidence of hearth-like structures at Liang Bua. Although the use of fire at Liang Bua has previously been attributed to *H. floresiensis* (Morwood et al., 2004, 2005), the current stratigraphic and chronological interpretation of the site (Sutikna et al., 2016) and analyses of the recovered findings raise doubts about the validity of this claim. The ‘charred bones’ initially reported by Morwood et al. (2004, 2005) within the *H. floresiensis*-bearing deposits are clearly the result of manganese staining, and no definitive evidence of burnt faunal remains has been recovered during subsequent excavations of these deposits. Similarly, analyses of the “clusters of reddened and fire-cracked rocks” (Morwood et al., 2005:1012) from within the *H. floresiensis*-bearing sediments have demonstrated that these stones were not exposed to any significant heat source (Roberts et al., 2009). Furthermore, the most extensive study so far of the Liang Bua stone artefact assemblages (Moore et al., 2009) found a marked discrepancy in terms of artefact exposure to fire, with negligible evidence (<1%) in assemblages associated with *H. floresiensis* remains, versus almost 18% of stone artefacts of Holocene age attributed to modern humans.

Given the available evidence, we suggest that the use of fire at Liang Bua—particularly the construction of hearth-like structures that were presumably used for warmth and/or cooking—is more likely a behavioural signature of modern humans than of *H. floresiensis*. Although this hypothesis requires confirmation by additional investigation at Liang Bua and elsewhere on Flores, the micromorphological evidence from Sector XXIV suggests that modern humans were present on Flores by ~41 ka cal. BP or shortly thereafter. If correct, these data corroborate the presence of modern humans in Island Southeast Asia during the last 40 millennia, as reported for sites in Laos Borneo, the Philippines, Sulawesi, Timor, Papua New Guinea and Australia (Fox, 1970; Roberts et al., 1990, 1994; Turney et al., 2001; Dizon et al., 2002; Bowler et al., 2003; Detroit et al., 2004; Storm et al., 2005, 2013; Barker et al., 2007; Summerhayes et al., 2010; O'Connor et al., 2011; Barker, 2013; Aubert et al., 2014; Allen and O'Connell, 2014; Clarkson et al., 2015; Demeter et al., 2015; Hiscock, 2015; O'Connell and Allen, 2015; O'Connor, 2015).

Much of the research concerning hominin use of fire originates from sites in arid, semi-arid and temperate climatic zones. In humid tropical Sri Lanka, combustion features have been recorded in Kitulgala Beli-lena rockshelter, where neither bones nor ash are preserved and the “absence of microscopic bone fragments contrasts sharply with the abundance of larger bone finds on site” (Kourampas et al., 2009: 692). Whether this is a function of accelerated diagenetic processes occurring at tropical sites, or reflects the fact that meat processing was not the primary purpose of these fires, remains an open question. Moreover, further work is warranted to explore the precise baseline conditions that promote or hinder bone preservation, and the potential bi-products or markers of bone dissolution processes (e.g., Stiner et al., 2001).

Volcanic activity

Sutikna et al. (2016) proposed that multiple processes were responsible for the emplacement of tephra T3 at Liang Bua, with the upper sub-unit associated with a period of water pooling and minor, localised reworking within the cave. This interpretation is consistent with the evidence of wetter conditions indicated by the micromorphological analysis of this stratum (Unit 3). However, given the absence of water-derived laminae and the generally pure composition of the tephra in this area, it is possible that this remnant of T3 preserved in the rear of the cave is still in primary, wind-emplaced position, with the reworked upper portion of T3 confined to lower-lying areas of the site. A discrete band of impure tephra, observed ~5 mm above the primary fall, may indicate minor reworking of T3 by sheetwash or represent evidence of a small, secondary fall-out event. At Dalan Serkot Cave on Luzon in the Philippines, Mijares and Lewis (2009) used micromorphology to identify a volcanic ash layer that displays grading characteristics, which they claim are consistent with reworking by flowing water. At Liang Bua, it is an open question whether the blanket of tephra across much of the cave floor and the catchment area

1 disrupted processes driving sedimentation within the cave, but colluviation was
2 likely sufficiently persistent to bury at least the distal end of T3 before other parts of
3 it were eroded by other sub-aerial mechanisms.
4

5 ***Cave floor topography and relief***

6
7 The floors of caves and rockshelters commonly exhibit complex topographies. This
8 is nowhere more prevalent than in humid tropical regions where cut, fill and
9 slumping events—often associated with marked changes in seasonal precipitation—
10 can create dramatic topographic features and highly irregular cave floor surfaces
11 (e.g., Glover, 1979; Gillieson, 1986; Barker et al., 2005; Stephens et al., 2005;
12 Gilbertson et al., 2013). Previous work at Liang Bua has shown that the topography
13 of the cave floor was highly irregular prior to, and in the early stages of, infilling
14 with sediments and chemical precipitates (Westaway et al., 2009b). This
15 topographic template dictated sediment deposition during the final Late and
16 terminal Middle Pleistocene, with clastic material funnelled down and through
17 conduits and channels in the limestone floor of the cave, and between large boulders
18 and stalagmites (e.g., Westaway et al., 2009a,b). This topography would have
19 regulated the erosional capabilities of overland flow. The stratigraphic sequence of
20 excavated sediments along the eastern wall of the cave is more than 11 m deep
21 (Morwood et al., 2009; Westaway et al., 2009b; Sutikna et al., 2016) and this area
22 appears to have acted as a low-lying sediment depo-centre—a local ‘sink’ for
23 sediments delivered from the rear, and most likely also from the front, of the cave.
24 This scenario suggests that if the cave originally formed as a collapsed doline, then
25 the rim of this chamber is likely to be preserved beneath the front aperture.
26

27 At least one major cut-and-fill event has been recorded in the cave that has had
28 profound implications for the preservation of archaeological sediments (Sutikna et
29 al., 2016). This pattern of repeated accumulation and erosion, often followed by
30 slumping and mass movements, is a common theme observed in many parts of the
31 stratigraphic sequence, which is similar to that recorded in New Guinea by Gillieson
32 (1986). Work is ongoing to identify the geomorphic processes that drive these cut-
33 and-fill events, and to ultimately link the sequence recorded inside the site to the
34 river valley outside. These are likely to include fluctuations in water throughput or
35 flow concentration from the rear of the cave to the front, linked to a reorganisation
36 of the karst hydrological system; a change in the topographic template of the site,
37 over which subsequent sediments are deposited; and/or a switch in the mode of
38 sediment deposition (e.g., from clastic to precipitate).
39

40 ***Correlation with palaeoenvironmental records in Island Southeast Asia***

41
42 The results of this study are spatially constrained to a limited area of the cave, so
43 correlating changes in cave environment to the wider catchment or regional climate
44 record is necessarily tentative. That said, we recognise three distinct phases of

1 environmental change in the sedimentological record at Liang Bua that appear to be
2 driven by reorganisation of the cave hydrology, presumably—but not as yet
3 demonstrably—linked to fluctuations in precipitation on Flores. Using the new
4 radiocarbon chronology presented here, we can provisionally correlate these
5 hydrological changes with isotopic ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) proxies measured on
6 speleothems from Flores and Java (Westaway et al., 2007b, 2009a) and make
7 comparisons with other proxy palaeoenvironmental data from Island Southeast
8 Asia.

9
10 A marked switch from humid colluviation to gravel production under a dry climate
11 occurs in the sequence sometime after ~47 ka and prior to ~41–38 ka. This may
12 correlate with a period of persistent groundwater conditions identified in the
13 speleothem record, with a peak in humidity occurring 44–41 ka (Westaway et al.,
14 2009a). The onset of autogenic gravel production and calcareous sedimentation
15 coincides with hominin fire-use at Liang Bua from ~41 to 38 ka and correlates with
16 a significant reduction in humidity from ~39 ka (Westaway et al., 2009a). This drier
17 period on Flores may correlate with the dry conditions and abundant C_4 grasses
18 indicative of an open savannah-type landscape recorded on Palawan in the
19 Philippines (Wurster et al., 2013). In the Liang Bua sedimentological record, we
20 observe a return to humid colluviation after 25–24 ka, perhaps as a southerly
21 expression of the wet event recorded on Palawan at ~23–21 ka (Bird et al., 2007;
22 Lewis et al., 2008). Stalagmite records from Flores show a sharp increase in
23 monsoonal precipitation after the LGM, with the interglacial atmospheric circulation
24 system fully restored by ~13 ka (Westaway et al., 2007b).

25
26 During the time period relevant here to hominin migrations into (and out of) the
27 region (~60–20 ka), maximum sea levels rarely attained elevations closer than 50 m
28 below current mean sea level (Lambeck and Chappell, 2001). Such low sea levels
29 suggest that most of the Sunda Shelf was exposed throughout this period (Voris,
30 2000), thus permitting overland crossings as far east as the eastern coasts of Bali
31 and Borneo, possibly via an open savannah corridor (Bird et al., 2005). Further
32 penetration eastward at this time required sea crossings over the perilous straits
33 separating the Indonesian islands east of Wallace's Line, or across the longer (but
34 potentially safer) passages from the north via either the Philippines or Sulawesi,
35 whether by choice or serendipitous circumstance (e.g., Birdsell, 1977; O'Connor,
36 2007; O'Connell et al., 2008; Morwood and Jungers, 2009; Dennell et al., 2014).

37
38 The environmental reconstruction for Liang Bua presented here is insufficiently
39 finely-resolved to correlate with extant, high-resolution palaeoenvironmental
40 datasets for Sunda and Wallacea, although we have endeavoured to situate our
41 findings within a regional biogeographic and palaeoclimatic framework. A larger
42 data set is required to explore in more detail the relationship between on-site
43 environmental change and precipitation-driven reorganisation of the karst
44 hydrology—this will be the focus of further study.

6. Conclusions

The results of this micromorphological study are derived from a single area of Liang Bua (a 1 m-wide by ~4 m-deep profile near the rear of the site), which represents only a small fraction of the voluminous deposits preserved in the cave. Despite this modest window into the evolution of the site, the results substantiate and refine previous work, extending our knowledge of the depositional and post-depositional history of the cave and of hominin activities taking place at the site.

Field observations suggest that colluviated sediments are derived primarily from the rear of the cave, and the micromorphological results show that these sediments were deposited during oscillations between drier and wetter conditions. Variations in flowstone morphologies are consistent with a variety of depositional processes, and these inferences are supported by observations of the thin sections, where thin laminae of biological derivation are clearly visible. Localised bioturbation of the Liang Bua depositional sequence is a typical occurrence, which is not surprising given studies of other tropical cave sediments such as at Niah Cave (Stephens et al., 2005, this volume). However, the degree to which bioturbation has affected the integrity of the archaeological evidence at Liang Bua appears to be minor, but further research on these effects is warranted.

Results of ongoing work in different areas of the cave should help refine interpretations of the sedimentary dynamics at Liang Bua. We have documented chemical diagenesis in the upper 20–35 cm of Unit 8 in Sector XXIV, but it remains to be shown if the same processes occur to the same extent—if at all—in other parts of the cave at the same or different depths and in other stratigraphic units. Documenting phosphatisation, for example, is significant in revealing locations of roosting animals, the presence of erosion, stabilisation of surfaces and gaps in the stratigraphic record (e.g., thin section MM4B). It may also be important for locating any regions of locally enhanced or reduced radioactivity, which could influence the radionuclide concentrations in sediments and faunal remains sampled for luminescence, electron-spin resonance and uranium-series dating (e.g., Weiner et al., 2002).

Our micromorphological observations of combustion features and bi-products from sediments dated to ~41–25 ka are of particular interest. First, the microstratigraphic organisation of these features reveals that we are dealing with largely undisturbed structures that can be used to make inferences about hominin behaviour, such as the spatio-functional use of specific areas of the site and food processing strategies. Second, the primary context of the combustion features and their stratigraphic association with a suite of new ¹⁴C ages suggests that modern humans are the most likely candidates for this fire-use. If this hypothesis is borne out by further research, then the initial arrival of modern humans at Liang Bua can be extended to at least ~41 ka cal. BP. As the gap narrows between the time of arrival of modern humans and the latest parts of the *H. floresiensis* sequence (~50 ka; Sutikna et al., 2016), ongoing investigations at the site will address the question

1 of whether deposits of intermediate age contain any evidence of overlap and
2 interaction between the two hominin groups.

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16

7. References

- Allen, J., & O'Connell, J. F. (2014). Both half right: Updating the evidence for dating first human arrivals in Sahul. *Australian Archaeology*, 79, 86-108.
- Aubert, M., Brumm, A., Ramli, M., Sutikna, T., Saptomo, E. W., Hakim, B., & Dosseto, A. (2014). Pleistocene cave art from Sulawesi, Indonesia. *Nature*, 514(7521), 223-227.
- Barker, G. (Ed.). (2013). *Rainforest foraging and farming in Island Southeast Asia*. Volume 1. McDonald Institute Monographs. Cambridge: McDonald Institute of Archaeological Research.
- Barker, G., Barton, H., Bird, M., Daly, P., Datan, I., Dykes, A., Farr, L., Gilbertson, D., Harisson, B., Hunt, C. & Higham, T. (2007). The 'human revolution' in lowland tropical Southeast Asia: the antiquity and behaviour of anatomically modern humans at Niah Cave (Sarawak, Borneo). *Journal of Human Evolution*, 52(3), 243-261.
- Bellwood, P. (2014). *First Migrants: ancient migration in global perspective*. John Wiley & Sons.
- Berna, F., Goldberg, P., Horwitz, L. K., Brink, J., Holt, S., Bamford, M., & Chazan, M. (2012). Microstratigraphic evidence of in situ fire in the Acheulean strata of Wonderwerk Cave, Northern Cape province, South Africa. *Proceedings of the National Academy of Sciences of the USA*, 109 (20), E1215-E1220.
- Bird, M. I., Taylor, D., & Hunt, C. (2005). Palaeoenvironments of insular Southeast Asia during the Last Glacial Period: a savanna corridor in Sundaland? *Quaternary Science Reviews*, 24 (20), 2228-2242.
- Bird, M. I., Boobyer, E. M., Bryant, C., Lewis, H. A., Paz, V., & Stephens, W. E. (2007). A long record of environmental change from bat guano deposits in Makangit Cave, Palawan, Philippines. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 98 (01), 59-69.
- Birdsell, J. B. (1977). The recalibration of a paradigm for the first peopling of greater Australia. *Sunda and Sahul: Prehistoric Studies in Southeast Asia, Melanesia, and Australia*, 113-167.
- Boivin, N., Fuller, D. Q., Dennell, R., Allaby, R., & Petraglia, M. D. (2013). Human dispersal across diverse environments of Asia during the Upper Pleistocene. *Quaternary International*, 300, 32-47.

- Bowler, J. M. Johnston, H., Olley, J.M., Prescott, J.R., Roberts, R.G., Shawcross, W., & Spooner, N.A. (2003). New ages for human occupation and climatic change at Lake Mungo, Australia. *Nature* 421, 837–840.
- Brown, P., Sutikna, T., Morwood, M.J., Soejono, R.P., Jatmiko, Saptomo, E.W., & Due, R.A. (2004). A new small-bodied hominin from the Late Pleistocene of Flores, Indonesia. *Nature* 431: 1055-1061.
- Buciuman, F., Patcas, F., Craciun, R., & Zahn, D.R.T. (1998). Vibrational spectroscopy of bulk and supported manganese oxides. *Physical Chemistry Chemical Physics* 1, 185-190.
- Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica J. X., Hostetler, S.W., & McCabe, A.M. (2009). The last glacial maximum. *Science* 325:710–714
- Clarkson, C., Smith, M., Marwick, B., Fullagar, R., Wallis, L.A., Faulkner, P., Manne, T., Hayes, E., Roberts, R.G., Jacobs, Z., & Carah, X. (2015). The archaeology, chronology and stratigraphy of Madjedbebe (Malakunanja II): A site in northern Australia with early occupation. *Journal of Human Evolution*, 83, 46–64.
- Cooper, A. & Stringer, C.B. (2013). Did the Denisovans cross Wallace’s Line? *Science*, 342 (6156), 321-323.
- Demeter, F., Shackelford, L., Westaway, K., Durringer, P., Bacon, A. M., Ponche, J. L., Wu, X., Sayavongkhamady, T., Zhao, J-X., Barnes, L., Boyon, M., Sichanthongtip, P., Senegas, F., Karpoff, A-M., Patole-Edoumba, E., Coppen, Y., & Braga, J. (2015). Early modern humans and morphological variation in Southeast Asia: fossil evidence from Tam Pa Ling, Laos. *PLoS One*, 10 (4), e0121193.
- Dennell, R., & Petraglia, M. D. (2012). The dispersal of *Homo sapiens* across southern Asia: how early, how often, how complex? *Quaternary Science Reviews*, 47, 15-22.
- Dennell, R. W., Louys, J., O'Regan, H. J., & Wilkinson, D. M. (2014). The origins and persistence of *Homo floresiensis* on Flores: biogeographical and ecological perspectives. *Quaternary Science Reviews*, 96, 98-107.
- Détroit, F., Dizon, E., Falguères, C., Hameau, S., Ronquillo, W., & Sémah, F. (2004). Upper Pleistocene *Homo sapiens* from the Tabon cave (Palawan, the Philippines): description and dating of new discoveries. *Comptes Rendus Palevol*, 3(8), 705-712.

- Dizon, E., Détroit, F., Sémah, F., Falguères, C., Hameau, S., Ronquillo, W., & Cabanis, E. (2002). Notes on the morphology and age of the Tabon Cave fossil *Homo sapiens*. *Current Anthropology*, 43 (4), 660-666.
- Ford, D., and Williams, P. D. (2007). *Karst Hydrogeology and Geomorphology*. John Wiley & Sons.
- Fox, R. B. (1970). *The Tabon Caves: archaeological explorations and excavations on Palawan Island, Philippines*. National Museum of Philippines Monograph, No. 1.
- Gilbertson, D., Bird, M., Hunt, C., McLaren, S., Banda, R. M., Pyatt, B., Rose, J., & Stephens, M. (2005). Past human activity and geomorphological change in a guano-rich tropical cave mouth: initial interpretations of the Late Quaternary succession in the Great Cave of Niah, Sarawak. *Asian Perspectives*, 16-41.
- Gillieson, D. (1986). Cave sedimentation in the New Guinea highlands. *Earth Surface Processes and Landforms*, 11(5), 533-543.
- Glover, I. C. (1979). The effects of sink action on archaeological deposits in caves: an Indonesian example. *World Archaeology*, 10 (3), 302-317.
- Goldberg, P., Miller, C. E., Schiegl, S., Ligouis, B., Berna, F., Conard, N. J., & Wadley, L. (2009). Bedding, hearths, and site maintenance in the Middle Stone Age of Sibudu cave, KwaZulu-Natal, South Africa. *Archaeological and Anthropological Sciences*, 1(2), 95-122.
- Groucutt, H. S., Petraglia, M. D., Bailey, G., Scerri, E. M., Parton, A., Clark-Balzan, L., Jennings, R.P., Lewis, L., Blinkhorn, J., Drake, N.A., Breeze, P.S., Inglis, R.H., Deves, M.H., Meredith-Williams, M., Boivin, N., Thomas, M.G. & Scally, A. (2015). Rethinking the dispersal of *Homo sapiens* out of Africa. *Evolutionary Anthropology: Issues, News, and Reviews*, 24 (4), 149-164.
- Hiscock, P., 2015. Cultural diversification and the global dispersion of *Homo sapiens*: lessons from Australia. In: Kaifu, Y., Izuhō, M., Goebel, T., Sato, H., Ono, A. (Eds), *Emergence and Diversity of Modern Human Behaviour in Paleolithic Asia*, pp. 225–236. Texas A&M University Press, College Station.
- Hocknull, S.A., Piper, P.J., van den Bergh, G.D., Due, R.A., Morwood, M.J., Kurniawan, I. (2009) Dragon's Paradise Lost: Palaeobiogeography, Evolution and Extinction of the Largest-Ever Terrestrial Lizards (Varanidae). *PLoS ONE* 4(9): e7241
- Hogg, A.G., Hua, Q., Blackwell, P.G., Niu, M., Buck, C.E., Guilderson, T.P., Heaton, T.J., Palmer, J.G., Reimer, P.J., Reimer, R.W., Turney, C.S.M. & Zimmerman, S.R.H.

- (2013). SHCal13 Southern Hemisphere calibration, 0–50,000 years cal BP. *Radiocarbon* 55, 1889–1903.
- Karkanias, P., & Goldberg, P. (2010). Phosphatic Features. In: Stoops, G. & Mees, F. (Eds.), *Interpretation of Micromorphological Features of Soils and Regoliths* (pp. 521–541). Elsevier B.V.
- Karkanias, P., Rigaud, J. P., Simek, J. F., Albert, R. M., & Weiner, S. (2002). Ash bones and guano: a study of the minerals and phytoliths in the sediments of Grotte XVI, Dordogne, France. *Journal of Archaeological Science*, 29(7), 721–732.
- Karkanias, P., Schepartz, L. A., Miller-Antonio, S., Wang, W., & Huang, W. (2008). Late Middle Pleistocene climate in southwestern China: inferences from the stratigraphic record of Panxian Dadong Cave, Guizhou. *Quaternary Science Reviews*, 27(15–16), 1555–1570.
- Kourampas, N., Simpson, I. A., Perera, N., Deraniyagala, S. U., & Wijeyapala, W. H. (2009). Rockshelter sedimentation in a dynamic tropical landscape: Late Pleistocene–Early Holocene archaeological deposits in Kitulgala Beli-lena, southwestern Sri Lanka. *Geoarchaeology*, 24(6), 677–714.
- Lambeck, K., & Chappell, J. (2001). Sea level change through the last glacial cycle. *Science*, 292 (5517), 679–686.
- Lewis, H., Johnson, K., & Ronquillo, W. (2008). Preliminary results of speleothem dating from Tabon Cave, Palawan, Philippines: moisture increase at the Last Glacial Maximum. *Hukay*, 12.
- López-González, F., Grandal-d'Anglade, A., & Vidal-Romaní, J. R. (2006). Deciphering bone depositional sequences in caves through the study of manganese coatings. *Journal of Archaeological Science*, 33(5), 707–717.
- Mijares, A. S. B., & Lewis, H. A. (2009). Cave sites in northeastern Luzon, Philippines: A preliminary soil micromorphological study. *Asian Perspectives*, 48(1), 98–118.
- Miller, C.E., Conard, N.J., Goldberg, P., & Berna, F. (2009). Dumping, sweeping and trampling: experimental micromorphological analysis of anthropogenically modified combustion features. *Paleoethnologie*, 2009, 25–37.
- Miller, C.E., Goldberg, P., & Berna, F. (2013). Geoarchaeological investigations at Diepkloof Rock Shelter, Western Cape, South Africa. *Journal of Archaeological Science*, 40(9), 3432–3452.

- 1 Moore, M.W., Sutikna, T., Jatmiko, Morwood, M.J. & Brumm, A. (2009). Continuities in
2 stone flaking technology at Liang Bua, Flores, Indonesia. *Journal of Human*
3 *Evolution* 57, 503–526.
4
- 5 Morley, M.W. & Woodward, J. C. (2011). The Campanian Ignimbrite (Y5) tephra at
6 Crvena Stijena Rockshelter, Montenegro. *Quaternary Research*, 75(3), 683-
7 696.
8
- 9 Morwood, M.J. & Jungers, W.L. (2009). Conclusions: implications of the Liang Bua
10 excavations for hominin evolution and biogeography. *Journal of Human*
11 *Evolution*, 57, 640–648.
12
- 13 Morwood, M.J., Soejono, R.P., Roberts, R.G., Sutikna, T., Turney, C.S.M., Westaway,
14 K.E., Rink, W.J., Zhao, J.X., van den Bergh, G.D., Due, R.A., Hobbs, D.R., Moore,
15 M.W., Bird, M.I., and Fifield, L.K. (2004). Archaeology and age of a new
16 hominin from Flores in eastern Indonesia. *Nature*, 431:1087-1091.
17
- 18 Morwood M.J., Brown P., Jatmiko, Sutikna T., Saptomo E.W., Westaway K.E., Due R.A.,
19 Roberts R.G., Maeda T., Wasisto S., and Djubiantono T. (2005). Further
20 evidence for small-bodied hominins from the Late Pleistocene of Flores,
21 Indonesia. *Nature*, 437:1012-1017.
22
- 23 Morwood, M.J., Sutikna, T., Saptomo, E.W., Jatmiko, Hobbs, D.R., & Westaway, K.E.
24 (2009). Preface: research at Liang Bua, Flores, Indonesia. *Journal of Human*
25 *Evolution*, 57, 437–449.
26
- 27 Northup, E. & Lavoie, D. (2001). Geomicrobiology of caves: a review.
28 *Geomicrobiology Journal*, 18 (3), 199-222.
29
- 30 O'Connell, J. F., Allen, J., & Hawkes, K. (2010). Pleistocene Sahul and the origins of
31 seafaring. In: Anderson, A., Barrett, J. H., & Boyle, K. V. (Eds), *The global*
32 *origins and development of seafaring*, pp. 57-68. Cambridge: McDonald
33 Institute of Archaeological Research.
34
- 35 O'Connell, J.F. & Allen, J. (2015). The process, biotic impact, and global implications
36 of the human colonization of Sahul about 47,000 years ago. *Journal of*
37 *Archaeological Science*, 56, 73-84
38
- 39 O'Connor, S. (2007). New evidence from East Timor contributes to our
40 understanding of earliest modern human colonisation east of the Sunda Shelf.
41 *Antiquity* 81, 523–535.
42
- 43 O'Connor, S. (2015). Crossing the Wallace Line: the maritime skills of the earliest
44 colonists in the Wallacean Archipelago. In: Kaifu, Y., Izuhō, M., Goebel, T.,
45 Sato, H., & Ono, A. (Eds), *Emergence and Diversity of Modern Human*

- 1 *Behaviour in Paleolithic Asia*, pp. 214–224. Texas A&M Univ. Press, College
2 Station.
- 3
- 4 O'Connor, S., Ono, R., & Clarkson, C. (2011). Pelagic fishing at 42,000 years before the
5 present and the maritime skills of modern humans. *Science*, 334, 1117–1121.
- 6
- 7 Reyes-Centeno, H., Hubbe, M., Hanihara, T., Stringer, C., & Harvati, K. (2015). Testing
8 modern human out-of-Africa dispersal models and implications for modern
9 human origins. *Journal of Human Evolution*, 87, 95–106.
- 10
- 11 Roberts, R.G., Jones, R., Smith, M.A., (1990). Thermoluminescence dating of a 50,000-
12 year-old human occupation site in northern Australia. *Nature*, 345, 153–156.
- 13
- 14 Roberts, R. G., Jones, R., Spooner, N. A., Head, M. J., Murray, A. S., & Smith, M. A.
15 (1994). The human colonisation of Australia: optical dates of 53,000 and
16 60,000 years bracket human arrival at Deaf Adder Gorge, Northern
17 Territory. *Quaternary Science Reviews*, 13(5), 575–583.
- 18
- 19 Roberts, R. G., Westaway, K. E., Zhao, J-x., Turney, C. S., Bird, M. I., Rink, W. J., &
20 Fifield, L. K. (2009). Geochronology of cave deposits at Liang Bua and of
21 adjacent river terraces in the Wae Racang valley, western Flores, Indonesia: a
22 synthesis of age estimates for the type locality of *Homo floresiensis*. *Journal of*
23 *Human Evolution*, 57(5), 484–502.
- 24
- 25 Sauer, G. R., Zunic, W. B., Durig J. R. & Wuthier R.E. (1994) Fourier Transform Raman
26 spectroscopy of synthetic and biological calcium phosphates. *Calcified Tissue*
27 *International* 54, 414–420.
- 28
- 29 Stephens, M., Rose, J., Gilbertson, D. D., & Canti, M. G. (2005). Micromorphology of
30 Cave Sediments in the Humid Tropics: Niah Cave, Sarawak. *Asian*
31 *Perspectives* 44(1), 42–55. University of Hawaii Press.
- 32
- 33 Stephens, M., Rose, J., & Gilbertson, D. D. (2016). Post-depositional alteration of
34 humid tropical cave sediments: Micromorphological research in the Great
35 Cave of Niah, Sarawak, Borneo. *Journal of Archaeological Science* (online, in
36 press).
- 37
- 38 Stiner, M. C., Kuhn, S. L., Surovell, T. A., Goldberg, P., Meignen, L., Weiner, S., & Bar-
39 Yosef, O. (2001). Bone preservation in Hayonim Cave (Israel): a macroscopic
40 and mineralogical study. *Journal of Archaeological Science*, 28 (6), 643–659.
- 41
- 42 Storm, P., Aziz, F., de Vos, J., Kosasih, D., Baskoro, S., & van den Hoek Ostende, L. W.
43 (2005). Late Pleistocene *Homo sapiens* in a tropical rainforest fauna in East
44 Java. *Journal of Human Evolution*, 49 (4), 536–545.
- 45

- Storm, P., Wood, R., Stringer, C., Bartsiokas, A., de Vos, J., Aubert, M., Kinsley, L., & Grün, R. (2013). U-series and radiocarbon analyses of human and faunal remains from Wajak, Indonesia. *Journal of Human Evolution*, 64 (5), 356-365.
- Stuiver, M., Reimer, P. J., & Reimer, R. W. (2016). CALIB 7.1. [WWW program and documentation], <http://calib.qub.ac.uk/calib/>
- Summerhayes, G. R., Leavesley, M., Fairbairn, A., Mandui, H., Field, J., Ford, A., & Fullagar, R. (2010). Human adaptation and plant use in highland New Guinea 49,000 to 44,000 years ago. *Science*, 330(6000), 78-81.
- Stoops, G. (2003). *Guidelines for analysis and description of soil and regolith thin sections*. Soil Science Society of America.
- Sutikna, T., Tocheri, M. W., Morwood, M. J., Saptomo, E. W., Jatmiko, Due, R. A., Wasisto, S., Westaway, K. E., Aubert, M., Li, B., Zhao, J.-x., Storey, M., Alloway, B. V., Morley, M. W., Meijer, H. J. M., van den Bergh, G. D., Grün, R., Dosseto, A., Brumm, A., Jungers, W. L., Roberts, R. G. (2016). Revised stratigraphy and chronology for *Homo floresiensis* at Liang Bua in Indonesia. *Nature* 532, 366–369.
- Taboroši, D., Hirakawa, K., & Sawagaki, T. (2005). Carbonate precipitation along a microclimatic gradient in a Thailand cave—continuum of calcareous tufa and speleothems. *Journal of Cave and Karst Studies*, 67(1), 69-87.
- Taboroši, D. (2006). Biologically influenced carbonate speleothems. *Geological Society of America Special Papers*, 404, 307-317.
- Turney, C.S.M., Bird, M.I., Fifield, L.K., Roberts, R.G., Smith, M., Dortch, C.E., Grün, R., Lawson, E., Ayliffe, L.K., Miller, G.H., Dortch, J., & Cresswell, R.G. (2001). Early human occupation at Devil's Lair, southwestern Australia 50,000 years ago. *Quaternary Research* 55, 3–13.
- van den Bergh, G. D., Meijer, H. J. M., Awe, R. D., Morwood, M. J., Szabó, K., van den Hoek Ostende, L. W., Sutikna, T., Saptomo, E. W., Piper, P. J. & Dobney, K. M. (2009). The Liang Bua faunal remains: a 95 k. yr. sequence from Flores, East Indonesia. *Journal of Human Evolution*, 57(5), pp.527-537.
- Voris, H. K. (2000). Maps of Pleistocene sea levels in Southeast Asia: shorelines, river systems and time durations. *Journal of Biogeography*, 27(5), 1153-1167.
- Weiner, S., Goldberg, P., & Bar-Yosef, O. (2002) Three-dimensional distribution of minerals in the sediments of Hayonim Cave, Israel: Diagenetic processes and archaeological implications. *Journal of Archaeological Science*, 29, 1289–1308.

- 1 Westaway, K. E., Morwood, M. J., Roberts, R. G., Zhao, J.-x., Sutikna, T., Saptomo, E. W.,
2 & Rink, W. J. (2007a). Establishing the time of initial human occupation of
3 Liang Bua, western Flores, Indonesia. *Quaternary Geochronology*, 2(1), 337-
4 343.
- 5
6 Westaway, K. E., Zhao, J.-x., Roberts, R. G., Chivas, A. R., Morwood, M. J., & Sutikna, T.
7 (2007b). Initial speleothem results from western Flores and eastern Java,
8 Indonesia: were climate changes from 47 to 5 ka responsible for the
9 extinction of *Homo floresiensis*? *Journal of Quaternary Science*, 22(5), 429-
10 438.
- 11
12 Westaway, K. E., Roberts, R. G., Sutikna, T., Morwood, M. J., Drysdale, R., Zhao, J.-x., &
13 Chivas, A. R. (2009a). The evolving landscape and climate of western Flores:
14 an environmental context for the archaeological site of Liang Bua. *Journal of*
15 *Human Evolution*, 57(5), 450-464.
- 16
17 Westaway, K. E., Sutikna, T., Saptomo, W. E., Morwood, M. J., Roberts, R. G., & Hobbs,
18 D. R. (2009b). Reconstructing the geomorphic history of Liang Bua, Flores,
19 Indonesia: a stratigraphic interpretation of the occupational
20 environment. *Journal of Human Evolution*, 57(5), 465-483.
- 21
22 White, W. B., Vito, C., & Scheetz, B. E. (2009). The mineralogy and trace element
23 chemistry of black manganese oxide deposits from caves. *Journal of Cave and*
24 *Karst Studies*, 71(2), 136-143.
- 25
26 Wurster, C. M., Bird, M. I., Bull, I. D., Creed, F., Bryant, C., Dungait, J. A., & Paz, V.
27 (2010). Forest contraction in north equatorial Southeast Asia during the Last
28 Glacial Period. *Proceedings of the National Academy of Sciences of the USA*,
29 107(35), 15508-15511.
- 30