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Cave stratigraphies and cave breccias: Implications for sediment accumulation and removal models and interpreting the record of human occupation

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ABSTRACT

Many of the key debates in archaeology hinge on the chronology and interpretation of data gathered from cave and rockshelter stratigraphies, especially those in karstic limestone environments which are selectively targeted by archaeologists because of their superior preservation characteristics. It has long been recognized that such sites often contain a variety of cemented deposits including cave breccias and that some breccias contain anthropogenic inclusions such as stone artefacts, shell and burnt animal bones. Cementation enhances the survival through time of such brecciated deposits. This can result in chrono-stratigraphic intervals surviving on cave walls and speleothems that are no longer represented in the stratigraphy of cave floors. This has important implications for understanding apparent presence/absence of human occupation and cultural continuity as seen in archaeo-stratigraphy in caves and rockshelters, especially in relation to human migration in the humid tropics in SE Asia and the Pacific, and over Pleistocene to Holocene timescales. Here we discuss localized breccia formation, the erosional processes that leave remnant deposits adhering to walls and speleothems at heights well above current cave floors, and the possible significance of local and regional processes, especially changing base levels, in triggering gutting out phases impacting cave floor sediment architectures. Equally significant in terms of chronological completeness, representativeness and bias is the contribution made by cultural materials encased in older breccias as they erode and are (re-)incorporated into younger accumulating cultural deposits. Case studies from cave sites in Papua New Guinea and Timor Leste are used to illustrate these issues.

1. Introduction

Breccias (poorly-sorted, cemented, angular clastic deposits) are common in caves in the Asia Pacific region. That such deposits can form valuable archives for investigating biostratigraphic sequences over long time spans has been recognized by paleontologists who have used them to date and document faunal successions (e.g. Westaway et al., 2007). Breccias are often also found in archaeological sites and can contain well preserved cultural materials. However, the potential use of remnant breccia deposits as patch archives of (otherwise missing) sequences of cave human occupation records has been largely neglected by archaeologists.

Breccias often form against cave walls or speleothem columns in areas where carbonate-rich water flows over, seeps into or drips onto, the floor deposit of archaeological sites, causing sediments to lithify *in situ*. Where breccias cement to the walls or cave features, they frequently survive when laterally adjacent unconsolidated sedimentary deposits erode away. From an archaeological perspective this means that residual cave breccias containing cultural material may provide sequence archives for time periods which are otherwise absent from the main body of cave infill. This makes such relict deposits valuable bio- and chrono-stratigraphic archives especially where cultural evidence of past human occupation interstratifies with other (often dateable) deposits which archive other aspects of Quaternary regional palaeo-environmental change. Such proxy environment-informative carbonate-cemented deposits include speleothem, conglomerates, flowstones, tufa and calcretes (see Brook et al., 1999; Fairchild and Baker, 2012). Artefacts, humanly discarded shell and bone refuse, ashy deposits

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and anthropogenic charcoal commonly preserve exceptionally well within such carbonate-cemented deposits in cave, cave-mouth, and open site settings.

Cemented deposits containing cultural materials have long been recognized as a feature of caves and rockshelters in limestone regions in many parts of the world. Such deposits are common in limestone caves in the humid tropics where seasonal rainfall is high, and water seeping through fissures in the cave walls causes the deposits in the caves to cement (e.g. Dominguez-Bella et al., 2012; Mijares et al., 2010:124). These deposits present problems for the fine scale removal and extraction of cultural materials and recent work has dealt with new methods for excavating such deposits (Dominguez-Bella et al., 2012). However the implications cemented deposits have for interpretation of the archaeological record have rarely been addressed in detail. Breccia deposits containing culturally-derived materials, preserved at heights above the current site deposit surface, are often overlooked by archaeologists who interpret discontinuities in the chrono-stratigraphic sequences from their excavations as reflecting phases of occupation and abandonment by humans using the sites, rather than the result of a diverse range of natural processes acting on the completeness of stratigraphy within cave systems. Here we discuss the mechanisms that form such cemented deposits and the potential for redeposition/incorporation of these remnant deposits into the accumulating archaeological record. We argue that while such deposits may bias the accumulating archaeological record, they also provide useful 'time capsules' allowing the recognition that periods of the human occupation record, as originally deposited, are missing from the excavated archaeological record. In other words, they allow us to recognize that our sample is biased and that the missing time is not due to site or regional human abandonment. The dating of these remnant 'time capsule' deposits is therefore critical for understanding the history of human occupation in the context of sediment accumulation and removal episodes.

1.1. *Early studies of archaeological breccia deposits in the Indo Pacific region*

Breccia deposits on cave walls, containing cultural materials, were first noted in Island Southeast Asia by Van Heekeren whilst he was exploring cave sites on the island of Sulawesi in 1949–50. He reported that Burung cave in the Lealleang valley of the Maros region contained lenses of shells, bones and stone artefacts which were attached to the walls at heights of up to 1.5 m above the floor of the cave, and hypothesized correctly that these were formed as a result of carbonate-rich waters cementing the cultural material (Van Heekeren, 1972:123). A detailed assessment of breccia deposits in the same region was later made by Ian Glover (1979) during the course of his archaeological research in Sulawesi. He noted remnant deposits of breccia at Leang Burung 2 (Van Heekeren's Burung Cave), Ulu Leang, Leang Timpusang and Leang Pattae (Glover, 1979:307). At Ulu Leang breccias were found in at least 30 places around the walls, and Glover records that:

> "Nearer the front of the cave, smaller patches of cemented deposit remained on the walls high above the present floor, where they seemed to reflect an earlier floor level sloping towards the front of the cave and between 1 and 2 m above the existing cave floor … The presence of bone fragments among the cemented shells, and occasional chert flakes was convincing proof that this was not a natural deposit, but habitational refuse." (Glover, 1979:307)

Glover (1979) attempted to understand the processes that resulted in the formation of such deposits, and how they came to be cemented so high above the current surface of the deposit. He initially hypothesized that they were the "truncated remains of an older cave fill eroded by water action and largely removed before the current cave deposits began to accumulate." Following on from this he excavated and dated one of the breccia deposits at Ulu Leang and confirmed that it contained a similar range of cultural material, and was of the same age as surface layers elsewhere in the cave, leading him to reject his earlier hypothesis that the breccias represented a remnant deposit from a Pleistocene or significantly earlier depositional episode. Instead he hypothesized that the breccias were all that remained after the underlying habitation deposits were dissolved "though solution and mechanical removal" thus undermining the cave floor. As deposit was lost from below, this would cause the cave floor to subside over time, leaving only patches of deposit cemented to walls or speleothems at heights above the current floor to attest to its prior fill level.

Here we re-evaluate Glover's hypotheses regarding the mechanisms for breccia formation and deposit loss, and look at their general applicability to other caves based on the dating of breccias and cultural sequences from two limestone caves in Timor Leste and one in Papua New Guinea [PNG] (Fig. 1). We identify a diverse array of mechanisms to account for the presence of cave breccias on walls and speleothems well above the current floor fill level, and suggest that these can only be understood by dating and analysis of individual cave systems and a range of deposits within a given cave. All three sites are located in high rainfall areas with marked seasonality in the humid tropics.

2. Case studies from Papua New Guinea (PNG) and Timor Leste

2.1. *Lachitu Cave (PNG)*

2.1.1. *Site location, environmental context and excavation*

Lachitu Cave is on the north coast of PNG (S 2.633888, E 141.136388) in karstic limestone terrain at the foot of the Oenake Range, between the coast and the Bewani-Torricelli mountain chain (Klootwijk et al., 2003). The area is tectonically active with net uplift rates >1.2 m/1000 years and likely movement associated with Holocene seismic events (see Tudhope et al., 2000). Today Lachitu is about 22–24 m above sea level and faces north to the shoreline ca. 150 m from the cave entrance (Fig. 1). A steep scree slope immediately below the mouth of the cave might be a product of recent cliff line retreat and roof collapse, perhaps during the 7000 cal BP marine relative high stand.

Lachitu was excavated by Paul Gorecki and colleagues from James Cook University in 1990/1991, and again by the authors in 2004/2005. The deposit can be divided into a thin upper unit with pottery, sparse bone, shell and stone artefacts, and a pre-ceramic unit comprising the majority of the deposit (Gorecki et al., 1991; O'Connor et al., 2010). Stone artefacts are abundant in the pre-ceramic unit and along with a diverse range of marine and terrestrial fauna are found to the base of the deposit. Gorecki et al. (1991) reported on one excavation Square, X1, which had a lower unit with a Pleistocene age of 17,399–16,389 cal BP (ANU-7603) and an upper Holocene unit (Table 1). They noted that the dates they obtained suggested several phases of non-occupation or cultural hiatus. Together with unpublished samples submitted from the 1991 season from excavation Square Y1 their results suggest a hiatus between ~14,000 and ~9500 cal BP, ~9500 and 6500 cal BP and ~6500 and 700 cal BP (Gorecki et al., 1991:121) (Table 1). A later publication reported a date of 42,412–36,507 cal BP (ANU-7610), for a shell sample from 130–140 cm below the surface (Gorecki, 1993:155). Gorecki (1993) does not discuss the provenance or context of this much older sample, but the depth information on

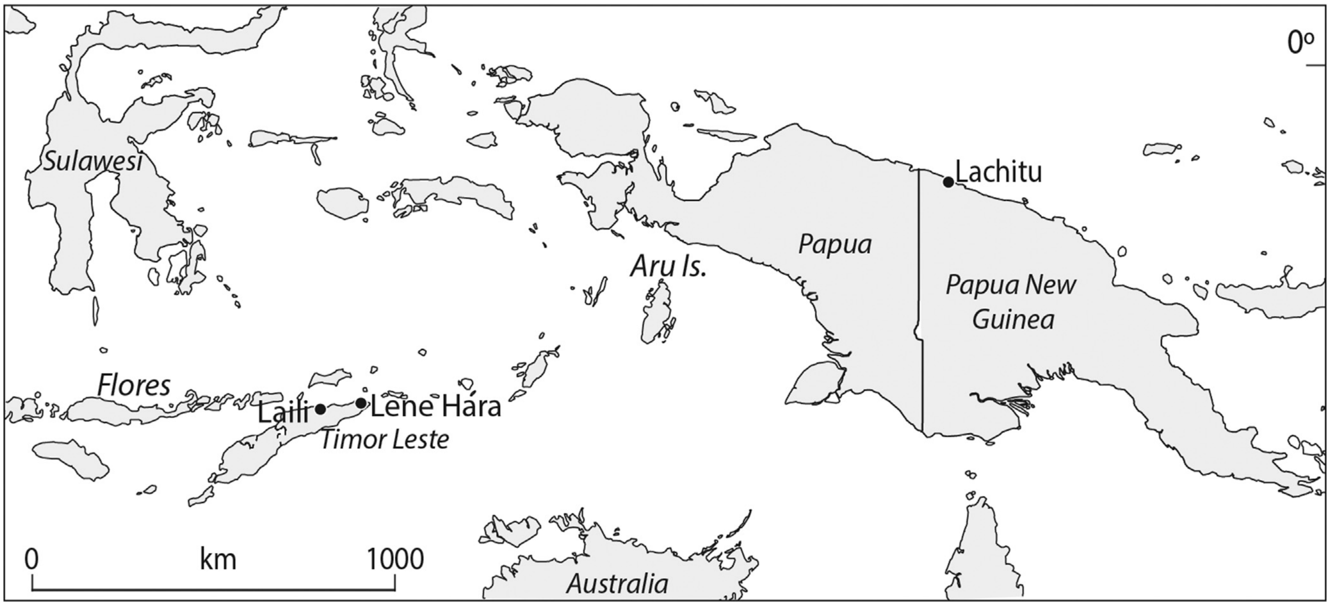

Fig. 1. Location map showing sites discussed in text.

Table 1
Lachitu radiocarbon dates from Gorecki 2004/2005 excavations.

Lachitu Square	EU	Material	Lab code	Curve	δ13C	Radiocarbon age	Age 2σ cal BP
X1	1	Charcoal	ANU-7697	SHcal 13	–	260 ± 60	450–354 (16.0%) 339–134 (68.7%) 120–57 (7.0%) 29–… (3.7%)
	2	marine shell	ANU-7698	Marine 13	–	1180 ± 70	892–626
	3	marine shell	ANU-7602	Marine 13	–	6040 ± 80	6641–6289
	4	marine shell	ANU-7609	Marine 13	–	6010 ± 90	6640–6260
	6	marine shell	ANU-7699	Marine 13	–	12,700 ± 110	14,862–13,938
	9	marine shell	ANU-7700	Marine 13	–	13,970 ± 200	16,990–15,809
	10–11	marine shell	ANU-7603	Marine 13	–	14,340 ± 160	17,399–16,389
	12	marine shell	ANU-7610	Marine 13	–	35,410 ± 1400	42,412–36,507
Y1	4	marine shell	ANU-7928	Marine 13	–	5850 ± 60	6404–6145
	10	marine shell	ANU-7927	Marine 13	–	8880 ± 70	9731–9405
	15	marine shell	ANU-7926	Marine 13	–	14,910 ± 90	17,934–17,442
	23	marine shell	ANU-7925	Marine 13	–	13,360 ± 90	15,790–15,204
	25	marine shell	ANU-7924	Marine 13	–	13,270 ± 120	15,786–15,017

the laboratory submission form would place it at 115–130 cm depth and directly beneath ANU-7603 dated to 17,399–16,389 cal BP (ANU Radiocarbon Laboratory).

Table 1. Dates from the 1990 and 1991 field seasons at Lachitu obtained from the ANU Radiocarbon Laboratory with the permission of Paul Gorecki. Dates are calibrated in Oxcal 4.2, using SHCal13 (Hogg et al., 2013) for charcoal samples, and Marine13 (Reimer et al., 2013) for marine shell samples. No DeltaR correction is applied for the marine shell calibrations as the ANU radiocarbon submission forms identify it only as marine shell and the table in Gorecki et al. (1991) as 'shell'. No δ13C is reported in Gorecki et al. (1991). Note the radiocarbon ages differ from those reported in Gorecki et al. (1991:121) which includes only the dates from Square X1 and which had a reservoir correction of 400 years deducted from the radiocarbon ages, and were uncalibrated.

In 2004/2005 the authors returned to Lachitu to try to replicate the 42,412–36,507 cal BP (ANU-7610) date and to clarify the provenance of the sample. Three test pits (Squares A, B and C) were excavated, each of 1 m^2, to a point where large rubble or bedrock hindered further removal (Fig. 2). Only Squares A and C have thus far been dated. The dates and cultural finds from the excavation have been reported elsewhere (O'Connor et al., 2011). Here we focus on some of the apparent dating anomalies, inversions and chrono-stratigraphic hiatuses revealed by our 2004/2005 excavations and discuss these and Gorecki's earlier results within the context of geomorphic processes acting on the cave sedimentary deposits.

2.1.2. *Lachitu: the chrono-stratigraphic sequence*

In brief, our 2004/2005 excavation sequences largely supported Gorecki et al.'s (1991) findings. Squares A and C had similar stratigraphic profiles (Fig. 4). The upper 20 cm in Square A, Excavation Units (EUs) 1–4, is a visibly active soil layer, with evidence of mixing by invertebrates and burrowing by land crabs. It consists of fine sandy grits or sandy calcareous earths, was less clastic than the lower levels, and had discrete sandy-silty lenses. Ashy layers, interpreted as the remains of hearths, occur within shallow depressions lying unconformably over lower shelly units. There is

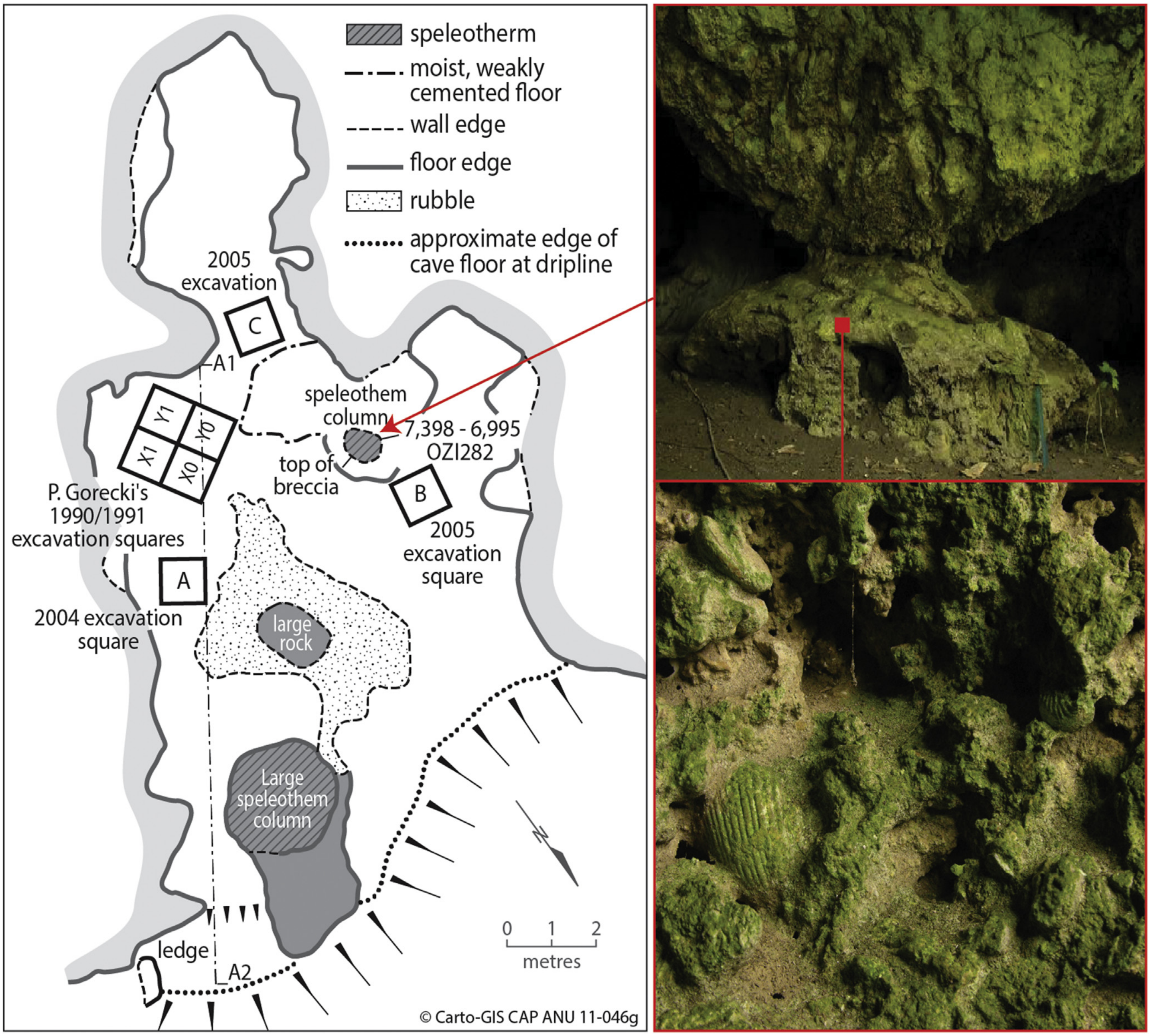

Fig. 2. Lachitu showing position of Gorecki's excavation and excavations from the 2004/2005 field seasons as well as the location of one of the dated breccia deposits, shown inset.

little or no evidence for net sediment accumulation in Square A between the shell rich deposit dated earlier than 6000 cal BP and the upper deposit dating to the historic period. The cultural assemblage at the interface, the upper excavation units of the shell rich deposit (EUs 5–7), is clearly a mixed-age palimpsest including mid Holocene-aged marine shells and pottery and pig teeth which are dated to within the last few thousand years (O'Connor et al., 2010).

The deposit underlying the mid Holocene unit shows episodic accumulation between ~6000 and 18,000 cal BP, has more shell and dense shelly lenses, and more rock and clastic aggregates. No samples dating as early as the 42,412–36,507 cal BP (ANU-7610) basal date obtained by Gorecki were recovered during the 2004/2005 excavations (O'Connor et al., 2010). However, two age estimates were obtained which were significantly older (and present an inversion) compared with all other dated samples in the sequence; 29,776–28,490 cal BP (Wk-16528) and 28,145–27,555 cal BP (Wk-16527), although no stratigraphic anomaly was evident in plan or section (Table 2, Fig. 4). These early dates alert us to the possibility of a much longer history of occupation at Lachitu, as well as the probability of several major erosional episodes prior to that which occurred subsequent to ~6500 cal BP. Whether any remnants of these earlier deposits remain *in situ* is currently unknown.

2.1.3. The Lachitu breccias

One factor noted during the 2004 excavation whose import was not immediately recognized was that many excavation units contained aggregates of marine shell, bone, and limestone rubble in cemented clasts (O'Connor et al., 2010). At the time, these were thought to result from *in situ* cementation of the deposit due to the passage of water, rich in calcium carbonate, through the deposit re-precipitating around rock fragments and cultural materials. What was not clear was why this process acted differentially – with some cultural materials appearing heavily cemented, while other finds from the same excavation unit and depth below surface were

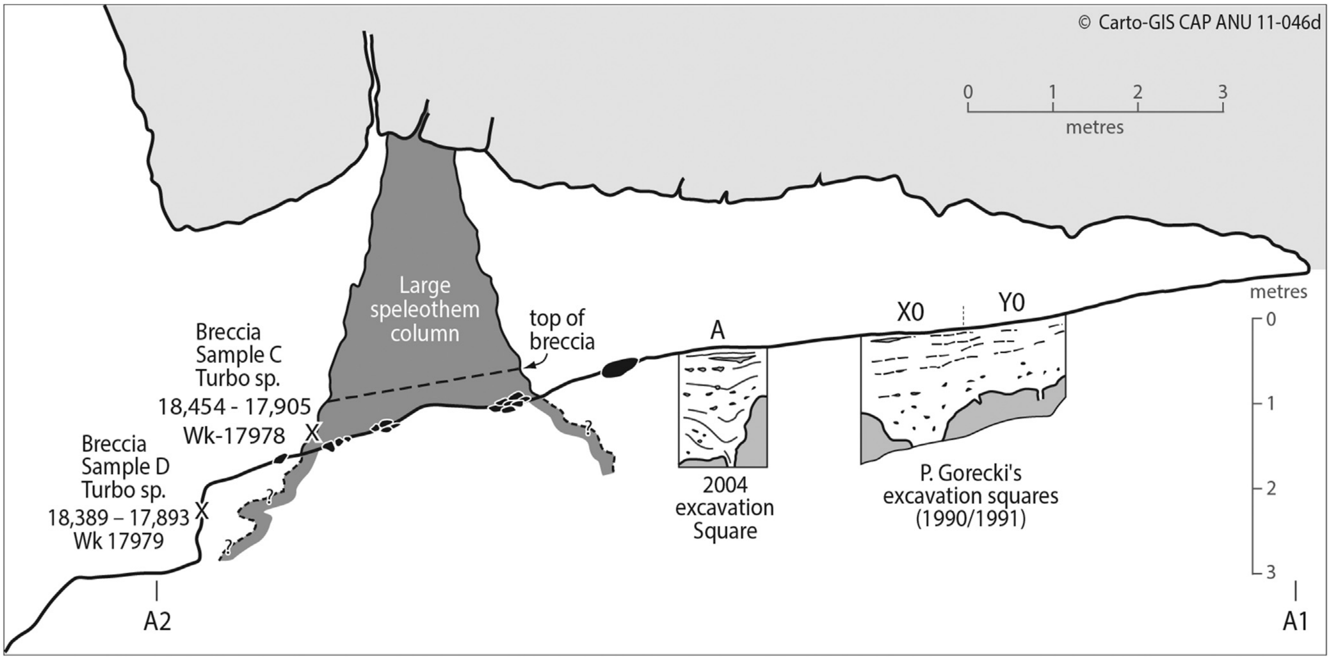

Fig. 3. Profile of Lachitu showing location of excavations and dated breccia deposits.

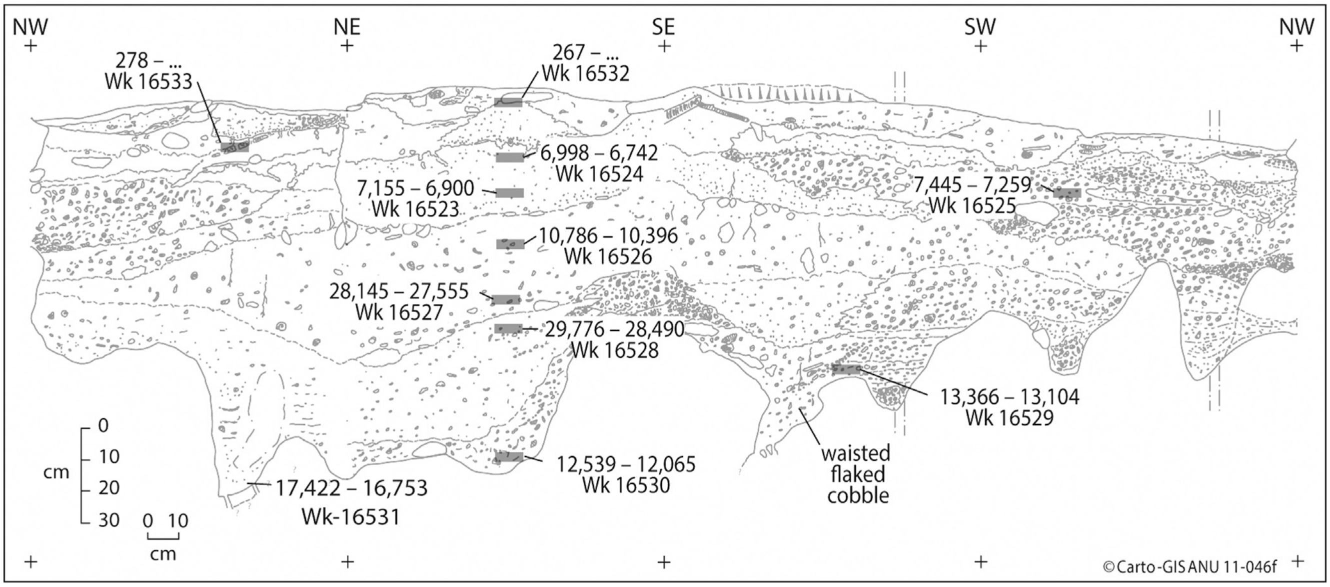

Fig. 4. Lachitu Square A section. Location of dated samples are shown on the section.

entirely unaffected. However it was not until the second excavation season in 2005 that perched breccia deposits were discovered by one of the authors (KA) adhering to the lower part of a speleothem near the entrance of the cave (Fig. 2). Significantly the perched breccia contained cultural material and the speleothem was heavily eroded at the base (Fig. 2). Two marine shells (*Turbo marmoratus*) from within this breccia produced dates of ~18,200 cal BP (Wk-17978 and Wk-17979). Cemented cultural deposits were subsequently identified in other locations within the cave. A *Turbo* sp. shell from an eroding breccia 30 cm above the current cave floor and behind Square B dated to ~7200 cal BP (OZF-282) (Fig. 2, Table 2).

Acetic acid treatment of the breccia clasts from within the deposit produced cultural assemblages of broken, burnt and unburnt marine shell and animal bones, as well as charcoal and stone artefacts, which were indistinguishable in terms of content to that in the unlithified sedimentary units. In the areas where breccia was actively eroding from the base of the speleothems detached clasts could be seen on the cave floor, indicating that fretting of the older cemented cultural deposits is an ongoing process, and this older cultural material is being actively re-deposited. Re-deposition and incorporation of older archaeological materials into the deposit as it has accumulated has clearly biased the archaeological record.

In short, dates on material from cemented breccias, as well as eroded and secondarily re-deposited clasts of breccia containing cultural materials found in the deposits, alert us to the likelihood

Table 2
Dates obtained from excavation units in Squares A and C from the 2004/2005 excavations at Lachitu and from the three sampled breccias shown in Figs. 2 and 3.

Lachitu Square	Excavation unit	Material	Lab code	Curve	δ^{13}C	Radiocarbon age	Age 2σ cal BP
A	2 (I)	Charcoal	Wk-16532	SHcal 13	−31.6 ± 0.2	132 ± 34	267–220 (19.3%) 148–… (76.1%)
	4 (I)	Charcoal	Wk-16533	SHcal 13	−28.7 ± 0.2	160 ± 34	278–207 (27.8%) 191–171 (2.3%) 154–… (65.3%)
	7	*Turbo* sp.	Wk-16524	Marine 13	2.8 ± 0.2	6399 ± 45	6998–6742
	10 (I)	*Turbo* sp.	Wk-16523	Marine 13	2.8 ± 0.2	6519 ± 46	7155–6900
	10 (II)	*Turbo* sp.	Wk-16525	Marine 13	1.4 ± 0.2	6842 ± 48	7445–7259
	14	*Turbo* sp.	Wk-16526	Marine 13	1.7 ± 0.2	9695 ± 69	10,786–10,396
	18	*Turbo* sp.	Wk-16527	Marine 13	2.9 ± 0.2	24,140 ± 155	28,145–27,555
	20 (I)	*Tectus niloticus*	Wk-16528	Marine 13	2.4 ± 0.2	25,436 ± 282	29,776–28,490
	24	*Turbo* sp.	Wk-16529	Marine 13	2.0 ± 0.2	11,753 ± 62	13,366–13,104
	28	*Turbo* sp.	Wk-16530	Marine 13	1.3 ± 0.2	10,825 ± 59	12,539–12,065
	31	*Turbo* sp.	Wk-16531	Marine 13	3.6 ± 0.2	14,464 ± 92	17,422–16,753
C	6	*Turbo setosus*	Wk-17536	Marine 13	3.2 ± 0.2	6062 ± 46	6621–6376
	8	*Turbo setosus*	Wk-17535	Marine 13	2.8 ± 0.2	6013 ± 50	6555–6299
	14	*Turbo argyrostomus*	Wk-17534	Marine 13	2.6 ± 0.2	5932 ± 45	6448–6259
	24	*Turbo setosus*	Wk-17537	Marine 13	0.9 ± 0.2	9897 ± 78	11,090–10,645
	38	*Turbo setosus*	Wk-17538	Marine 13	3.2 ± 0.2	15,053 ± 167	18,267–17,439
Breccia Samples	C	*Turbo marmoratus*	Wk-17978	Marine 13	3.6 ± 0.2	15,357 ± 109	18,454–17,905
	D	*Turbo marmoratus*	Wk-17979	Marine 13	3.6 ± 0.2	15,325 ± 97	18,389–17,893
	Sample Behind Sq. B	*Turbo* sp.	OZI-282	Marine 13	1.4 ± 0.2	6680 ± 90	7398–6995

that the 'missing time' at Lachitu is due to major phases of erosion and sediment loss, rather than a lack of human occupation.

2.2. Timor Leste, Lene Hara Cave

In Timor Leste perched breccia deposits have been identified in many limestone caves and shelters (pers. obs). Here we focus on deposits in two sites which have been excavated, Lene Hara and Laili.

2.2.1. Site location, environmental context and excavation

Lene Hara (S 8.408809, E 127.292700) is a large limestone solution cave at the extreme eastern tip of Timor Leste (Fig. 1). It is situated at ca.100 m above sea level in an uplifted coral terrace, less than 1 km from the current shoreline. The cave entrance faces east, with a well-developed drip-line overhanging a vegetated terrace at the front of the cave. The drip-line area at the entrance is over 40 m wide, and the main cave extends more than 50 m into the hillside before entering narrow fissure systems (Fig. 5). Under the drip-line, large mounded areas of block fall, comprising both limestone and fallen speleothem, form 2–5 m high piles of block debris (Fig. 5). Isolated speleothems occur within the interior of the cave as 2–4 m wide columns and 1–2 m high mounds (Fig. 6). Many of the speleothems have elevated eroded pedestals, where past erosion events have removed unconsolidated sediments from around the base of the columns and caused net lowering of the cave floor abutting these structures (O'Connor et al., 2010).

The current floor of Lene Hara Cave is highest in the south (near Square A) and slopes away to the north and northeast (Fig. 5). Surficial cave floor sediment is generally a loose organic cave earth, composed of fine sands to silt. High areas around the speleothem columns serve to channel episodic surface water flow from fissures at the rear of the cave during extreme storm events. Surface water flow has produced micro-fans and fine gravel lags by winnowing away fines. This has caused some exposure of flowstones on the surface (Fig. 5). Recent sedimentation within the cave has been further complicated by the construction of linear stone walls of boulder rock fall. In places *in situ* speleothem columns are incorporated into the constructed wall of limestone blocks. The central outer mounded rampart area of rock fall and, further inside, the large speleothem column, effectively separate the mouth of the cave into two chambers (Fig. 6). To date four 1 m^2 test pits, Squares A, B, D and F have been excavated in Lene Hara. The results show that different chrono-stratigraphic sequences are preserved in different areas of the cave.

2.2.2. Lene Hara: the chrono-stratigraphic sequence

Square A, excavated in 2000 in the higher southern part of the cave produced an 80 cm deep sequence that predominantly dated between ~39,000 and 34,000 cal BP (Table 3). Square A can be broadly divided into an upper and lower deposit. The upper and lower deposits are further divisible into four litho-stratigraphic units (LUI–LUIV) (Fig. 7). The upper deposit (LUI) is unconsolidated and consists of dark brown well sorted sandy silts, with near horizontal bedding. This unit conformably overlies the slightly undulating surface of LUII, comprised of denser and more organic darker brown sandy silts. The well-defined hearth feature in this unit suggests minimal bioturbation (Fig. 7). LUIII has coarse to fine sandy silts, mixed with variable proportions of coarser gravels and shell. The lower deposits, LUIV are much coarser, poorly sorted sediments, ranging from gravelly silty sands to very coarse clast-supported cobble gravels and boulder rubble (see Fig. 7). The deposits become progressively more lithified below 60 cm, where roof fall and cultural material are variably cemented to the base of the test pit.

Eight radiocarbon dates obtained from the 2000 excavation indicated that most of the marine shell within the sampled sequence was of Pleistocene age, dating between 40,266 and 36,971 cal BP (ANU-11418) and 34,485–33,258 cal BP (ANU-11398) (Table 3). A single sample of *Tectus* sp. cf. *niloticus* shell from EU 2 (5–10 cm depth) produced a late Holocene age of 691–508 cal BP (ANU-11400). This suggested either that occupation of the cave was discontinuous or spatially uneven, or that substantial erosion of the deposit had occurred, creating a major chrono-stratigraphic hiatus. Most pottery occurred in the top 25 cm of the deposit dating to the Holocene, along with stone artefacts, marine shell and animal bone. Occasional sherds found in the deposit dated to the Pleistocene indicate some intermixing. Stone artefacts, marine shell and bones continue to bedrock (O'Connor and Aplin, 2007). In our initial publication we suggested that the cave was occupied between 35,000 and 30,000 and abandoned thereafter until the late Holocene (O'Connor et al., 2002a). Subsequently a program of direct

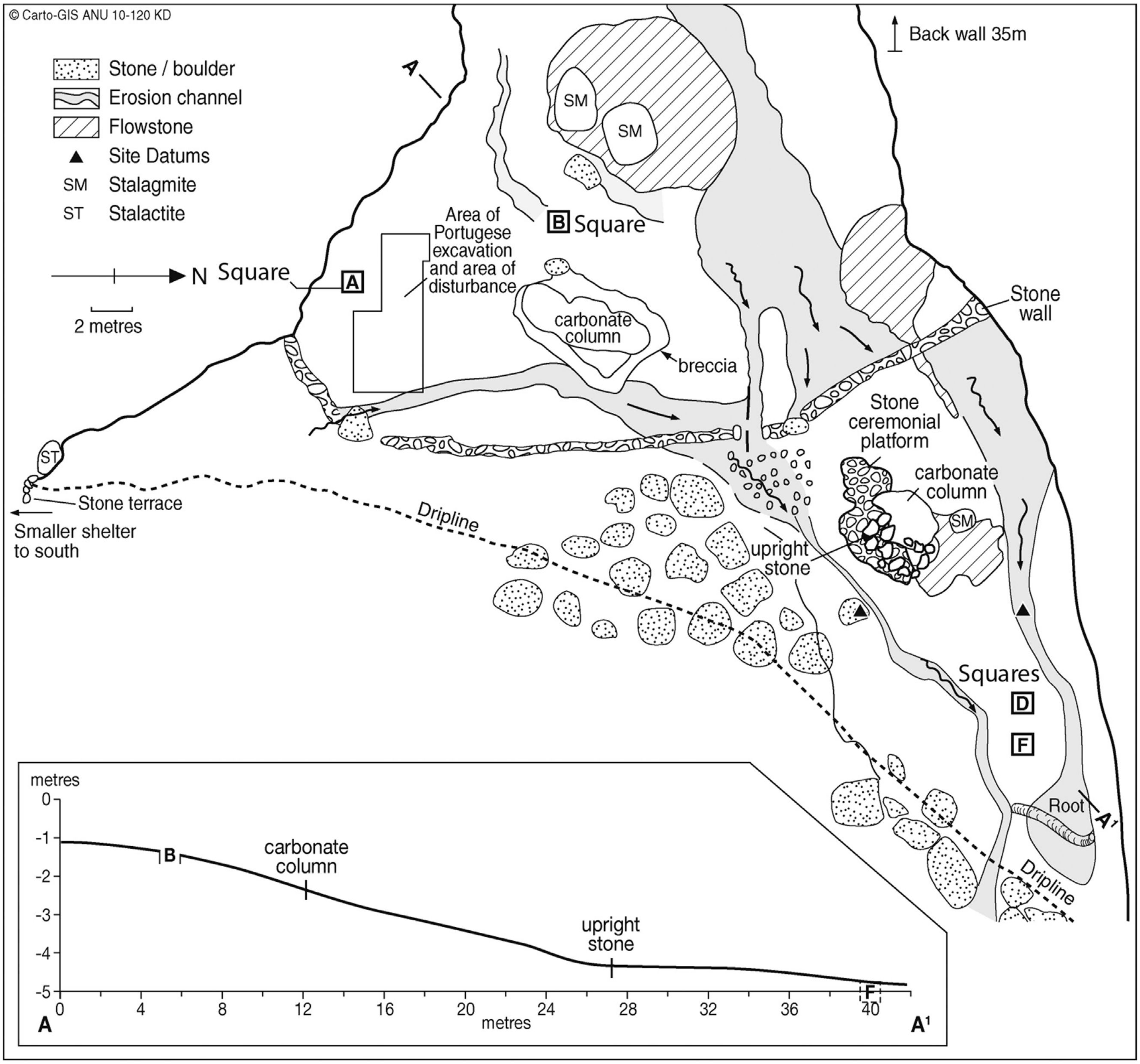

Fig. 5. Lene Hara site plan and profile showing location of Squares A, B, D and F, speleothems, sampled breccia and wall.

dating of artefacts from Square A produced two shell beads in EUs 7 and 10 dating to the mid to late Holocene, 4705–4415 cal BP (OZF-212) and 3628–3404 cal BP (OZF-213) (O'Connor et al., 2002b:19). This demonstrated that the cave had been used during the mid-Holocene and that some Holocene-aged cultural materials were intermixed with Pleistocene-aged materials in the predominantly late Pleistocene sediments of Square A.

In 2002 new excavations were carried out at Lene Hara. The three 1 m^2 test pits, Squares B, D and F were excavated to compare the litho- and chrono-stratigraphy in other parts of the cave floor with Square A. Square B was located in the same southern higher area of the cave as Square A. Two other Squares, D and F, were located in the lower, northern chamber outside the walled part of the deposit (Fig. 5). Squares A, B and F were found to have little overlap in terms of the chronology of the occupation phases represented. However it was the discovery of a significant breccia deposit containing cultural materials in 2009, adhering to a large broken speleothem column, which radically revised our interpretation.

Square B is ca. 60 cm deep with a stratigraphic sequence broadly similar to Square A. Radiocarbon dating indicates that the sediments in B largely accumulated between ~30,000 and 21,000 cal BP (Table 3), again with a thin upper veneer of late Holocene age. The cultural sequence in Square B also mirrors that of Square A, with pottery found in the top 20 cm of the deposit and bone, marine shell and stone artefacts recovered throughout. The loose, surficial sediments occur in the upper 0–6 cm of the deposit and are well-sorted fine sands and silts, with some fine gravel (Fig. 8). This upper unit is interpreted as a recent wash accumulation and overlies denser deposits on a largely planar contact. Underlying deposits comprise weakly-bedded coarse sandy silts with frequent larger boulders and cobbles. These coarser gravelly earths in turn overlie horizontally-bedded, finer deposits. The deposit becomes courser with depth and lowest sediments comprise partly cemented light

Fig. 6. Speleothems inside the entrance of Lene Hara with stone wall in foreground.

Table 3
Radiocarbon dates: Lene Hara Squares A, B, D and F, 2000 and 2002 excavations.

Lene Hara Square	Excavation unit	*Tectus niloticus*	Lab code	Curve	δ^{13}C	Radiocarbon age	Age cal BP 2σ
A	2	*Tectus* sp. *cf. niloticus*	ANU-11400	Marine 13	3.0 ± 2.0	1030 ± 60	691–508
	4 (A)	*Lambis lambis*	ANU-11419	Marine 13	0.0 ± 2.0 est.	33,150 ± 550	38,415–35,669
	4 (B)	*Conomurex luhuanus*	ANU-11420	Marine 13	2.2 ± 0.1	30,970 ± 460	35,474–33,809
	5	*C. luhuanus*	ANU-11398	Marine 13	2.3 ± 2.0	30,110 ± 320	34,485–33,258
	7	*Tectus* sp. bead	OZF-212	Marine 13	0.0 ± 2.0 est.	4400 ± 40	4705–4415
	10	*Conomurex* sp. bead	OZF-213	Marine 13	0.0 ± 2.0 est.	3620 ± 40	3628–3404
	10	*C. luhuanus*	ANU-11399	Marine 13	1.9 ± 2.0	32,440 ± 400	36,920–35,004
	14 (A)	*C. luhuanus*	ANU-11397	Marine 13	2.1 ± 2.0	30,990 ± 340	35,188–33,945
	14 (B)	*Tectus* sp.	ANU-11418	Marine 13	2.9 ± 0.1	34,650 ± 630	40,266–36,971
	18	*C. luhuanus*	ANU-11401	Marine 13	1.9 ± 2.0	30,950 ± 360	35,192–33,896
B	2	*Turbo argyrostomus*	ANU-12138	Marine 13	0.0 ± 2.0 est.	18,740 ± 400	23,133–21,156
	5	*Tectus niloticus*	ANU-12141	Marine 13	0.0 ± 2.0 est.	18,380 ± 220	22,353–21,192
	10	*T. niloticus*	ANU-12139	Marine 13	0.0 ± 2.0 est.	23,790 ± 210	27,892–27,271
	15	*T. niloticus*	ANU-12142	Marine 13	0.0 ± 2.0 est.	25,770 ± 630	30,885–28,330
D	18	*T. niloticus*	ANU-12059	Marine 13	0.0 ± 2.0 est.	3820 ± 80	3985–3556
	20	*T. niloticus*	ANU-12060	Marine 13	0.0 ± 2.0 est.	3650 ± 70	3745–3377
F	5	*T. niloticus*	ANU-12140	Marine 13	0.0 ± 2.0 est.	1170 ± 190	1146–444
	10	*T. niloticus*	ANU-12136	Marine 13	0.0 ± 2.0 est.	3305 ± 190	3603–2721
	16	Charcoal	ANU-12029	SHcal13	−24 ± 2.0	3200 ± 240	3612–2421
	16	*T. niloticus*	ANU-12041	Marine 13	0.0 ± 2.0 est.	3850 ± 70	4003–3607
	20	*T. niloticus*	ANU-12042	Marine 13	0.0 ± 2.0 est.	4370 ± 70	4775–4345
	23	*T. niloticus*	ANU-12045	Marine 13	0.0 ± 2.0 est.	5270 ± 80	5841–5466
	27	*Nautilus* sp. shell bead	NZA 16998	Marine 13	1.95 ± 0.2	5782 ± 45	6300–6085
	30	*T. niloticus*	ANU-12044	Marine 13	0.0 ± 2.0 est.	6200 ± 90	6866–6426
	35	*T. niloticus*	ANU-12043	Marine 13	0.0 ± 2.0 est.	6140 ± 100	6816–6340
	40	*Oliva* sp. shell bead	NZA 16999	Marine 13	0.97 ± 0.2	7945 ± 65	8556–8283
	42	*T. niloticus* fish hook	NZA 17000	Marine 13	2.57 ± 0.2	9741 ± 60	10,841–10,491
	43	*T. niloticus*	ANU-12040	Marine 13	0.0 ± 2.0 est.	10,050 ± 80	11,209–10,791
Breccia Samples	Sample 1	*Tectus* sp. cf. *niloticus*	Wk-26404	Marine 13	2.5 ± 0.2	37,956 ± 506	42,681–41,206
	Sample 2	*Tectus* sp. cf. *niloticus*	Wk-26405	Marine 13	3.3 ± 0.2	38,207 ± 610	42,998–41,251
	Square F EU 4	*Nerita textilis*	S-ANU 42729	Marine 13		39640 ± 590	44,182–42,269

brown silty gravels, infilling an undulating surface over flowstone, breccia and/or bedrock.

Squares D and F were located 1 m apart in the northern chamber of the cave (Fig. 5). They are much closer to the drip-line, and within a well-defined, 5–8 m wide area of floor that experiences surface wash from smaller rivulets originating in various clefts at the rear of the cave. Excavation of Square D was discontinued at the wish of the traditional owners at ca. 70 cm when a human burial was encountered (Fig. 8). The date of 3745–3377 cal BP (ANU-12060) from the lowest excavated EU (20) provides a maximum age for the

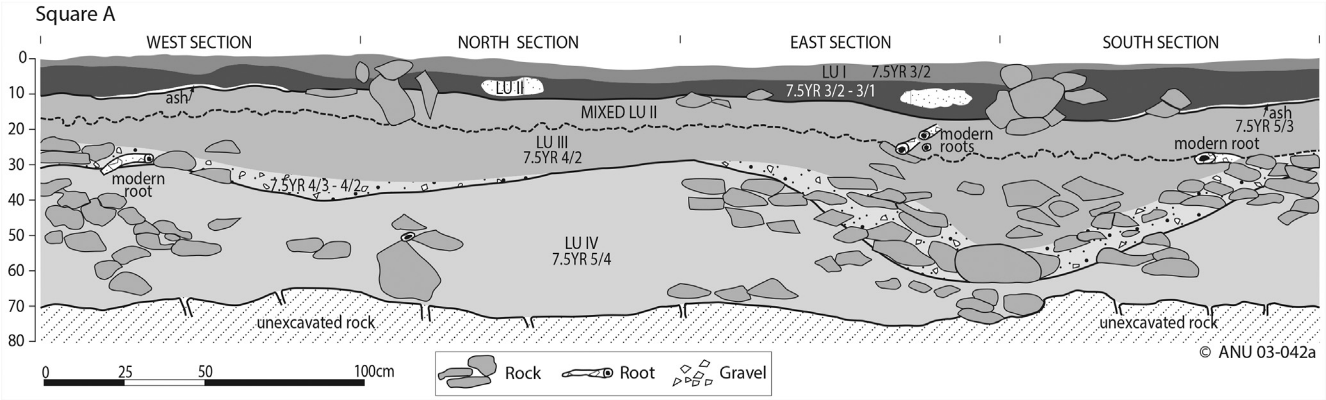

Fig. 7. Lene Hara test Square A section showing stratigraphy and depth.

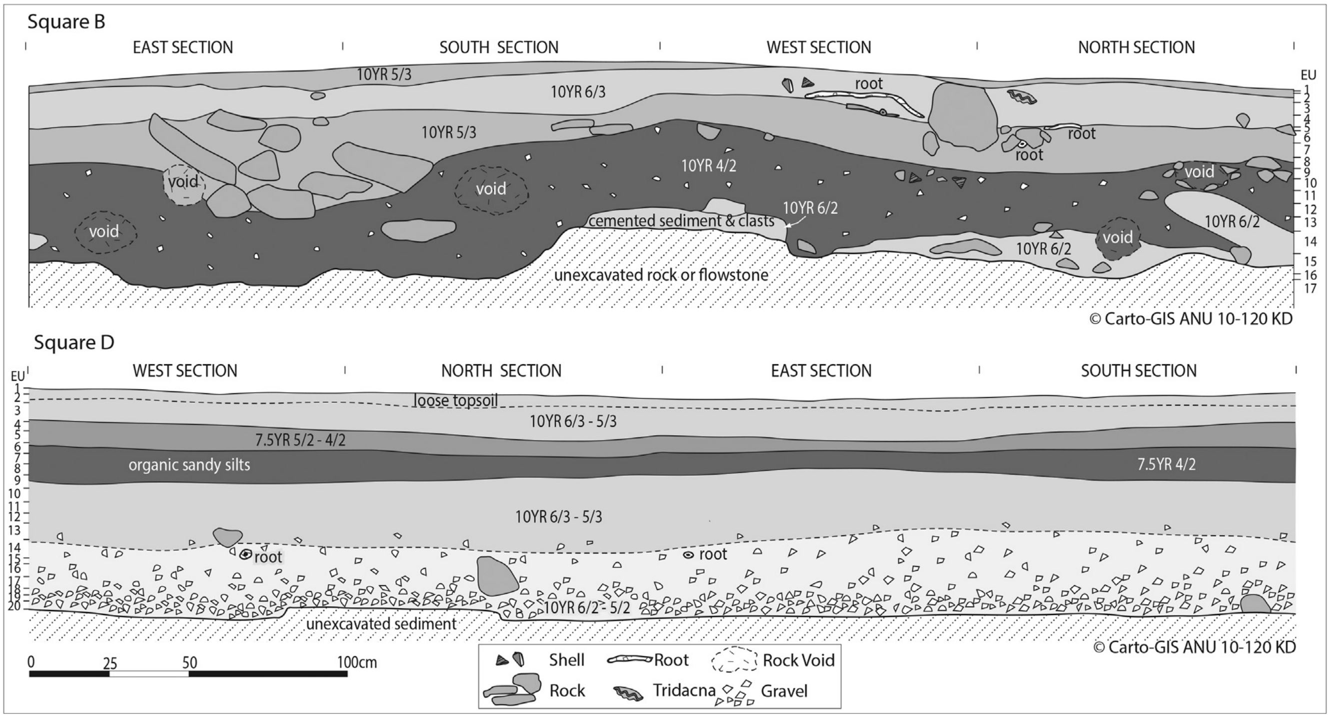

Fig. 8. Lene Hara test Square B and D sections, showing stratigraphy and excavation units.

burial (Table 3).

Square F was excavated to a depth of ca. 220 cm where excavation was discontinued prior to reaching bedrock owing to safety concerns (Fig. 9). The surficial sediments in F are sandy silts, with patches of fine gravels. Weakly-bedded sands with variable gravel and silt content form a well-defined unit down to 70 cm. At this level a distinct thin bed of light grey ashy sands and silts form a continuous band across the Square. From 70 cm to 220 cm the deposit comprises a moderately to well-stratified fining upwards sequence of fine sandy gravels and sandy silts, variably interstratified and mixed with medium and coarse gravels. Cycles of deposition are evident in the bedding structures and the age-depth intervals of radiocarbon ages in the vertical sequence. Brief episodes of erosional surface wash and winnowing across the cave floor are interspersed with deposition through creep, roof fall and human discard. The lowest 50–60 cm of the Square F deposit was significantly coarser than the overlying deposit (Fig. 9). Radiocarbon dates from Square F demonstrate that the entire sequence is of Holocene age, dating between 11,209 and 10,791 cal BP (ANU-12040) at the base and 1146–444 cal BP (ANU-12140) close to the surface in EU 5 (Fig. 9).

The broad stratigraphic sequence observed across the four test pits in Lene Hara Cave is interpreted as follows. In the southern, higher parts of the cave sampled by Squares A and B, early rock fall debris formed platforms against the walls. These areas were occupied in the late Pleistocene, probably starting around 39,000 cal BP, and significant rapid infilling of natural hollows with midden refuse resulted. Sediment and cultural debris continued in this area of the cave for at least 5000 years. Sometime prior to 30,000 years ago, the adjacent area sampled by Square B was probably scoured to bedrock, followed by infilling with coarse sediment mixed with clastic roof fall and cultural material from 30,885–28,330 cal BP (ANU-12142), through to 23,133–21,156 cal BP (ANU-12138). Scouring action evidently truncated the deposit

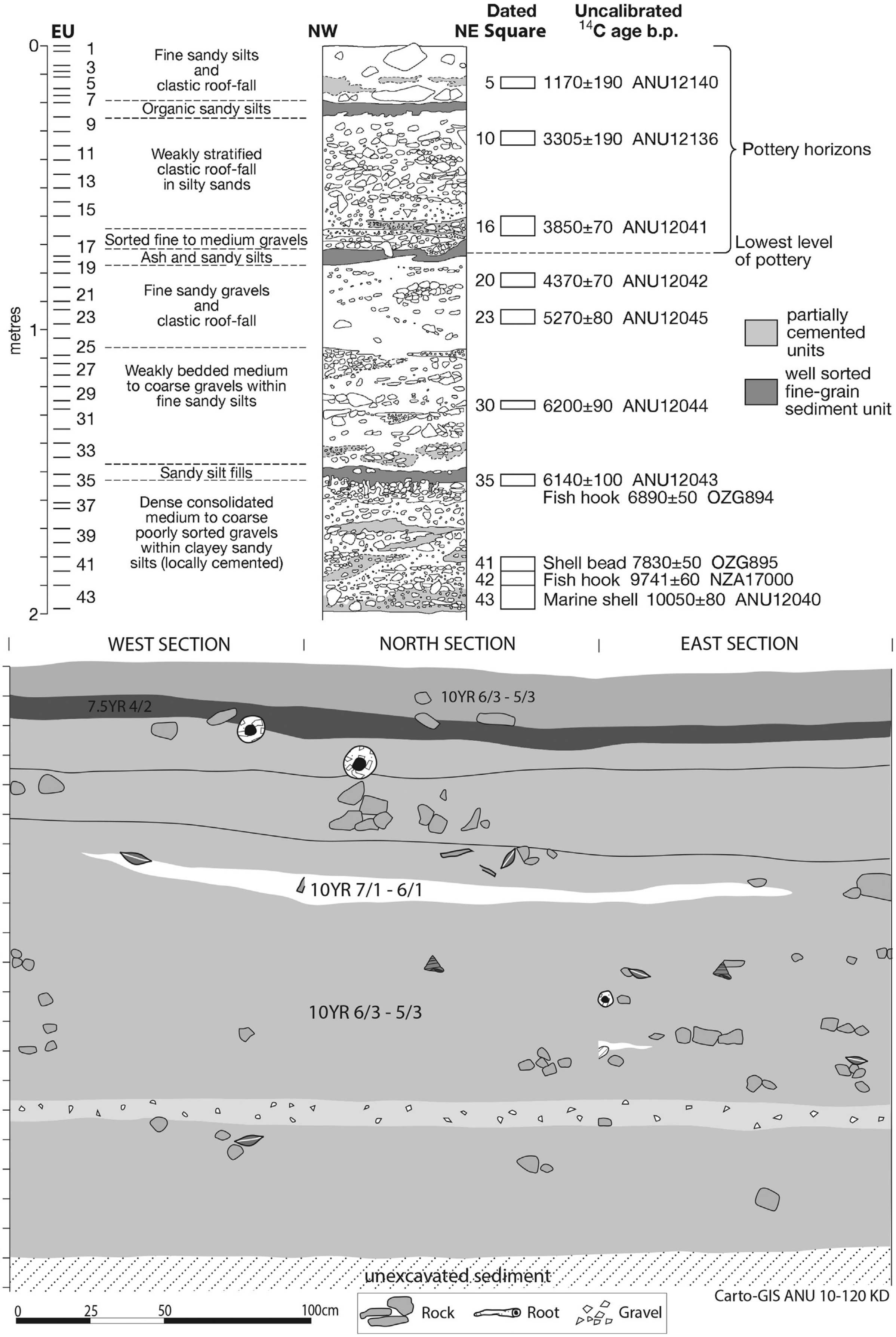

Fig. 9. Lene Hara Square F section showing stratigraphy and depths for excavation units, and radiocarbon dates.

on at least one more occasion in the area of Square B, such that nothing survives apart from a thin veneer of Holocene wash deposits unconformably capping the truncated sequence. The same Holocene veneer probably caps the sedimentary sequence in the area of Square A, but without an obvious unconformity. Further evidence that ancient erosional episodes have removed significant volumes of sediment in this part of the site is found around the base of the larger speleothems in the southern chamber of the cave, where the elevated brecciated units signify a formerly higher cave floor level.

2.2.3. The Lene Hara breccias

In September 2009 two of the authors (SOC, KA) returned to Lene Hara Cave. The survey resulted in the discovery of a breccia with inclusions of cultural materials such as marine shell, stone artefacts and bone, cemented underneath the large speleothem located between the southern and northern chambers of the cave (Fig. 5). In the area sampled the breccia was approximately 50 cm higher than the current floor surface in this part of the cave and itself supports the speleothem column. Cultural material extracted *in situ* from the breccia included a flake made on red chert and marine shellfish. Two well preserved marine gastropods (*Tectus* sp.) produced radiocarbon ages of between ~43,000 BP and ~41,000 BP (Wk-26404, Wk-26405) (Table 4, samples 1 and 2).

In 2009 it was also noted that marine shells cemented in carbonate clasts could be found on the washed surface on the cave floor. These included a high proportion of the marine gastropod *Nerita textilis*. This species is common in the breccias on the sampled speleothem and is one of the dominant species in the Pleistocene shell assemblages at Lene Hara, but is much less abundant in the Holocene archaeological layers. Formerly the defined range for this species was thought not to extend east of India but recent collecting has identified it in Flores Island and Maluku although population sizes are apparently very small (Eichhorst and Szabó, 2004:10). One carbonate encrusted shell of *Nerita textilis* from the SW corner of EU 4 Square F was submitted for dating and returned an age of 44,182–42,269 cal BP (S-ANU-42729) (Table 4, sample Square F4). Based on the age, this specimen is interpreted as eroded from older breccias, and then transported into the lower northern area of the cave floor where it was subsequently incorporated into the accumulating deposit, illustrating a process which has likely operated throughout the human occupation period. The Pleistocene date makes it difficult to ascertain whether Timor Leste is within the current range of the species.

2.3. Laili Cave, Timor Leste

2.3.1. Site location, environmental context and excavation

Laili is a large cave in a karstic limestone outcrop approximately 5 km inland of the north coast of Timor Leste (S 08.54048, E 126.16405), and within the modern village of Laleia (Fig. 1). Located on a ridgeline ~86 m above sea level, the cave overlooks the Laleia River braidplain about 350 m to the east.

Two 1 m^2 test pits, Square A and B, were excavated at Laili in 2011 (Fig. 10). Square A positioned closer to the rear wall of the cave was excavated to a depth of about 220 cm where large rocks covered most of the Square in plan. Square B was excavated to a depth of about 80 cm and discontinued when the deposit was found to be disturbed by termite activity, and no analysis has been carried out on Square B. Square A stratigraphic layers were rich in stone artefacts and contained marine and terrestrial fauna, shellfish from the freshwater reaches of the river as well as the more distant sea, and small quantities of urchin and crustacean. Dating of Square A shows that Laili was first occupied ~44,000 BP. Surprisingly, however, the upper part of the deposit was found to date to ~10,000 BP, with merely a thin sedimentary lens of unconsolidated silty sand, goat dung and leaf litter, with occasional shells and earthenware sherds, mantling the early Holocene/terminal Pleistocene deposits (Fig. 11). The chrono-stratigraphic sequence in Square A at Laili records no use of the cave between Modern and ~10,000 cal BP (Fig. 11).

2.3.2. Laili: the chrono-stratigraphic sequence

A total of 40 excavation units (average = 4.93 cm, range = 2.2–8 cm) were removed in Square A. Nineteen samples from the deposit have been dated; most are charcoal samples collected during excavation or from the sections at the completion of the excavation (Fig. 11; Table 4). An additional ten breccia samples containing shell, bone and stone artefacts were removed from the back wall of the cave above the current floor (Table 4 provides the heights of the samples above datum). The deposit has been divided into eleven Stratigraphic Units (1–11), based on sediment texture, colour and sorting. The relationship between the stratigraphic units and the excavation units is shown in Fig. 11. The stratigraphic units are described with reference to the radiocarbon dates.

Unit 1 is comprised of loosely compacted fine sands and silt. This unit is rich in humic material and dung as goats are sometimes penned inside the overhang. A radiocarbon date on charcoal from one of the lowest lenses in Unit 1 returned a Modern age (D-AMS-007343) (Fig. 11). Unit 2 is a poorly sorted coarse silty sand (10YR 6/2). Radiocarbon samples from the west section for Unit 2 produced ages of 10,992–10,650 cal BP (D-AMS 007342), and 12,362–11,764 cal BP (D-AMS 001654) indicating that these units formed in the terminal Pleistocene to early Holocene.

Stratigraphic Units 3, 4 and 5 are similar in texture and sorting, and have overlapping radiocarbon ages, possibly representing a continuous phase of occupation and deposition. Unit 3 gets progressively finer down the profile, changing from coarse silty sand at the boundary of Unit 2 and 3 to fine sandy silt, rich in charcoal and ash at the boundary of Unit 3 and 4. An *in situ* charcoal sample from Unit 3 produced a date of 15,366–14,988 cal BP (D-AMS 001649). Stratigraphic Unit 4 is also fine sandy silt and extremely rich in charcoal and comminuted ash. Bioturbation was observed in the form of small roots and a burrow-like feature in the east wall. A hearth (4a) occurs between EU 8 and 9. Charcoal from the west section below hearth 4a dated to 16,115–15,755 cal BP (D-AMS 001655). Charcoal from the base of Stratigraphic Unit 4 was dated to 16,104–15,714 cal BP (D-AMS 001656). Concentrations of charcoal and ash were found across the lower part of Unit 5, including a hearth in the west wall (5a). Charcoal from the EU overlying the hearth (EU 16) dated to 16,401–15,958 cal BP (D-AMS 001650). Charcoal from hearth 5a returned an age of 17,468–17,038 cal BP (D-AMS 001661). Stratigraphic Units 6 and 7 are coarse silty sand. A charcoal sample from the west section of Unit 6 was dated to 16,298–15,902 cal BP (D-AMS 001657). Stratigraphic Unit 7 is similar texturally but with more inclusions of rock. Five radiocarbon dates were obtained from Unit 7 (Table 4), ranging between ca. 18,600–22,000 cal BP.

Stratigraphic Units 8–11 show progressive fining down the profile. A charcoal sample collected from this Unit 8 during excavation has an age range of 38,258–36,831 cal BP (D-AMS 001652). Unit 9 is sandy silt. Two charcoal samples were collected from the west section within Unit 9, the first returned an age of 12,409–11,828 cal BP (D-AMS 001663), a notable inversion, and the second, 18,975–18,540 cal BP (D-AMS 001660), which is also considerably younger that the date from Unit 8. An additional charcoal sample from Unit 9, from the sieved fraction of EU 31, was dated to 27,856–27,530 cal BP (D-AMS 001653). A hearth feature (9a) occurs near the base of Stratigraphic Unit 9. Stratigraphic Unit

Table 4
Laili radiocarbon dates.

Laili Square	Excavation unit	Wall sample	Material	Lab code	Curve	δ^{13}C	Radiocarbon age	Age cal BP 2σ
A	1	–	Charcoal	D-AMS-007343	SHcal13	−22.2	modern	modern
	2	A	*Terebralia* sp.	D-AMS 007342	Marine 13	−22.2	9858 ± 47	10,992–10,650
	2	B	Charcoal	D-AMS 001654	SHcal13	−19.3	10295 ± 43	12,362–12,346 (1.2%) 12,261–12,233 (2.5%) 12,085–11,764 (91.8%)
	5	–	Charcoal	D-AMS 001649	SHcal13	−24.9	12789 ± 47	15,366–14,988
	9	C	Charcoal	D-AMS 001655	SHcal13	−31.5	13303 ± 38	16,115–15,755
	10	D	Charcoal	D-AMS 001656	SHcal13	−28.6	13277 ± 50	16,104–15,714
	12	–	Charcoal	D-AMS 001650	SHcal13	−29.0	13490 ± 56	16,401–15,958
	12	F	Charcoal	D-AMS 001661	SHcal13	−21.2	14206 ± 52	17,468–17,038
	14	G	Charcoal	D-AMS 001657	SHcal13	−31.7	13434 ± 51	16,298–15,902
	16	I	Charcoal	D-AMS 001659	SHcal13	−19.3	16280 ± 51	19,835–19,421
	17	–	Charcoal	D-AMS 001651	SHcal13	−24.5	17036 ± 64	20,705–20,264
	17	H	Charcoal	D-AMS 001658	SHcal13	−26.9	16461 ± 52	20,018–19,602
	17	N	Charcoal	D-AMS 001664	SHcal13	−24.7	18625 ± 71	22,634–22,300
	20	L	Charcoal	D-AMS 001662	SHcal13	−19.1	15579 ± 61	18,927–18,643
	25	–	Charcoal	D-AMS 001652	SHcal13	−26.2	33319 ± 168	38,258–36,831
	26	M	Charcoal	D-AMS 001663	SHcal13	−24.0	10347 ± 67	12,409–11,913 (87.5%) 11,908–11,828 (7.9%)
	29	J	Charcoal	D-AMS 001660	SHcal13	−23.4	15545 ± 106	18,975–18,540
	31	–	Charcoal	D-AMS 001653	SHcal13	−25.8	23607 ± 74	27,856–27,530
	35	–	Charcoal	D-AMS-007344	SHcal13	−18.4	40417 ± 332	44,631–43,283
Breccia Sample	**Height Above Datum (m)**	**Height Above Floor (m)**	**Material**	**Lab Code**	**Curve**		**Radiocarbon Age**	**Age cal BP 2ʊ**
LB8	2.577	2.16	*Terebralia* sp.	D-AMS 011029	Marine 13	−5.3	5566 ± 26	6032–5880
LB8	2.577	2.16	Charcoal	D-AMS 011026	SHCal 13	−22.2	5482 ± 25	6296–6191
LB7	2.399	1.37	*Terebralia* sp.	D-AMS 007340	Marine 13	−4.5	3219 ± 28	2925–3140
LB6	1.879	0.37	Charcoal	D-AMS 011025	SHCal 13	−27.5	7858 ± 30	8702–8668 (3.5%) 8660–8514 (90.5%) 8494–8479 (1.3%)
LB6	1.879	0.37	*Terebralia* sp.	D-AMS 011028	Marine 13	3.3	5400 ± 30	5876–5681
LB5	1.658	0.19	*Terebralia* sp.	D-AMS 007341	Marine 13	−11.2	7917 ± 46	8289–8495
LB3	1.723	0.2	*Terebralia* sp.	D-AMS 011027	Marine 13	−4.2	6011 ± 27	6509–6331
LB2	1.913	1.34	Charcoal	D-AMS 011024	SHCal 13	−17.4	2038 ± 23	2005–1898
1(2010)	–	~1.2	*Terebralia* sp.	Wk 28438	Marine 13	0.0	6268 ± 30	6817–6634
2(2010)	–	~1.3	*Terebralia* sp.	Wk 28439	Marine 13	−3.6	6068 ± 33	6596–6396

10 is texturally similar to 9, but has abundant ash and charcoal. A strong boundary separates units 10 and 11. The sediment in Stratigraphic Unit 11 changes sharply to a pale brown fine silt. While this unit had sparse cultural material, a prominent hearth feature occurs in the west wall between EUs 34 and 36 (11a) dated to 44,631–43,283 cal BP (D-AMS007344).

2.3.3. The Laili wall breccias

When Laili cave was first located in 2010 it was noted that there were pockets of breccia containing cultural materials such as stone artefacts, charcoal and shell adhering to areas of the rear wall of the cave. Two samples were removed (1 2010 and 2 2010) and *Terebralia palustris* shells encased in them were dated to ~ 6500 BP (Wk-28438 and Wk-28439) (Table 4). During excavation in 2011 an additional 8 breccia samples from the cave rear wall were recorded with height datums and subsequently shell and charcoal from six of these was dated (Table 4).

The Laili breccias cover the time that is 'missing' from the cave floor occupation deposit – the Holocene. The dates and heights above current floor of these samples are shown in Table 4. The remnant breccias on the walls at Laili tell us that the cave originally contained a deep Holocene stratigraphy deposited between at least 1900 and 8500 cal BP, comprising stone artefacts, charcoal, shell and animal bones in a fine sediment matrix. In the breccia samples processed for dating the edible mangrove gastropod *Terebralia* sp. was the dominant shell species. Only one specimen of the freshwater species *Stenomelania* sp. was recovered, as well as some small fragments of terrestrial snail. In terms of shell composition the Holocene breccias closely match the deposit dated to the terminal Pleistocene (EUs 1–5) which is also dominated by *Terebralia* sp. followed by the freshwater species *Stenomelania* sp.

Although our occupation dates at Laili are derived from a 1 m^2 × 2.2 m sample of the deposit, the perched breccias sampled from heights above the current floor, spread across an extensive area of the rear wall of the cave all date to the Holocene. This would suggest that deposit has been lost over a large area of the cave floor. Establishing the extent of removal would require much more intensive sampling and dating of the occupation deposit and the breccias. It is possible that Holocene deposits may still be intact in the higher western part of the cave floor (Fig. 10).

Laili Cave is located over 4 km from the coast. It seems inconceivable that sea level rise, and processes of coastal trimming and readjustment hypothesized as possibly destabilizing the talus in front of Lachitu and leading to deposit loss, would have effected Laili. Voids relating to post-depositional animal activity like burrowing, and tree roots, are evident and such processes may cause local subsidence, but this is unlikely to be uniform across the floor of the cave, or to result in the level of deposit loss seen at Laili. Processes leading to local subsidence or slumping would also presumably be evident in deformation of the stratigraphy. Excavation of Squares A and B did not reveal any major post-depositional subsidence although the stratigraphy in these test pits did provide evidence of some burrowing by small animals (probably rats), root and burrow fill features as well as extensive termite activity in Square B. Generally the stratigraphy at Laili is horizontally bedded and the fact that discrete hearths with ash and charcoal lenses are evident in the section of A suggests minimal bioturbation.

Dissolution of organics in the lower basal deposits, as hypothesized by Glover (1979) could produce deposit slumping, however, in this case the radiocarbon dates for the cemented raised remnant

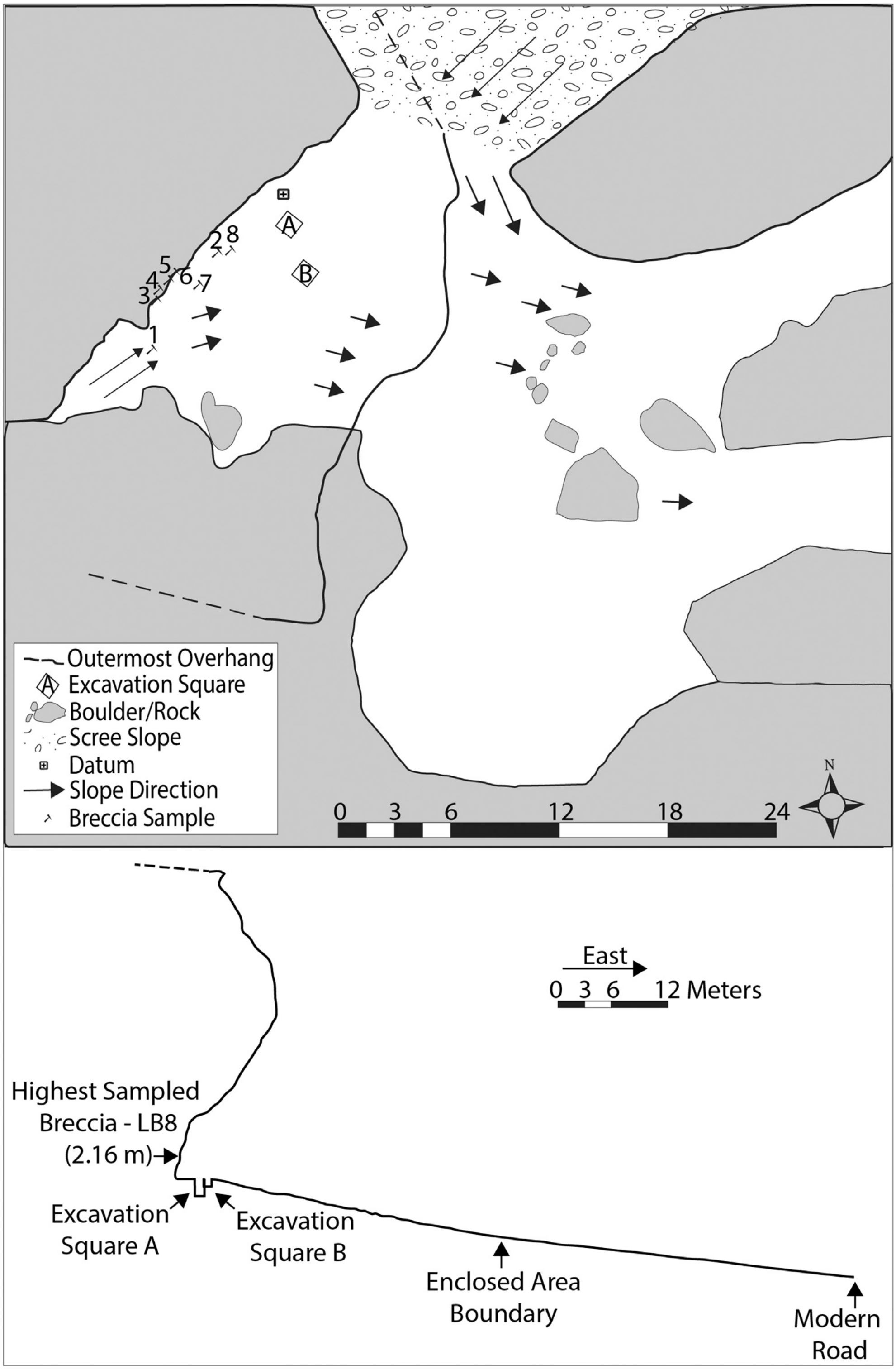

Fig. 10. Laili plan of site showing location of excavations and sampled breccia deposits on rear wall and profile showing position of highest sampled breccia above the cave floor. Note the SW corner of Square B is 0.00 (same height as the datum), the SW corner of Square A is 0.010.

breccia deposits should be replicated by dates in the upper part of the deposit, as was the case in Leang Burung (Glover, 1979). Water erosion within the cave could remove significant quantities of sediment however it is unlikely that this process would be uniform across floor as suggested by the spread of breccia.

3. Discussion

As with all caves in tropical regions the processes acting on the sedimentary deposits are complicated (Gillieson, 1996). The completeness, or not, of the stratigraphic record within individual caves typically reflects lateral shifts in facies deposition over a few

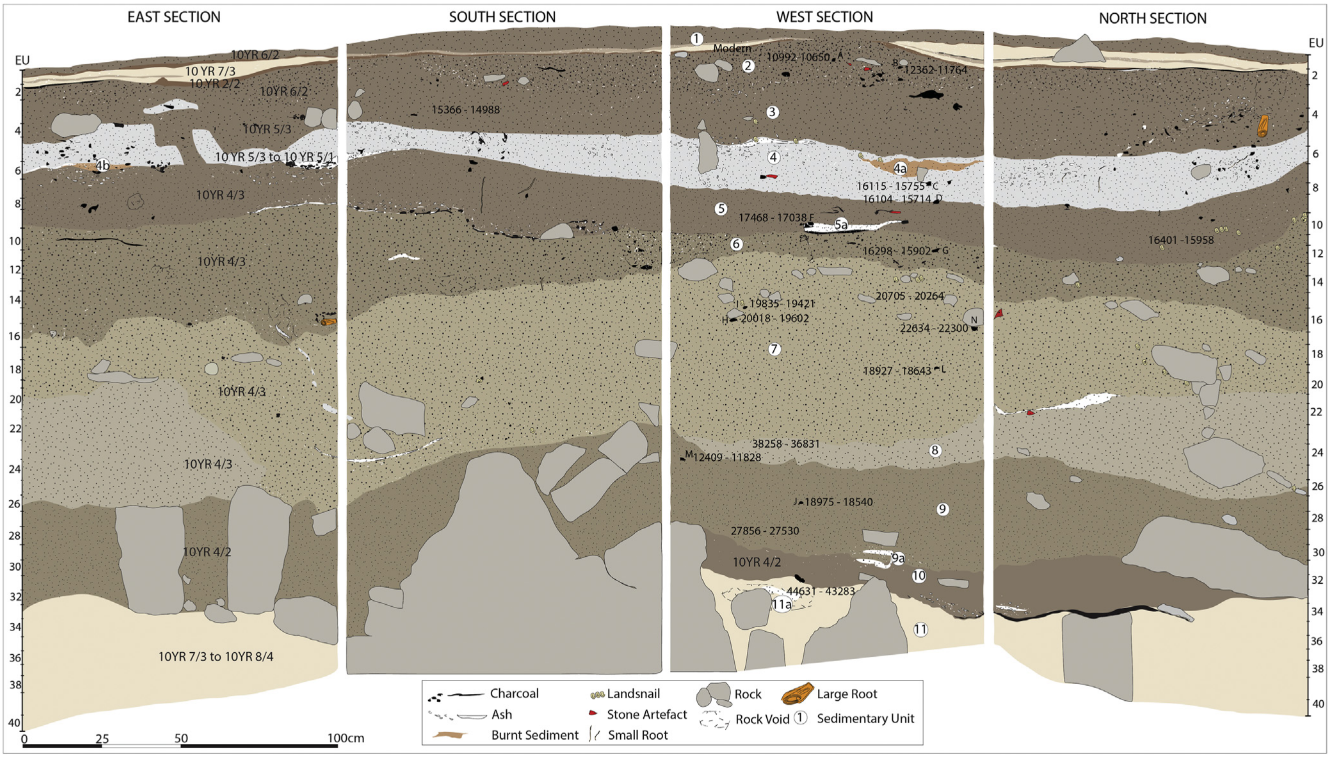

Fig. 11. Laili Square A section showing stratigraphy and position of dated samples.

metres (Farrand, 2001). In the humid tropics pulsed and sudden shifts in hydrological inputs drive alteration of sediment pathways in caves and often initiate sudden threshold switching from infilling of localized depocentres to phases of gutting out and sediment re-deposition (Farrand, 2001; Gillieson, 1986; Osborne, 2008). The complex nature of sedimentary deposits in limestone caves in the humid tropics has been recognized and broadly discussed in reports on the Niah Caves, Sarawak (Barker et al., 2005:4; Gilbertson et al., 2005), caves in the Maros region of Sulawesi (Glover, 1979), and elsewhere in Southeast Asia (Anderson, 1997). Such complex deposits pose major challenges for interpretation of the archaeological record.

The three sites discussed above in PNG and Timor Leste are located in tectonically active areas of net coastal uplift, and are associated with small coastal catchments, or narrow coastal margins and/or with uplifted coral reef terraces. At each site excavation squares sample depositional sequences within the cave and most of the excavation squares are within 5–20 m of the drip-line. Areas close to the drip-line and cave mouth are renowned for stratigraphic complexity and interstratification driven by hydrological outputs and weathering of the host-rock, quasi-stochastic block inputs derived from structural failures, and high inputs of deposits produced from human and animal activities (Fairchild and Baker, 2012:69; Woodward and Goldberg, 2001).

At these sites there is little evidence of direct geomorphological coupling between breccia formation and the broader landscape hydrology or major zones of sediment storage suggesting localized breccia forming processes. Breccia formation at each of these sites takes place variably from the back to the mouth of the cave, under overhangs and at the bedrock margins of the cave floor. Water seepage reflects seasonal patterns of local hydrology of slopes and the host rock. Each site is perched on slopes either separated from the main valley floor (Laili), or upslope of the active shoreline on strongly structurally controlled karstic slopes where gradients are partly inherited from the morphology of palaeo-reefal shoreline and uplifted coral terraces (Lachitu and Lene Hara).

Major phases of breccia formation in caves at valley floodplain margins, linked to alluvial-karst local base-level hydrology, were identified by Glover (1979). Duringer et al. (2012) link breccia formation at regional scales to net drop of alluvial plain elevations at sites in tower karst of Laos and Vietnam. The timing of breccia formation at some sites in north-east Laos is predicated on changing sediment storage in valley floors and reversals of drainage into and out of floodplain marginal caves producing polyphasic cemented sequences of sandstones and conglomerates capped by breccias.

Such regional geomorphological processes and diagnostic sediment facies shifts do not apply to the case studies presented here. Breccia formation, and the capacity of breccias to act as patch stores of chrono-stratigraphy not present in the adjacent cave floor is highly localized at our sites in Timor Leste and PNG. More importantly, the bio-stratigraphic and cultural materials contained in the breccias are well-stratified with autochthonous ashy layers and food refuse, contain both fragile and robust skeletal materials, and not uncommonly preserve articulated skeletal elements, artefacts which conjoin or other indicators of minimal reworking. As such, these breccias are taphonomically and chrono-stratigraphically dissimilar from bone beds accumulated through multiple phases of deposition and reworking (Bacon et al., 2004, 2008; Duringer et al., 2012), and show much higher stratigraphic integrity and temporal resolution.

Our re-excavation of Lachitu and dating of marine shell in perched cemented breccias attached to the speleothem columns and cemented clasts from within the deposit containing cultural materials, alert us to the likelihood that 'missing time' at Lachitu is due to major phases of erosion and sediment loss, rather than a lack of human occupation. Potentially, Gorecki's date of 42,412–36,507 cal BP (ANU-7610) from the base of Square X1 represents an *in situ* brecciated unit separated by an erosional hiatus from the terminal Pleistocene/Last Glacial Maximum deposits dated to ~18,000 cal BP evident in both Gorecki's and the 2004/2005 excavations, and in the two dated breccias C and D (Wk-17978 and Wk-17979). The marine shells dated to ~28,000 cal BP from EUs 18 and 20 in Square A (Table 2) alert us to a phase of human occupation which is otherwise 'missing' from the archaeological record and is likely also evidence of a major erosional event. We hypothesize that cultural material cemented to the walls or columns may have survived this erosional event, and been redeposited at a later date onto the cave floor as it stabilized with the drier conditions prevailing during the height of the Last Glacial Maximum. This cultural material could then have been incorporated into the younger accumulating deposits. This interpretation is speculative as perched cemented cultural deposits dating between 40,000 and 20,000 have not yet been found, although we currently have only three dated sample points. Intensive sampling of such deposits would be productive here. It also seems likely that sediments dating between ~6700 and ~1000 cal BP have been lost from the cave system due to one or more erosional episodes, leaving a lag of mixed age finds of different ages at the contact. This may have been a result of cliffline retreat and roof collapse destabilizing the area in front of the cave, leading to loss of cultural deposits from within the cave, perhaps during the 7000 cal BP marine relative high stand. While this is speculative it could potentially be tested through a more extensive sampling and dating program.

We think that cycles of deposit cut and fill are also responsible for the perched cemented cultural deposits at Lene Hara where temporal resolution and completeness varies markedly across different areas of the cave floor. Short intervals of Pleistocene time are well-preserved in the more elevated, southern chamber, but local erosion and infill events make the record non-synchronous over a distance of a few tens of metres. Holocene occupation is sparsely represented in this part of the cave, with some mixture of Holocene cultural materials such as pot sherds into late Pleistocene sedimentary units in Squares A and B, and the shell beads with Holocene ages in Square A (Table 3). In the northern chamber of the cave, a major scour or subsidence event, probably dating to the terminal Pleistocene or early Holocene, created a deep trough that infilled progressively through the Holocene by the combined action of episodic surface wash and the deposition of cultural debris. The resultant infill unit provides an extended, well-stratified and temporally well-resolved Holocene sequence. In this area of the cave breccia incorporating cultural material is found attached to and under the eroded bases of the speleothems suggesting that contemporary sedimentary processes, involving transport of finer sediments in episodic surface wash flowing northeast across the cave floor, between and around the larger speleothems, has existed since the terminal Pleistocene or early Holocene. Most likely this was preceded either by a major scour episode or by subsidence of deposits in the northern chamber, thereby creating a depocentre lying as a southwest-northeast aligned trough close to the northern margin of the cave. Infilling of this trough has averaged net rates of 20 cm/ka but has been irregular. Infilling sediments are both reworked cave earths and washed in sands and gravels but, significantly, they contain little clastic roof fall.

The combined evidence from Squares A, B, D and F thus suggests a significant change in cave floor sedimentation between the terminal Pleistocene and the Holocene – the earlier period characterised by deposition of large quantities of coarse clastic rock fall and by speleothem activity, and the Holocene by lower rates of clastic roof fall, coupled with redistribution of finer sediment fractions by surface wash channeled by a local template of flowstones, speleothems and roof fall. Finally, the cave possibly saw a major shift in depocentre into the northern chamber during the terminal Pleistocene or early Holocene.

The parsimonious explanation for the Laili Holocene breccia and absence of unconsolidated Holocene deposit is that an enormous quantity of cave-floor deposit has been removed by people. During the 2011 excavation the site was visited by a group of local residents equipped with sacks, shovels and a wheelbarrow. They proceeded to dig away an area of deposit about 10 m forward of the excavation towards the cave entrance. When all the sacks were full they pushed them away in the wheelbarrow. We inquired of our senior local worker about this activity and were told that they were taking away the cave's soil to put on their gardens for fertilizer, that people from the village collected it regularly and had for as long as he could remember. On the basis that the current floor area bounded by the back and side walls and within the drip-line is 236 m^2, and the maximum breccia height of above the current cave floor is 2.16 m (the height of breccia sample 8); the volume of missing sediment could be as much as 510 m^3. A lower boundary, a floor 2.16 m above the current floor sloped to meet the current surface at the outer edge of the cave, would be about half of this estimate – 250 m^3. While this seems like a daunting amount of sediment for local villagers to have removed, given the 3000 year history of agriculture in ISEA, the recorded practice of using caves to pen animals thus further enriching the organic rich cave sediments with nitrogen, and the ready proximity of Laili to the village and house gardens, it is a plausible explanation to account for the missing Holocene deposits. Whether all areas of the cave floor are similarly affected requires extensive intra site sampling across the cave floor.

4. Conclusion

Breccia deposits containing cultural materials occur in many caves and shelter sites where water seepage has cemented the occupation deposit. Here we have discussed three caves where breccia formation and removal have different causes and where mapping of time discontinuities and lateral sequence gaps is informative about the occupation and geomorphic history of the sites. Notably most of the breccias sampled have no chronostratigraphic equivalent in the unlithified cave-floor archaeological deposits. The chronological intervals preserved in the breccias would not be evident if one were to look at the deposits in the floor excavation in isolation. In Lachitu and Lene Hara we have suggested water erosion as the likely mechanism of cave floor deposit removal. In Laili we have argued that physical removal by local people is the best fit interpretation. Glover's (1979) mechanism – dissolution of organic sediment from below does not seem consistent with the evidence for well preserved organics at depth in Lachitu, Lene Hara and Laili, which indicates little decay or volume reduction of the organic material.

The broader issue remains of what is responsible for the temporal "switching" of breccia formation and gutting out erosional episodes in humid tropical caves of the type reported here. We find no compelling evidence of direct links to regional scale hydrology, and can exclude floodplain alluvial floor-karst interactions of the type described by Duringer et al. (2012). In all three case studies sloping deposits at cave mouths across the drip-line either store the archaeological deposits or play a significant role in maintaining stability of the stored archaeological deposits upslope and within the cave. All three sites locate on generally steeper hill slopes where bedrock outcrop orientation, slope angle and stability of large blocks and overhang collapse have combined to produce low angle protected depocentres at the cave mouth which serve to stabilize and retain stratigraphic sequences further back in the cave.

This points towards geomorphic stability at and downslope of the cave mouth as a key controlling factor in determining a depositional mode for sediment accumulation of unconsolidated fills, breccias and flowstones within the sites in Timor Leste and PNG. All of these sites are well upstream of the first knickpoint, and weakly connected to the main gully networks or ephemeral creeks operating on adjacent slopes. Two of the three sites (Lachitu and Lene Hara) situate in geologically young landscapes where uplifting bedrock structure, lithology and outcrop plays a major role in river abrasion capacity and therefore a control over response timescales of the sedimentary routing systems to base level change (Allen, 2008; Sklar and Dietrich, 2001). Any local landscape response to either climate or tectonic forcing is likely to be lagged and involve complex behavior in relation to knickpoints (Bonnet and Crave, 2003) with local slope hydrology and host limestone aquifer capacities essentially decoupled from catchment-scale geomorphic response (Bishop, 2007; Bishop et al., 1985; Grimaud et al., 2015). Further research on the relationship of regolith stability and hillslope regolith ages upslope and downslope of these caves and the chronology of breccia storage is likely to be instructive.

Our interim conclusion is that chronologies for active speleothem deposition, flowstone accumulation and stop-start storage of sediments as breccia are likely to be intimately coupled, as sediments cementing to breccias tend to form adjacent to carbonate charged water on impermeable surfaces. A climate-driven chronology is therefore likely linked to phases of breccia formation. However, rates of net unconsolidated sedimentation clearly relate in part to accumulation of anthopogenically-imported deposits. Hearth pits, stone lines, fences and deposit removal (as at Laili) show the very considerable human role in determining the nature and stability of sedimentation around and within the cave entrance. At all three sites mid to late Holocene anthropogenic destabilization of soils and slopes, latterly from human sedentism and agriculture, may be significant (and temporally lagged) processes destabilizing the slopes below the caves and thus indirectly re-setting the local (micro) base levels determining depocentre architectures within and at the cave mouth.

In summary, data from the three sites suggests local, autogenic and quasi-stochastic processes drive the development of depocentre space into which sediments then accumulate and store. Similarly the erosive gutting events may be largely set by local hydrodynamic processes specific to the cave (Bosch and White, 2004; Gillieson, 1996), operating in relation to stability of adjacent slopes and hydrology and mass transfer within the host limestone rock architecture. Human activity may be a major contributor and driver of sediment inputs and outputs over late Quaternary timescales producing the occupation deposits and then extracting them as fertilizer. The phasing of cementation into breccias is more likely to be coupled to regional climate trends. The relationship of the time sequences of archaeological record preserved as unconsolidated sediments as compared with those cemented as remnants on cave walls and speleothem structures is therefore likely to be extremely complex reflecting both regional climate, lagged catchment effects on slopes below the cave mouth, co-seismic rock fall and endogenic processes in the cave mouth.

This points to the considerable research potential in small tropical humid caves for comparing chronologies and proxy records from flowstone and speleothem with archaeological chronologies stored i) in remnant lithified cave breccias and ii) adjacent cave floors as unconsolidated deposit sequences.

One of the most significant findings from all three archaeological sites discussed therefore concerns sampling. The results clearly demonstrate that cave deposits in humid tropical regions are stratigraphically complex, reflecting multiple erosional and depositional episodes together with long term shifts in sedimentary processes. This complexity means that a complete cultural and chronological sequence may not survive as a stratigraphic column in any single part of a site. Rather, the history of human occupation may only be recovered by integrating data from a number of different stratigraphic columns, each preserving parts of the depositional and erosional history of the site, coupled with the dating of cemented cultural deposits perched on walls to tell us about 'missing time' which might not be recoverable in any of the cave floor stratigraphy.

A problem of equal magnitude, in terms of our interpretation of the human occupation record is the demonstrated re-deposition of old shell, charcoal and bone into deposits which are much younger. This can potentially bias the chronological and archaeological record. As many of the caves in tropical regions (e.g. Lachitu and Lene Hara) demonstrate cementation with depth it may not be possible to distinguish cultural material which has cemented into breccia *in situ* from that which has been re-deposited as cemented clasts, without an extensive program of dating.

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Methodology

Excavation

Excavation Units (EUs) (cf. spits) varied in depth between 2 and 8 cm and where possible followed visible stratigraphic changes or divisions in the deposit. With the exception of large rocks excavated material was wet-sieved through a 1.5 mm sieve and dried prior to sorting.

Selection of samples for radiocarbon dating

With the exception of the dates obtained by Gorecki et al. (1991) all radiocarbon dates presented are AMS dates on charcoal or marine shell. Where available charcoal was selected for radiocarbon dating, however, charcoal was not preserved below the surficial EUs at Lene Hara or Lachitu and thus marine shell was used for dating. Suspension feeding marine bivalves are believed to produce the most reliable marine shell ages however these shellfish are uncommon along the north coasts of Timor and Papua New Guinea and are correspondingly poorly represented in the archaeological assemblages. We have thus had to use a variety of fully marine gastropods such as *Turbo* sp. and *Tectus* sp. for dating at Lene Hara and Lachitu. The parts of the shells selected for dating varied. In some cases opercula were used as this part of the shell is dense and preserves well. In other cases the entire shell was sent to the dating laboratory. Marine shells used for dating were tested by the laboratories for recrystallisation and were not dated if they were less than 96% primary aragonite. A DeltaR correction has not been applied to any of the shell dates as no research has been undertaken on DeltaR for these species for the north coast of PNG or for Timor Leste and DeltaR is known to vary even within individual species depending on the substrate on which they live and graze and freshwater input to the environment (Petchey et al., 2012).

Few studies have been carried out into ^{14}C variation in deposit-feeding mangrove species but a recent study undertaken at Caution Bay in Papua New Guinea on the mud whelk *Cerithidae* indicates that mangrove/mudflat gastropods produce the least reliable calendar ages as they ingest sediment within the estuary that contains ^{14}C derived from both enriched and depleted sources (Petchey et al., 2012). However researchers in Australia have used these species for dating open middens and cave deposits where they are the dominant or exclusive species in northern Australian sites (Bradshaw, 1995; Faulkner, 2013:172–3). This was the case at Laili where the mangrove-dwelling gastropod *Terebralia* sp. was used for dating some of the perched cemented breccia samples as only *Terebralia*, freshwater gastropods and bone were identified in some of the aggregate clasts. A *Terebralia* was also used to date EU 2 Wall sample A at Laili to compare with charcoal Wall sample B. *Terebralia* Wall sample A appears to be in good accord overlying and being about 1000 years younger than charcoal Wall sample B.

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