

Rapid minimally invasive subsurface archaeological site prospection on Roti Island, Indonesia

Kasih Norman^{a,b,c,d,*}, Kelsey Lowe^d, Matthew Forbes^{a,e,f}, Thomas Sutikna^g, Anton Ferdianto^{a,g}, Rachel Wood^h, Stewart J. Fallonⁱ, Rebecca Esmayⁱ, Jatmiko^j, I Putu Yuda Haribuana^g, I Made Agus Julianto^k, Ashleigh J. Rogers^{l,m,n}, Chris Clarkson^c, Tim J. Cohen^a

^a ARC Centre of Excellence for Australian Biodiversity and Heritage, University of Wollongong, Wollongong, New South Wales, 2522, Australia

^b Department of Archaeology, Max Planck Institute of Geoanthropology, Jena, Germany

^c Australian Research Centre for Human Evolution, Griffith University, Brisbane, Australia

^d School of Social Science, The University of Queensland, St Lucia, QLD, 4072, Australia

^e SGME Pty Ltd, Brisbane, Australia

^f Environmental Futures, School of Science, University of Wollongong, Wollongong, New South Wales, 2522, Australia

^g Archaeometry Research Center, Research Organization for Archeology, Language, and Literature, National Research and Innovation Agency, Indonesia

^h School of Archaeology, University of Oxford, Oxford, OX1 3TG, UK

ⁱ Research School of Earth Sciences, The Australian National University, Canberra, ACT, 2601, Australia

^j Research Center for Prehistoric and History Archeology, Research Organization for Archeology, Language, and Literature, National Research and Innovation Agency, Indonesia

^k Department of Archaeology, Faculty of Humanities, Udayana University, Bali, Indonesia

^l Monash Indigenous Studies Centre, Monash University, Clayton, Victoria, 3800, Australia

^m ARC Centre of Excellence for Indigenous and Environmental Histories and Futures, Monash University, Clayton, Victoria, 3800, Australia

ⁿ ARC Centre of Excellence for Australian Biodiversity and Heritage, Monash University, Clayton, Victoria, 3800, Australia

ARTICLE INFO

Keywords:

Archaeological site prospection

Archaeological sampling

Indonesia

Wallacea

Roti

Rote

Ground penetrating radar (GPR)

ABSTRACT

The Wallacean archipelago is a vast, unique maritime area where many islands remain archaeologically largely unexplored. Alternatives to conventional excavation are crucial to increase the rapidity of exploration and discovery in this under-investigated region. Here we show that a minimally invasive method of site prospection involving the coordinated use of ground-penetrating radar, augering, microscopic identification of artefacts from sediment auger samples, dating, magnetic susceptibility and isotope analysis facilitates rapid discovery of the nature of archaeological deposits. We demonstrate that this approach was successful in rapidly characterising the subsurface structure of six very different archaeological sites on Roti, Nusa Tenggara, determining the depth of deposit, yielding numerous artefacts and other cultural materials and dating first occupation up to 30 ka. We recommend this approach to archaeologists seeking to rapidly characterise the archaeological record of a region and guide decision-making around where to conduct future archaeological excavation.

1. Introduction

Archaeological excavation is an inherently destructive, expensive, and time-consuming enterprise. Moreover, sites chosen for excavation based on surface characteristics alone can prove disappointing and consume valuable project resources. It is therefore desirable to employ approaches that increase the probability of excavating only those sites

that best address project aims and answer key research questions. Exploring alternatives to conventional excavation is therefore worthwhile as a means of increasing the probability of discovering appropriate sites to excavate while maximising returns on research budgets and field time. This is particularly so in under-explored or poorly understood regions where informed decisions about how to allocate project resources can be difficult to make.

* Corresponding author. ARC Centre of Excellence for Australian Biodiversity and Heritage, University of Wollongong, Wollongong, New South Wales, 2522, Australia.

E-mail address: norman@gea.mpg.de (K. Norman).

<https://doi.org/10.1016/j.quaint.2026.110372>

Received 21 July 2025; Received in revised form 2 June 2026; Accepted 6 June 2026

Available online 19 June 2026

1040-6182/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

One such region that presents a suite of unique challenges for the archaeologist is the Wallacean archipelago, a vast biogeographic maritime area comprising over 1600 islands spread over an area of 340,000 km² (Fig. 1). The physical challenges of the region are compounded by the complexity of the archaeological and fossil record, with Wallacea and greater Island Southeast Asia having the largest number of archaic hominin species found outside of Africa (Brumm et al., 2016; Detroit et al., 2019; Ingicco et al., 2018; Jacobs et al., 2019; Mahirta, 2003; Mijares et al., 2010; Rizal et al., 2020; Sutikna et al., 2016; Zaim et al., 2011). The archaeological record of the region has already greatly enriched our understanding of hominin diversity and evolution, early human behaviour, and the great antiquity of seafaring, pelagic fishing, human surgery and figurative art (Maloney et al., 2022; O'Connor et al., 2011; Oktaviana et al., 2024). Despite many decades of research, much of the archipelago still remains archaeologically unknown (Norman et al., 2021).

In this study we test an alternative to traditional surface-guided excavation. The first phase aims through subsurface prospection and augering to quickly and inexpensively obtain the age of first occupation, the types of cultural materials present, the resolution and density of deposits, and the geochemistry of the sediments in a site. When conducted across a range of sites, this enables the regional distribution of

site types, chronologies and cultural contents to be assessed. It also aids the determination of which sites are most suitable for answering certain questions (e.g. about subsistence, technology or first occupation) and thus which sites to excavate. This first stage can also help understand any trade-offs that might exist between age and resolution of the deposit, for instance shallow but ancient sites versus deep sites covering shorter timespans at higher resolution. Rapid prospection is particularly critical when searching for rare phenomena, such as sites with older occupation records, with a larger sample enhancing the probability of success. Once the first phase is complete, archaeologists can make informed decisions about where to excavate in the second phase of research.

In this paper we report on the results of an extensive rapid survey, subsurface imaging and augering program designed to characterise the diversity and age of archaeological sites on the island of Roti in Nusa Tenggara, Indonesia. Survey and excavations were undertaken on Roti in 1986 and between 2006 and 2009 by the Indonesian National Archaeological Research and Development Center (Jakarta) and identified a number of occupation sites across the island (Jatmiko, 2010; Mahirta, 2003). In 2018, we returned to Roti to test the rapid prospection and subsurface testing techniques to determine which sites were suitable for answering questions about long-term human occupation of the island. The approach adopted involved the coordinated use of ground

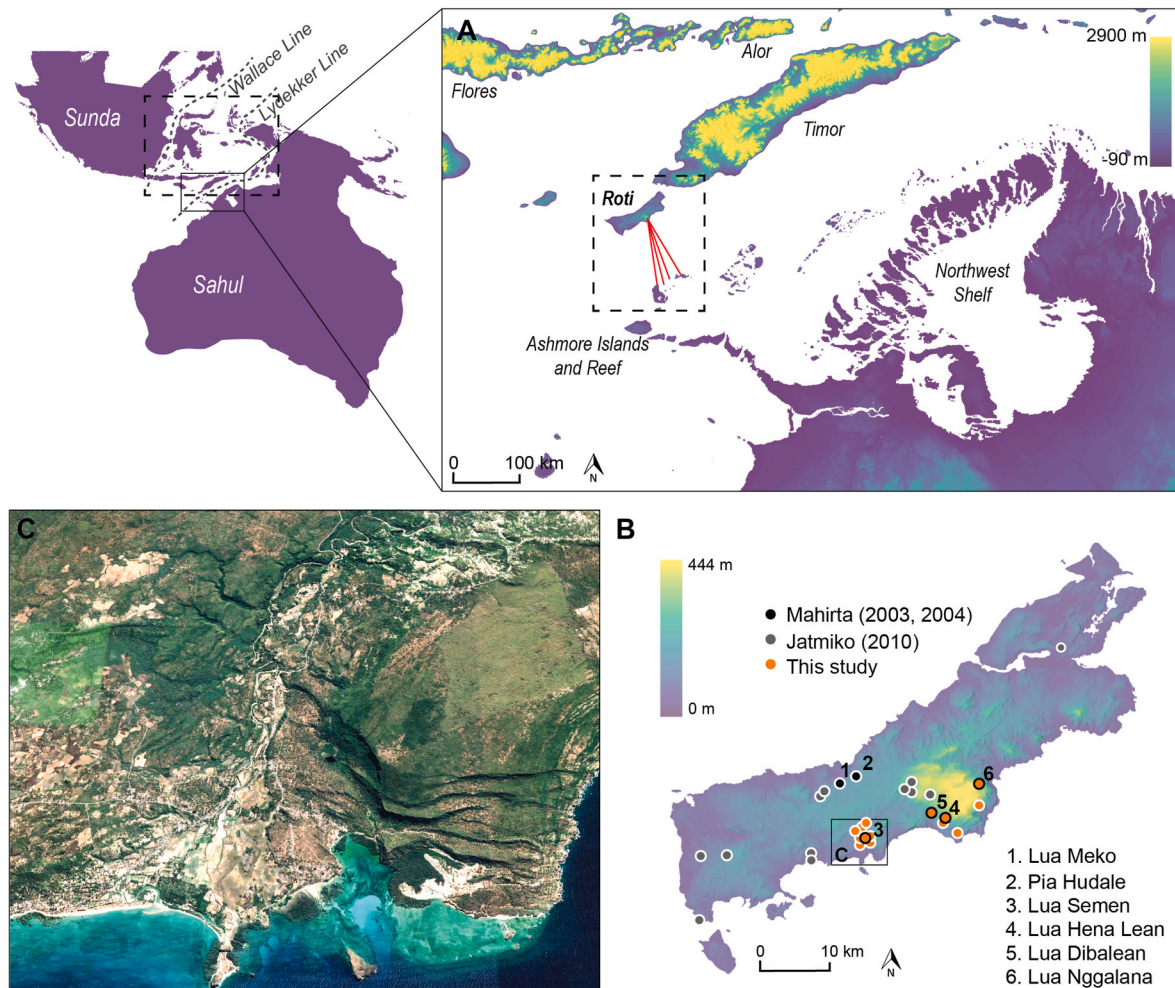


Fig. 1. Map of study area with the Wallacean archipelago shown by the dashed box and bordered by the Pleistocene continents of Sunda and Sahul. Wallace and Lydekker biogeographic boundaries shown to the east and west. **A** The Nusa Tenggara region showing the location of Roti in the archipelago, with intervisibility between Roti and the Sahul palaeo-island chain to the south shown by red lines (Norman et al., 2018). **B** Topographic map of Roti showing the distribution of known archaeological sites. Sites 1-6 show the location of caves and rockshelters where rapid prospection was undertaken. **C** Satellite imagery of a large valley in south-central Roti with a high concentration of archaeological sites. Data: 1 s SRTM Level 2 Derived Digital Elevation Model v1.0, Australian Bathymetry and Topography Grid, courtesy of Geoscience Australia. Landsat image courtesy of the U.S. Geological Survey. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

penetrating radar (GPR), sediment sample collection via augering, macro and microscopic identification of artefacts, dating of cultural material, magnetic susceptibility and sedimentary geochemistry. The study had four main objectives: (1) assess the success of the rapid prospecting approach in evaluating new archaeological sites; (2) to estimate the distribution of site establishment across Roti; (3) to assess the subsurface topography and depth of deposit, stratigraphic changes, presence or absence of cultural materials, range of artefact types, presence of dateable materials and their age, indications of *in situ* burning, and soil geochemistry at each site; and (4) to identify sites suited to answering key questions about long-term cultural change, which can then be explored in future targeted excavations. Here we present the results of our survey and rapid sampling of six sites with varying characteristics. We illustrate the value of this method in quickly appraising the archaeological record of the region and addressing the four aims outlined above.

1.1. Physical environment

The island of Roti (or Rote) (Fig. 1) is in the East Nusa Tenggara province of the Indonesian archipelago and forms part of the biogeographic region of Wallacea. It is 80 km long and 20 km wide with an area of ~1200 km² and is located approximately 12 km south-west of Timor, with the two islands separated by a ~100 m bathymetric sill. Roti formed between 200 and 400 ka, with regional uplift rates of 0.3 to 0.5 m ka⁻¹ (Major et al., 2013; Pedoja et al., 2018). The island is comprised of Australian continental plate crust overlain with uplifted coralline limestone and karst. The underlying geology is exposed across large regions of the northwest and southeast, and comprises formations rich in shale, mudstone and chert (Roosmawati and Harris, 2009). The topography is generally flat, with a pronounced bulge on the central southeast side of the island with a maximum elevation of 444 m above sea level. Roti has a tropical landscape with a monsoon wet season between November–March and a dry season between April–November. Much of the island is dominated by savannah vegetation, with palm savannah predominating on the flood plains, and areas of remnant monsoon vine forest in the central interior and in gullies and valleys.

2. Materials and methods

Nine days of survey were undertaken across the south-central region of the island, with previous surveys (Jatmiko, 2010; Mahirta, 2003) focusing on the north-central and western regions of Roti (Fig. 1B). Survey was focused on areas where a combination, or all, of the following criteria were present: (1) the underlying geology provided abundant raw material suitable for stone tool making; (2) there was access to freshwater in the form of rivers and springs; and (3) the coastline was within foraging distance of the site, allowing access to marine resources due to the depauperate terrestrial fauna on the island. Regions across the island were selected following these criteria, with permission sought from local landowners and officials to undertake research. Due to field-season time constraints, surveys followed a targeted strategy, with the team guided to locations where landowners knew of caves and rockshelters. The previously excavated north-central sites of Lua Meko and Pia Hudale, and four of the new sites located during survey (Lua Semen, Lua Hena Lean, Lua Dibalean and Lua Nggalana) were selected for rapid prospecting, with the subsurface deposits first imaged using GPR, then cored and sampled over five days.

2.1. Ground penetrating radar

Ground-penetrating radar (GPR) was completed at the six selected sites to provide information on subsurface material associated with geological features such as bedrock and roof fall and to assist in determining suitable locations for deep penetration of auger holes. The use of GPR in rockshelters and caves globally has been limited in archaeology,

however more recent studies are highlighting its applicability for detecting the depth of bedrock, burials, stratigraphy and roof fall, and identifying areas for targeted excavation (Armstrong et al., 2021; Conyers, 2012; David et al., 2013; Lowe et al., 2014; Porsani et al., 2010). GPR was chosen for several reasons, firstly it is extremely efficient to use and has the ability to provide two- and three-dimensional visualisation of the collected data, which was critical for determining suitable locations for coring both horizontally and vertically. In this study, the goal was to locate core areas with weaker GPR reflections in order to obtain deep cores, and to avoid areas that contained high reflections such as bedrock or roof fall, as these would impact coring and core depth. Due to in-field time constraints, using an instrument that allowed for quick and efficient data collection was imperative. Secondly, due to the size of some of the cave/shelters' floor (e.g., 4 × 6 m) and height of the cave/shelter's roof (<2 m), GPR can be one of the easier prospecting methods to navigate in tight spaces such as this, especially the one used for this project. Furthermore, it provides a higher resolution of collected data as transects can be collected at 0.25–0.5 m spacing. Lastly, many of the site locations were not easily accessible by vehicle and only by foot, meaning that the gear had to be carried some distances into the sites, as such, an instrument that could be broken down and carried some distance was ideal. At each site, a grid was placed adjacent to the back wall and extended out from the wall anywhere from 0.54 to 12 m. A Geophysical Survey Systems, Inc. (GSSI) SIR-3000, 400 MHz antenna and a model 620 survey wheel were used to collect the GPR data. Sixteen-bit data were collected with an 80 nS time window, 512 samples/scan and with 25 scans/meter. Transects were spaced every 0.50 m. The collected GPR data were processed in GPR-SLICE v7.0. Processing steps included a time zero correction so that the start and end of all samples were defined for each reflection profile. This was followed by a background removal and bandpass filtering. Time slices were made using the hyperbola fitting function to estimate the velocity (m/nS) of the electromagnetic signal in each volume of the medium. This velocity was then used to calculate the two-way travel time to get a depth estimate (Goodman and Piro, 2013; Jacob and Urban, 2016). These depth estimates generated in the software were then verified in the auger data.

2.2. Sample collection

The GPR reflections for each site guided the choice of sampling locations, with areas in the caves and rockshelters that returned weak reflections (dark blue) in the amplitude slice-maps selected for augering. One to six locations per site were selected and sampled using hand augers with a 7.5 cm circumference. Each location was augered until an impermeable barrier (such as a large rock) terminated the sample location, or sediments transitioned to limestone/presumed bedrock. Sediment samples were collected at 10 cm intervals for low magnification artefact analysis, magnetic susceptibility, physical and chemical soil properties, and dating. The auger head was cleaned between each sampling episode and the auger hole cleared prior to collection of the next depth range. The excavation depth of the auger hole was measured before and after each collection to gauge the interval collected. Following sample collection, the location of each auger hole was mapped onto the site plan and backfilled.

2.3. Cultural material

After each sediment sample was sub-sampled for magnetic susceptibility and soil analysis it was wet sieved through a 1 mm mesh. Stone artefacts and raw material were identified under low magnification (x10) and artefacts counted, weighed, and photographed. Heat-affected artefacts were identified by crazing, pot-lid scarring and high lustre. Marine remains (molluscs and finfish) were identified to the lowest taxonomic classification using an Indo-Pacific comparative collection housed at The University of Queensland and published manuals (Petuch and Berschauer, 2020; Rojo, 1991). Due to fragmentation,

identifications were conservative and predominantly to the superfamily level. Taxonomic nomenclature was verified using the World Register of Marine Species online database (Board, 2023). Marine remains were quantified using weight (g), Number of Identified Specimens (NISP), and Minimum Number of Individuals (MNI). Charcoal fragments and burnt earth were weighed, and suitable pieces of marine shell and charcoal were selected for radiocarbon dating.

2.4. Radiocarbon dating

Eight samples of charcoal and three samples of shell were prepared for radiocarbon dating at the Australian National University following published methods (Fallon et al., 2010; Wood et al., 2023). After inspection and physical cleaning under a light microscope, charcoal was pretreated using an acid-base-acid methodology. One sample did not survive pretreatment. Visibly recrystallised material was removed from shell with a Dremel drill, the sample was leached in acid and the presence of calcite was determined using Feigl's stain. All charcoal contained more than 50%C, and shell did not contain calcite. Cleaned material was converted to carbon dioxide by combustion in a sealed tube or by reaction with phosphoric acid, cryogenically collected and purified, and converted to graphite by reaction with hydrogen over an iron catalyst. Samples were dated in a NEC SSAMS at the ANU. Dates were calculated following Stuiver and Polach (1977) and corrected using an AMS-derived $\delta^{13}\text{C}$. Ages have been calibrated using Oxcal 4.4 (Ramsey, 2009) and the SHCal20 (Hogg et al., 2020) atmospheric curve for charcoal, and Marine20 for marine shell (Heaton et al., 2020). Marine shell dates are calibrated without ΔR as this data is currently unavailable for Wallacea.

2.5. Magnetic susceptibility

Magnetic susceptibility measures how susceptible a material is to being magnetised when in the presence of a magnetic field. It reflects the concentration and composition of magnetic minerals within archaeological sediments and is commonly used to characterise magnetic enhancement. Higher abundances of magnetic minerals generally result in increased magnetic susceptibility. Sediment samples were packed in small non-magnetic Althor P15 boxes (5.28-cc volume) and measured on a Bartington Instruments MS2B and MS3 sensor. Low-field readings were taken at the maximum sensitivity setting using a 200 A/m field oscillating at low (465 Hz) and high (4650 Hz) frequencies for the frequency dependence of susceptibility (χ_{fd}). The χ_{fd} allows for the detection of ultrafine or superparamagnetic (SP) grains, as they have the most pronounced frequency dependence (Dalan and Banerjee, 1998; Dearing et al., 1996) (See Supplementary Information). Increases in χ_{fd} can indicate burned sediments (e.g. anthropogenic burning) or developed surfaces, the former being more common in older cratonic rockshelter environments (Lowe et al., 2016). The goal of this analysis was to compare the χ_{fd} signals to the artefactual and geochemical data and determine if anthropogenic burning was present in the sediment samples.

2.6. Sedimentary analysis

2.6.1. Grain size

Grain size was determined using laser diffraction on a Malvern Mastersizer 2000 at the University of Wollongong. A small (~1 g) representative portion of the clastic sediment was added via a mixing beaker to attain adequate beam obscuration. Three grain size distributions were determined and then averaged. Between each measurement the instrument was flushed clean with tap water and the background was measured to re-calibrate the instrument.

2.6.2. Stable nitrogen isotope analysis

Total carbon and nitrogen contents (%) and Stable $\delta^{15}\text{N}$ values and %

N were determined via a EuroVector Elemental Analyser (EA), in conjunction with constant flow to a Nu Horizon isotope ratio mass spectrometer (IRMS) at the University of New South Wales. Samples were calibrated against internal standards acid, glycine and TPA through USGS-42 ($\delta^{15}\text{N} = 8.05\text{‰}$) at the beginning and end of each run. After every nine samples, glycine standards were checked, and one repeat sample was analysed.

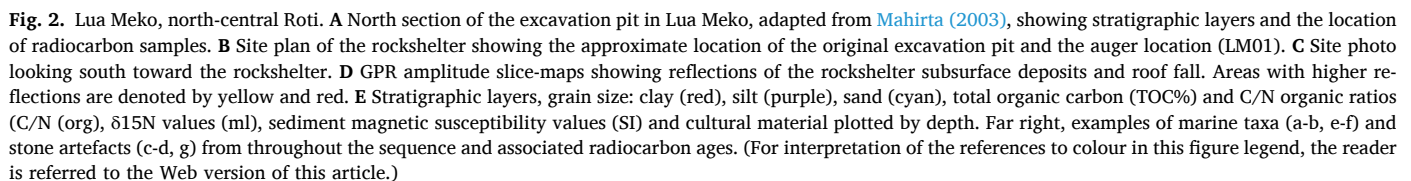
3. Results

Twenty-six cave and rockshelter sites were located during survey, of which thirteen contained surface evidence of human occupation in the form of stone artefacts, marine remains, and pottery sherds, or were of a size and position to make human habitation a likely possibility (Fig. 1B, orange).

3.1. Lua Meko

Located approximately 4 km inland from the north-central coast of Roti is a complex of sites known as Tonggobatu ($-10.75583, 123.03559$, height 116 m ASL) (Fig. 2). Tonggobatu was identified in 1986 by a team from the Indonesian Archaeological Research Centre, Jakarta. Tonggobatu is a small hill formed by an uplifted coral reef with five northwest-facing rockshelters with abundant surface artefacts and several smaller southeast-facing shelters (Mahirta, 2003). Two northwest-facing shelters (Lua Meko and Lua Manggetek) were excavated by Mahirta pre-2003 and yielded shallow deposits with Terminal Pleistocene to mid-to-late Holocene occupation. Excavations at Lua Meko revealed a greater depth of deposit and an older age of occupation than Lua Manggetek. At Lua Meko, a 2×1 m test pit excavated in 14 spits to a depth of 70 cm revealed five stratigraphic layers (Layers 1–5) (Fig. 2A–B), with artefacts occurring in all units. Calibrated age ranges for samples from Layers 1–3 of the excavation pit are mid-Holocene (Table 1), with the base of Layer 4 returning an early Holocene age. A marine shell sample from 60 cm depth gave a measured radiocarbon age of $24,420 \pm 250$ (ANU-10908), which corresponds to a calibrated age range (at the 95.4% confidence interval) of 28,469–27,342 cal BP.

In 2018, we returned to Lua Meko to replicate the sedimentary and cultural sequence in the earlier excavations using our rapid site prospection approach. The GPR amplitude slice-maps of the deposit indicated a low reflection region suitable for augering to the east of the original excavation pit (Fig. 2B–D, Supplementary Information Fig. S2–S3). Augering revealed the deposit extended to 130 cm depth at this location before reaching an impermeable barrier or bedrock. Lua Meko is comprised of coarse silt, with very coarse silt predominating in the bottom 30 cm of the deposit (Fig. 2E). The sediment column replicated Layers 1, 4 and 5, with Layers 2 and 3 absent in this location. The cultural deposit began at 100 cm depth, with marine resources (burnt and unburnt), stone artefacts and enhanced magnetic susceptibility values (most probably indicating heating of the deposit from hearths) all appearing at this depth (Fig. 2E–Supplementary Information Tables S1 and S12–S13). Both marine shell and stone artefacts have an initial peak just above 100 cm depth (Fig. 2E). While the number of marine shells and stone artefacts from the auger samples is too small to allow meaningful comparison with the excavated assemblage, marine shell does increase above 40 cm depth (Fig. 2E), tracking the pattern in the larger assemblage (Mahirta, 2003). Trophic enriched signatures of $\delta^{15}\text{N}$ values $> 10\text{‰}$ have been shown to reflect guano contributions to cave sediment organic matter (Forbes and Bestland, 2006; Forbes et al., 2007; Wurster et al., 2015). $\delta^{15}\text{N}$ values became increasingly enriched ($> 8\text{‰}$) above 100 cm depth at Lua Meko, suggesting trophic enrichment and the likelihood of some form of faecal contribution to the sedimentary deposits (Fig. 2E–Supplementary Information Table S19). A date on marine shell from the auger sample at 60 cm depth gave an age of 30257–29657 cal BP (Table 1), confirming occupation at the site at the onset of Marine Isotope Stage 2 (MIS 2, 29–12 ka). A second age was



In 2018, we revisited Pia Hudale to investigate if deeper cultural deposits existed at the rockshelter complex using our rapid site prospecting approach. The rockshelter had become difficult to access due to the dumping of municipal waste, and a sampling location ~25 m northwest of the original excavation and near the second large rockshelter was selected (Fig. 3A). Amplitude slice-maps in front of the shelter revealed a complex subsurface deposit, borne out by the amount of limestone rubble and roof fall found on the surface and noted in the earlier excavations. These appear as small circular strong reflections in the slice-maps (Fig. 3E–Supplementary Information Figs. S4–S5). A series of six locations were augered with increasing distance from the rockshelter, revealing a variable but deepening profile to the limestone basement, beginning at 20 cm (PH01) and reaching 230 cm depth in places (PH04) (Fig. 3C–F).

Table 1

New and previously published radiocarbon ages for Roti. Ages have been calibrated using Oxcal 4.4 (Ramsey, 2009) and the SHCal20 (Hogg et al., 2020) atmospheric curve for charcoal, and Marine20 for marine shell (Heaton et al., 2020). Marine shell dates are calibrated without ΔR as this data is currently unavailable for Wallacea. Calibrated age ranges are given at the 95.4% confidence interval. $F^{14}C$, fraction modern¹⁴C.

Lab code	Site name	Sample material	Depth (cm)	$F^{14}C$	Radiocarbon age (yr BP)	Calibrated age range 2 σ (modelled cal. yr BP)	Reference
ANU-10911	Lua Meko	<i>Turbo opercula</i>	5	–	5590 $\pm$ 110	6088–5520	Mahirta (2003)
ANU-10910	Lua Meko	<i>Turbo opercula</i>	10	–	4720 $\pm$ 100	5072–4450	Mahirta (2003)
ANU-10909	Lua Meko	<i>Turbo opercula</i>	15	–	5420 $\pm$ 60	5831–5422	Mahirta (2003)
ANU-11103	Lua Meko	<i>Turbo opercula</i>	35	–	10,030 $\pm$ 120	11236–10547	Mahirta (2003)
ANU-10908	Lua Meko	<i>Strombus</i> sp	60	–	24,420 $\pm$ 250	28347–27240	Mahirta (2003)
SANU-69916	Lua Meko	Mollusca	60	0.0365 $\pm$ 0.0006	26,582 $\pm$ 131	30257–29657	This study
SANU-69923	Lua Meko	Mollusca	130	0.3864 $\pm$ 0.0010	7638 $\pm$ 26	8037–7759	This study
ANU-11102	Pia Hudale	<i>Turbo opercula</i>	10	–	10,440 $\pm$ 500	12759–10217	Mahirta (2003)
ANU-10912	Pia Hudale	<i>Turbo opercula</i>	20	–	11,290 $\pm$ 150	12999–12264	Mahirta (2003)
ANU-11000	Pia Hudale	<i>Melanoides feniculus</i>	55	–	11,160 $\pm$ 220	12980–11871	Mahirta (2003)
SANU-69926	Pia Hudale	Charcoal	60	1.1555 $\pm$ 0.0018	Modern		This study
–	Pia Hudale	Charcoal	200	–	Failed		This study
SANU-69932	Lua Semen	Charcoal	50	1.1033 $\pm$ 0.0017	Modern		This study
SANU-69931	Lua Semen	Charcoal	150	0.8207 $\pm$ 0.0015	1587 $\pm$ 19	1515–1371	This study
SANU-69929	Lua Hena Lean	Charcoal	20	0.9781 $\pm$ 0.0016	178 $\pm$ 18	278–210	This study
SANU-69930	Lua Hena Lean	Charcoal	140	0.9735 $\pm$ 0.0016	216 $\pm$ 18	222–143	This study
Wk 49060	Lua Dibalean	Charcoal	100	104.9000 $\pm$ 0.2	104.9 $\pm$ 0.3%	58–28	This study
SANU-69927	Lua Dibalean	Charcoal	100	1.0318 $\pm$ 0.0016	–252 $\pm$ 18		This study
SANU-69917	Lua Nggalana	Trochoidea	50	0.3356 $\pm$ 0.0009	8771 $\pm$ 26	9419–9096	This study

The four stratigraphic units identified in the auger sample profile do not match those identified in the nearby excavation (Fig. 3B–F), suggesting heterogeneous sediment deposition across the site. At Pia Hudale, medium to fine silts are dominant, with a finer mean grain size than observed at Lua Meko. The deposit represents a cultural sequence with stone artefacts increasing with depth to 230 cm (base of PH04) (Fig. 3F–Supplementary Information Tables S2–4). Heat shattered raw material, characterised by high gloss, crazing and pot-lidding, occurs in two peaks that correspond to peaks in burnt earth and very small peaks in charcoal. Peaks in the magnetic susceptibility values coincide with evidence for heating and burning at the site (charcoal, burnt earth and heat shatter) (Fig. 3F–Supplementary Information Table S14). Marine shell was almost non-existent in the samples, with only one very small fragment identified in the upper 10 cm (Supplementary Information Table S12). This contrasts with the nearby excavation, which contained a large assemblage of both freshwater and marine shell (Mahirta et al., 2004). Charcoal was also largely absent from all samples, with only 0.22 g from all samples collected from the upper 60 cm of the site, and only microscopic quantities (<0.02 g) below this depth. A paucity of datable charcoal in the Pia Hudale deposits was also noted during the excavation (Mahirta et al., 2004). The absence of shell below 10 cm, and of charcoal of a suitable quantity for dating below 60 cm, serves as a useful indication that any future excavations at Pia Hudale will require additional dating methods. A date obtained from charcoal from the auger sample at 60 cm depth returned a modern age, and a second small sample (0.01 g) at 200 cm failed pre-treatment (Fig. 3F–Table 1). The modern age at 60 cm depth and the contrasting sedimentary sequence found in the auger profile indicate the missing Holocene deposit may be

found outside the rockshelters.

3.3. Lua Semen

The south-central cave site of Lua Semen (–10.82686, 123.06789, height 62 m ASL) is in a deep and broad valley on the southern side of the island (Fig. 1C) and was shown to the 2018 survey team by local landowners. The chamber is 20 m deep with a 4 m ceiling and flat 6 $\times$ 4 m sediment floor (Fig. 4A–B). The floor had a number of pottery sherds on the surface.

Sediment delivery to the cave is down a sloping sediment and rubble scree leading from the northeast-facing entrance to the cave chamber. The GPR amplitude slice-maps of the deposit indicated a low reflection region suitable for augering in the western corner of the cave floor (Fig. 4C–Supplementary Information Figs. S6–S7). Three locations were selected, reaching variable depths of 247 cm (LS01), 30 cm (LS02), and 130 cm (LS03), with the GPR wave signal weakening just above the base of LS01. Augering revealed uniform red-brown fine silt-clay sediments with a transition to limestone rubble at the base of LS01 (Fig. 4D). The magnetic susceptibility values increased above 150 cm depth, matching the first appearance of charcoal within the deposit (Fig. 4D–Supplementary Information Table S15). Pterioidea (oyster) shell occurred at 50 cm, at the same depth as a peak in charcoal (Fig. 4D–Table S5–7 and Table S12). Enriched $\delta^{15}N$ (>8‰) (>8‰) are again identified at Lua Semen indicating the possibility of faecal contribution to the sediment's organic matter content (Supplementary Information Table S21). A date on charcoal from 150 cm depth gave an age of 1515–1371 cal BP, while a sample at 50 cm depth returned a

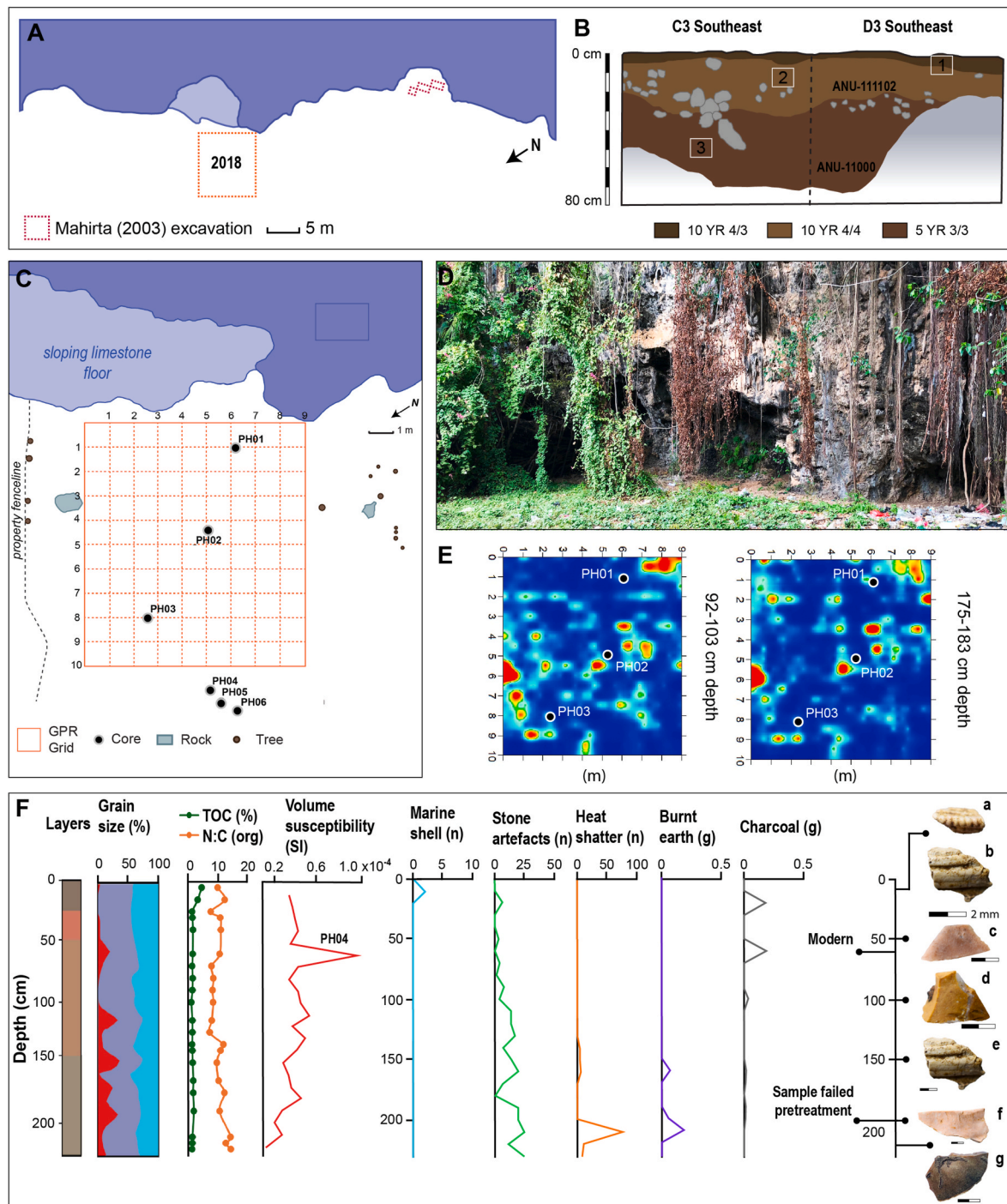


Fig. 3. Pia Hudale, north-central Roti. **A** Plan showing location of rockshelters, excavations (Mahirta, 2003; Mahirta et al., 2004) and 2018 sampling area. **B** Southeast sections of the D3 and C3 excavation squares at Pia Hudale, adapted from Mahirta (2003) and Mahirta et al. (2004) and showing stratigraphic layers and the location of radiocarbon samples. **C** Site plan of the rockshelter showing the auger locations (PH01–6). **D** Site photo looking west toward the rockshelter. **E** GPR amplitude slice-maps showing reflections of the rockshelter subsurface deposits with several small higher reflections. Areas with higher reflections are denoted by yellow and red. **F** Stratigraphic layers, grain size: clay (red), silt (purple), sand (cyan), total organic carbon (TOC%) and C/N organic ratios (C/N (org)) (PH04), sediment magnetic susceptibility values (SI) (PH04) and cultural material plotted by depth. Cultural material came from PH04, PH05 and PH06. Far right, examples of shell (a–b) and stone artefacts (c–g) from throughout the sequence and associated radiocarbon ages. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

modern age (Table 1). The enhanced magnetic susceptibility and presence of charcoal from 150 cm likely represents the first use of the cave chamber by people.

3.4. Lua Hena Lean

The south-central cave site of Lua Hena Lean (−10.81117, 123.16969, height 109 m ASL) is a single chamber cave located at the southwestern end of a 30 × 40 m depression in the surrounding landscape, with a palm forest growing inside. Several stone artefacts were

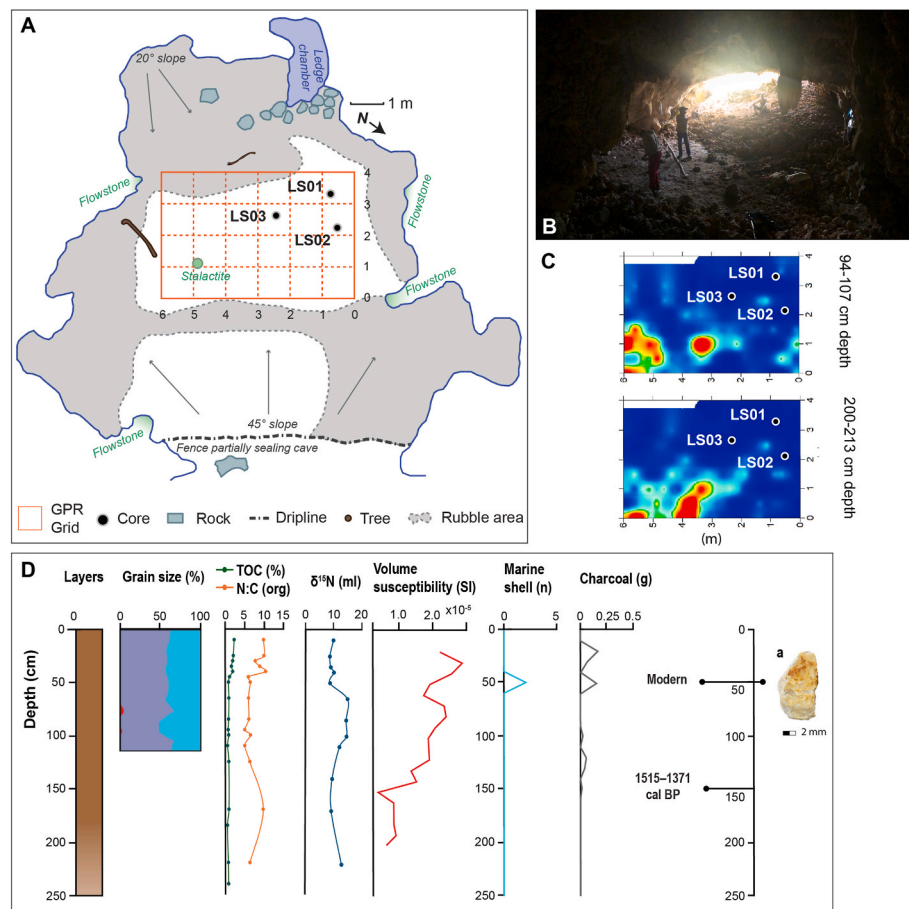


Fig. 4. Lua Semen, south-central Roti. **A** Site plan of the rockshelter showing the auger locations (LS01-3). **B** Site photo from south corner of chamber looking north toward the entrance. **C** GPR amplitude slice-maps showing several strong reflections of the subsurface deposits. Areas with higher reflections are denoted by yellow and red. **D** Stratigraphic layers, grain size: clay (red), silt (purple), sand (cyan), total organic carbon (TOC%) and C/N organic ratios (C/N (org)), $\delta^{15}\text{N}$ values (ml) (LS01 and LS03 sediment magnetic susceptibility values (SI) (LS01), and cultural material plotted by depth (LS01-LS03). Far right, example of marine shell from the sequence (a) and associated radiocarbon ages. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

found on the surface outside the cave entrance. The cave is 13 m (length) $\times$ 8 m (width), with a 20 m high entrance with a sloping rubble and sediment scree leading down to a flat earth floor (Fig. 5A–B).

The GPR amplitude slice-maps of the deposit indicated a low reflection region suitable for augering towards the rear of the cave (Fig. 5C–Supplementary Information Fig. S8). Two locations were chosen for augering, reaching depths of 234 cm (LHL01) and 158 cm (LHL02). Sediment samples were silt dominated (coarse to very coarse), with a smaller component of fine sand. Grain size decreased markedly towards the surface, with a particular shift from silt to clay at 120 cm. Microbone was present in the samples from 234 cm to 150 cm depth, with the deposit containing no cultural material below 150 cm (Fig. 5D–Supplementary Information Table S8). Charcoal is present in small quantities above 150 cm depth to the surface, coinciding with a sharp increase in $\delta^{15}\text{N}$ values (Supplementary Information Table S22), and a gradual increase in the magnetic susceptibility values (Fig. 5D–Supplementary Information Table S16). Two radiocarbon samples on charcoal at 140 cm and 20 cm depths returned ages of 222–143 cal BP and 278–210 cal BP (Table 1), indicating human use of Lua Hena Lean is very recent.

3.5. Lua Dibalean

The site of Lua Dibalean (−10.79804, 123.15552, height 166 m ASL) is in the same region of south-central Roti as Lua Hena Lean, with both

sites shown to the 2018 survey team by local landowners. Lua Dibalean is a roughly circular depression 15 $\times$ 16 m, with a pronounced overhang on the northern and southern side, with roof clearance of $\sim$ 2 m in the southern shelter area (Fig. 6A–B).

The site has surface pottery sherds and is still in use by local people. Two locations at the north-eastern margin of the GPR grid were selected for augering (Fig. 6C–Supplementary Information Figs. S9–S10), reaching depths of 153 cm (LD01) and 116 cm (LD02), with sediments a uniform red-brown throughout the deposit. Magnetic enhancement was visible throughout the profile, decreasing after 100 cm (Fig. 6D–Supplementary Information Table S17). This enhancement coincided with charcoal, burnt earth and burnt food remains (Fig. 6D–Supplementary Information Tables S9–10 and S12). A single stone artefact on limestone and a burnt Balistoidea (triggerfish) scale and burnt coconut shell were found in the samples between 50 and 100 cm depth, with a date on charcoal from 100 cm indicating the human activities detected in the samples had occurred in the recent past (Table 1, Fig. 6D).

3.6. Lua Nggalana

Located on the northern side of the south-central topographic bulge (−10.75751, 123.21654, 359 m ASL) and $\sim$ 2 km from the coastline, Lua Nggalana is a small rockshelter on the southeastern side of an isolated piece of uplifted limestone reef. The rockshelter is 12 m long and 2–4 m

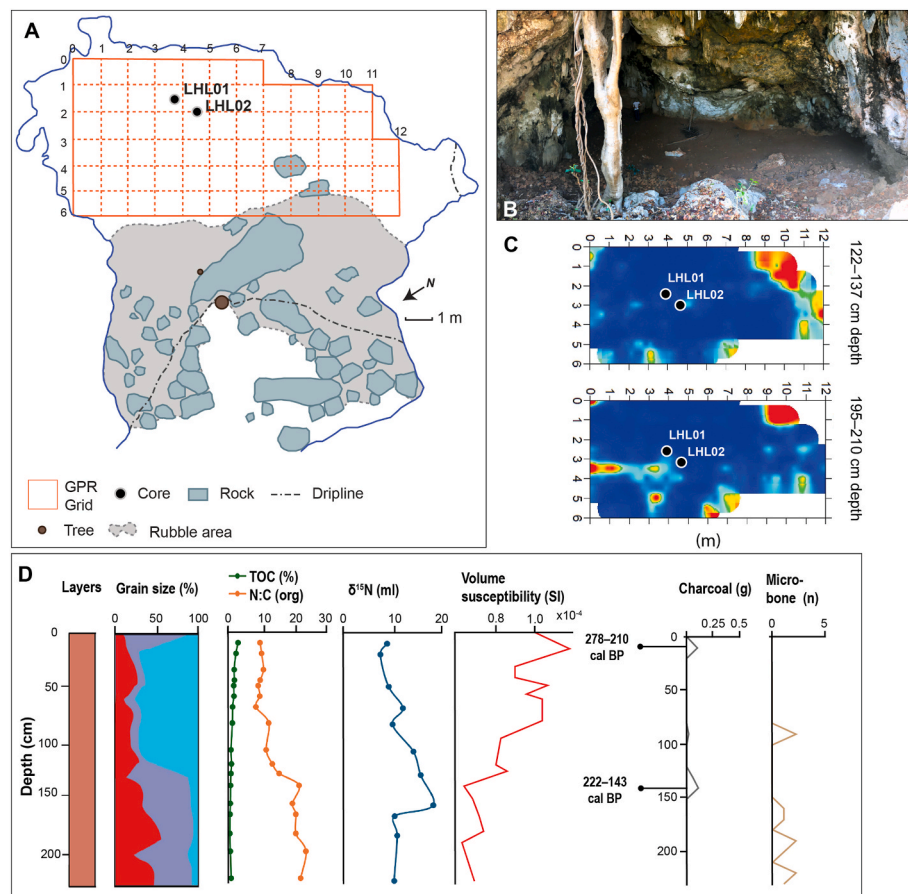


Fig. 5. Lua Hena Lean, south-central Roti. **A** Site plan of the rockshelter showing the auger locations (LHL01–2). **B** Site photo taken from the entrance to the cave chamber. **C** GPR amplitude slice-maps showing strong reflections near the shelter walls. Areas with higher reflections are denoted by yellow and red. **D** Stratigraphic layers, grain size: clay (red), silt (purple), sand (cyan), total organic carbon (TOC%) and C/N organic ratios (C/N (org)), $\delta^{15}\text{N}$ values (ml), sediment magnetic susceptibility values (SI), and charcoal and micro-bone plotted by depth with associated radiocarbon ages (LHL01). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

deep from the dripline with a flat earth floor (Fig. 7A–B). Stone artefacts and marine shell were found on the deposit surface within the shelter and eroding out from the hill slope in front. Two locations with weak reflections were selected for augering within the shelter (Fig. 7C–Supplementary Information Figs. S11–S12), reaching 55 cm depth (LN01) and 38 cm (LN02) before encountering bedrock. Stone artefacts and marine shell occurred in all samples below 10 cm depth, with stone artefacts peaking at the base of the deposit (Fig. 7D–Supplementary Information Tables S11–S12).

A peak in the magnetic susceptibility occurred in samples containing charcoal fragments. Identified marine taxa include Trochoidea (top and turban snails) and Balistoidea (triggerfish), usually associated with rocky shores and coral reefs and lagoons, bays, and seaward reefs, respectively. Top and turban snails and triggerfish are frequently identified food resources in archaeological middens. A radiocarbon date on marine shell from the lowest auger sample gave an age of 9419–9096 cal BP (Table 1), demonstrating early Holocene occupation of the rockshelter.

4. Discussion and conclusions

Our results highlight the success of the rapid site prospection approach, quickly demonstrating that three of the six sampled sites (Lua Semen, Lua Hena Lean and Lua Dibalean) contain deep sedimentary deposits but are extremely young with sparse cultural assemblages. The results also indicate the usefulness of the approach in quickly garnering a greater understanding of complex subsurface stratigraphy within a

cave/rockshelter site, demonstrating the missing Pia Hudale Holocene record may be present in front of the rockshelters, with the deposit reaching considerable depth (>2 m) with a modern age at 50 cm. The deposit has the potential to preserve a high-resolution late-Holocene record, representing the only example so far known on the island, with only a single sample from a disturbed excavation square at one of the Tonggobatu sites dating to this period (Mahirta, 2003). Inside the shallow rockshelter sites on north-central Roti, a Terminal Pleistocene and early Holocene record is preserved, with this pattern replicated at Lua Nggalana on the south-central coast. At the other extreme, our results demonstrate a pre-Marine Isotope Stage 2 cultural record is also present on Roti, with a previously unidentified deeper region of cultural deposit at the shallow rockshelter site of Lua Meko, extending below an age of 30,257–29,657 cal BP. This additional 40 cm of cultural deposit has the potential to extend occupation on Roti into Marine Isotope Stage 3 (57–30 ka).

The approach can be further improved using a percussion corer to obtain light-safe sleeved cores (retaining sedimentary bedding) that can then be split and sampled in the laboratory. This method allows for a more flexible approach to dating, with the option to collect sediment samples for optical dating using published protocols (De Deckker et al., 2019; Lewis et al., 2021). This may be needed in the absence of charcoal (such as at Pia Hudale), if the site chronology extends beyond the radiocarbon barrier, or for generating a comparative chronology. GPR can also be applied in tandem with Electrical Resistivity Tomography (ERT) which has been used very successfully to detect subsurface features, stratigraphy and the depth of bedrock in archaeological sites in

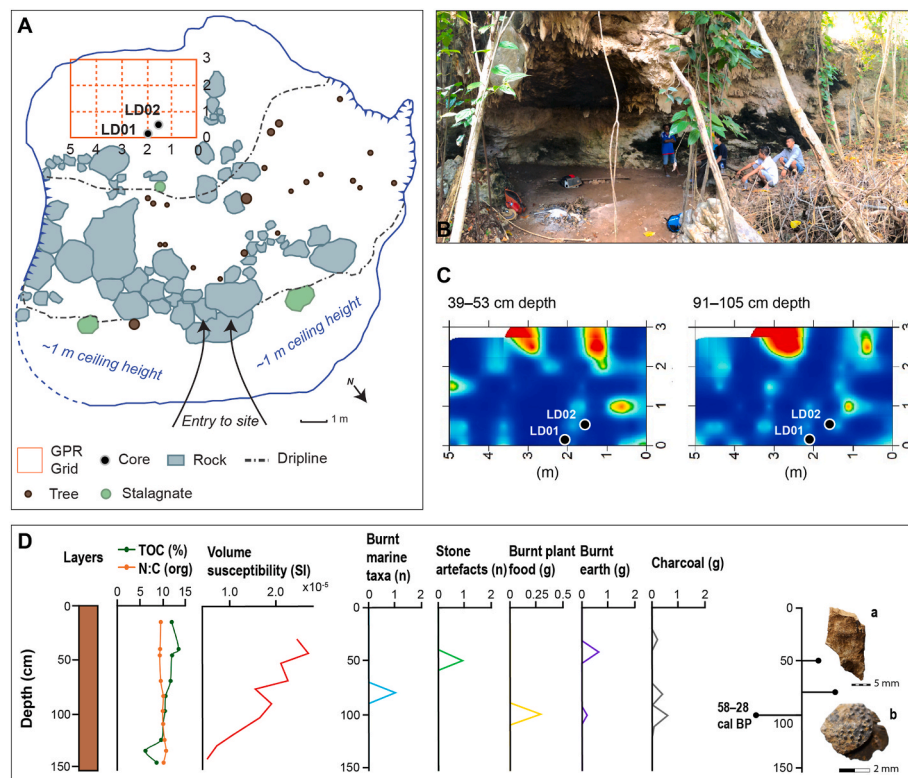


Fig. 6. Lua Dibalean, south-central Roti. **A** Site plan showing the auger locations (LD01–2). **B** Site photo looking south towards the larger overhang. **C** GPR amplitude slice-maps showing strong reflections near shelter wall. Areas with higher reflections are denoted by yellow and red. **D** Stratigraphic layers, total organic carbon (TOC %) and C/N organic ratios (C/N (org) (LD01), sediment magnetic susceptibility values (SI) (LD01), and cultural material plotted by depth (LD01–LD02). Far right, the stone artefact (a) and marine taxa (b) from the sequence and the associated radiocarbon age. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

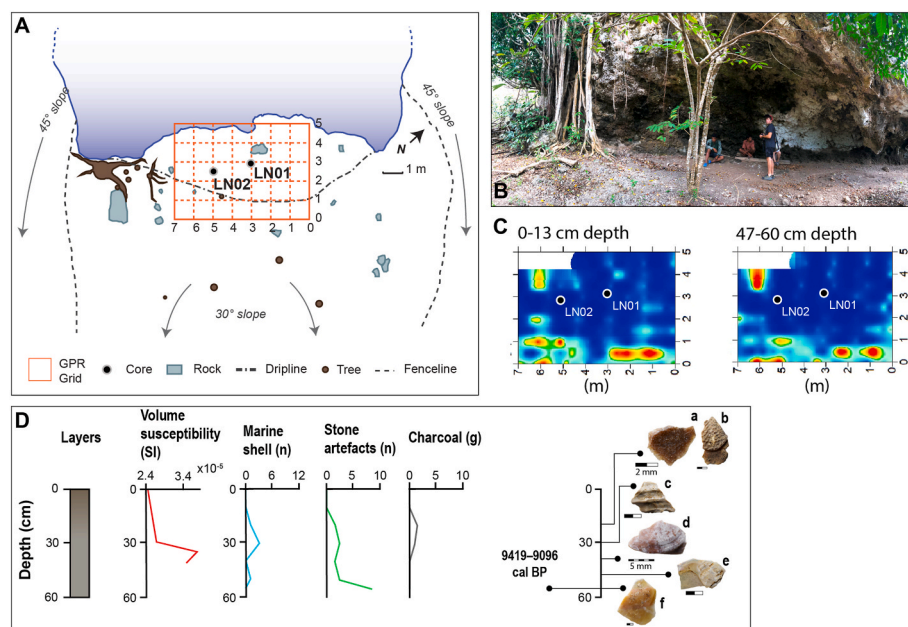


Fig. 7. Lua Nggalana, south-central Roti. **A** Site plan of the rockshelter showing the auger locations (LN01–2). **B** Site photo looking west towards the rockshelter. **C** GPR amplitude slice maps showing strong reflections near the shelter dripline indicating roof fall. Areas with higher reflections are denoted by yellow and red. **D** Stratigraphic layers, sediment magnetic susceptibility values (SI) (LN01), and cultural material plotted by depth (LN01–LN02). Far right, examples of stone artefacts (a, d–f) and marine taxa (b–c) from throughout the sequence and the associated radiocarbon age. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

South Africa (Mackay et al., 2023) and Borneo (Maloney et al., 2022).

The approach outlined here has broad applicability to any area where

researchers wish to gain a rapid sense of regional site distribution, composition and occupation chronologies, with very low site impact. More globally, the ability to make informed decisions prior to large-scale excavation in caves and rockshelters will be of use to researchers in many parts of the world.

Funding

This study was funded by the Australian Research Council through a Centre of Excellence Grant (CE170100015) to T.C., and an Australian Government Research Training Program Award to K.N.

CRediT authorship contribution statement

Kasih Norman: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Kelsey Lowe:** Formal analysis, Investigation, Resources, Writing – review & editing. **Matthew Forbes:** Formal analysis, Investigation, Writing – review & editing. **Thomas Sutikna:** Project administration, Supervision, Writing – review & editing. **Anton Ferdianto:** Project administration, Writing – review & editing. **Rachel Wood:** Formal analysis, Writing – review & editing. **Stewart J. Fallon:** Formal analysis, Investigation. **Rebecca Esmay:** Investigation. **Jatmiko:** Project administration, Writing – review & editing. **I Putu Yuda Haribuana:** Project administration, Writing – review & editing. **I Made Agus Julianto:** Project administration, Writing – review & editing. **Ashleigh J. Rogers:** Investigation, Writing – review & editing. **Chris Clarkson:** Conceptualization, Investigation, Writing – review & editing. **Tim J. Cohen:** Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We extend our warmest thanks to E. Wahyu Saptomo for his skilful management and invaluable advice at every step of the project. Our thanks to Dr Sam Lin for including us on his research permit and for bearing the administrative load of the research, for which we are most grateful. Our most grateful and sincere thanks to our colleague Jublina Lina, who was fundamental to the success of our field season and who tragically passed away in 2021. We also thank Mr Folkes Panie for his invaluable assistance during surveys and field sampling. We would like to thank the landowners and villagers of Roti who guided us during surveys and gave permission for us to undertake field sampling. We gratefully acknowledge the field support and camaraderie of Alex Wall and Fabien Boesl. Permission for the research was granted by the Indonesian Government - RISTEK Foreign Research Permit (34/SIP/FRP/E5/Dit.KI/II/2018).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.quaint.2026.110372>.

Data availability

All data are available in the main text and the Supplementary Information.

References

- Armstrong, B.J., Edwards-Baker, S., Penzo-Kajewski, P., Herries, A.I., 2021. Ground-penetrating radar analysis of the Drimolen early Pleistocene fossil-bearing palaeocave, South Africa. *Archaeol. Prospect.* 28 (4), 419–433.
- Board, W.E., 2023. World register of marine species. <https://doi.org/10.14284/170>.
- Brumm, A., van Den Bergh, G.D., Storey, M., Kurniawan, I., Alloway, B.V., Setiawan, R., Setiyabudi, E., Grün, R., Moore, M.W., Yurnaldi, D., 2016. Age and context of the oldest known hominin fossils from Flores. *Nature* 534 (7606), 249–253.
- Conyers, L.B., 2012. Interpreting ground-penetrating radar for archaeology. Left Coast Press.
- Dalan, R.A., Banerjee, S.K., 1998. Solving archaeological problems using techniques of soil magnetism. *Geoarchaeology* 13 (1), 3–36.
- David, B., Barker, B., Petchey, F., Delannoy, J.-J., Geneste, J.-M., Rowe, C., Eccleston, M., Lamb, L., Whear, R., 2013. A 28,000 year old excavated painted rock from Nawarla Gabarnmang, northern Australia. *J. Archaeol. Sci.* 40 (5), 2493–2501. <https://doi.org/10.1016/j.jas.2012.08.015>.
- De Deckker, P., Arnold, L.J., van der Kaars, S., Bayon, G., Stuut, J.-B.W., Perner, K., Lopes dos Santos, R., Uemura, R., Demuro, M., 2019. Marine isotope stage 4 in Australasia: a full glacial culminating 65,000 years ago – global connections and implications for human dispersal. *Quat. Sci. Rev.* 204, 187–207. <https://doi.org/10.1016/j.quascirev.2018.11.017>.
- Dearing, J.A., Hay, K.L., Baban, S.M., Huddleston, A.S., Wellington, E.M., Loveland, P., 1996. Magnetic susceptibility of soil: an evaluation of conflicting theories using a national data set. *Geophys. J. Int.* 127 (3), 728–734.
- Detroit, F., Mijares, A.S., Corny, J., Daver, G., Zanolli, C., Dizon, E., Robles, E., Grun, R., Piper, P.J., 2019. A new species of Homo from the late Pleistocene of the Philippines. *Nature* 568 (7751), 181–186. <https://doi.org/10.1038/s41586-019-1067-9>.
- Fallon, S., Fifield, L.K., Chappell, J., 2010. The next chapter in radiocarbon dating at the Australian national university: status report on the single stage AMS. *Nucl. Instrum. Methods Phys. Res. Sect. B Beam Interact. Mater. Atoms* 268 (7–8), 898–901.
- Forbes, M.S., Bestland, E.A., Wells, R.T., Krull, E.S., 2007. Palaeoenvironmental reconstruction of the late Pleistocene to early Holocene Robertson cave sedimentary deposit, Naracoorte, South Australia. *Aust. J. Earth Sci.* 54 (4), 541–559.
- Forbes, M.S., Bestland, E.A., 2006. Guano-derived deposits within the sandy cave fills of Naracoorte, South Australia. *Alcheringa* 30 (S1), 129–146.
- Goodman, D., Piro, S., 2013. GPR Remote Sensing in Archaeology. Springer.
- Heaton, T.J., Köhler, P., Butzin, M., Bard, E., Reimer, R.W., Austin, W.E.N., Bronk Ramsey, C., Grootes, P.M., Hughen, K.A., Kromer, B., Reimer, P.J., Adkins, J., Burke, A., Cook, M.S., Olsen, J., Skinner, L.C., 2020. Marine20—The marine radiocarbon Age calibration curve (0–55,000 cal BP). *Radiocarbon* 62 (4), 779–820. <https://doi.org/10.1017/rdc.2020.68>.
- Hogg, A.G., Heaton, T.J., Hua, Q., Palmer, J.G., Turney, C.S., Southon, J., Bayliss, A., Blackwell, P.G., Boswijk, G., Ramsey, C.B., Pearson, C., Petchey, F., Reimer, P., Reimer, R., Wacker, L., 2020. SHCal20 Southern hemisphere calibration, 0–55,000 years cal BP. *Radiocarbon* 62 (4), 759–778.
- Ingicco, T., van den Bergh, G.D., Jago-On, C., Bahain, J.-J., Chacón, M.G., Amano, N., Forestier, H., King, C., Manalo, K., Nomade, S., 2018. Earliest known hominin activity in the Philippines by 709 thousand years ago. *Nature* 557 (7704), 233–237.
- Jacob, R.W., Urban, T., 2016. Ground-penetrating radar velocity determination and precision estimates using common-midpoint (CMP) collection with hand-picking, semblance analysis and cross-correlation analysis: a case study and tutorial for archaeologists. *Archaeometry* 58 (6), 987–1002.
- Jacobs, G.S., Hudjashov, G., Saag, L., Kusuma, P., Darusallam, C.C., Lawson, D.J., Mondal, M., Pagani, L., Ricaut, F.-X., Stoneking, M., 2019. Multiple deeply divergent Denisovan ancestries in Papuans. *Cell* 177 (4), 1010–1021. e1032.
- Jatmiko, 2010. Gua-Gua Hunian Prasejarah Di Pulau Rote, Indonesia Timur. *Berkala Arkeologi Tahun* 1, 1–22.
- Lewis, R.J., Tibby, J., Arnold, L.J., Gadd, P., Jacobsen, G., Barr, C., Negus, P.M., Mariani, M., Penny, D., Chittleborough, D., Moss, E., 2021. Patterns of aeolian deposition in subtropical Australia through the last glacial and deglacial periods. *Quat. Res.* 102, 68–90. <https://doi.org/10.1017/qua.2020.117>.
- Lowe, K.M., Shulmeister, J., Feinberg, J.M., Manne, T., Wallis, L.A., Welsh, K., 2016. Using soil magnetic properties to determine the onset of Pleistocene human settlement at Gledswood shelter 1, northern Australia. *Geoarchaeology* 31 (3), 211–228.
- Lowe, K.M., Wallis, L.A., Pardoe, C., Marwick, B., Clarkson, C., Manne, T., Smith, M.A., Fullagar, R., 2014. Ground-penetrating radar and burial practices in western Arnhem Land, Australia. *Archaeol. Ocean.* 49 (3), 148–157.
- Mackay, A., Saktura, R.B.K., O'Driscoll, C.A., Boyd, K.C., Marwick, B., Moffat, I., Jacobs, Z., 2023. The Middle Stone Age sequence at Klipfonteinrand 1 (KFR1), Western Cape, South Africa. *J. Paleolithic Archaeol.* 6 (1), 20. <https://doi.org/10.1007/s41982-023-00147-x>.
- Mahirta, K.P.A., 2003. Human Occupation on Rote and Sawu Islands. *Nusa Tenggara Timur Australian National University [Unpublished PhD Thesis]*, Canberra.
- Mahirta, K.P.A., Aplin, K.P., Bulbeck, D., Boles, W.E., Bellwood, P., 2004. Pleistocene occupation site on Roti Island, Nusa Tenggara Timur, Indonesia. In: Keates, S.G., Pasveer, J.M. (Eds.), *Modern Quaternary Research in Southeast Asia: Quaternary Research in Indonesia*. A. A. Balkema Publishers, pp. 361–394.
- Major, J., Harris, R., Chiang, H.W., Cox, N., Shen, C.C., Nelson, S.T., Prasetyadi, C., Rianto, A., 2013. Quaternary hinterland evolution of the active Banda Arc: surface uplift and neotectonic deformation recorded by coral terraces at Kisar, Indonesia. *J. Asian Earth Sci.* 73, 149–161.
- Maloney, T.R., Dilkes-Hall, I.E., Setiawan, P., Oktaviana, A.A., Geria, I.M., Effendy, M., Ririmasse, M., Febryanto, Sriputri, E., Priyatno, A., Atmoko, F.T., Moffat, I., Brumm, A., Aubert, M., 2022a. A late Pleistocene to Holocene archaeological record

- from East Kalimantan, Borneo. *Quat. Sci. Rev.* 277, 107313. <https://doi.org/10.1016/j.quascirev.2021.107313>.
- Maloney, T.R., Dilkes-Hall, I.E., Vlok, M., Oktaviana, A.A., Setiawan, P., Priyatno, A.A.D., Ririmasse, M., Geria, I.M., Effendy, M.A.R., Istiawan, B., Atmoko, F.T., Adhityatama, S., Moffat, I., Joannes-Boyau, R., Brumm, A., Aubert, M., 2022b. Surgical amputation of a limb 31,000 years ago in Borneo. *Nature* 609 (7927), 547–551. <https://doi.org/10.1038/s41586-022-05160-8>.
- Mijares, A.S., Detroit, F., Piper, P., Grun, R., Bellwood, P., Aubert, M., Champion, G., Cuevas, N., De Leon, A., Dizon, E., 2010. New evidence for a 67,000-year-old human presence at Callao Cave, Luzon, Philippines. *J. Hum. Evol.* 59 (1), 123–132. <https://doi.org/10.1016/j.jhevol.2010.04.008>.
- Norman, K., Inglis, J., Clarkson, C., Faith, J.T., Shulmeister, J., Harris, D., 2018. An early colonisation pathway into northwest Australia 70–60,000 years ago. *Quat. Sci. Rev.* 180, 229–239.
- Norman, K., O'Connor, S., Bird, M., 2021. Island hopping to Sahul. In: McNiven, I.J., David, B. (Eds.), *The Oxford Handbook of the Archaeology of Indigenous Australia and New Guinea*. Oxford University Press. <https://doi.org/10.1093/oxfordhb/9780190095611.013.8>.
- O'Connor, S., Ono, R., Clarkson, C., 2011. Pelagic fishing at 42,000 years before the present and the maritime skills of modern humans. *Science (Washington, D.C.)* 334 (6059), 1117–1121.
- Oktaviana, A.A., Joannes-Boyau, R., Hakim, B., Burhan, B., Sardi, R., Adhityatama, S., Hamrullah, Sumantri, I., Tang, M., Lebe, R., Ilyas, I., Abbas, A., Jusdi, A., Mahardian, D.E., Noerwidi, S., Ririmasse, M.N.R., Mahmud, I., Duli, A., Aksa, L.M., Aubert, M., 2024. Narrative cave art in Indonesia by 51,200 years ago. *Nature* 631 (8022), 814–818. <https://doi.org/10.1038/s41586-024-07541-7>.
- Pedaja, K., Husson, L., Bezos, A., Pastier, A.M., Imran, A.M., Arias-Ruiz, C., Sarr, A.C., Elliot, M., Pons-Branchu, E., Nexer, M., Regard, V., 2018. On the long-lasting sequences of coral reef terraces from SE Sulawesi (Indonesia): distribution, formation, and global significance. *Quat. Sci. Rev.* 479, 37–57.
- Petuch, E.J., Berschauer, D.P., 2020. *Tropical Marine Mollusks - an Illustrated Biogeographical Guide*. CRC Press.
- Porsani, J.L., Jangelme, G.M., Kipnis, R., 2010. GPR survey at Lapa do Santo archaeological site, Lagoa Santa karstic region, Minas Gerais state, Brazil. *J. Archaeol. Sci.* 37 (6), 1141–1148.
- Ramsey, C.B., 2009. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51 (1), 337–360.
- Rizal, Y., Westaway, K.E., Zaim, Y., van den Bergh, G.D., Bettis III, E.A., Morwood, M.J., Huffman, O.F., Grün, R., Joannes-Boyau, R., Bailey, R.M., 2020. Last appearance of *Homo erectus* at Ngandong, Java, 117,000–108,000 years ago. *Nature* 577 (7790), 381–385.
- Rojo, A.L., 1991. *Dictionary of Evolutionary Fish Osteology*. CRC Press.
- Roosmawati, N., Harris, R., 2009. Surface uplift history of the incipient Banda arc-continent collision: geology and synorogenic foraminifera of Rote and Savu Islands, Indonesia. *Tectonophysics* 479, 95–110.
- Stuiver, M., Polach, H.A., 1977. Discussion reporting of ¹⁴C data. *Radiocarbon* 19 (3), 355–363.
- Sutikna, T., Tocheri, M.W., Morwood, M.J., Saptomo, E.W., Jatmiko, Awe, R.D., Wasisto, S., Westaway, K.E., Aubert, M., Li, B., Zhao, J.X., Storey, M., Alloway, B.V., Morley, M.W., Meijer, H.J., van den Bergh, G.D., Grun, R., Dosseto, A., Brumm, A., Roberts, R.G., 2016. Revised stratigraphy and chronology for *Homo floresiensis* at Liang Bua in Indonesia. *Nature* 532 (7599), 366–369. <https://doi.org/10.1038/nature17179>.
- Wood, R.E., Esmay, R., Usher, E., Fallon, S.J., 2023. Sample preparation methods used at the Australian National University radiocarbon facility. *Radiocarbon* 65 (2), 573–589. <https://doi.org/10.1017/RDC.2022.97>.
- Wurster, C.M., Munksgaard, N., Zwart, C., Bird, M., 2015. The biogeochemistry of insectivorous cave guano: a case study from insular Southeast Asia. *Biogeochemistry* 124, 163–175.
- Zaim, Y., Ciochon, R.L., Polanski, J.M., Grine, F.E., Bettis III, E.A., Rizal, Y., Franciscus, R.G., Larick, R.R., Heizler, M., Eaves, K.L., 2011. New 1.5 million-year-old *Homo erectus* maxilla from Sangiran (Central Java, Indonesia). *J. Hum. Evol.* 61 (4), 363–376.