



HAL
open science

A micro-geoarchaeological investigation of a cultivation pit (maite) on Teti'aroa atoll, Central-East Polynesia

Elisa Scorsini, Tim Denham, Emilie Dotte-sarout, Yannick Devos, Luc Vrydaghs, Guillaume Molle

► To cite this version:

Elisa Scorsini, Tim Denham, Emilie Dotte-sarout, Yannick Devos, Luc Vrydaghs, et al.. A micro-geoarchaeological investigation of a cultivation pit (maite) on Teti'aroa atoll, Central-East Polynesia. *Archaeology in Oceania*, 2024, 10.1002/arco.5345 . hal-04855820

HAL Id: hal-04855820

<https://hal.science/hal-04855820v1>

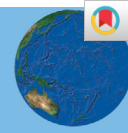
Submitted on 25 Dec 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



A micro-geoarchaeological investigation of a cultivation pit (*maite*) on Teti'aroa atoll, Central-East Polynesia

Elisa Scorsini , Tim Denham , Emilie Dotte-Sarout , Yannick Devos , Luc Vrydaghs 
and Guillaume Molle 

ES, TD: School of Archaeology and Anthropology, Australian National University, Australia; ED-S: Archaeology, School of Social Sciences, The University of Western Australia; YD, LV: Archaeology, Environmental Changes & Geo-Chemistry Research Group (AMGC), Vrije Universiteit Brussel, Belgium; GM: Centre International de Recherche Archéologique sur la Polynésie (CIRAP) Université de la Polynésie Française

ABSTRACT

Cultivation pits represented the principal form of horticultural features developed by past atoll communities in Central-East Polynesia (CEP), and they are still utilised on some atolls in Oceania. The majority of information about the use of cultivation pits in CEP derives from ethnographic and preliminary archaeological investigations. The lack of excavations with rigorous stratigraphic sampling and analyses has constrained the recovery of environmental information associated with these agro-technical features. Using a combination of geoarchaeological techniques, including field observations, physico-chemical analyses and soil micromorphology, this study focuses on sedimentary deposits from a cultivation pit (MAITE-01) on Teti'aroa atoll, in the Society Islands. We demonstrate how micro-geoarchaeological investigations can advance research and offer new interpretations to study past human interactions within environments long considered “lost causes” to detailed archaeostratigraphic interpretation. High-resolution geoarchaeological techniques reveal details about pit construction and provide indirect evidence of the integration of human-animal interaction into the horticultural system.

Keywords: micro-geoarchaeology, horticulture, cultivation pits, Polynesia, atolls

RESUME

Les fosses de culture représentent la principale forme d'aménagement horticole développée par les anciennes communautés installées sur les atolls de Polynésie centre-orientale (PCO). Cette technique horticole est toujours pratiquée sur certains atolls d'Océanie. La majorité des connaissances sur l'utilisation des fosses de culture en PCO proviennent d'enquêtes ethnographiques et d'études archéologiques préliminaires. L'absence de fouilles, d'échantillonnage et d'analyse stratigraphique rigoureux ont fortement restreint notre compréhension des informations environnementales associées à ces spécificités agrotechniques. En s'appuyant sur une combinaison de techniques géoarchéologiques, incluant des observations de terrain, des analyses physico-chimiques et de micromorphologie des sols, cette étude se concentre sur les dépôts sédimentaires d'une fosse de culture (MAITE-01) sur l'atoll de Teti'aroa, dans les îles de la Société. Nous démontrons comment les investigations micro-géoarchéologiques peuvent faire progresser la recherche sur ce sujet et proposer de nouvelles interprétations pour étudier les interactions humaines passées dans des environnements longtemps considérés comme des « causes perdues » sans interprétation archéostratigraphique possible. Les techniques géoarchéologiques à haute résolution portent aujourd'hui un nouveau regard sur la construction de telles fosses et témoignent indirectement des interactions homme-animal ainsi que de leur intégration dans le système horticole traditionnel.

Mots-clés: micro-géoarchéologie, horticulture, fosses de culture, Polynésie, atolls

Correspondence: Elisa Scorsini, The Australian National University, Canberra, ACT 2601, Australia. Email: Elisa.Scorsini@anu.edu.au

INTRODUCTION

Studies on agricultural techniques used by past Pacific Island communities highlight the significant challenges posed by their unique environments, particularly in

low-lying reef islands in the Eastern Pacific. These challenges arise from the perceived limited space and resources, diverse rock types, and the presence of less well-developed soil profiles that characterise this type of island (i.e., Clarke, 1994; Kirch 1994; Kirch et al., 2022;

Quintus & Cochrane, 2018; McCoy & Graves, 2010; Vitousek et al., 2014). On atolls, the terrestrial environment is particularly constraining, and the long-term survival of a community is hampered by multiple factors including access/lack of freshwater resources and soils to enable cultivation (Reepmeyer et al., 2016; Weisler, 1999a, 2001). To successfully settle in these unique ecological contexts Pacific Islanders developed, among others, a technique consisting of digging pits into the substrate to reach the freshwater lens below the surface, with artificial development of associated soils (Burley et al., 2018; Kirch & Lepofsky, 1993). In Central-East Polynesia (CEP), this wet cultivation system, called *maite*, is still part of local traditional knowledge and has been ethnographically documented, yet it remains understudied from an archaeological perspective (Chazine, 1977, 1982, 1985, 1990, 2001, 2008).

Archaeological research on atolls is particularly challenging due to the less-developed stratigraphy and preservation issues, unlike volcanic or continental islands (Conte et al., 2017; Nolet, 2021). Coralline atolls consist of low-lying, unconsolidated sediments that accumulate from the living reef crest. Changes in the surrounding reef system greatly impact the geomorphology of the atolls, making them more vulnerable to both environmental and human-induced changes, which in turn affect the preservation of archaeological deposits. Consequently, studies that apply multiproxy methods combining geomorphology, archaeobotany and archaeology have been limited. However, pioneering research has shown that coral atolls are still valuable for palaeoenvironmental and archaeological investigations (Conte et al., 2017, Chazine, 2008; Davidson, 1971; Nolet, 2021; Nunn et al., 2024; Rainbird, 2004; Shun & Athens, 1990; Steibl et al., 2024, p. 258; Thomas, 2001, 2015, 2019; Weisler, 1999a, 1999b). The aim of this paper is to contribute to the understanding of traditional cultivation pit technology in the Pacific through the first application of geoarchaeology on an atoll of CEP, via a case study on Teti'aroa. We demonstrate how micro-geoarchaeological investigations can advance research and offer both new methodologies and interpretations to study past human interactions within these peculiar environments.

BACKGROUND AND CONTEXT: CULTIVATION PITS AND ATOLLS ARCHAEOLOGY IN THE PACIFIC

The cultivation pits: a long horticultural tradition in the Pacific

Pacific Islanders encountered a wide variety of island environments during their exploration eastwards, some being more constraining than others with regards to potential for agricultural development. Coralline sand atolls are scattered from the Western Pacific to Central-Eastern Polynesia and proved particularly challenging due to the difficulty in accessing freshwater and the scarcity of

well-developed soils. To adapt to such conditions, atoll-dwelling islanders came to develop an innovative horticultural system through aroid pit cultivation (Chazine, 2012; Weisler, 2001). This technique consists in digging pits through the coral substrate to reach the subterranean freshwater, namely the Ghyben–Herzberg lens, sitting atop of the salty groundwater (Jamet & Trichet, 1987). Based on ethnographic data, construction of these pits took place on a large scale, some covering hundreds of square metres (Chazine, 2012). They were used to grow large quantities of crops, mostly aroids (Araceae) including giant swamp taro *Cyrtosperma merkusii* (syn. *chamissonis*) and taro *Colocasia esculenta*, as well as sometimes the giant taro *Alocasia macrorrhizos*. Crops were planted at the bottom of the pit, enriched with topsoil and additions of organic mulch mainly from leaves of indigenous and Polynesian introduced trees (species of *Guettarda*, *Hibiscus*, *Messerschmidia*, *Pisonia* and *Scaevola*, possibly *Artocarpus altilis*, *Cocos nucifera* and *Pandanus*) (Chazine, 2012; Manner, 1993). The excavated sediment was set on the edge of the pit forming an undulating landscape. The slopes of the pits were used for planting breadfruit trees (*A. altilis*), sugarcane (*Saccharum officinarum*) and cordyline (*Cordyline fruticosa*), as well as the cultivated trees, bananas, pandanus and palms noted above.

Whether aroid pit horticulture was an Austronesian innovation or originated in Island Southeast Asia (Sulu Sea and Borneo) is much debated (Barrau, 1961; Chazine, 2008; Kirch & Lepofsky, 1993; Manner, 1993; Reepmeyer et al., 2016, p. 57; Yen, 1993). Aroid planting pits are associated with early human settlement on Tonga, dating back to the first Lapita landfall (pooled age of 2813 ± 6 cal BP on sample TO2:Ho-T3) then filled between 2690 and 2390 cal BP after being abandoned (Burley et al., 2018). Other pit-deriving dates from the Marshall Islands also suggest that this cultivation technique accompanied first colonisers around 1910 ± 70 cal BP (Beta-79076) on Maloelap (Weisler, 1999b) or started a few centuries after human colonisation, such as on Majuro at 1720 ± 45 cal BP (PLD-2788 in Yamaguchi et al., 2005). Pit cultivation spread to numerous Pacific atolls including Kiribati, the Cook Islands and the Tuamotu archipelagos. In Micronesia, this horticultural practice has continued until the present which has enabled in-depth ethnographic investigation by anthropologists and botanists (i.e., Luomala, 1974; Manner, 1993; Thaman, 1990). In French Polynesia, most of the *maite* (cultivation pits) were rapidly abandoned following the imposition of coproculture by the Catholic missionaries in the second half of the 19th century (Nolet, 2021). The expansion of the coconut plantations coupled with a lack of management and cyclone-induced wash-overs of the islets contributed to the progressive filling of the abandoned pits.

Ethnoarchaeological research on cultivation pits

During the 1980s in CEP, Chazine conducted ethno-archaeological investigations on *maite* cultivation pits in the Tuamotu archipelago. Especially important were his case-studies on Reao, Anaa, Makemo, Takapoto and

Rangiroa atolls (Figure 1). Using a combination of surveys, large-scale mapping, pedological analyses and traditional knowledge, he reconstructed the sequence of construction and use of the pits (Chazine, 2008, p. 123).

A location was often chosen where vegetation of *Scaevola frutescens* (beach cabbage) and *Pisonia grandis* (cabbage tree) had already created a topsoil that was first removed and stored nearby. Soil analyses showed that phosphate levels were up to 25% higher beneath *Pisonia* vegetation which is a favourite nesting place for guano-producing seabirds (Chazine, 2008, p. 129). The pits were usually dug between 1 and 2 m deep through the hardened sand layer using *Tridacna*, pearl-shell or turtle bone shovels and spades, and hard-wood picks. The digging continued to about 20 cm below the soil in which the freshwater lens appeared, then the topsoil was put back in the bottom. A drainage ditch was sometimes dug around the edge of the pit. Once the crops were planted, the soil was further enriched with a mixture of leaves, sand and humus forming a black earth favouring the growth of the underground storage organs, mostly varieties of taro (*C. esculenta*). The cultivation pits occur in a variety of shapes (elongated, square, rectangular, circular) and dimensions which could be the result of expansion and restoration through time. Chazine further identified smaller nursery pits where propagules were transplanted, attesting to long-term sustainable management.

By heavily focusing on surface mapping, Chazine further documented the spatial relationship between areas of pit cultivation and house sites as part of land tenure organisation. He extrapolated productive capacity of these agricultural systems to infer demographic processes on atolls. While Chazine's work offered new insights into the life of atoll-dwelling populations in CEP, archaeological excavations of pits are very limited in scope with limited geoarchaeological and micromorphological analyses.

Weisler first excavated *Cyrtosperma* pits on Kaven islet, on Maloelap atoll in the Marshall Islands, leading him to identify a palaeo-A horizon marking the ancient organic-rich topsoil (Weisler, 1999b; see also Weisler, 2001 on Utrök atoll). Documentation of the method of pit construction and determination of the properties and sediment sources of the individual layers were amongst the main objectives of the research. To do so, Weisler established a discontinuous excavation trench perpendicular to the targeted pit. He conducted grain size analyses, geochemistry, and point counted constituents on petrographic slides. In addition to radiocarbon dating, Christensen and Weisler (2013) identified non-marine mollusc species, while Horrocks and Weisler (2006) analysed pollen, starch grains, calcium oxalate crystals and xylem cells of introduced non-*Colocasia* Araceae to reconstruct early atoll ecology and human modification of the landscape.

Horrocks and Thomas (2022) conducted a study on Tarawa Atoll, Kiribati, focusing on the analysis of botanical remains associated with cultivation pits. The results from the sediments of the test pits which were excavated in the

centre of the pit rim mounds indicate local cultivation of *Cyrtosperma merkusii* and *Colocasia esculenta*. Additionally, microfossils of other subsistence taxa, such as *C. nucifera* (coconut palm), *Morinda citrifolia* (noni tree) and *Pandanus tectorius* (Tahitian screwpine), were identified, along with radiocarbon-dated macrofossil charcoal from *A. altilis* (breadfruit).

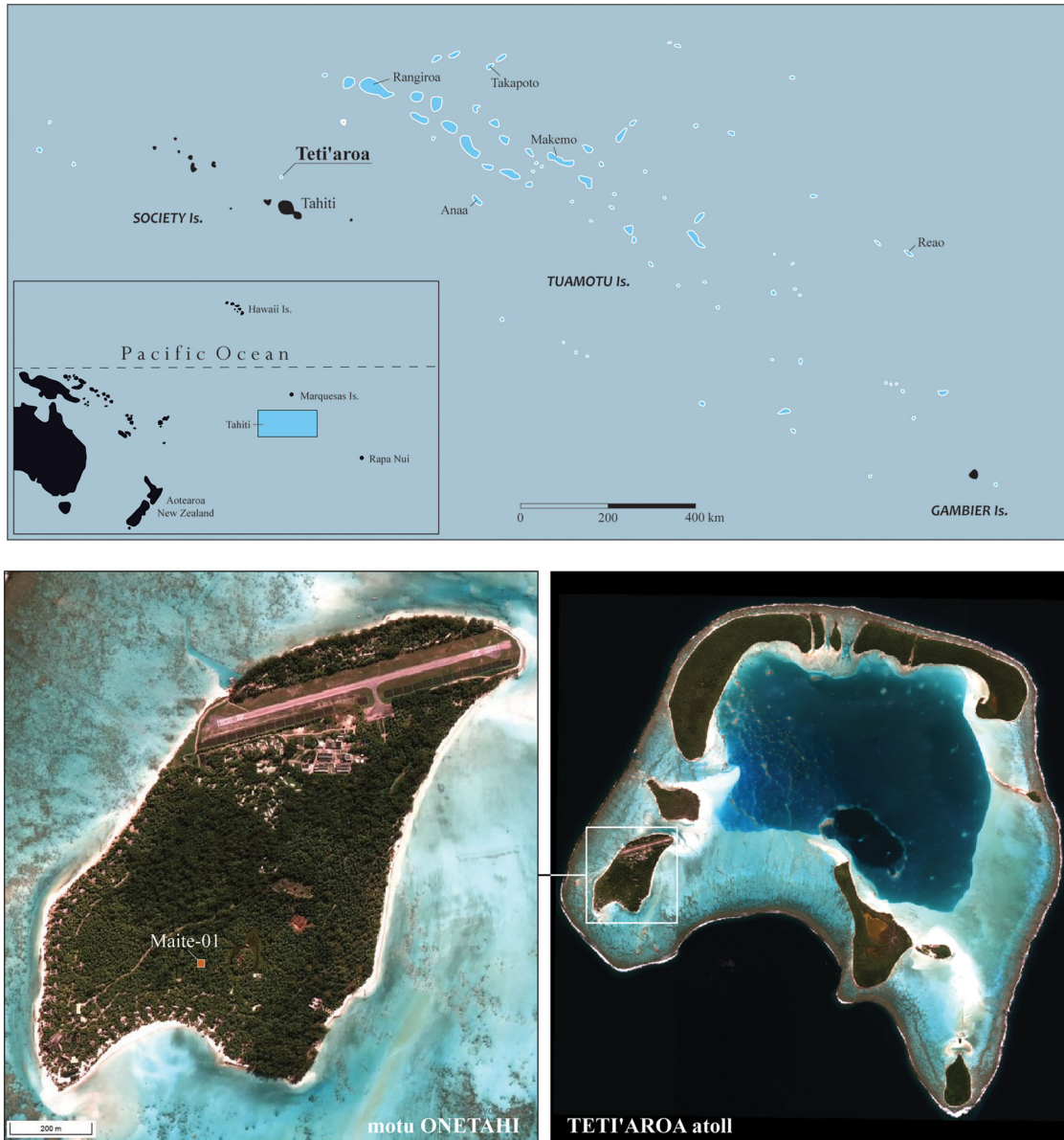
On Majuro atoll, also in the Marshall Islands, Yamaguchi et al. (2005) excavated a 2 m × 4 m trench located on a mound between two *Cyrtosperma* cultivation pits on Laura islet. Complex stratigraphy combined with a suite of radiocarbon dates indicate that the pit landscape was artificially constructed around 2000–1890 cal BP (PLD-2790 AMS) and its use continued until the present. The authors explored the general geomorphology of the atoll in relation to human occupation. However, the lack of high-resolution analyses limited the ability to interpret soil formation and the detailed construction sequence of the pit.

Burley et al. (2018) excavated an aroid planting pit discovered on a small sandy islet at the entrance of Tongatapu lagoon, Kingdom of Tonga. A trench measuring 11 m in length was dug across the feature, uncovering a silty-sand layer at the pit's bottom, interpreted as the planting matrix containing degraded organics believed to be mulch. The excavation also unearthed several ceramic sherds, which the authors suggested were added intentionally to fill the pit and also served as part of the mulch. Complementary plant micro-fossil studies were undertaken to identify the content of the pit including giant swamp taro (*C. merkusii*), taro (*C. esculenta*), banana (*Musa sp.*), candle nut (*Aleurites moluccana*), pandanus (*P. tectorius*) and coconut (*C. nucifera*).

As recent micro-geoarchaeological research in the Sahul area has shown, the application of micro-geoarchaeological techniques in tropical and sub-tropical environments is a valuable tool to contextualise archaeological deposits and nuance interpretation (Denham, 2003; Denham et al., 2009a, 2009b; Denham & Grono, 2017; Hughes et al., 2017; Morley et al., 2023; Vannieuwenhuysse et al., 2017; Ward et al., 2017). Micro-scale studies can provide higher-resolution analysis of archaeological contexts by characterising stratigraphic units and ensuring stratigraphic integrity, which might otherwise be overlooked in macro-scale investigations. Until now, there have been very few mixed-method and multiproxy investigations, including micro-geoarchaeological studies, on Pacific Islands (Gumbley, 2021; Grono, 2017, 2020a; Khamnueva et al., 2018; Kirch, 2005; Kirch et al., 2003; Wozniak, 2003). Multiproxy micro- and macro-geoarchaeological approaches have been used to record the construction of pit features and their contents in southeast Asia and northeast Europe (i.e., Balbo et al., 2015; Macphail et al., 2008; Robert et al., 2022; Simpson et al., 1999). In particular, Deák et al. (2017) and Macphail et al. (1990) applied these techniques to stratigraphic layers containing evidence of past agricultural activities.

Building on such approaches, this paper aims to apply micro-geoarchaeological methodologies to assess site

FIGURE 1. Top – location of Teti'aroa and other atolls in the Tuamotu cited in the text (map G.Molle); Bottom – Map of Teti'aroa atoll with detail of motu Onetahi and location of site MAITE-01 (Pleiades2014©IDEA).



integrity and characterise depositional contexts in CEP, through a case study providing a high-resolution reconstruction of ancient cultivation pit techniques on the atoll of Teti'aroa (Scorsini, 2023).

TETI'AROA ATOLL

Teti'aroa environmental and geomorphological settings
 Teti'aroa is a small atoll located 52 km north of Tahiti and Mo'orea islands, in the Windward group of the Society Islands (Figure 1). It comprises 12 coralline islets (*motu*) for a total of 5.5 km² of emerged land.

The sediments on Teti'aroa are mainly biogenic carbonate sands accumulated from the atoll reef rim. Coral

fragments, being the base of the atoll's *motu* (islets), constitute one of the main components of these biogenic carbonate sediments and the layers accumulated atop are further enriched with bioeroding organisms and the calcified skeletal remains of reef fauna (Jamet & Trichet, 1987; Steibl et al., 2024). The presence of coral reefs plays a fundamental role within the nature of atolls below and above the sea-level. Reefs constitute the basis for marine and vegetative biodiversity and are the main contributors to the sedimentary presence of calcium and magnesium carbonate rocks from the time the now-submerged island initially subsided and/or sea-levels rose, giving rise to the atoll itself (Rougerie & Wauthy, 1989; Tercinier, 1956).

Teti'aroa archaeological context

Early human settlement of Teti'aroa is poorly documented although its geographic location and natural settings likely attracted people as early as the 11–12th century AD (Kahn, 2022; Kahn & Sinoto, 2017). By the time of European contact in the late 18th century AD, Teti'aroa had become a secondary place of residence for the chiefly family of Te Porionu'u district on the north coast of Tahiti. Some communities lived permanently on the atoll, exploiting its various resources on behalf of the Tahitian chiefs and exchanging lithic resources with other Pacific islands (Hermann et al., 2019; Molle et al., 2019). Such permanent settlements required horticultural production to complement the exploitation of marine resources and to provide surplus for specialised ritual and cultural activities. They were progressively abandoned as the atoll became a copra plantation in the early 20th century. Since the 1960s and its acquisition by actor Marlon Brando, Teti'aroa is managed both as a natural reserve and privately owned luxury resort, now with a small permanent population mainly made up of the hotel staff.

Early archaeological surveys by Emory (1933, p. 121), Vérin (1962) and Tessier (1962) did not mention the location of cultivation pits. A larger project by Sinoto and McCoy (1974) mostly focused on domestic and ceremonial sites with very little attention to horticultural features. Since 2015, the *Centre International de Recherche Archéologique sur la Polynésie* (CIRAP) team has been conducting a long-term archaeological research project on the atoll with the support of the Tetiaroa Society, a scientific station and organisation based on the island. The first phase of the project saw the extensive survey of all *motu* and the recording of more than 130 sites, including large areas of ancient *maite* pits on all main islets (Molle et al., 2019). The detailed mapping of cultivation pits is currently underway, utilising recent LiDAR coverage of the atoll.

In 2022, the team began the second phase of the project consisting of targeted excavations at various sites to document the long-term history of Teti'aroa. We therefore seized this opportunity to conduct an innovative geoarchaeological study of an abandoned cultivation pit on the main Onetahi *motu*.

METHODS

Field methods

The excavated cultivation pit was initially selected in agreement with the Tetiaroa Society who wished to restore an ancient *maite* (MAITE-01) for pedagogic and touristic purposes. It is part of a pit cluster located in the centre of the Onetahi *motu* (Figure 1). The complete mapping of the area was impossible within the constraints of this fieldwork, as the thick layer of coconut leaves on the ground prevented a clear understanding of the surface. We first cleared the vegetation from an area that proved suitable for the excavation, extending from upslope to the edge of the pit.

A [E–W] 6-m long and 1-m wide trench was excavated downslope to crosscut the cultivation pit (Figure 2). A metric grid was established from test pits TP-01 (E) to TP-06 (W). Another test pit (TP EX) was excavated about 30 m away southwest of our main trench to provide a stratigraphic section unmodified by *maite* construction (similarly to Weisler's methodology on Maloelap, 1999a, p. 631). Vertical control was referenced to a fixed datum located on a coconut tree. Excavation followed natural stratigraphy, with strata subdivided into 10 cm thick levels for finer control. Most of the excavation was done by hand with trowels, but time limitations and dense sediments in some levels occasionally required the use of small picks. Sediment was wet screened through nested 3- and 1-mm mesh sieves. Bone, shell and charcoal were bagged separately for laboratory analyses.

Nine stratigraphic units were identified in the field during excavation (Layers A–H, Z) (Table 1 – see Figure 3). The sedimentary composition of all units was dominated by calcareous (calcium carbonate) sands with *C. nucifera* roots. Fragments of *Pinctada margaritifera* (pearl oyster), coral branches and a fishhook were found in Layer B. Layer H comprised more compact coralline sand, with less coconut roots and a slightly darker appearance in comparison to overlying layers (Figure 2). Layer Z designated the pit fill and contained a higher percentage of organic materials and coconut roots. The stratigraphic matrix at the base of Layer Z was similar to the units found within the natural control test-pit (TP EX B and TP EX C).

Subsequent micro-geoarchaeological research was designed to address a suite of concerns:

- (1) Use microstratigraphic investigations to evaluate field interpretations in order to characterise the formation of major and minor stratigraphic units.
- (2) Investigate stratigraphic units associated with the construction, use and abandonment of the pit feature and characterise the nature of the deposits.
- (3) Evaluate the integrity of stratigraphic deposits for further analyses, especially reliability for inferring palaeoenvironments and potential crops using plant microfossils (principally pollen, microcharcoal and phytolith analyses).

Field sampling strategies

The on-site stratigraphic sampling at MAITE-01 comprised:

- Disaggregated bulk samples from each major stratigraphic unit for particle size and geochemical analyses; and,
- Systematic and targeted collection of intact micromorphology block samples (monoliths) from the North, East and South Walls (Figure 3).

Comparable stratigraphic samples were collected from the off-site, control test pit (TP EX). Bulk samples were collected from each of the major stratigraphic units at MAITE-01 and labelled in plastic bags for shipment back to Australia for further analysis.

FIGURE 2. (a) View of excavated trench (view to east); (b) Western end of trench showing cultivation pit (view to north); and, (c) Monolith sampling from the north wall of the trench (view to east).



Monolith samples targeted major stratigraphic units, stratigraphic boundaries and deposits potentially associated with cultivation. Additional monolith samples targeted the edge of the cultivation pit. Detailed reasons for monolith sampling and retention for analysis are provided in Table 2.

Monolith sampling was challenging due to the unconsolidated nature of the stratigraphy in coarse coral sand and often dense coconut root systems. Consequently, most monoliths were collected using plaster bandages in areas with less dense roots (Figure 2), while two were collected in plastic/metal pipe sections pushed into the excavation wall. Sampling locations were chosen to target areas with minimal disturbance in different trench walls yet were still representative of each major stratigraphic unit and addressed the research aims (following Grono, 2020b). Seventeen monoliths and two plastic/metal tins were collected at MAITE-01 and three were collected from the control test pit. Due to time and budgetary constraints, only four monoliths and two tins from MAITE-01 were imported into Australia and processed for thin section analysis.

Laboratory methods

All stratigraphic samples shipped to Australia were irradiated at Steritech Pty Ltd. using gamma irradiation at 50k Gy to comply with biosecurity requirements of the Department of Agriculture, Fishery and Forestry (BAA984542). Upon arrival at the ANU, all stratigraphic

samples (bulk and monolith samples) were “air dried” at 40°C for three days to remove pore water.

Bulk samples from MAITE-01 and the control test pit were used for complementary physical and geochemical characterisations.

Physical characterisation comprised particle size analysis (PSA), which determines the particle size distribution of the fine earth fraction (sand, silt, clay) within a sample. This is used to infer changes to environments of deposition, namely formation processes, for stratigraphic units (Houghton et al., 2024). Prior to PSA, the bulk samples were pre-treated using hydrogen peroxide (H₂O₂) digestion over three days to remove organic material (Scott-Jackson & Walkington, 2005) and sieved through a 2 mm mesh to isolate the fine earth fraction. Particle size distributions were determined using a laser diffractometer Mastersizer 2000 (Malvern Instruments, Malvern, UK) with a Hydro G dispersion unit (Polakowski et al., 2021). Pump speed was set at 2600 rpm and obscuration values were between 10% and 20% (Malvern Instruments Ltd., 2007). Four sets of measurements were obtained from each sample, from which an average was used for interpretation. Similarity indices (S.I.) were calculated using Comparative Particle Size Distribution index matrices, following the methods of Langohr et al. (1976) and Devos et al. (2017). This method is used to test the uniformity of the parent material and to detect lithological discontinuities.

Table 1. Field stratigraphic descriptions at MAITE-01 (see Figure 2). The pH levels of each stratigraphic unit and feature, identified and recorded in the field, were tested on-site using a colorimetric field pH test for soil acidity and alkalinity.

Square	Layer	Colour (Munsell-natural sunlight, moist)	Sediments	pH (field colorimetric test kit)
TP 1	A	10 YR 2/1 (Black)	Loamy sand, single grain structure, very loose. Diffuse transition to B	8 $\frac{1}{2}$ to 9
TP1	B	10 YR 4/1 (Dark Gray)	Sand, single grain structure, very loose consistency, abundant coconut roots. Mottling (upper), becoming more homogenous with depth. Diffuse boundary to C.	8
TP1	C	10 YR 7/2 (Light Gray)	Sand, single grain structure, loose consistency, abundant coconut roots. Gradual transition to D	8
TP1	D	10 YR 6/2 (Light Brownish Gray)	Sand, single grain structure, very loose consistency. Gradual transition to E.	8
TP 1	E	2.5 YR 6/2 (Light Brownish Gray)	Sand, single grain structure, very loose consistency. Distinct transition into F.	8 $\frac{1}{2}$ to 9
TP 2- TP3	A	10 YR 2/1 (Black)	Humic, sand with coconut roots. Diffuse transition to B	8 $\frac{1}{2}$ to 9
TP 2- TP3	B	10 YR 4/1 (Dark Gray)	Sand, single grain structure, very loose consistency, abundant coconut roots, light grey lenses. Diffuse transition to C.	8
TP 2- TP3	C	10 YR 7/2 (Light Gray)	Sand, single grain structure, loose consistency, abundant coconut roots. Gradual transition to D.	8
TP 2- TP3	D	10 6/2 (Light Brownish Gray)	Sand, single grain structure, very loose consistency. Gradual transition to E.	8
TP 2- TP3	E	10 YR 8/2 (Very Pale Brown)	Sand, single grain structure, very loose consistency. Distinct transition to F.	8 $\frac{1}{2}$ to 9
TP 2-3	F	10 YR 8/1 (White)	Sand, single grain structure, very loose. Gradual transition to G	9 $\frac{1}{2}$ to 10
TP 2-3	G	2.5 YR 8/2 (Pinkish White)	Sand, single grain structure, very loose	9 $\frac{1}{2}$
TP 2-3	H	10 YR 4/1 (Dark Gray)	Loamy sand, single grain structure, partially cemented layer of coralline sand. Sharp transition from overlying layers.	8 $\frac{1}{2}$
TP 4	B/D	10 YR 4/1 (Dark Gray)	Sand, single grain structure, loose consistency, abundant coconut roots. Gradual transition to D	8
TP 5	H/Z	10 YR 4/1 (Dark Gray)	Loamy sand, single grain structure, very compact layer of coralline sand. Distinct transition into Z.	8 $\frac{1}{2}$
TP 6	A	10 YR 2/1 (Black)	Humic, sand with abundant coconut roots. Gradual transition to Z.	8 $\frac{1}{2}$ to 9
TP 6	Z	10 YR 4/1 (Dark Gray)	Loamy sand, single grain structure, very compact layer of coralline sand.	ND
TP EX	A	7.5 YR 2.5/1 (Black)	Top soil, humic, sand with abundant coconut roots. Diffuse transition to B	8 $\frac{1}{2}$
TP EX	B	10 YR 3/2 (Very Dark Grayish Brown)	Sandy-silty texture with abundant coconut roots. Diffuse transition to C	8 $\frac{1}{2}$
TP EX	C	10 YR 6/2 (Light Brownish Gray)	Sandy loam with abundant coconut roots.	8 $\frac{1}{2}$

Geochemical analyses were used to determine total phosphorus (Pt), available phosphorus (Pa), carbon/nitrogen ratios (C/N) and the total organic carbon (TOC). In combination, these geochemical analyses provide information on site formation processes in the past, particularly in terms of soil formation and potential human activities (Fischer, 2001). Geochemical analyses followed standard protocols for Pt (Latimer & Buss, 2022), Pa (Colwell method; Higgins & Latimer, 2022), C/N (Latimer, 2022) and SOM (Soil Organic Matter) was calculated by multiplying the TOC values by a conversion factor of 1.724 (Chon, 2021). TOC was calculated and analysed by the Skalar SNAcess software.

The oriented blocks of sediment collected for soil micromorphological sampling were impregnated with epoxy resin at the Adelaide Petrographic Laboratory. Eight

30- μ m thick sections were prepared measuring 5 cm \times 7.5 cm or 7.5 cm \times 10 cm. Whole thin sections were initially scanned with Epson Perfection V7000 Photo at 1200 DPI in reflected light. Thin sections were then examined using ZEISS Axsioscope under PPL (Polarized Light), XPL (Cross Polarized Light) and OIL (Oblique Incident Light) at magnifications \times 2, \times 5, \times 10, \times 20, \times 40 and \times 63. Thin section analysis was undertaken within the Geoarchaeology Research Group Laboratory at the School of Archaeology and Anthropology. Thin section description followed identification and quantification criteria for the related distribution and microstructure set out by Stoops (2021). Microstratigraphic units (MSUs) were identified and described for each slide, and these formed the basis for subsequent interpretation. C/f ratio was $>$ 2 μ m Coarse and $<$ 2 μ m Fine for all the MSUs (see Supporting Online

FIGURE 3. Section drawing of MAITE-01 stratigraphy (north wall). The section drawing shows the sampling locations of some of the micromorphology blocks (black rectangles). Other consolidated samples were collected during the excavation from walls of the trench not represented in this drawing (east to west profile). The surfaces coloured in grey represent unexcavated areas of the trench. For section drawings of the east and west profile refer to Scorsini, 2023.

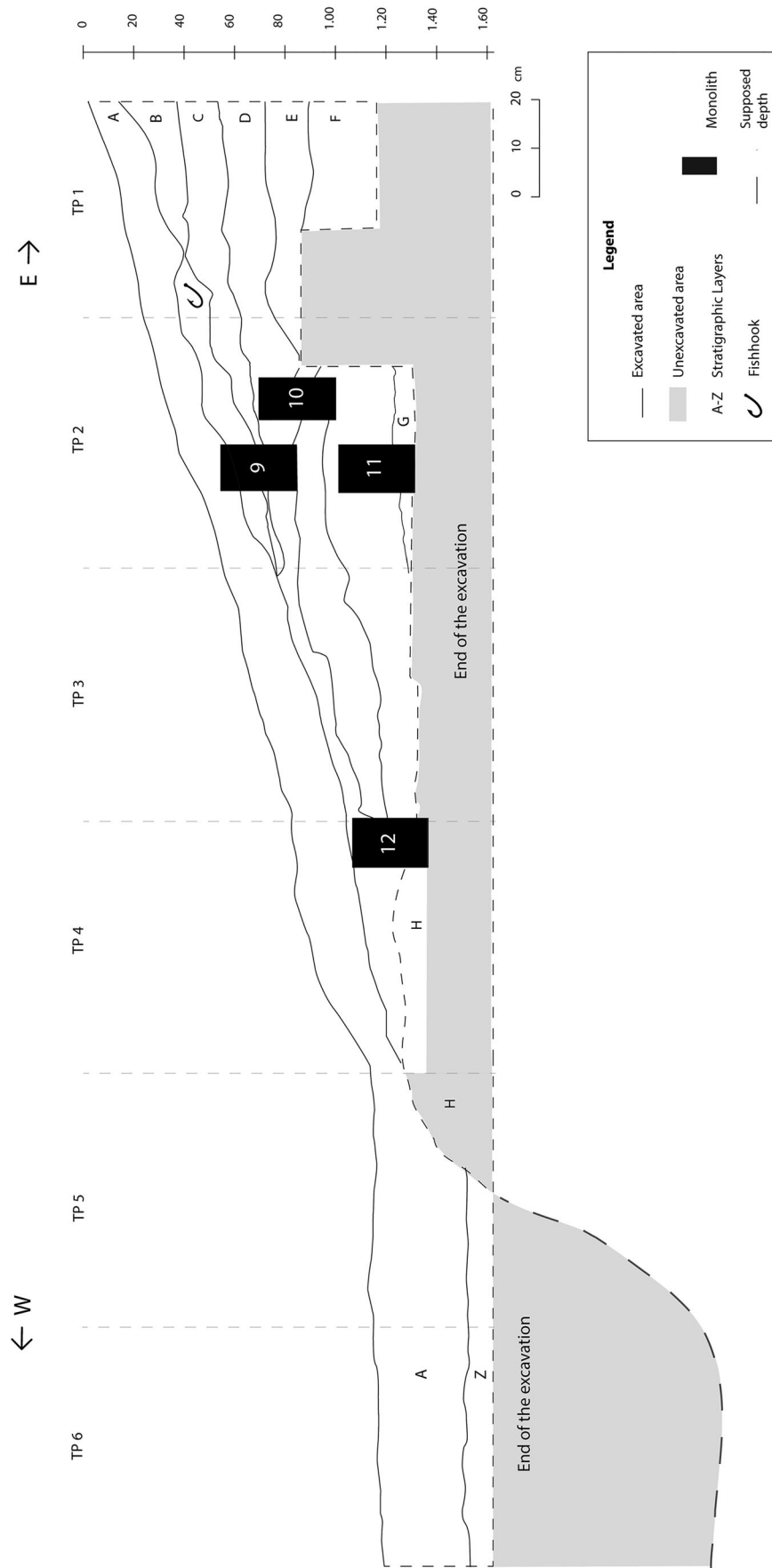


Table 2. Rationale for monolith sampling and retention for analysis.

Basis for Geoarchaeological Samples	Micromorphology Block Samples	Sample Type	Wall Sampled and Test Pits	Layers Overlapped and Sample ID
Characterise the human and/or natural formation process of the stratigraphic units and determine association with cultivation pit	1–6	Bandage monolith	East (TP 1)	1 (A-B) 2 (B-C) 3 (B-C-D) 4 (C-D) 5 (D-E-F) 6 (E-F)
	7–8	Bandage monolith	East (TP 2)	7 (F-G) 8 (F-G)
	9–11	Bandage monolith	North (TP 2)	9 (A-B-C-D-E) 10 (D-E-F) 11 (F-G)
Characterise Layer H – if a potential horticultural palaeosol	12	Bandage monolith	North (TP 3–4)	12 (D-E-F-H)
Characterise Layers H and Z – if potential horticultural palaeosol and cultivation fill, respectively	13–14	Metal tin	South (TP 5)	13 (A-H) 14 (H-Z)
Stratigraphic control location	A-B C	Bandage monolith Plastic tube		External Test Pit

Material). Microelement frequencies were calculated excluding porosity and refer to the surface percentage occupied by a specific micro-feature (Stoops, 2021, p. 57). A preliminary screening for opal phytolith and, more opal of biological origin, based on methods of Vrydaghs and Devos (2018) and Kaczorek et al. (2018) complemented these descriptions. Subsequent observations of opal phytolith were carried out using a Zeiss Axioscope under PPL, XPL and fluorescent lights (UV and Blue).

RESULTS

Physical and geochemical characterisation of the stratigraphy

The PSA results confirm that most deposits are sands while Layers A, H and Z are loamy sands (Figure 4 – upper). Gravel (>2 mm) compositions are minor in all samples and vary between 0.1% and 0.3%. Within the sands, silt compositions are <15%, attaining c. 23.0%–24.0% in loamy sands. Clay values are consistently low; however, peak values are 1.5% in Layer A, 1.3% in Layer D and 0.7% in Layer H.

The results from the geochemical analyses were plotted to reveal trends throughout the stratigraphy and to evaluate readings from the vicinity of the cultivation pit with those from the control test unit (Figure 4 – Bottom). TOC values and Pt are higher in Layers A–B and Z, with more muted increases in Layer H, and SOM is also higher in Layers A and Z. The C/N ratio varies in similar correlation with TOC values in layers A, H and Z. Pt values also vary inversely and increase in Layer Z, whereas Pa is uniformly low through the profile.

The results of the similarity-indices (S.I.) are summarised in Table 3. S.I. indicate the distinct sedimentary signatures of Layers C, D, H and Z. It also

shows high similarity between stratigraphic Layers E, F and G, as well as between these sedimentary deposits and Ex C, suggesting a potentially identical sedimentary matrix.

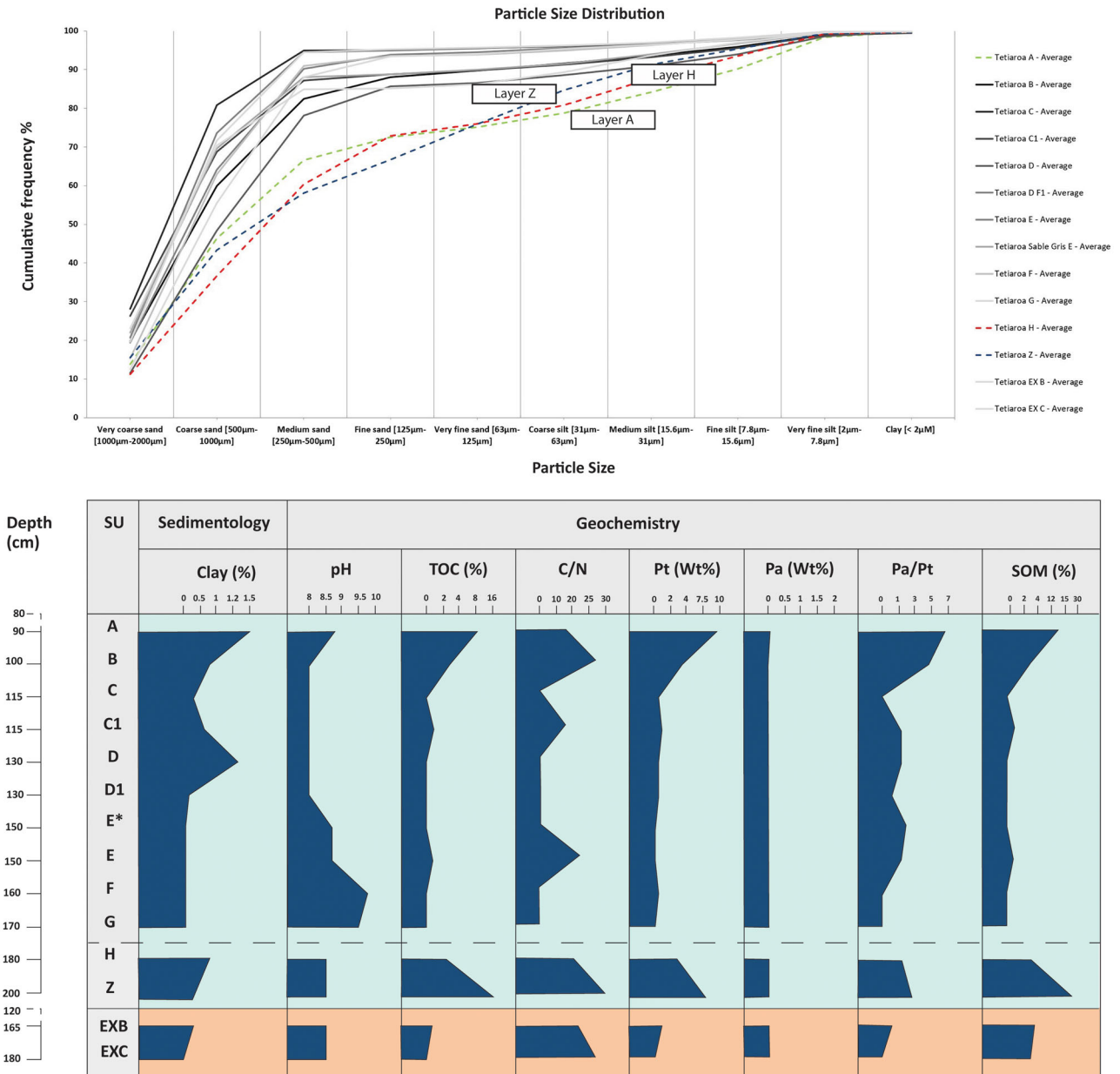
A relative comparison of the PSA and geochemical results are generally consistent with nascent sediment accumulation on a calcareous sand substrate. The calcareous sands were originally wave deposited (Martin-Garin & Montaggioni, 2023), with subsequent aeolian and anthropic reworking. The higher TOC and Pt values in Layers A and B, as well as silt, clay and SOM in Layer A, are consistent with the incorporation of organic matter and fine particles within topsoil. Comparably high TOC, Pt, silt and SOM values in Layer Z are suggestive of organic and fine particle enrichment of this deposit, which is consistent with the field interpretation of it being the sediment fill within the cultivation pit. The more subdued increases in clay, TOC and Pt within Layer H are potentially indicative of a weathered palaeosol/buried A horizon (Figure 3).

While clay percentages in Layers A and D could be associated with a modern A-horizon and formerly disturbed A-horizon sediments, respectively, it is unclear whether these elevated clay contents in Layer H represent a buried surface in the past (namely, incorporation of fine particles at the surface of a palaeosol) or translocated clay (namely, clay illuviated to these layers). Moreover, no clay particles were detected in the TP EX, indicating it is not part of the natural environment. Therefore, qualitative micromorphological investigation of the stratigraphy can clarify the formation processes occurring within Layers A, D, H and Z, left uncertain by compositional analyses alone.

Micro stratigraphic results: key observations

Twenty-five MSUs were identified through micromorphological analysis of eight thin sections from MAITE-01. A MSU represents a distinct zone identified in a thin section and analysed at the micro-scale. MSUs are

FIGURE 4. Top – cumulative frequency distributions for particle size analyses for samples at MAITE-01. Layers A, H and Z are labelled individually to highlight significance. Bottom - Distributions of clay, pH, TOC (%), C/N, Pt Wt%, Pa Wt%, Pa/Pt and SOM (%) at MAITE-01. Each column summarises the distribution of physical and geochemical analyses performed at MAITE-01 throughout its stratigraphic layers. For individual geochemical analysis, see Supplementary Online Material and Scorsini (2023).



then discussed in terms of site formation processes, including pedogenesis and human modification. Detailed micromorphological descriptions of MSUs are presented in the Supporting Online Material. Here, the key results are presented in terms of mode of formation and potential anthropic significance.

Calcareous sands (Layers B–G)

Monoliths 9–11 sampled the calcareous sands, Layers B–G (Figure 5). Thin Sections 9b, 10a, 10b and 11 contained thirteen MSUs: 9b-1, 9b-2, 9b-3, 9b-4, 9b-5, 10a-1, 10a-2,

10a-3, 10b-1, 10b-2, 11-1, 11-2 and 11-3 (Figures 6, 7, 8 and 9). MSU9b-1 to MSU9b-5 (Layers B–D) have a bridged grain microstructure, c/f ratio of 80:20, gefuric c/f related distribution (i.e., finer material forms bridges or braces between the coarse particles) and simple packing voids. MSU10a-2 and MSU10a-3 (Layer E) have a bridged grain microstructure, c/f ratio of 90:10, gefuric c/f related distribution and simple packing voids. MSU10a-1 (Layer D) – as well as MSU10b-1 (Layer E), MSU10b-2 (Layer F), MSU11-1 (Layer F), MSU11-2 (Layer F/G transition), MSU11-3 (Layer G)—have single grain microstructure, c/f

Table 3. Similarity-indices (in%). These S.I. indices reveal the extent to which the particle size distributions of two samples are identical. Low values indicate significant differences between the samples. For individual fraction percentages see Supplementary Online Material.

	Tetiarioa A	Tetiarioa B	Tetiarioa C	Tetiarioa D	Tetiarioa E	Tetiarioa F	Tetiarioa G	Tetiarioa H	Tetiarioa Z	Ex B	Ex C
Tetiarioa A	100	84	66	85	72	76	76	87	82	77	72
Tetiarioa B		100	79	87	87	87	85	77	75	88	87
Tetiarioa C			100	67	92	81	89	56	63	74	90
Tetiarioa D				100	75	86	74	82	75	90	77
Tetiarioa E					100	89	88	64	63	82	98
Tetiarioa F						100	83	69	67	92	91
Tetiarioa G							100	67	73	76	87
Tetiarioa H								100	83	72	66
Tetiarioa Z									100	67	64
Ex B										100	84
Ex C											100

ratio of 90:10, dominant coarse monic c/f related distribution (i.e., only coarse particles occur) and simple packing voids.

The calcareous sands are comprised of admixed fragments of bivalve and gastropod shell, foraminifera, coral, sea urchin and land snails. Identifiable organic materials include plant roots and micro-faunal excrements, which represent post depositional processes (i.e., changes within the sedimentary structure after its deposition). Potential anthropogenic materials, comprising fishbones and charred plant material, occur variably throughout Layers B–E, as well as in the upper part of Layer F.

The digging of the pit and a possible palaeosol/buried A horizon (Layer H)

Monolith 12 sampled Layers E, F and H, and Monolith 13 sampled Layers A and H at the edge of the cultivation pit. The MSUs are described in terms of relative stratigraphic position, namely, Layer A (13-1), Layers E (12-1) and F (12-2), and Layer H (13-2, 13-3, 12-3). Calcareous sand substrates are similar to those previously described, with plant roots and variable occurrences of micro-fauna excrements and charred plant material/charcoal. However, stratigraphic units within Monoliths 12 and 13 exhibited much higher percentages of fine material than previously described, even for comparable units (such as Layers E and F).

MSU13-1 (Layer A) is a loamy sand characterised by an intergrain micro-aggregate, locally crumb microstructure, a c/f ratio of 60:40, an enaulic c/f related distribution (i.e., aggregates of finer material partially fill the intergranular spaces between the coarser particles) and simple packing voids (Figure 11).

MSU12-1 (Layer E) has an intergrain micro-aggregate structure, c/f ratio of 70:30 and enaulic c/f related distribution (Figure 12). MSU12-2 (Layer F) has an intergrain micro-aggregate structure, c/f ratio of 60:40, enaulic c/f related distribution and simple packing voids.

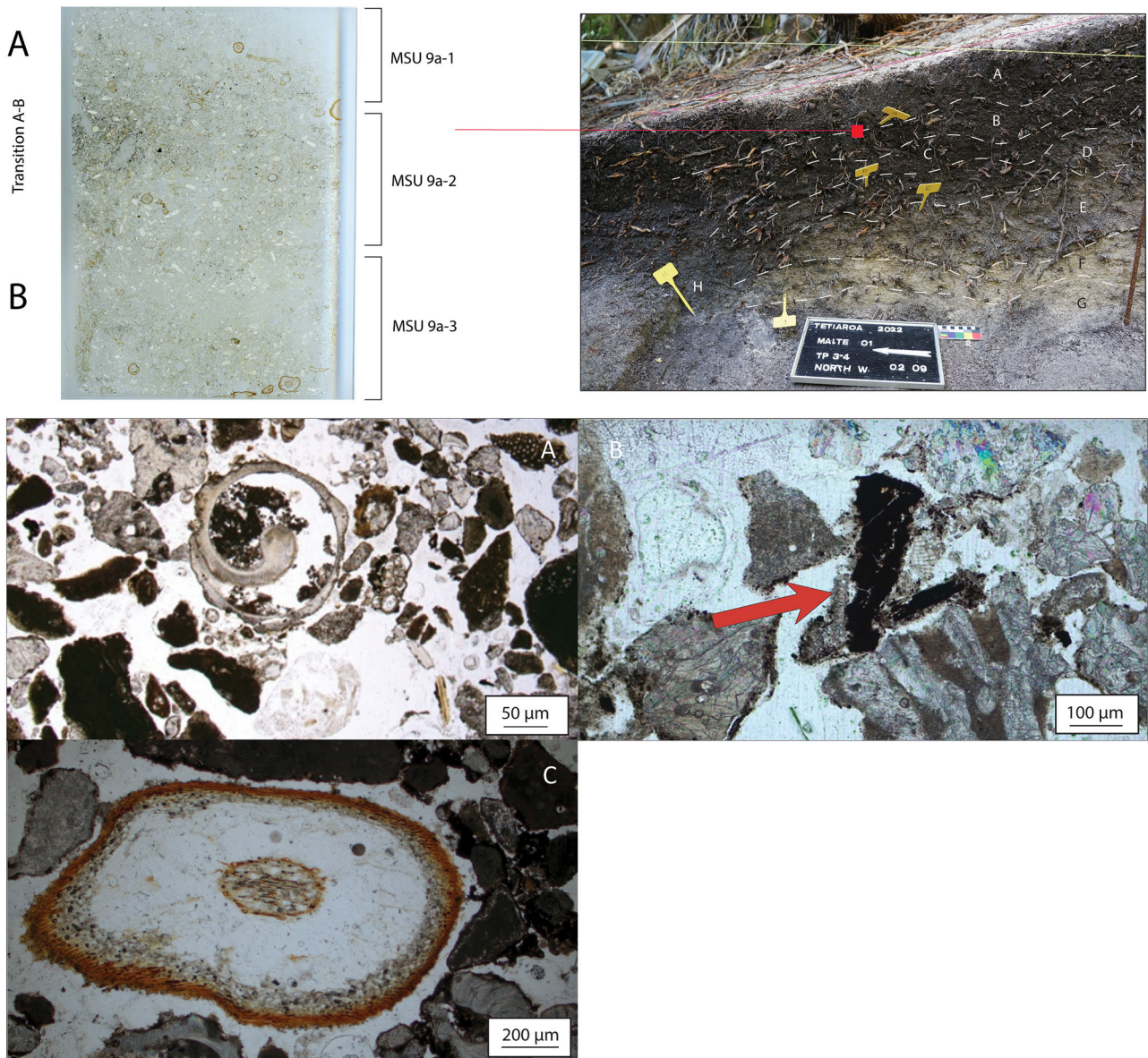
MSU12-2 (Layer F) has an intergrain micro-aggregate structure, c/f ratio of 60:40, enaulic c/f related distribution

and simple packing voids. In thin section, these units appear more like loamy sands/sandy loams than single grain, loose sand deposits.

Although Layer F was recorded in the field as calcareous sand, with comparable PSA results and micromorphological descriptions in Monolith 11, the thin section of this unit in Monolith 12 contains greater proportions of fine material which is only observable in this layer through micromorphology. Layer H, noted in the field as a slightly compact and darker unit, also exhibits some variability between its occurrence in Monoliths 12 and 13. MSU 12–3 (Layer H) has an intergrain micro-aggregate microstructure, c/f ratio of 30:70, porphyric c/f related distribution (i.e., the larger fabric units are observed within a dense groundmass of smaller units) and channel voids. In Monolith 13, MSUs 13-2 and 13-3 (Layer H) are loamy sands characterised by an intergrain micro-aggregate, locally angular blocky microstructure, a c/f ratio of 50:50, a porphyric c/f related distribution and channel voids. These MSUs show the presence of a fine fraction (clay) and an increase in micro-anthropogenic artefacts (i.e., bone fragments, charcoal) which are not observed in the overlying layers (B–G).

Of note, Layer H contained bone fragments, a phytolith cluster/isolated phytolith and a fragment of a potential pig coprolite (MSU12-3; Figure 12). Despite the extreme difficulty in identifying pig coprolites based on micromorphological features—owing to their limited documentation and the potential for confusion with dog or human coprolites due to similar characteristics—reference images from Nicosia and Stoops (2017) suggest that the pedofeature observed in TS 12 (Layer H) meets multiple criteria indicative of a potential pig coprolite (Brönnimann et al., 2017, p. 69; Stoops et al., 2018). This pedofeature displayed: spores, bone fragments, calcareous material from local sediment and organic plant tissues. Further, within the same layer, an agglomeration of possible *Saccobolus* fungi, which is a type of fungal spores predominantly coprophilous, might be interpreted as in association with the coprolite (Figure 10). However, as the identification of

FIGURE 5. TS 9a showing four photomicrographs (A)–(C) along with the corresponding stratigraphic layers depicted in the top right corner. (A) displays a transverse section of an unidentified gastropod (G. Traversat, pers. comm., June 2023) observed in 9a-2; (B) shows charcoal fragments embedded in the calcareous material observed in 9a-1 (red arrow); and (C) shows a cross section of a root observed in 9a-2.



faecal fossils in archaeological contexts is difficult to identify to species of origin, further analyses and hopefully comparative results involving a mixed-method approach using soil micromorphology, parasitology, phytolith analysis, pXRF, gas chromatography mass spectrometry (GC-MS) and other microscopic techniques will provide a more robust interpretation (Bortolini et al., 2024; Elliott & Matthews, 2024).

Stoops et al. (2018) established criteria to identify palaeosols. *In situ* palaeosols are recognised by undisturbed features from soil biological activity, pedogenic microstructure, b-fabric and other intact pedofeatures. Conversely, transported palaeosols lack these biogenic features, have a massive microstructure, and show a

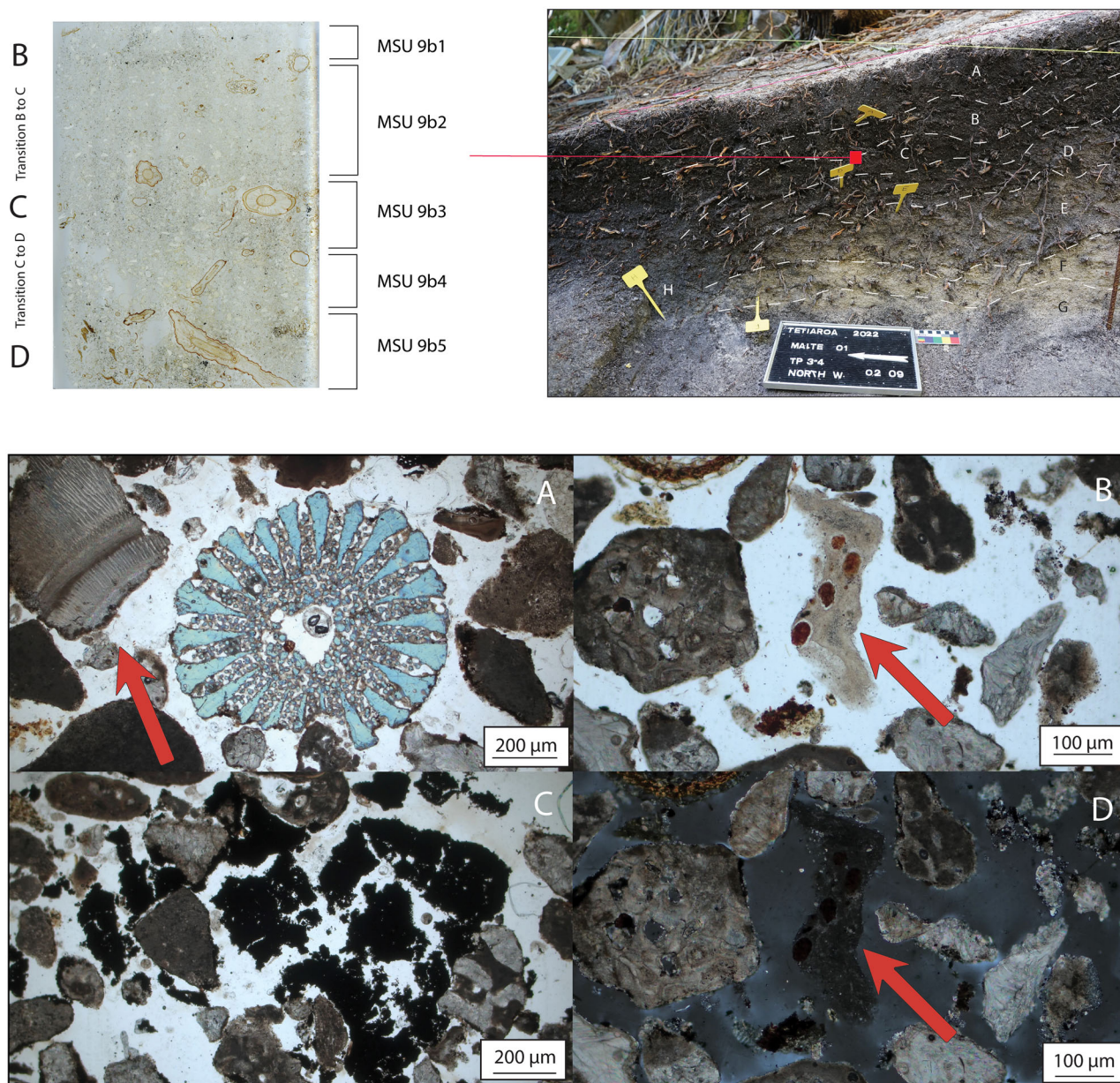
structure dominated by aggregates with a clear sedimentary pattern.

Layer H, observed in MSU12-3 and formed on the edge of the cultivation pit, shows pedogenic b-fabric, microstructure, phytoliths, pollen and coprolites, showing characteristics for both *in situ* or transported palaeosols which do not entirely align with typical palaeosols due to recent root activity and associated biological interference. Therefore, Layer H is best classified as a buried A-horizon representing an immature, A/C palaeosol profile.

The fill of the cultivation pit (Layer Z)

Monolith 14 sampled across the transition from Layers A to Z. Thin Section 14 contained three MSUs: 14-1 (Layer

FIGURE 6. TS 9b showing four photomicrographs (A)–(C) along with the corresponding stratigraphic layers depicted in the top right corner. (A) shows a sea urchin, and a shell fragment (red arrow) observed in 9b-2; (B) and (D) displays a potential phosphatic remain (red arrow, isotropic in XPL) observed in 9b-4; and (C) shows charcoal fragment progressively breaking apart observed in 9b-4.



A), 14-2 (Layer A/Z transition) and 14-3 (Layer Z). Layer A (MSU14-1) has an intergrain micro-aggregate structure, locally crumbly microstructure, c/f ratio of 50:50 and a porphyric c/f related distribution. Transitioning from Layer A into Layer Z, the fill of the cultivation pit, MSU14-2 and MSU14-3 have an intergrain micro-aggregate structure, locally crumbly microstructure, c/f ratio of 40:60, and a porphyric c/f related distribution (Figure 13).

All MSUs comprise calcareous sands with plant roots, microfaunal excrements, charred plant materials and soil organic matter. Layer Z fills (MSU14-2 and 14-3) contain

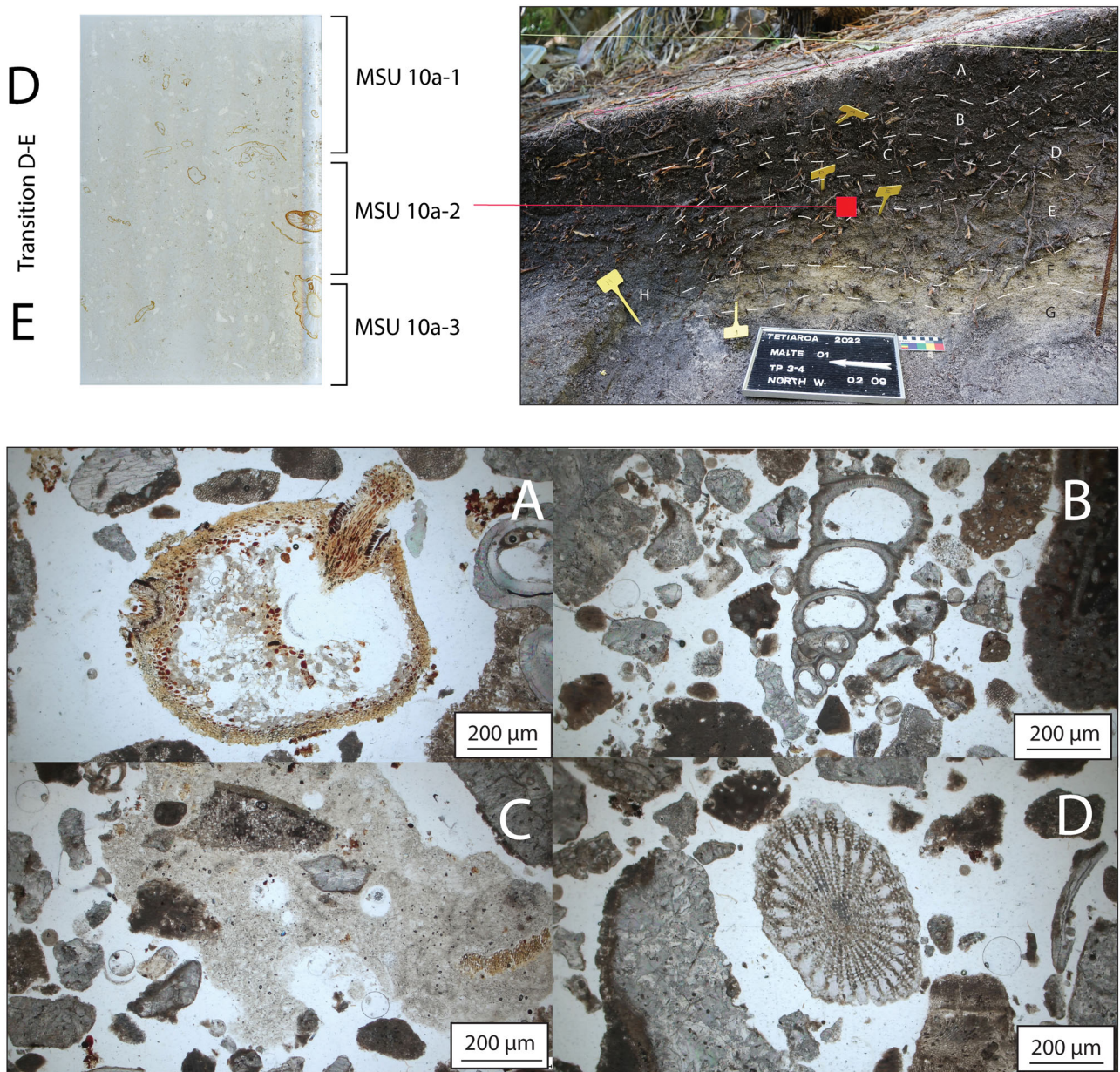
more abundant and identifiable plant remains, including a seed, wood residues and potentially a fragment of coconut husk.

DISCUSSION

Reconstructing the relative microstratigraphic chronology of pit use: more than just sand

Micro-geoarchaeological analyses offer a more nuanced interpretation of the sediments associated with a pit feature

FIGURE 7. TS 10a showing four photomicrographs (A)-(D) along with the corresponding stratigraphic layers depicted in the top right corner. (A) displays the cross section of a root, observed in 10a-1; (B) shows a traverse section of a gastropod in 10a-2; (C) displays micritic dust observed in 10a-3; and (D) shows a sea urchin observed in 10a-3.

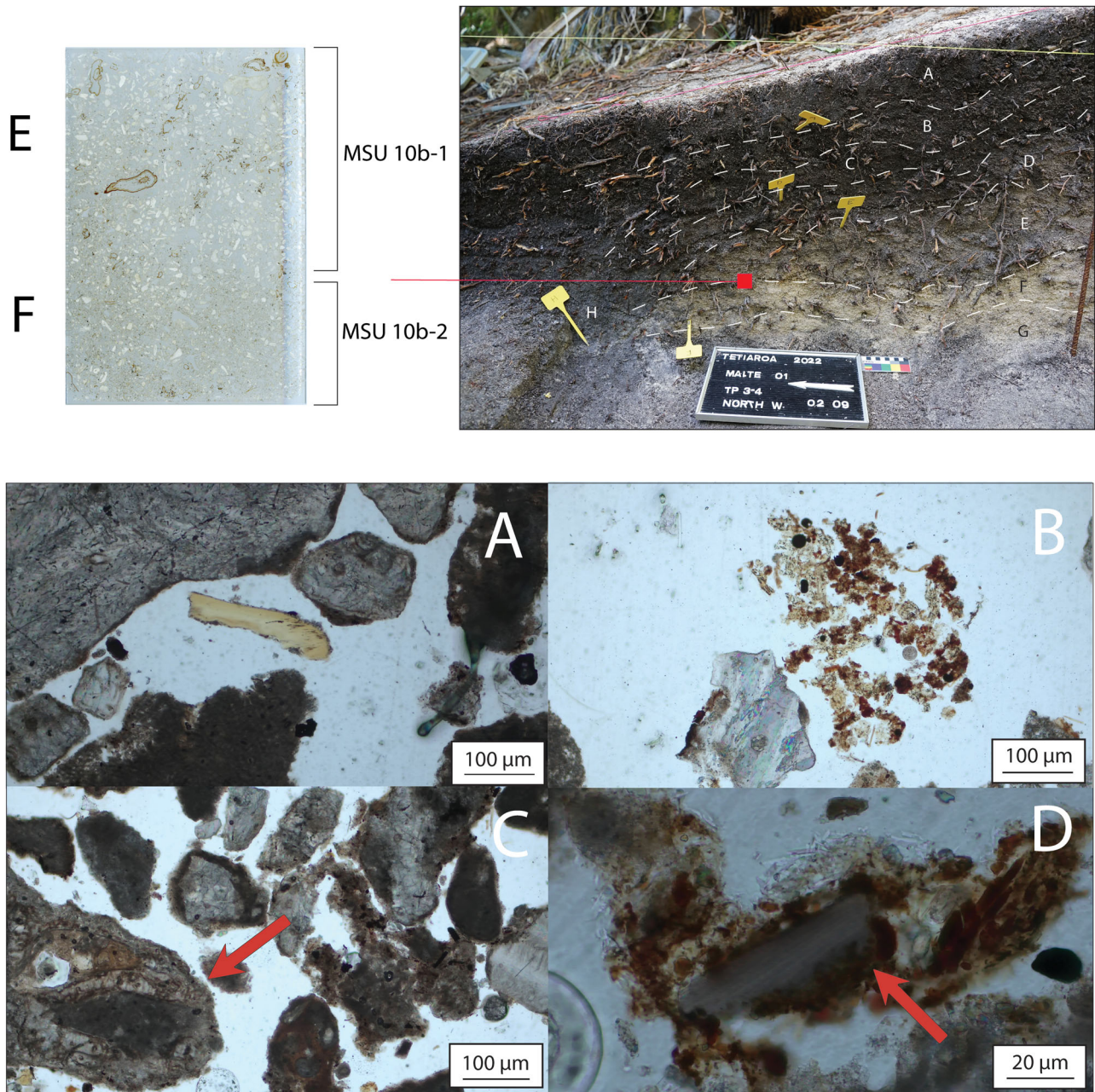


than is possible from field recording of the stratigraphy. Of note, many of the models and interpretations of soil formation and soil micromorphology at archaeological sites have been developed in temperate and arid climates, they do not readily transfer to wet, tropical climates and coralline sands such as atoll environments (Denham, 2003; Morley & Goldberg, 2017). Here, for the first time, soil micromorphological analyses are applied to the investigation of an archaeological site on an atoll in the Pacific. A relative chronology of cultivation pit construction, use and abandonment is proposed based on an integration of the field descriptions with micro-geoarchaeological results (Figure 14).

Phase 0: pre-pit construction stratigraphy

The micro-geoarchaeological analyses of the various sand layers did not allow for a clear differentiation of units associated to the pre-existing stratigraphy (namely, calcareous sediments) and upcast from the pit construction (namely, anthropically reworked calcareous sediments). However, based primarily on field interpretations and the similarity to layers from an external test pit as observed in the S.I. results, Layers F and G are believed to represent the pre-existing stratigraphy into which the pit was dug. Thin section analysis of these sediments was largely consistent with coarse, calcareous sands (including MSU11-2, Layer F) similar to the S.I. results from the TP EX; however,

FIGURE 8. TS 10b showing four photomicrographs (A)–(D) along with the corresponding stratigraphic layers depicted in the top right corner. (A) displays a burnt bone, observed in MSU 10b-2; (B) shows an aggregate of micro-fauna excrements in 10b-2; (C) displays micritic capping observed in 10b-3 (red arrow); and (D) shows a burnt shell 10b-1. The shell fragment exhibits faint lamination (red arrow), it has a dark colour in PPL, and it shows a low birefringence on XPL (Courty et al., 1989, pp. 109-110; Villagran et al., 2017, p. 31).



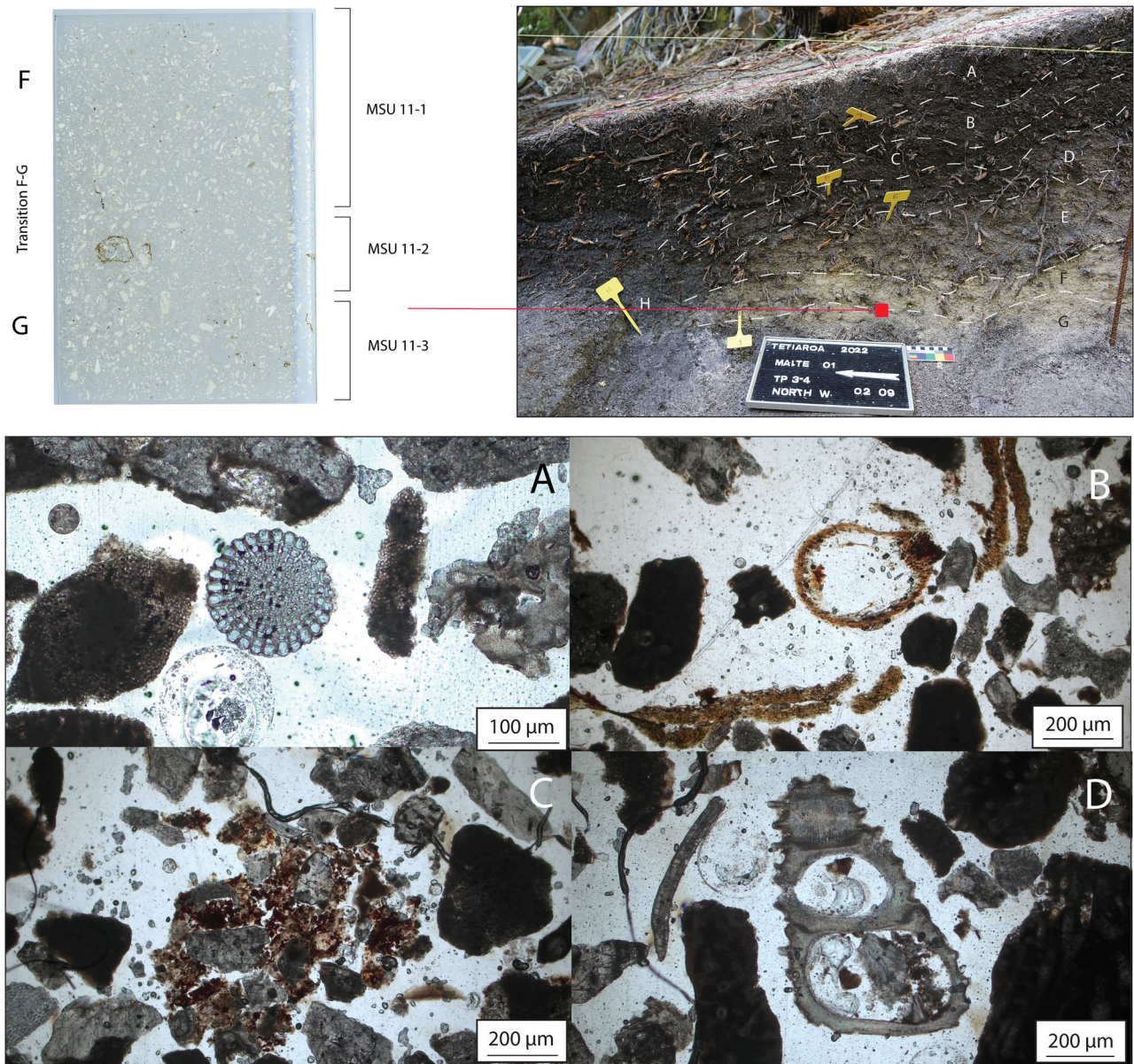
MSU12-2, Layer F (Figure 12) did exhibit an intergrain micro-aggregate microstructure and compositional elements suggestive of a much higher silt and clay content than present in the sample analysed by PSA and MSU11-2 (Figure 11). MSU12-2 exhibited characteristics akin to a loamy sand/sandy loam, which may represent the incorporation of fine material within a nascent A horizon forming on calcareous sands. The thin sections show

minimal meso-faunal excrements and root inclusions implying that these layers are undisturbed. As such, Layer F could represent the former surface deposits before the pit was dug.

Phase 1: pit construction and dumping of upcast

PSA, geochemistry and thin section analyses for Layers E–B are consistent with coarse-to-medium grain, calcareous

FIGURE 9. TS 11 showing four photomicrographs (A)–(D) along with the corresponding stratigraphic layers depicted in the top right corner. (A) displays a sea urchin, observed in MSU 11-1; (B) shows a cross section of a leaf observed in MSU 11-1; (C) displays an organic aggregate observed in 11-2; and (D) shows a gastropod observed in MSU 11-2.



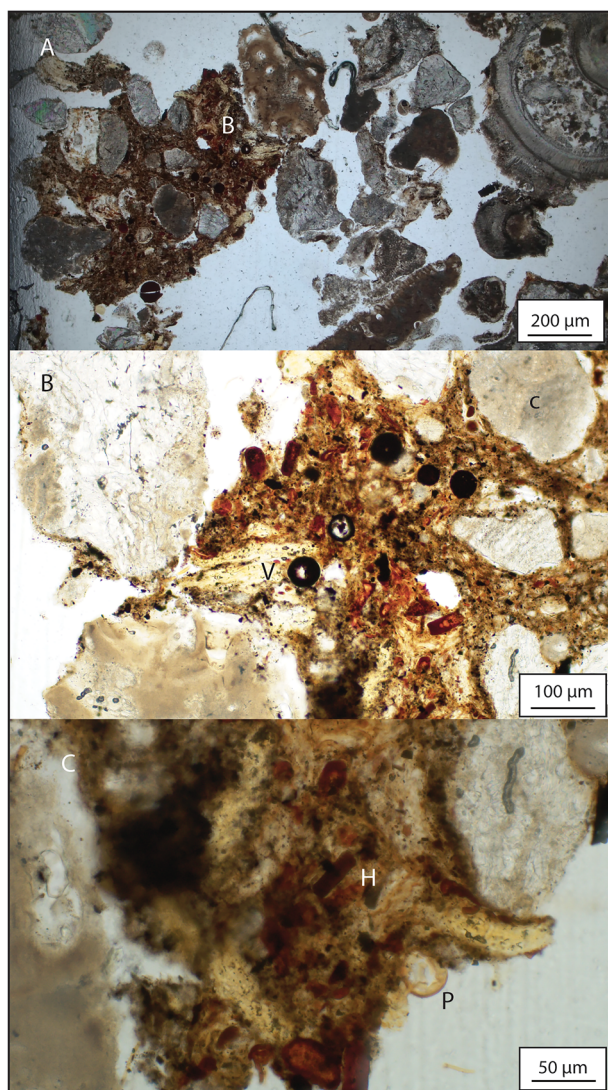
sands. Their stratigraphic position and relationship to the pit, namely, upslope and above the stratigraphic level into which the pit was dug, are suggestive of upcast that was then dumped upslope. Upcast was probably generated during original digging of the pit, as well as possibly during maintenance activities. However, none of the upcast layers (Layers B–E) exhibit geochemical signatures similar to the pit fill (Layer Z) and they contain only limited macro botanical remains. This suggests that these layers are displaced calcareous sands, likely originating from the initial digging event, incorporating subsequent depositional activities during the pit's use and gradual abandonment, as evidenced by materials from Layers B and C.

Phase 2: pit use and palaeosol formation

Two stratigraphic units appear directly associated with the use of the cultivation pit: Layer Z, the pit fill; and, Layer H, a potential buried A horizon formed immediately adjacent to the pit. PSA analyses for Layers Z and H are similar to those for Layer A, not only in that they have slightly elevated clay contents, but primarily because they contain >20% silt (Figure 2 – upper). Additionally, Layers Z and H have comparable TOC, C/N, SOM and Pt values. The distinctive characteristics of Layers H and Z in comparison to the rest of the profile are evident from the low S.I. values.

Layer Z is the fill of the cut for the cultivation pit. Carbonate sands and silts form most of the sedimentary

FIGURE 10. Potential pig coprolite. (Photomicrograph A) 12 MSU-3, Layer H, Scale bar is 200 μm potential pig coprolite. The matrix consists of brown amorphous, fine-grained organic material. Calcium carbonate (C) and phosphatic fragments (B) from the local soil and spores (black dots) (see Brönnimann et al., 2017, p. 69); (Photomicrograph B) Same coprolite, vegetative plant material (V); (Photomicrograph C) Same coprolite showing hyphae (H) and pollen (P) trapped on it.



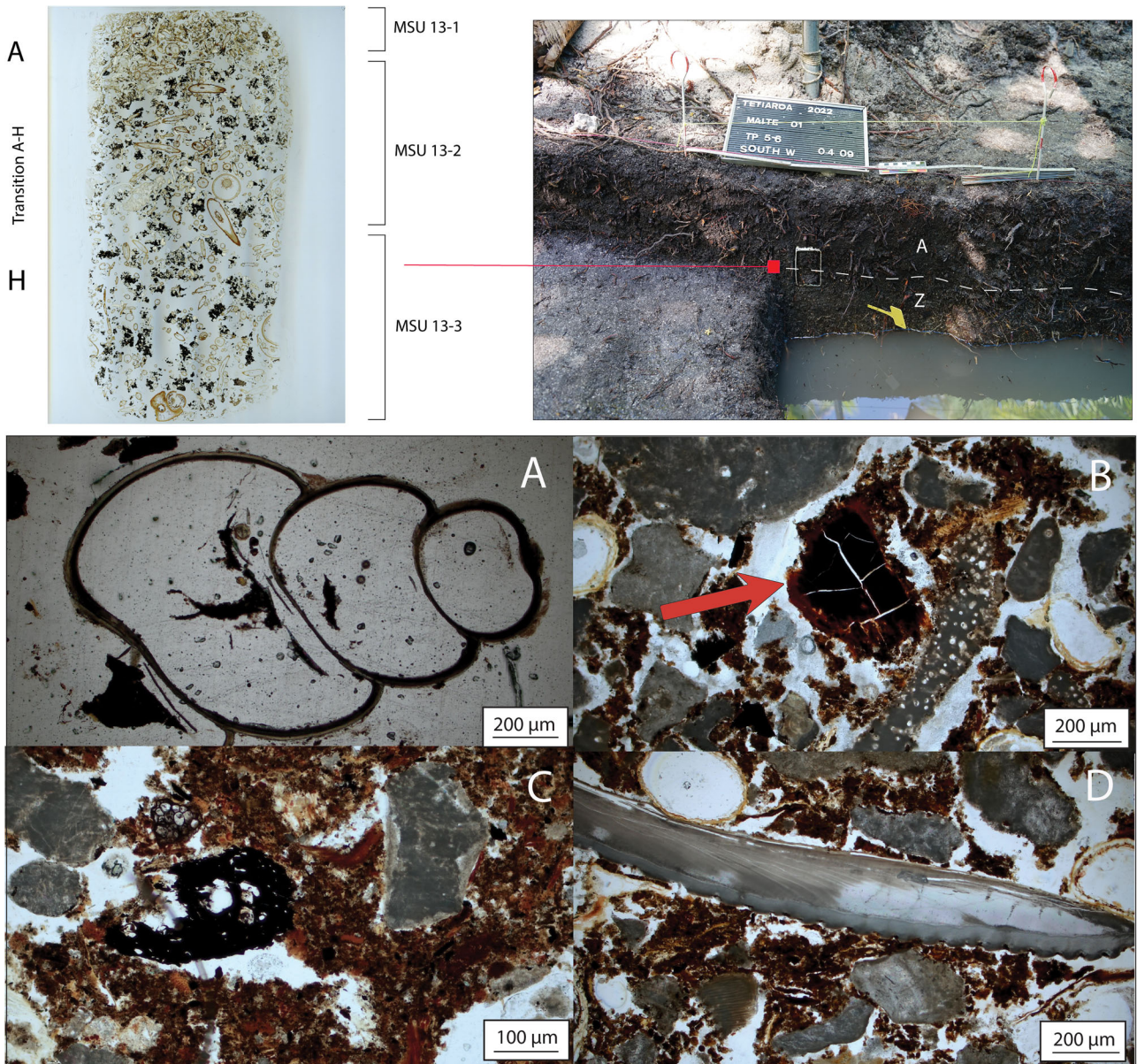
matrix, reflecting the parent material. During cultivation, it is possible that the fill of the pit was enriched with organic debris (hence the elevated TOC and SOM values) (noted by Chazine, 1990 in the Tuamotu), which here would have included local coconut, woody and other organic materials (potentially associated with mulching practices). This suggests that mulch was possibly added to the pit. However, it remains unclear whether the pit fill accumulated naturally or was anthropogenically deposited. This distinction is crucial for future paleoecological studies on this or similar features. The pit fill might be partly anthropogenic (primary

sedimentary deposition), linked to cultivation practices, or it could result from natural sediment and vegetation accumulation after abandonment (secondary sedimentary deposition). This ambiguity, compounded by post-depositional processes (e.g., root intrusion, faunal burrows, moisture) and endemic environmental factors like frequent storms, complicates the interpretation of archaeological and natural layers. No phytoliths or opal residues from biological remains (such as diatoms, sponge spicules or chrysophyceae) were observed in Layer Z after a preliminary screening. However, these remains may have been obscured by finer material, as noted by Vrydaghs and Devos (i.e., *Visibility sensu*; 2020). Therefore, the absence of phytoliths in Layer Z cannot be definitively concluded. The current findings emphasise that subsequent phytolith extraction from bulk samples would expand microfossil results at the site.

Layer H plausibly represents a weathered buried A horizon that was formed on carbonate sands adjacent to the edge of the former cultivation pit. Layer H was not extensively exposed in the stratigraphic section during the excavations and its character is largely derived from the micro-geoarchaeological investigations and subsequent microstratigraphic interpretations. As discussed above, Layer H had PSA and geochemical signatures similar, but in terms of geochemistry muted, in comparison to Layer A (topsoil). Layer H also contained a potential pig excrement, possibly alluding to integrated horticultural-husbandry practices on the atoll. Another microscopic feature that characterised the buried A horizon and allowed us to classify it as such, was the initial detection through geophysical analyses, followed by the micromorphological observation of clay. Micromorphology revealed that clay was only visible in Layer H from TS 12, an unusual concentration for the natural atoll environment. Control test pit samples showed that clay is otherwise absent (TP EX B/C). At this stage, it is not possible to fully understand the nature and deposition of the clay, as extensive sedimentological research on atoll environments is needed to provide a more nuanced discussion to understand its origin. These characteristics suggest Layer H is an A/C palaeosol profile, namely, it comprised a weakly developed A horizon that formed on carbonate sands. The immature character of A horizon development suggests that Layer H was exposed at the surface for only a short period of time.

Layer H (buried A horizon) could have formed at the edge of the cultivation pit during its use. Given that it has only been documented adjacent to the pit in the geoarchaeological investigations, this interpretation is favoured here. Layer H likely formed from the sediment excavated during the pit construction and the regular maintenance of the pit, with the sediment being deposited to create an embankment. This is consistent with the unclear transition from Layer H to Layer F observed both in the field and microscopically. The characteristics of Layer H differ from those of MSU12-2 (Layer F) due to the superimposed pedogenesis it underwent when exposed at or

FIGURE 11. TS 13 showing four photomicrographs (A)–(D) along with the corresponding stratigraphic layers depicted in the top right corner. (A) displays a gastropod, observed in MSU 13-1; (B) shows an organic burnt fragment observed in MSU 13-2 (red arrow); C displays blackened vegetative material observed in 13-2; and (D) shows a shell fragment observed in MSU 13-3.



near the surface adjacent to the cultivation pit. This indicates that Layer H consists of sediments from Layers F and G that were excavated and redeposited on the side.

Phase 3: abandonment, burial and pedogenesis

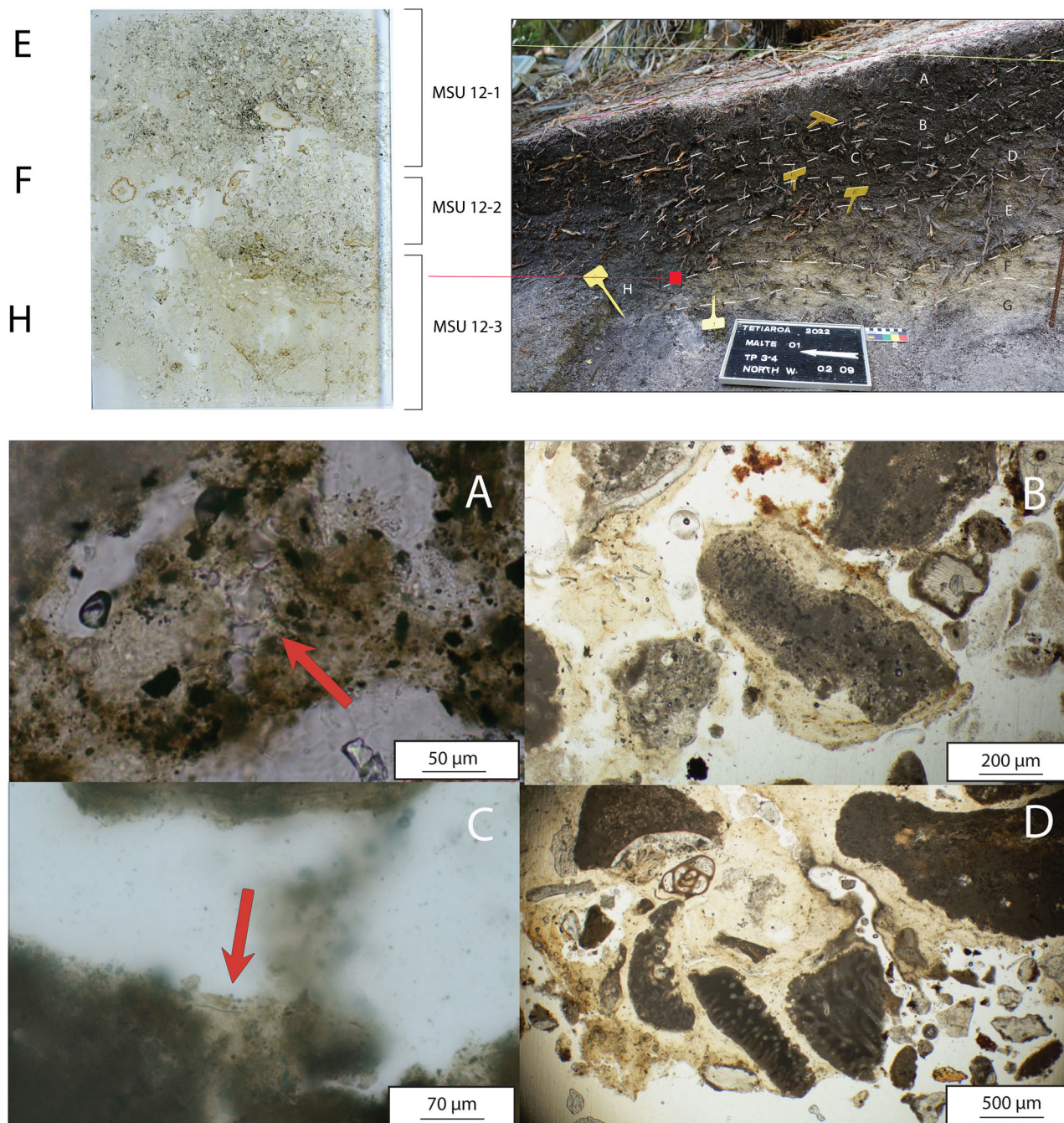
Layer A comprises calcareous sands and silts that have buried the cultivation pit and adjacent slope after it was abandoned. Over time, the components of the upcast began to slide down the slope towards the pit, likely due to the abandonment and lack of maintenance, as evident in the profile. These sands have been subject to pedogenesis and development of the present-day A/C soil profile.

Contributions and perspectives of geoarchaeology to Polynesian tropical horticulture

The project was designed to document the life history of a cultivation pit through a combination of geoarchaeological approaches (macro- and micro-geoarchaeology, palaeobotany), physico-chemical and micromorphological methodologies (detailed in Scorsini, 2023). The application of this multi-proxy method was critical in assessing the integrity of the site and characterised the deposits of MAITE-01.

Sampling methods in the field proved challenging at first in a tropical atoll context. Acknowledging an inherent “experimental” aspect in the field, we came to use a

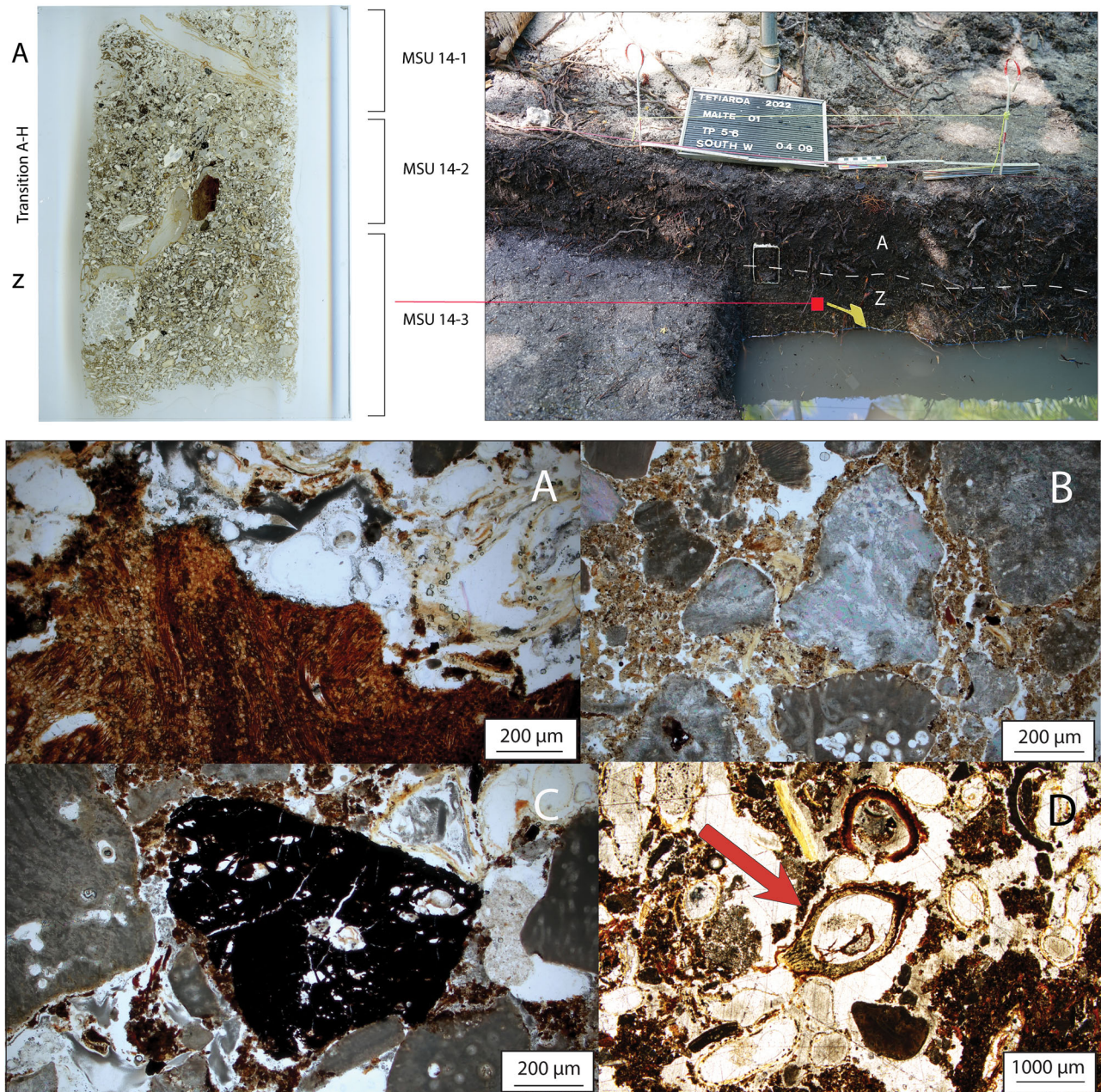
FIGURE 12. TS 12 showing four photomicrographs (A)–(D) along with the corresponding stratigraphic layers depicted in the top right corner. (A) displays a cluster of phytoliths 12 MSU-3 (red arrow); (B) shows clay coatings (fine material -light brown PPL dotted, XPL poorly birefringent, b-fabric speckled, randomly oriented) surrounding calcareous material from local sediment in MSU 12-3; (C) displays an isolated ELONGATE phytolith 12 MSU-3 (red arrow); (D) shows clay fabric on the groundmass in MSU 12-3 (E. Grono, pers. comm., January 2024).



combination of bandages and metal and plastic tins to successfully secure monoliths from the stratigraphy of the trench. This allowed for the implementation of a suite of laboratory analyses as reported in this article. Our results thus attest to the feasibility of such geoarchaeological approaches in CEP and atoll environments in general.

The phased reconstruction sequence presented above is the first interpretation of a Polynesian *maite* based on soil micromorphological analyses. As this technique evaluates finds which are *in situ*, its application offers more nuanced interpretations and rigorous methodologies to study past human interactions within environments through observations of the stratigraphy at a micro-scale. These

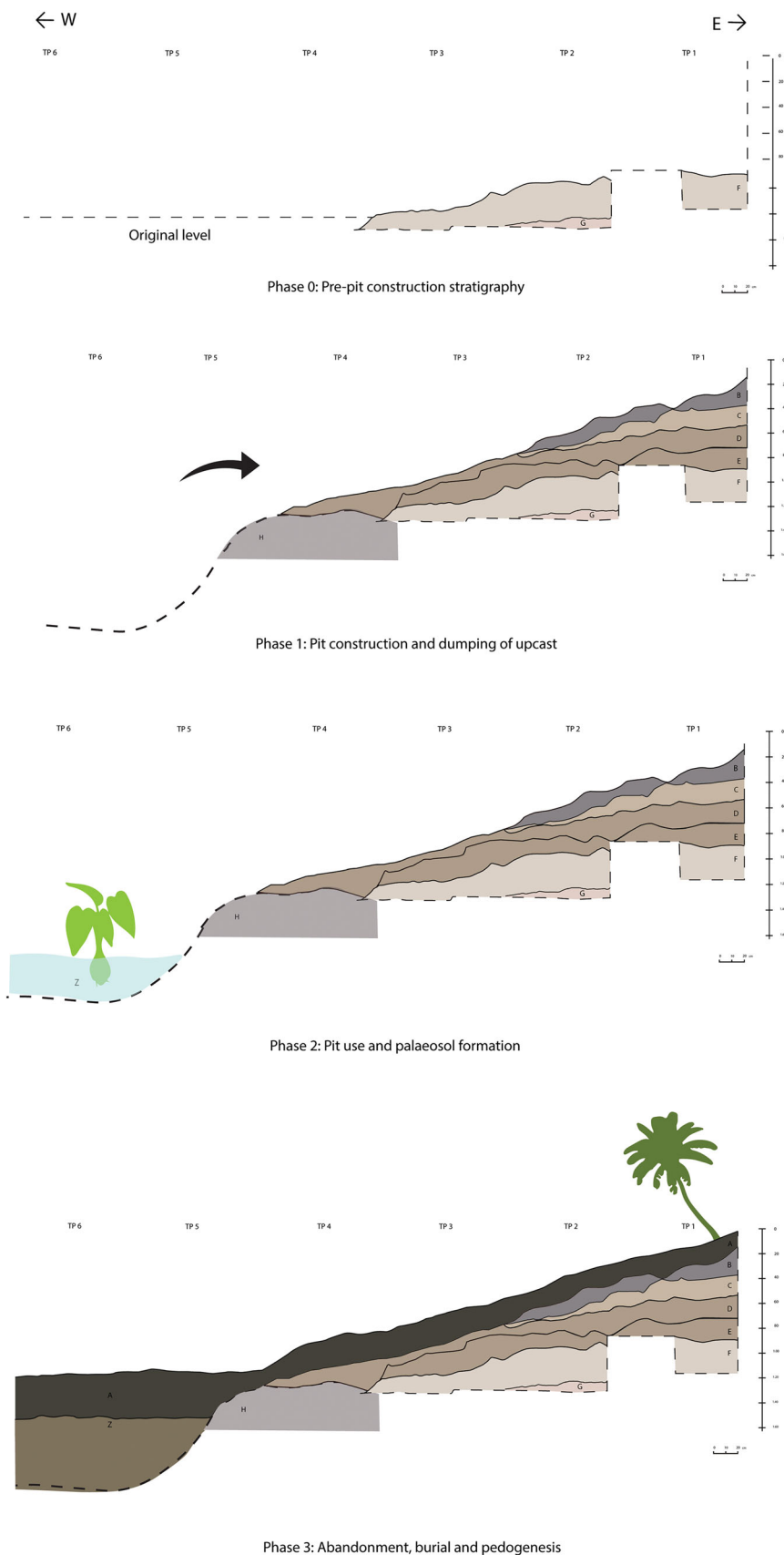
FIGURE 13. TS 14 showing four photomicrographs (A)–(D) along with the corresponding stratigraphic layers depicted in the top right corner. (A) displays a fragment of a coconut husk observed in 14 MSU-2; (B) shows a matrix composed of brown organic dotted, poorly birefringent (not shown in picture) fine material, observed in MSU 14-2; (C) displays charred vegetative material observed in 14-3; and (D) shows an unidentified seed, observed in MSU 14-1 (red arrow).



interpretations contributed to new knowledge on the formation of depositional contexts at MAITE-01 like the buried A horizon and related clay deposits. Although it cannot replace radiometric dating or stratigraphic correlations, soil micromorphology can estimate the lifespan of a palaeosol/buried A-horizon based on the number and nature of pedogenic phases, as proposed in our analysis. As such, this technique aids in understanding cultivation pit construction, use and abandonment, and established a useful point of comparison for understanding

this form of horticultural development in CEP. While our interpretation of the sequence of the history of the pit tends to match Chazine's ethnographic observations in the Tuamotu, we call for caution in generalising our results. Our case-study may reflect the emergence of this technical and practical knowledge on Teti'aroa, while regional variations are likely based on local environmental conditions and cultural contexts, especially in the Tuamotu archipelago where dense and intensive *maite* cultivation truly formed an essential economic basis for the inhabitants.

FIGURE 14. Relative chronological phases at MAITE-01 (Layer F is likely to extend westward).



Further analyses, some ongoing, will refine our understanding of the *maite*'s history. A detailed anthracological study of charcoal fragments recovered in each layer will contribute to an assessment of atoll vegetation and secure short-lived material to be radiocarbon-dated. An absolute chronology for the construction, use and abandonment of the pit is essential to anchor the development of horticultural practices within the cultural sequence of Teti'aroa and the Society Islands. Analyses of micro-botanical remains, including phytoliths and pollen, which have been detected via the micromorphological analysis in limited numbers, will provide complementary data to anthracological analyses for an archaeological assessment of plants cultivated both in the pit and possibly on the slopes. These will be compared with records from Micronesia and ethnographic information (i.e., Chazine, 2012; Horrocks et al., 2009; Reepmeyer et al., 2016; Yamaguchi et al., 2005; Weisler, 2001) and add to the growing datasets on Polynesian traditional agriculture usually limited to high-island settings, further documenting the dynamics between humans and terrestrial atoll environments.

Upcoming geomorphological investigation on Teti'aroa may contribute to the interpretation of the clay presence in our excavations. The potential identification of pig coprolite through micromorphological observations opens new perspectives to serve as a proxy for the presence of pigs on the atoll and complements zooarchaeological identification of faunal remains at nearby sites (ongoing). More investigation is needed to characterise this material and its associated microfossils (i.e., fungal spores and phytoliths), opening novel opportunities for environmental reconstructions and studies of translocation processes in archaeological sites across the Pacific.

Eventually, a multifocal understanding of ancient horticultural *maite* features can further guide reactivation projects for both pedagogical and economic purposes, in which the Ministry of Agriculture in French Polynesia and the Tuamotu inhabitants show a great interest. Archaeological research such as that presented here can be relevant in contemporary settings and help atoll-dwelling communities to regain agricultural autonomy in a context of growing economic dependence on imported foods.

ACKNOWLEDGEMENTS

This project was primarily funded through the CIRAP's Tetiaroa Archaeological program and the Seeley Foundation. It receives additional funding support from Molle's ARC DECRA (DE190100187), the Maison des Sciences de l'Homme du Pacifique (UAR2503, CNRS-UPF) and ANR project PASTatolls (ANR-23-CE27-0020). We are grateful to the Tetiaroa Society for their logistical support on the atoll. For their help in the field, we wish to thank V.A. Rurua and more specifically A. Hermann for his collaboration and support during the excavation and sampling of the *maite*. We also

thank Adelaide Petrographics for assistance with thin section preparation and the two anonymous reviewers and editors whose comments helped us improve our manuscript. ES would also like to thank other researchers who directly or indirectly contributed to offer training and some interpretation for geochemical analyses and micromorphological identification; B. Shaw, G. Clark, J. Latimer, S. Cain and A. Minicucci for helping with the particle size analyses and geochemical analyses, as well as L. Prossor, E. Grono, G. Traversat, L. Montaggioni, E. Nutman and I. Claringbold.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

- Balbo, A. L., Cabanes, D., García-Granero, J. J., Bonet, A., Ajithprasad, P., & Terradas, X. (2015). A microarchaeological approach for the study of pits. *Environmental Archaeology*, 20(4), 390–405.
- Barrau, J. (1961). *Subsistence Agriculture in Polynesia and Micronesia* (Bernice P. Bishop Museum Bulletin 223). Bishop Museum.
- Bortolini, M., Nicosia, C., Argiriadis, E., Pojana, G., Devos, Y., & Battistel, D. (2024). Fecal biomarkers in Italian anthropogenic soil horizons and deposits from middle ages and bronze age. *Quaternary Science Reviews*, 329, 108541.
- Bronnimann, D., Pümpin, C., Ismail-Meyer, K., Rentzel, P., & Égüez, N. (2017). Excrements of omnivores and carnivores. *Archaeological Soil and Sediment Micromorphology*, 67–81.
- Burley, D. V., Horrocks, M., & Weisler, M. I. (2018). Earliest evidence for pit cultivation provides insight on the nature of first Polynesian settlement. *Journal of Island and Coastal Archaeology*, 15(1), 127–147. <https://doi.org/10.1080/15564894.2018.1501441>
- Bullock, P., Fedoroff, N., Jongerius, A., Stoops, G., & Tursina, T. (1985). *Handbook for soil thin section description*. Waine Research.
- Chazine, J. M. (1977). Prospections archéologiques à Takapoto. *Journal de la Société des Océanistes*, 33(56), 191–215.
- Chazine, J. M. (1982). Archaeological research (preliminary). *Reao report, a study of the Polynesian migration to the eastern Tuamotus* (pp. 267–347). University of Kanazawa.
- Chazine, J. M. (1985). Les fosses de culture dans les Tuamotu. Travaux en cours et perspectives. *Journal de la Société des Océanistes*, 41(80), 25–32.
- Chazine, J. M. (1990). Contraintes et ressources de l'environnement, l'exemple des Tuamotu. *Notes et Documents de Sciences Humaines* (p. 13). ORSTOM.
- Chazine, J.-M. (2001). Compte-rendu de mission Archéologique à Makemo, 28 Juillet-16 Août 2001 (p. 20). CNRS-CREDO, Université de Provence.
- Chazine, J.-M. (2008). The spread of horticultural techniques during the settlement of atolls in the Pacific. *At the Heart of Ancient Societies – French contributions to Pacific Archaeology*, 119–132.

- Chazine, J.-M. (2012). Wet taro cultivation on atolls: A techno-cultural paradox? *Irrigated Taro (Colocasia esculenta) in the Indo-Pacific* (pp. 83–94). National Museum of Ethnology. *Senri Ethnological Studies*.
- Christensen, C. C., & Weisler, M. I. (2013). Land Snails from archaeological sites in the Marshall Islands, with remarks on prehistoric translocations in tropical Oceania, *Pacific Science*, 67(1), 81–104.
- Chon, N. Q. (2021). *Soil organic matter*. Eurofins Sac Ky Hai Dang.
- Clarke, W. (1994). Traditional land use and agriculture in the Pacific Islands. *Science of Pacific Island Peoples: Land Use and Agriculture*, 2, 11–13.
- Conte, E., Molle, G., & Nolet, E. (2017). Des atolls et des hommes. In T. Bambridge, J.-P. Latouche (Eds.), *Les atolls du Pacifique face au changement climatique. Une comparaison Tuamotu-Kiribati* (pp. 51–82). Éditions Karthala.
- Courty, M. A., Goldberg, P., & Macphail, R. I. (1989). *Soils and micromorphology in archaeology*. Cambridge University Press.
- Davidson, J. M., 1971. Archaeology on Nukuoro Atoll: A Polynesian outlier in the eastern Caroline Islands. *Bulletin of the Auckland Institute and Museum Auckland*, 9, 1–108.
- Deák, J., Gebhardt, A., Lewis, H., Usai, M. R., & Lee, H. (2017). Soils disturbed by vegetation clearance and tillage. *Archaeological soil and sediment micromorphology*, 231–264.
- Denham, T. (2003). *The Kuk Morass: Multidisciplinary Investigations of Early to Mid-Holocene Plant Exploitation at Kuk Swamp, Wahgi Valley, Papua New Guinea* [PhD thesis]. Australian National University.
- Denham, T. P., Sniderman, K., Saunders, K., Winsborough, B., & Pierret, A. (2009a). Contiguous multi-proxy analyses (X-radiography, diatom, pollen and micro charcoal) of Holocene archaeological features at Kuk Swamp, Upper Wahgi valley, Papua New Guinea. *Geoarchaeology*, 24, 715–742.
- Denham, T. P., Haberle, S. G., & Pierret, A. (2009b). A multi-disciplinary method for the investigation of early agriculture: Learning lessons from Kuk. *New Directions in Archaeological Science* (pp. 139–154). ANU Press.
- Denham, T., & Grono, E. (2017). Sediments or soils? Multi-scale geoarchaeological investigations of stratigraphy and early cultivation practices at Kuk Swamp, highlands of Papua New Guinea. *Journal of Archaeological Science*, 77, 160–171. <https://doi.org/10.1016/j.jas.2016.07.007>
- Devos, Y., Nicosia, C., Vrydaghs, L., Speleers, L., Van der Valk, J., Marinova, E., Claes, B., Albert, R. M., Esteban, I., Ball, T. B., Court-Picon, M., & Degraeve, A. (2017). An integrated study of dark earth from the alluvial valley of the Senne river (Brussels, Belgium). *Quaternary International*, 460, 175–197.
- Elliott, S., & Matthews, W. (2024). Dung detective! A multi-scalar, multi-method approach to identification and analysis of ancient faecal material, *Quaternary International*, 683, 162–181.
- Emory, K. P. (1933). *Stone remains in the society Islands* (p. 116). B.P. Bishop Museum Bulletin.
- Fischer, L. E. (2001). Recovering elements in historical archaeology: The use of soil chemical analysis for overcoming the effects of post-depositional plowing, MA Thesis, College of William & Mary, <https://doi.org/10.21220/s2-j0re-3d71>
- Grono, E. (2017). *Pedogenesis and anthropogenic soil modification practices at S14/198 and S14/248 archaeological sites and Hooker Road experimental garden, Waikato, New Zealand: Results from archaeological micromorphology*, Unpublished Research report.
- Grono, E. (2020a). *Archaeological micromorphology of stratigraphy and horticultural features from S15/424 (Landon Park), Waikato, New Zealand*. [Unpublished Research report].
- Grono, E. (2020b). *Settlement at the Micro Scale: Microstratigraphy and micromorphology of transitional Neolithic settlement sites in Vietnam (5000 cal BP to 2500 cal BP)*. [PhD thesis]. The Australian National University.
- Gumbley, W. (2021). *The Waikato Horticultural Complex: An archaeological reconstruction of a Polynesian horticultural system*. [PhD Thesis]. The Australian National University.
- Hermann, A., Molle, G., Maury, R., Liorzou, C., & McAlister, A. (2019). Geochemical sourcing of volcanic materials imported into Teti'aroa Atoll shows multiple long-distance interactions in the Windward Society Islands, French Polynesia. *Archaeology in Oceania*, 54(3), 184–199.
- Higgins, A., & Latimer, J. (2022). Standard Operating Procedure Colwell Phosphorus FSES-SOP-4.
- Horrocks, M., & Thomas, F. (2022). Botanical Remains of the Last 1800 Years from Tarawa, Republic of Kiribati, Reveal Ancient Aroid (Cyrtoasperma Merkusii and Colocasia Esculenta) Pit Cultivation and Other Cultigens. *Journal of Island and Coastal Archaeology*, 17, 1–16.
- Horrocks, M., & Weisler, M. I. (2006). Analysis of Plant microfossils in archaeological deposits from two remote archipelagos: The Marshall Islands, Eastern Micronesia, and the Pitcairn Group, Southeast Polynesia I. *Pacific Science*, 60(2), 261–280.
- Horrocks, M., Bedford, S., & Spriggs, M. (2009). A short note on banana (Musa) phytoliths in Lapita, immediately post-Lapita and modern period archaeological deposits from Vanuatu. *Journal of Archaeological Science*, 36(9), 2048–2054.
- Houghton, J. E., Behnsen, J., Duller, R. A., Nichols, T. E., & Worden, R. H. (2024). Particle size analysis: A comparison of laboratory-based techniques and their application to geoscience, *Sedimentary Geology*, 464, 106607. <https://doi.org/10.1016/j.sedgeo.2024.106607>.
- Hughes, P. J., Denham, T. P., & Golson, J. (2017). *The Kuk swamp. 10,000 Years of Cultivation at Kuk Swamp in the Highlands of Papua New Guinea* (pp. 87). ANU Press.
- Jamet, R., & Trichet, J. (1987). Etude du milieu terrestre des atolls de la Polynésie française: Caractéristiques et potentialités agricoles. *Cahier de l'ORSTOM*, 13(4), 275–293.
- Kaczorek, D., Vrydaghs, L., Devos, Y., Petö, A., & Effland, W. R. (2018). Biogenic Siliceous Features. In G. Stoops, V. Marcelino, & F. Mees (Eds.), *Interpretation of micromorphological features of soils and regoliths* (2 ed., pp. 157–176). Elsevier.
- Kahn, J. G. (2022). The ScMo-350 Site, Haumi, Mo'orea (Society Islands): Preliminary analysis of coastal occupation spanning the colonization phase to classic phase. *Archaeology in Oceania*, 57(2), 73–94.
- Kahn, J. G., & Sinoto, Y. (2017). Refining the society island cultural sequence: Colonization phase and developmental phase coastal occupation on mo'orea island. *Journal of the Polynesian Society*, 126(1), 33–60.
- Khamnueva, S., Mieth, A., Deibrodt, S., Out, W. A., Madella, M., & Bork, H. R. (2018). Interpretation of prehistoric reddish pit fillings on Easter Island: A micromorphological perspective. *Spanish Journal of Soil Science: SJSS*, 8(2), 236–257.
- Kirch, P. V., (1994). *The wet and the dry: Irrigation and agricultural intensification in Polynesia*. University of Chicago Press.
- Kirch, P. V. (2005). Archaeology and global change: The Holocene record. *Annual Review of Environment and Resources*, 30(1), 409–440.
- Kirch, P. V., O'Day, S., Coil, J., Morgenstein, M., Kawelu, K., & Millerstrom, M. (2003). The Kaupikiawa Rockshelter, Kalaupapa Peninsula, Moloka'i: new investigations and

- reinterpretation of its significance for Hawaiian prehistory. *People and Culture in Oceania*, 19, 1–27.
- Kirch, P. V., Kahn, J. G., & Chadwick, O. A. (2022). Soils, agriculture, and land use in island socio-ecosystems: Three case studies from Southeastern Polynesia. *Geoarchaeology*, 38(1), 20–34.
- Kirch, P. V., & Lepofsky, D. (1993). Polynesian irrigation: Archaeological and linguistic evidence for origins and development. *Asian Perspectives*, 32(2), 183–204.
- Langohr, R., Scoppa, C. O., & Van Wambeke, A. (1976). The use of a comparative particle size distribution index for the numerical classification of soil parent materials: application to Mollisols of the Argentinian pampa. *Geoderma* 15, 305–312.
- Luomala, K. (1974). Aspects of production in the Gilbert Islands. *Journal of the Polynesian Society* 83(1), 14–34.
- Latimer, J. (2022). Standard Operating Procedure Carbon and Nitrogen Soil Extracts FSES-SOP-3.
- Latimer, J., & Buss, W. (2022). Standard Operating Procedure Determination of Total Kjeldahl Nitrogen and Total Phosphorus in Soil and Plant Samples FSES-SOP-9.
- McCoy, M. D., & Graves, M. W. (2010). The role of agricultural innovation on Pacific Islands: a case study from Hawai'i Island. *World Archaeology*, 42(1), 90–107.
- Macphail, R. I., Haita, C., Bailey, D. W., Andreescu, R., & Mirea, P. (2008). The soil micromorphology of enigmatic Early Neolithic pit-features at Magura, southern Romania. *Studii de Preistorie*, 5, 61–77.
- Macphail, R. I., Courty, M. A., & Gebhardt, A. (1990). Soil micromorphological evidence of early agriculture in north-west Europe. *World Archaeology*, 22(1), 53–69.
- Malvern Instruments Ltd. (2007). Masterizer 2000 Essentials, United Kingdom.
- Manner, H. I. (1993). Taro (*Colocasia esculenta* (L.) Schott) in the atolls and low islands of Micronesia. *Proceedings of the Sustainable Taro Culture for the Pacific Conference. Sustainable Taro Culture for the Pacific Conference* (pp. 88–100). University of Hawaii.
- Martin-Garin, B., & Montaggioni, L. F. (2023). *Corals and reefs: From the beginning to an uncertain future*. Springer Nature.
- Molle, G., Hermann, A., Lagarde, L., & Stoll, B. (2019). The long-term history of Teti'aroa (Society Islands, French Polynesia): new archaeological and ethnohistorical investigations. *Journal of Pacific Archaeology*, 10(2), 55–62.
- Morley, M. W., Moffat, I., Kotarba-Morley, A. M., Hernandez, V. C., Zerboni, A., Herries, A. I., Joannes-Boyau, R., & Westaway, K. (2023). Why the geosciences are becoming increasingly vital to the interpretation of the human evolutionary record. *Nature ecology & evolution*, 7(12), 1971–1977.
- Morley, M. W., & Goldberg, P. (2017). Geoarchaeological research in the humid tropics: A global perspective. *Journal of Archaeological Science*, 77, 1–9.
- Nicosia, C., & Stoops, G. (2017). *Archaeological soil and sediment micromorphology*. Wiley Blackwell.
- Nolet, E. (2021). For a *History of low Islands' history*: The Tuamotus as a case study. *Towards a History of Pacific Prehistory: Historiographical approaches to francophone archaeology in Oceania*. (pp. 251–279) Publication de la Maison des Sciences de l'Homme du Pacifique (Papeete).
- Nunn, P. D., Kumar, R., Barrowman, H. M., Chambers, L., Fifita, L., Gegeo, D., Gomese, C., McGree, S., Rarai, F., Cheer, K., Esau, D., Fa'anunu, O., Fong, T., Fong-Lomavatu, M., Geraghty, P., Heorake, T., Kekeubata, E., Korovulavula, I., Kubunavanua, E., Lui, S., MacLaren, D., Malsale, P., Nemani, S., Plotz, R. D., Puairana, G., Rantes, J., Singh-Peterson, L., & Waiwai, M. (2024). Traditional knowledge for climate resilience in the Pacific Islands. *Wiley Interdisciplinary Reviews: Climate Change*, e882.
- Polakowski, C., Ryzak, M., Sochan, A., Beczek, M., Mazur, R., & Bieganski, A. (2021). Particle size distribution of various soil materials measured by laser diffraction—the problem of reproducibility. *Minerals (Basel)*, 11(5), 465.
- Prossor, L. (2023). *Investigating Early Natufian Sedentism: The Microstratigraphy of Wādī Hammeh 27, Jordan*. [Unpublished PhD Thesis]. Australian National University.
- Quintus, S., & Cochrane, E. E. (2018). The prevalence and importance of niche construction in agricultural development in Polynesia. *Journal of Anthropological Archaeology* 51, 173–186.
- Rainbird, P. (2004). *The archaeology of Micronesia*. Cambridge University Press.
- Reepmeyer, C., Clark, G., Liston, J., & Ussher, E. (2016). On the importance of freshwater access in successful island colonisation. In F. Valentin & G. Molle (Eds.), *Spatial dynamics in Oceania: Discovery, appropriation and the emergence of traditional societies*. Société préhistorique française (pp. 49–62). Société Préhistorique Française.
- Robert, S., Bhiry, N., & Bain, A. (2022). Micromorphological analysis of archaeological Abenaki Pit features from the Fort Odanak Site (CaFe-7), Québec, Canada. *Geosciences*, 12(12), 437.
- Rougerie, F., & Wauthy, F. (1989). Une nouvelle hypothèse sur la genèse des phosphates d'atolls: le rôle du processus d'endo-upwelling. *Comptes Rendus de l'Académie des Sciences*, 308(II), 1043–1047.
- Scorsini, E. (2023). *Beyond the reef: past lives on the atolls. A geoarchaeological investigation of an ancient cultivation pit (maite) on Teti'aroa atoll, Society Islands (French Polynesia)*. [Unpublished MA Thesis]. The Australian National University.
- Scott-Jackson, J. E., & Walkington, H. (2005). Methodological issues raised by laser particle size analysis of deposits mapped as Clay-with-flints from the Palaeolithic site of Dickett's Field, Yarnhams Farm, Hampshire, UK. *Journal of archaeological science*, 32(7), 969–980.
- Shun, K., & Athens, J. S. (1990). Archaeological investigations of Kwajalein Atoll, Marshall Islands, Micronesia. *Micronesica Supplement* 2, 231–240.
- Steibl, S., Kench, P. S., Young, H. S., Wegmann, A. S., Holmes, N. D., Bunbury, N., Teavai-Murphy, T. H., Davies, N., Murphy, F., & Russell, J. C. (2024). Rethinking atoll futures: local resilience to global challenges. *Trends in Ecology & Evolution (Amsterdam)*, 39(3), 258–266. <https://doi.org/10.1016/j.tree.2023.11.004>
- Simpson, I. A., Milek, K. B., & Guðmundsson, G. (1999). A reinterpretation of the Great Pit at Hofstaðir, Iceland using sediment thin section micromorphology. *Geoarchaeology*, 14(6), 511–530.
- Sinoto, Y., & McCoy, P. C. (1974). *Archaeology of Teti'aroa Atoll, Society Islands*, Interim Report No.1. Department of Anthropology, B.P. Bishop Museum, Report 74-2.
- Stoops, G. (2021). *Guidelines for analysis and description of soil and regolith thin sections* (2nd ed.). ACSEES.
- Stoops, G., Marcelino, V., & Mees, F. (2018). Micromorphological features and their relation to processes and classification: general guidelines and keys. In G. Stoops, V. Marcelino, & F. Mees (Eds.), *Interpretation of micromorphological features of soils and regoliths* (2nd ed., pp. 895–917). Elsevier.
- Tercinier, G. (1956). Contribution à l'étude des sols coralliens des atolls (les sols de Rangiroa - Tuamotu). In : *Sixième congrès international de la science du sol*. p. 37–42. Congrès International de la Science du Sol, 6., Paris (FRA), 1956.

- Tessier, R. (1962). Note sur l'île Tetiaroa. *Bulletin de la Société des Etudes Océaniques*, 140, 97–102.
- Thaman, R. R. (1990). Kiribati agroforestry: Trees, people and atoll environment. *Atoll Research Bulletin*, 333, 1–29.
- Thomas, F. R. (2001). Mollusk habitats and fisheries in Kiribati: An assessment from the Gilbert Islands. *Pacific Science*, 55, 77–97.
- Thomas, F. R. (2015). 'Sustainability archaeology' and landscape transformation in eastern Micronesia: Kiribati case study. *Samoa III Conference: Opportunities and Challenges for a Sustainable Cultural and Natural Environment*. Centre for Samoan Studies.
- Thomas, F. R. (2019). Sustainable extractive strategies in the pre-European contact Pacific: Evidence from mollusc resources. *Journal of Ethnobiology* 39, 240–261.
- Vannieuwenhuysse, D., O'Connor, S., & Balme, J. (2017). Settling in Sahul: Investigating environmental and human history interactions through micromorphological analyses in tropical semi-arid north-west Australia. *Journal of Archaeological Science*, 77, 172–193.
- Vérin, P. (1962). Prospection archéologique préliminaire de Tetiaroa. *Bulletin de la Société des Etudes Océaniques*, 140, 103–124.
- Villagran, X. S., Huisman, D. J., Mentzer, S. M., Miller, C. E., & Jans, M. M. (2017). Bone and other skeletal tissues. In C. Nicosia & G. Stoops (Eds.), *Archaeological Soil and Sediment Micromorphology* (pp. 11–38). John Wiley and Sons.
- Vitousek, P. M., Chadwick, O. A., Hotchkiss, S. C., Ladefoged, T. N., & Stevenson, C. M. (2014). Farming the rock: a biogeochemical perspective on intensive agriculture in Polynesia. *Journal of Pacific Archaeology*, 5, 51–61.
- Vrydaghs, L., & Devos, Y. (2018). Phytolith analysis of soil and ceramic thin sections. In C. Smith (Ed.), *Encyclopedia of global archaeology*. Springer.
https://doi.org/10.1007/978-3-319-51726-1_3286-1
- Ward, I., Veth, P., Prossor, L., Denham, T., Ditchfield, K., Manne, T., Kendrick, P., Byrne, C., Hook, F., & Troitzsch, U. (2017). 50,000 years of archaeological site stratigraphy and micromorphology in Boodie Cave, Barrow Island, Western Australia. *Journal of Archaeological Science: Reports*, 15, 344–369.
- Weisler, M. I. (1999a). Atolls as settlement landscapes: Ujae, Marshall Islands. *Atoll Research Bulletin*, 460, 1–51.
- Weisler, M. I. (1999b). The antiquity of aroid pit agriculture and significance of buried A horizons on Pacific atolls. *Geoarchaeology*, 14(7), 621–654
- Weisler, M. I. (2001). *On the margins of sustainability: Prehistoric settlement of Utrok Atoll, northern Marshall Islands*. BAR Publishing.
- Wozniak, J. A. (2003). *Exploring landscapes on Easter Island (Rapanui) with geoarchaeological studies: settlement, subsistence, and environmental changes*. [PhD thesis]. Department of Anthropology, University of Oregon.
- Yamaguchi, T., Kayanne, H., Yamano, H., Najima, Y., Chikamori, M., & Yokuri, H. (2005). Excavation of pit agriculture landscape on Majuro Marshall Islands and its implications. *Global Environmental Research*, 9(1), 25–36
- Yen, D. E. (1993). The origins of subsistence agriculture in Oceania and the potentials for future tropical food crops. *Economic Botany*, 47(1), 3–14.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Supporting Online Material