A Late Holocene palaeoenvironmental reconstruction of Ulong Island, Palau, from starch grain, charcoal, and geochemistry analyses

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\textbf{ABSTRACT}

This study represents the first starch grain analysis undertaken in Palau, performed on a sediment core extracted from a sinkhole on Ulong Island. Radiocarbon dating indicates the core spans the likely period of human occupation on Ulong (ca. 3000 years) as established by prior archaeological evidence. Samples were analysed for macrocharcoal, starch content, and geochemical composition. The results of the analyses indicate an initial period of intensive clearance and gardening from ca. 3000–2000 BP, during which banana (\textit{Musa} spp.), yams (\textit{Dioscorea} spp.), Polynesian arrowroot (\textit{Tacca leontopetaloides}), Tahitian chestnut (\textit{Inocarpus fagifer}), and breadfruit (\textit{Artocarpus} sp.) were being utilised and/or cultivated. This initial phase was then followed by a period of reduced and stabilized gardening activity until ca. 1000 BP, during which banana (\textit{Musa} spp.) disappears from the starch record. The period after 1000 BP represents the transition between the first permanent settlements on Ulong, abandoned between 500 and 300 BP, and the arrival of Europeans in 1783. This period is marked by a dearth of charcoal indicating the absence of significant burning, as well as a decrease in the variety of starch grains from cultigens.

1. Introduction

1.1. Starch grain analysis in the Pacific Islands

The analysis of starch grains preserved in sediments as a means of palaeoenvironmental reconstruction is a relatively new but potentially important technique (Lentfer et al., 2002). Exploratory studies have shown that starch grains preserve particularly well in sediments from tropical environments, and they have been utilised successfully for palaeoenvironmental reconstruction in the Pacific Islands (e.g., Denham et al., 2003; Fullagar et al., 2006; Horrocks and Nunn, 2007; Horrocks and Rechtman, 2009; Horrocks and Weisler, 2006; Lentfer et al., 2002). This study applies, for the first time, starch grain and geochemical analyses of ponded sediments from Palau as proxies to better understand human arrival and environmental changes in this archipelago.

Starch is a complex, insoluble carbohydrate that is the main substance of food storage for plants and is most commonly found in underground stems (i.e. rhizomes and tubers), roots, and seeds. Because their semi-crystalline nature makes them birefringent, an extinction cross is visible in each grain when viewed under cross-polarized light, and the presence of this cross allows starch granules to be differentiated from other microscopic plant fossils with relative ease (Horrocks et al., 2004).

In the past, starch grains were often assigned to species based on their morphological characteristics, relying upon the visual comparison between individual archaeological granules with reference granules (Wilson et al., 2010). However, this approach is not ideal as the comparison of discrete granules is likely to be unreliable (Torrence et al., 2004). To address this problem, multivariate analysis of data recorded from digital images can be used to construct a system of classification that facilitates the discrimination of the starch grains among different plant types with a high degree of consistency by recording a number of metric and nominal variables (Torrence et al., 2004). However, a potential limitation to this method for analysing starch is the representation of three-dimensional starch granules in a two-dimensional image. Since any species of plant starch will contain a variety of granule shapes, a population approach to the analysis can address this problem, resulting in more reliable starch grain identifications than can be achieved with single-grain identification (Wilson et al., 2010).

Starch grain analysis is a particularly useful technique in the Pacific region, where research on the age, development, and diversity of early...
agriculture has been hindered by an archaeological scarcity of crop fossils (Horrocks and Weisler, 2006). Furthermore, archaeological deposits in the Pacific often have limited pollen and phytolith production, and the more robust starch grains are therefore ideal proxies to add to the line of evidence for cultivation and other environmental changes in that region (Horrocks et al., 2004).

In this study, we tested whether or not starch grains can be assigned to species with a high degree of confidence in ponded sediments of Ulong Island in Palau. We were specifically interested in using the variation in starch assemblages to interpret human utilisation and/or

Fig. 1. Maps showing the location of Palau within the Pacific (inset) and the location of Ulong Island within Palau.

Fig. 2. Photograph of Ulong Island.
(Photo taken by G. Clark)
cultivation of plant species over time. Finally, we correlated the starch data with charcoal and geochemical data in an attempt to reconstruct an occupational history for the coring site.

1.2. Geography and human settlement of Palau

Palau is an archipelago composed of > 350 islands stretched along a 150 km north to southwest-trending arc in the western Caroline Islands of Micronesia (Fig. 1). The main volcanic island is Babeldaob, which comprises roughly 80% of the total land area of the archipelago. Near Babeldaob are the volcanic/limestone islands of Koror, Malakal and Ngerekebasang. South of these are the ‘Rock Islands,’ which consist of > 300 small uplifted coraline islands, including Ulong Island (Masse et al., 2006) (Fig. 2). Most of the islands range between 10 m and 100 m above mean sea level (AMSL) and are “highly weathered with steep slopes, narrow ridges, and pinnacles fronted by fringing sand plains and wave-cut limestone perimeters” (Clark and Reepmeyer, 2012, p. 30). At 7° north of the equator and 134° longitude east, Palau is in the Indo-Pacific Warm Pool (IPWP) and meteorological core of the Intertropical Convergence Zone (ITCZ), giving the islands a maritime tropical climate with a mean annual temperature of 28.1 °C and annual rainfall of approximately 3000 mm (Republic of Palau National Government, 2018).

Differences in the geological substrate result in variations of topography, drainages, and soils that promote different vegetation communities throughout the archipelago (Masse et al., 2006). Moreover, the proximity of Palau to the Philippines and New Guinea has resulted in the presence of a variety of endemic plants, birds, and reptiles, creating the greatest diversity of terrestrial flora and fauna in Micronesia. At least 118 plant families, representing several hundred species, are present in Palau, including dozens of cultivated species; food plants are present in Palau, including Ulona Island (Masse et al., 2006) (Fig. 2). Most of the islands range between 10 m and 100 m above mean sea level (AMSL) and are “highly weathered with steep slopes, narrow ridges, and pinnacles fronted by fringing sand plains and wave-cut limestone perimeters” (Clark and Reepmeyer, 2012, p. 30). At 7° north of the equator and 134° longitude east, Palau is in the Indo-Pacific Warm Pool (IPWP) and meteorological core of the Intertropical Convergence Zone (ITCZ), giving the islands a maritime tropical climate with a mean annual temperature of 28.1 °C and annual rainfall of approximately 3000 mm (Republic of Palau National Government, 2018).

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2.1. Core collection

The coring site is at the interior of Ulong Island, which is part of the Rock Islands south of the volcanic island of Babeldaob. The traverse to the center of the island involved a steep climb over raised coral limestone to ca. 60 m AMSL before descending into a depression or sinkhole feature ca. 20 m AMSL. The base of the sinkhole is a flat area ca. 100 m in diameter that is covered with ferns, sparse shrubs, and some taller trees. The sides of the sinkhole are composed of exposed limestone rubble, and in some areas, there is construction of terrace-like features, with limestone rocks aligned parallel to the contours of the sinkhole, possibly to assist in soil retention. Since the Rock Islands are subject to recurrent droughts that limit the production of starchy crops to sinkholes and back beach swamps (Clark and Reepmeyer, 2012), these sinkholes serve as sensitive barometers of human-climate interaction.

The sediment core was extracted from the center of the sinkhole feature to a depth of 6.5 m using a soil auger, and sediment samples were collected into plastic Ziploc bags at 2-cm intervals.

2.2. Charcoal analysis

A total of 261 samples were analysed for charcoal content. Each sample was subsampled (2 cm3) for macrocharcoal analysis (> 125 μm fraction) using the method employed at the Department of Archaeology and Natural History, Australian National University (Stevenson and Haberle, 2005). The analysis included bleaching overnight and sieving through 125 μm, after which the concentrations of fragments per unit volume were counted under a Zeiss stereomicroscope at 100× magnification.

2.3. Starch grain analysis

Twenty samples, each prepared using 2.5 cm3 of sediment, were examined for starch and pollen content. The pollen assemblage was found to be too poorly preserved; therefore, the study concentrated on starch grain analysis. Samples were extracted at intervals ranging between 10 and 60 cm along the entire length of the core. A lycopodium spike (20,848 lycopodium spores per tablet) was added, and the samples were settled in deionized water repeatedly over several days to remove the clay size fraction. Each sample was then placed in a 500-mL container and mixed vigorously before being left to settle over a three-hour period, whereby all pollen and starch had reached the bottom of the container. Any remaining suspended sediments were poured off, and this process was repeated until the water became clear.

The samples were then filtered at 125 μm, with the residue saved separately. Twenty milliliters of potassium hydroxide (KOH) were added to each sample, and the samples were placed in a hot bath for 20 min to remove humic acids. All KOH was washed out of the samples, and 20 mL of lithium heteropolytungstate (LST) SG 2.0 were added. The samples were then placed in a centrifuge and spun at 2760 rpm for 60 min, after which they were filtered with 10 μm mesh to remove the LST. Finally, safranin coloring was added for clarity, and the samples were mounted on glass slides in glycerol.

The starch samples were examined with a Leica DM6000 light microscope following the methods of Usher (2015). Each slide was scanned in horizontal transects using a 20× magnification water immersion lens under cross-polarized illumination. Each starch grain encountered, identified by the presence of the extinction cross, was then examined with a 63× magnification water immersion lens under both brightfield and cross-polarized illumination.

Two digital photographs (one brightfield and one cross-polarized) were taken of each grain. Up to 50 grains were photographed for each sample, with additional grains photographed in samples where the initial 50 did not represent the full variation of grains found in the sample. Species identifications were made using a combination of visual analysis and statistical (linear discriminant) analysis to compare the fossil grains with grains from a reference collection (courtesy of Ella Usher). Further details on the methods of digital and multivariate analyses are provided in the Supplementary material.

2.4. Dating analysis

Samples were analysed for 14C using bulk organic matter. Ages were
obtained by accelerated mass spectrometry at DirectAMS (Washington, USA). NOSAMS Woods Hole Oceanographic Institution (Massachusetts, USA). The dried, crushed samples were pre-treated with HCl–NaOH–HCl to remove carbonates and washed with Milli-Q; the insoluble residue was freeze-dried for AMS analysis (Fallon et al., 2010). Radiocarbon ages were calibrated using the northern hemisphere terrestrial curve IntCal13 (Reimer et al., 2013), and the age-depth model was constructed using the package Clam in the R programme (Blaauw, 2010).

2.5. Geochemistry analysis

All sediment core sections were freeze-dried for 72 h (Labconco Freezone plus 6). After freeze drying, samples were placed into 200-mL tubes and homogenised by intensive manual mixing of sediment. Approximately 0.2 g of freeze-dried material was weighed into a 60-mL polystyrene centrifuge tube (PFA) closed digestion vessel (Mars Express), and 2 mL of concentrated nitric acid (Aristar, BDH, Australia) and 1 mL of 30% concentrated hydrochloric acid (Merck Suprapur, Germany) were added (Telford et al., 2008). Each PFA vessel was then capped and placed into an 800-W microwave oven (CEM model MDS-81, Indian Trail, NC, USA), and the samples were heated at 120 °C for at least 15 min. The diluted digests were cooled to room temperature and diluted to 50 mL with deionized water (Sartorius). The tubes were then centrifuged at 5000 rpm for 10 min. One millilitre of the digest was transferred into a 10-mL centrifuge tube and then diluted to 10 mL with ICP-MS internal standard (Li6, Y19, Se45, Rh103, In115, Tb159 and Ho165).

Digests were stored (0–5 °C) until analysis. Samples were analysed for metals using inductively coupled plasma mass spectrometry (ICP-MS) (Perkin-Elmer DRC-e) with an AS-90 auto-sampler. For every 36 samples, two certified reference materials (CRMs) and two blanks were used. The CRMs (BCSS1, National Research Council Canada; MESS1, National Research Council Canada; 1646, The National Institute of Standards and Technology; PACS1, National Research Council Canada) were used to check the accuracy of metal analysis.

Metal concentrations were in agreement, between 90% and 110%, with the CRMs. All metal concentrations in this study are reported as mg/kg dry weight.

3. Results and discussion

3.1. Age-depth model

Radiocarbon dating indicates sediment core UC-SH1 spans at least 3000 years, coinciding with the likely span of human occupation (initially only intermittent/temporary) in the Rock Islands as supported by the current archaeological evidence (e.g., Clark et al., 2006; Fitzpatrick, 2003; Nelson and Fitzpatrick, 2006) (Fig. 3). The brown silty-clays above 220 cm depth show a robust age-depth profile using a smooth spline fitted curve (Blaauw, 2010). The sediments below 220 cm in depth are brown silty-clays with fragments of degraded coral indicative of inclusion of reworked or eroded sediment from the steep catchment slopes. This limits our ability to determine the chronology of sediments below 220 cm, and we do not attempt to apply an age-depth model in this section of the sediment profile.

3.2. Macrocharcoal analysis

Macrocharcoal analysis reveals three phases of land use at the site (Fig. 3). During Phase 1, from ca. 3000–2000 BP, the elevated quantities of charcoal presumably relate to early clearance/gardening and/or food gathering activities mobilizing sediment in the steep sinkhole sides. The reduced charcoal of Phase 2 represents a period of reduced and stabilized gardening activity until ca. 1000 BP. During Phase 3, after 1000 BP, the dearth of charcoal indicates the absence of significant burning until the uppermost samples representing the European period (post-1783).

3.3. Geochemistry of three phases of land use at the coring site

The geochemistry results reinforce the three phases of land use at the coring site. Furthermore, geochemical results below 220 cm in depth show a strong marine signal, demonstrated by the higher concentrations of calcium (Ca) and sodium (Na) (Fig. 4). Therefore, the mixing of sediments below 220 cm indicated by radiocarbon dating may be a result of marine influxes to the basin.

Phase 1 of land use at the site is marked by high variability of most elements. This includes the alkali element potassium (K), which is relatively water soluble and therefore a good proxy for weathering, as well as titanium (Ti), which is a chemically stable and resistant element and therefore a good proxy of detrital inputs and catchment erosion (Davies et al., 2015). The increase of weathering and erosion on the island indicated by K and Ti, in addition to the high charcoal frequency, suggests this was a period of clearing and burning activities for agriculture.

Phase 2 of land use, from ca. 2000–1000 BP, is marked by stabilization of the chemical elements, which, coupled with the reduced charcoal concentrations noted above, indicates a period of land use stabilization. In the subsequent Phase 3, after 1000 BP and prior to the arrival of Europeans in 1783, the geochemical signals of sediments were stable, with some influence of the periods bracketing this shorter phase. The surface sample, representing the post-European period, shows an increase in magnesium (Mg), K, and zirconium (Zr), indicating increased erosion and weathering.

3.4. Changes in the starch assemblage over time

The use of the study site for human cultivation is indicated by the stacked rock terracing observed around the sinkhole. Since cultivation of crops in the Rock Islands of Palau was limited mainly to sinkholes and back beach swamps (Clark and Reppmeyer, 2012), it is reasonable to assume that our coring site was utilised for cultivation.

A total of 939 starch grains from sediment core UC-SH1 were analysed in this study. For the 212–214 cm sample, only five grains could be analysed due to a high percentage of shattered grains in the sample. For all other samples, at least 20 grains were analysed, with an average of 49 grains per sample.

Of the 939 fossil grains, 136 were identified to species/genus, and 259 were assigned to three distinct morphological types (MT1, MT2, and MT3), which could not be matched with any of the reference species (Tables 1 and 2). The remainder of the grains either was not sufficiently diagnostic to be placed within a group, or the discriminant and visual analyses were in conflict with one another. Quantitative analysis was not performed on the assemblage due to the still relatively poor understanding of the “differential decay of starches from different species and of different sizes” (Haslam, 2009, p.99). Therefore, starch grains are discussed in terms of presence/absence for each sample and/or land use phase.

The identification of starch grains at various depths in the sediment core can illuminate environmental changes that have occurred over time; of particular interest are those changes which may be anthropogenic. The starch reference collection utilised for grain identification is composed mainly of cultigens, with only four of the 22 species being native or endemic to Palau, and one (Artocarpus sp.) representing a possible hybrid of native and introduced species; the presence or absence of these cultigens at various depths provides a good indication of human activity in the area.

The classification of grains to genus or family may provide sufficient data for research questions dealing with past environmental change; however, since this study was concerned primarily with identifying introduced/cultivated species, it was important to explore the potential of differentiating between native and introduced varieties of plants.
Palau has the greatest diversity of terrestrial flora in Micronesia, including native varieties of plants like yam (*Dioscorea flabellifolia*), taro (*Cyrtosperma merkusii*), and breadfruit (*Artocarpus mariannensis*), which are typically considered indicators for human arrival and cultivation in the Pacific Islands.

The starch analysis is in agreement with the land use phases identified in the macrocharcoal and geochemistry analyses. Phase 1 of land use at the coring site is represented by four samples. *Artocarpus* sp. is present in all four samples, while *Inocarpus fagifer* and *Tacca leontopetaloides* are present in three samples. Grains initially identified as *A. altilis* are reported here as *Artocarpus* sp., since *A. mariannensis* and/or a hybrid variety cannot be ruled out as the origin of some or all of the grains. *Artocarpus altilis*, or seedless breadfruit, is a species of flowering tree in the mulberry family named for its flavor, which is similar to freshly baked bread. It is considered a staple food throughout the Pacific Islands and was introduced to Palau by early settlers (University of Hawaii at Manoa Botany Department, 2014). *Artocarpus mariannensis*, a wild seeded variety of breadfruit, is native to the Rock Islands of Palau, where it is well-suited due to its high salt tolerance. The seeds are an important nutritious food source, and the wood is used for canoes and handicrafts (Kitalong et al., 2013).

*Inocarpus fagifer*, the Tahitian chestnut, is typically found in wetland areas and is the only edible member of its genus, with a large seed that is a staple starch food. The leaves and bark are used to treat tuberculosis, while the wood is used for canoe paddles (Kitalong et al., 2013). *Tacca leontopetaloides*, or Polynesian arrowroot, is a species of flowering plant in the yam family (*Dioscoreaceae*) and, like *A. altilis* and *I. fagifer*, is another early introduction to Palau (University of Hawaii at Manoa Botany Department, 2014).

Other species present during Phase 1 include *Musa* sp. (banana) and *Dioscorea bulbifera* (air potato), each present in one of the four samples. *Musa* is not specified to species because most contemporary plants are hybrids, with the genus containing both bananas and plantains. Morphological Type 1 (MT1) is also present in three samples. Based on the resemblance of MT1 grains to the grains of an unidentified species of *Dioscorea* collected from Indonesia (Lentfer, CJ 2014, pers. comm., 23 April), MT1 may represent a species of *Dioscorea*. Several species of *Dioscorea* known as yams serve as important agricultural crops in the Pacific Islands, as their large tubers provide another staple starch food. Morphological Type 3 (MT3) is also present in every Phase 1 sample; however, it remains unclear if MT3 represents a native or introduced species.

Interestingly, *Barringtonia asiatica*, which is quite prevalent throughout the sediment core, is nearly absent from Phase 1, identified in only one of the four samples. *Barringtonia asiatica* is native to Palau’s mangrove habitats, and all parts of the tree are poisonous. In many parts of the Pacific, it was traditionally used to aid in fishing by stupefying fish or octopi—hence the name ‘fish poison tree’ or ‘sea poison tree’ (University of Hawaii at Manoa Botany Department, 2014). The lack of the native *B. asiatica* in the Phase 1 samples reinforces the charcoal and geochemistry results, which indicate a period of intensive clearing and burning during this time.

During the subsequent Phase 2, the starch assemblage is similar to the previous phase, with *Artocarpus* sp. (breadfruit), *I. fagifer* (Tahitian chestnut), *T. leontopetaloides* (Polynesian arrowroot), and MT1 (possible *Dioscorea* sp.) remaining the most prevalent species. In addition, *Dioscorea esculenta* (lesser yam) is present in two of the four Phase 2 samples, and *Dioscorea nummularia*, the spiny-base yam, is present in one of the samples. *Barringtonia asiatica* (sea poison tree), which was nearly absent during the previous phase, is present in all four Phase 2 samples, suggesting the return of some native species that may have declined during the intensive clearing and burning of Phase 1.

In contrast, there is an indication that some native species may have declined during Phase 2. Morphological Type 2 (MT2) is interpreted as a possible species of *Pandanus*, as MT2 grains resemble photos of starch grains from the leaves of *Pandanus furcatus* (Himalayan/Nepal Screw Pine) (Lentfer, CJ 2014, pers. comm., 23 April). Although MT2 grains are quite prevalent in the lower depths of the sediment core, they do not appear above the 96–98 cm sample, near the beginning of Phase 2. *Pandanus* is a genus of palm-like, dioecious trees and shrubs, which are
of cultural, health, and economic importance in the Pacific. Eight Pandanus species are native or endemic to Palau (Kitalong et al., 2013); therefore, the disappearance of MT2 grains from the starch record may indicate a decline in Pandanus after this time, ca. 1700 BP.

In Phase 3, the starch record suggests a decrease in agricultural activity. This phase is marked by a decrease in the variety of cultigens in comparison to the two previous phases, with only three (T. leontopetaloides [Polynesian arrowroot], Dioscorea esculenta [lesser yam], and MT1 [possible Dioscorea sp.]) represented. However, it is worth noting that some cultigens reappear (or appear for the first time) in the uppermost two samples representing the European period. These include Musa sp. (banana), Dioscorea alata (greater yam), D. nummularia (spiny-base yam), and I. fagifer (Tahitian chestnut).

Species identified below the 220 cm sample, where the chronology is uncertain, include Dioscorea spp. (yams; D. esculenta, D. nummularia, MT1), Alocasia macrorrhiza (giant taro), Artocarpus sp. (breadfruit), Musa sp. (banana), I. fagifer (Tahitian chestnut), Spondias dulcis (ambarella), and T. leontopetaloides (Polynesian arrowroot). The presence of introduced species in even the lowest portions of the core may indicate that the core spans only the time period from the earliest human arrival at Ulong ca. 3000 BP (Clark et al., 2006). More likely, it is a product of the mixing of sediments in the lower portion of the sediment core indicated by radiocarbon dating and geochemistry analysis. In either

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**Table 1**

Total number of starch grains analysed per sample and the presence/absence of each morphological type.

<table>
<thead>
<tr>
<th>Chronology</th>
<th>Sample</th>
<th>No. of Grains</th>
<th>MT1</th>
<th>MT2</th>
<th>MT3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Island Abandoned</td>
<td>Surface</td>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(from ca. 500 BP)</td>
<td>16–18 cm</td>
<td>36</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase 3 (ca. 1000–500 BP)</td>
<td>26–28 cm</td>
<td>55</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Phase 2</td>
<td>56–58 cm</td>
<td>54</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(ca. 2000–1000 BP)</td>
<td>72–74 cm</td>
<td>51</td>
<td></td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td></td>
<td>96–98 cm</td>
<td>58</td>
<td>•</td>
<td>•</td>
<td>•</td>
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<tr>
<td></td>
<td>116–118 cm</td>
<td>55</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Phase 1</td>
<td>132–134 cm</td>
<td>24</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>(ca. 3000–2000 BP)</td>
<td>166–168 cm</td>
<td>52</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td></td>
<td>196–198 cm</td>
<td>51</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td></td>
<td>212–214 cm</td>
<td>5</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>Uncertain</td>
<td>256–258 cm</td>
<td>65</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td></td>
<td>266–268 cm</td>
<td>57</td>
<td>•</td>
<td>•</td>
<td>•</td>
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<tr>
<td></td>
<td>282–284 cm</td>
<td>49</td>
<td>•</td>
<td>•</td>
<td>•</td>
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<tr>
<td></td>
<td>326–328 cm</td>
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<td>•</td>
<td>•</td>
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<tr>
<td></td>
<td>362–364 cm</td>
<td>46</td>
<td>•</td>
<td>•</td>
<td>•</td>
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<tr>
<td></td>
<td>396–398 cm</td>
<td>52</td>
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<td>•</td>
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<tr>
<td></td>
<td>456–458 cm</td>
<td>54</td>
<td>•</td>
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<td>•</td>
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<tr>
<td></td>
<td>482–484 cm</td>
<td>46</td>
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<tr>
<td></td>
<td>522–524 cm</td>
<td>57</td>
<td>•</td>
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</tr>
</tbody>
</table>

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Fig. 4. Element concentrations (mg/kg, dry mass) in sediment core UC-SH1; the smooth red line fits the element concentration (x-axis) to the response of age (y-axis as a predictor). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Table 2: The presence/absence of each species per sample in sediment core UC-SH1, based on a combination of discriminant and visual analysis.

<table>
<thead>
<tr>
<th>Native/Introduced</th>
<th>Sample</th>
<th>Native</th>
<th>Introduced</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. asiatica</td>
<td>C. merkusii</td>
<td>H. palauensis</td>
<td>M. citrifolia</td>
</tr>
<tr>
<td>I. fagifer</td>
<td>M. esculenta</td>
<td>S. dulcis</td>
<td>T. leontopetaloides</td>
</tr>
</tbody>
</table>

Chronology Sample

<table>
<thead>
<tr>
<th>Island Abandoned</th>
<th>Surface</th>
<th>Phase 1 (ca. 3000–2000 BP)</th>
<th>Phase 2 (ca. 2000–1000 BP)</th>
<th>Phase 3 (ca. 1000 BP)</th>
<th>Uncertain</th>
</tr>
</thead>
<tbody>
<tr>
<td>(from ca. 500 BP)</td>
<td>16–28 cm</td>
<td>16–14 cm</td>
<td>24–10 cm</td>
<td>36–16 cm</td>
<td>40–36 cm</td>
</tr>
</tbody>
</table>
| Phase 3 (ca. 1000 BP, Fig. 5) represents the transition between those permanent settlements and the arrival of Europeans in 1783 (Masse et al., 2006). During this time, the geochemical signals of sediments were stable, with some influence of the periods bracketing this shorter phase. The starch record suggests a decrease in agricultural activity, as this phase is marked by a decrease in the variety of cultigens present in comparison to the two previous phases.

The surface sample shows an increase in Mg, K, and Zr, which is most likely a result of increased erosion and weathering from post-European arrival events, such as World War II and the shipwreck survivor-camp of 1783 described in a previous study by Clark and de Biran (2010). The study describes how the East India Company Packet Antelope struck the western barrier reef in 1783, and that a shipwreck survivor-camp was established on Ulong in a bay not far from the current coring site. Forty-nine crew members spent three months on the island logging timber, clearing vegetation, and engaging in “activities that would have produced copious amounts of charcoal (iron forge, plank-heating furnace, cooking)” (Clark and de Biran, 2010, p. 348). An increase in charcoal and the variety of starch grains from cultigens in the uppermost samples representing the European period are likely a result of these activities.

3.5. Multiproxy interpretation

The results of the three proxies (geochemistry, charcoal, and starch grains) are in agreement and provide a concise history of human arrival and subsequent land use at Ulong Island in Palau. Phase 1 (ca. 3000–2000 BP, Fig. 5) is marked by geochemical signals of detrital inputs, catchment erosion, and high charcoal frequency, suggesting this was a period of clearing and burning activities for agriculture and perhaps food gathering. Further evidence of agriculture during this phase is provided in the starch record, which includes cultigens such as *Dioscorea* spp. (yam), *Musa* sp. (banana), *I. fagifer* (Tahitian chestnut), and *T. leontopetaloides* (Polynesian arrowroot), which are among the early introductions to Palau brought by settlers (Kitalong et al., 2013; Masse et al., 2006; University of Hawaii at Manoa Botany Department, 2014). These results corroborate with previous results in the literature indicating this period as the time of human arrival at Ulong, ca. 3000 BP, although early occupation would have been intermittent (Clark et al., 2006).

Phase 2 (ca. 2000–1000 BP, Fig. 5) is marked by stabilization of the chemical elements and reduced charcoal concentrations, indicating a period of land use stabilization. In conjunction with the starch record, which reflects a wide variety of cultigens, these results suggest more permanent habitation arose on Ulong as early as 2000 BP. This date is earlier than indicated by previous studies (Masse et al., 2006; Clark and Reepmeyer, 2012), which found that permanent settlements likely arose between 900 and 1200 BP and were abandoned between 300 and 500 BP. However, it should be noted that evidence for permanent or semi-permanent use as early as ca. 1700 BP has been documented at Chelechol ra Orrak in the northern Rock Islands, closer to the large island of Babeldaob (Fitzpatrick and Kataoka, 2005; Fitzpatrick et al., 2011).

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3.6. Recommendations for future studies

This study, which is the first starch grain analysis undertaken in Palau, indicates that large quantities of starch grains are recoverable from ponded sediments in Palau. Using the current analytical methods, nearly half (42%) of the grains could be assigned to a species or morphological type group, providing robust data for investigating human occupation and activity in the archipelago. Future improvements on the current method could include the use of a larger reference collection, as...
well as the sourcing of reference samples from the same geographic region as the fossil grains to further facilitate species identifications.

4. Conclusion

Starch analysis as a means of palaeoenvironmental reconstruction is a relatively new but potentially important technique, particularly when the starch data can be corroborated with other proxies. This study applied starch grain, charcoal, and geochemical analyses of ponded sediments from Palau as proxies to better understand human arrival and environmental changes. The results of the analyses indicate three phases of land use on Ulong. Phase 1 was an initial period of intensive clearance and gardening from ca. 3000–2000 BP, during which a variety of introduced plants were being utilised and/or cultivated. The subsequent Phase 2 was a period of reduced and stabilized gardening activity until ca. 1000 BP, suggesting permanent settlements were established during this period. Phase 3, after ca. 1000 BP, represents the transition between the abandonment of those settlements and the arrival of Europeans in 1783.

The land use sequence established by the current results is generally in agreement with previous studies, which indicate intermittent use of Ulong from ca. 3000 BP, with permanent settlements arising between 900 and 1200 BP and abandoned between 300 and 500 BP. However, the current results suggest permanent settlements may have been established earlier than previously thought, closer to 2000 BP. This date corresponds with evidence from another Rock Island site, Chelechol ra Orrak, which suggests permanent or semi-permanent use of Orrak Island from ca. 1700 cal BP. Orrak, in the northern Rock Islands, is closer to the large volcanic island of Babeldaob, where palaeoenvironmental studies have suggested a considerably earlier colonization date, ca. 4500 cal BP. Future studies of Babeldaob and the Rock Islands employing a multi-proxy approach, including starch grain analysis, could continue to shed light on the sequence of colonization and land use in Palau.

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Appendix A. Supplementary data

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References


