JOURNAL OF
Pacific
Archaeology

– RESEARCH REPORT –

Plant microfossils reveal human activity in and around Hawaiian Island fishponds, including introduced Polynesian and European multi-cropping

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Abstract

Archaeological research of Hawaiian Island pre-contact fishponds is hindered by loss of many because of erosion, land reclamation, and urban development. Understanding early Hawaiian resource activity is hindered because, to date, plant macroremains are rarely reported. We use plant microfossil analysis in three fishponds, on Maui, Oʻahu, and Molokaʻi, to explore these archaeological features and build on previous studies. The results differentiate aquatic/marine and dryland environments, and provide direct evidence of indigenous and introduced cultigens, including *Aleurites moluccana*, *Cocos nucifera*, *Colocasia esculenta*, *Pandanus tectorius*, and *Zea mays*. The surviving ponds, many infilled with sediments, and their surrounds represent a sink of bio-archaeological evidence of Hawaiian aqua-agricultural activity.

Keywords: *Hawaiian Islands; paleoenvironmental; horticulture; pollen; phytoliths, starch*

To cite this article:

Horrocks, M., Sroat, E., Swift, J., Mulrooney, M., McElroy, W., Lee-Greig, T., & Bickler, S. 2025. Plant microfossils reveal human activity in and around Hawaiian Island fishponds, including introduced Polynesian and European multi-cropping. Journal of Pacific Archaeology, 15(1): Article 3:1-22. DOI: https://doi.org/10.70460/jpa.v15i1.372

Submitted: 12/12/2024, Accepted 03/04/2025, First online 23/04/2025

The Journal of Pacific Archaeology is a peer-reviewed open access journal published by the New Zealand Archaeology Association

1. Introduction

The Hawaiian Islands was one of the regions where early integrated farming systems, including aquaculture, were developed (Kikuchi 1976, Costa-Pierce 1987, Estioko-Griffin 1987, Athens 2000, Kurashima & Kirch 2011). Hawaiian aquaculture involved several types of fishponds. Costa-Pierce (1987) described four major types: upland freshwater *Colocasia esculenta* (taro) ponds, inland freshwater ponds, brackish water ponds, and seawater ponds. The ponds are often associated with simultaneous cultivation of taro, which is generally saline intolerant. The ponds were fed with cut grasses, *C. esculenta* leaves, shellfish, and seaweed (Wilder 1923, Titcomb 1952).

The upland taro ponds were developed to cultivate taro and grow euryhaline and freshwater fish, prawns, and algae (Costa-Pierce 1987). The inland freshwater ponds focused on prawns and Hawaiian gobies. Fish that migrated from the sea, namely mullet, milkfish, and silver perch, were channeled or introduced into both freshwater pond types, sometimes carried long distances. Brackish water ponds, closer to the sea, had natural freshwater inflow or seepage, and were connected to the sea by channels to allow seawater entry on the rising tide. The brackish water provided higher fish diversity. Seawater ponds, contained by a sea wall of coral or lava rock, replicated the highly diverse aquatic biota of the original reef environment.

Our increased knowledge of the pre-contact history of the Hawaiian fishponds is hindered by erosion, urban development, and land reclamation activities resulting in the partial or total loss of many of the known fishponds. Many of the catchments are in large part also built over, hampering archaeological excavations in those areas. A further hindrance in the understanding of early Hawaiian resource activity generally is a paucity of direct evidence of actual cultigen remains reflecting the crops.

Analysis of plant micro-remains from archaeological sites allows the direct identification of cultigens and during the last two decades a substantial body of data have been collected in the Pacific Island region. As well as traditional pollen analysis, formerly confined largely to palaeoecological studies using wetland and lake sediment cores, the addition of other plant microfossil types, notably phytoliths and starch grains, has enabled identification of specific crop species and aquatic effects at archaeological sites (e.g, Horrocks & Weisler 2006; Horrocks *et al.* 2012a, 2023, 2024, in press; Burley *et al.* 2018; Horrocks 2020; Horrocks & Thomas 2022; Flexner *et al.* 2024; Kirch *et al.* 2024). For example, the latter can be shown by aquatic biosilicates extracted along with phytoliths, notably diatoms and sponge spicules.

Several plant microfossil studies of Hawaiian Island fishponds, all estuarine/marine, have previously been carried out. Athens (2000) conducted ^{14}C and palynological analyses of cores from four fishponds in Pearl Harbor, Oʻahu. The longest record, from 8500-9000 cal. BP., showed undisturbed and highly diverse indigenous forest of leeward Oʻahu. The Polynesian period is evidenced by large-scale vegetation changes, namely lowland forest clearance resulting in a floristically depauperate anthropogenic landscape. The dating results could not provide a chronological framework sufficiently detailed to write a history of traditional Hawaiian fishpond construction in the harbor (See Study Area and Sites section for further details).

Athens *et al.* (2002) carried out sedimentary, 14C, pollen, diatom, and stable carbon isotope analyses on cores from an unnamed fishpond at the Pearl Harbor shipyard. Based on the sedimentary and diatom results, they considered that the suspected fishpond layer commenced accumulating naturally as a shallow water mud flat and was only later modified by people to seal off the natural enclosure from the main channel of the harbor. Because the sedimentary transition period was low resolution, the dating of the use of the wetland for a fishpond could only be assigned to a time after 651-543 cal. BP (AD 1299-1407). Pollen results indicated a history of both Dry-Mesic (lowland) and Mesic-Wet (upland) forest taxa. (See Study Area and Sites section for further details.)

Sedimentary analysis of three fishponds on Kauaʻi is given in the coring work of Burney (2002), in which pollen is briefly mentioned with the intention of analysing it at a later stage. Alekoko fishpond (estuarine) results suggested pond construction or increased local human activity dated 580 ± 30 BP (AD cal. 1305-1420). Lawa Kai fishpond (fresh water) results suggested that sea level approached the base level of the site c. 6000 cal. BP, depositing marine sediments. This was followed by brackish or freshwater ponding, with periodic coarse-clastic influx, possibly from storm surges. Further dating was required to evaluate Polynesian impact at this site. Kekepua fishpond (fresh water) results suggested a minimum age for construction at 830 ± 50 BP; AD cal. 1050-1095, 1140-1280. Overlying clay layers suggested subsequent erosion, possibly a result of early adjacent cultivation.

Recent archaeological excavations at three coastal fishpond areas, on the islands of Maui, Oʻahu, and Molokaʻi, have provided the opportunity for further Hawaiian Island fishpond and agricultural research (Lee-Greig 2021, McElroy & McElroy 2023, Sroat *et al.* 2023) (Fig. 1) described here. Using a combined microfossil approach, the study builds on previous studies and address the hindrances regarding research of Hawaiian Island fishpond and horticultural history, shedding light on former aquacultural activity.

2. Study area and sites

2.1. Waiohuli Kai, Maui

Pau *et al.*'s (2012) Maui fishpond pollen record is from Keālia Pond on the southwest Maui coast and shows that indigenous forests were subject to natural fires prior to human arrival. Charcoal increased around AD 840-1140, indicating Polynesian activity in the region, but with no evidence of rapid, extensive forest clearance after arrival. The greatest reduction in pollen diversity occurred during the European period (after 1778), with a decline in montane forest taxa and disappearance of indigenous lowland taxa, and the first appearance of the exotic taxa *Batis* and *Prosopis*. No Polynesian-introduced pollen types were recorded.

A sediment core from the coastal Waiohuli Kai Wetland, south of Keālia at Kihei, was recently collected as part of a restoration project (Fig. 1) (Lee-Greig 2021). The wetland, spring-fed and once part of a much larger coastal lagoon complex, has been partially built on. The remains of the wall of the associated ancient Waiohuli Pond are visible extending offshore.

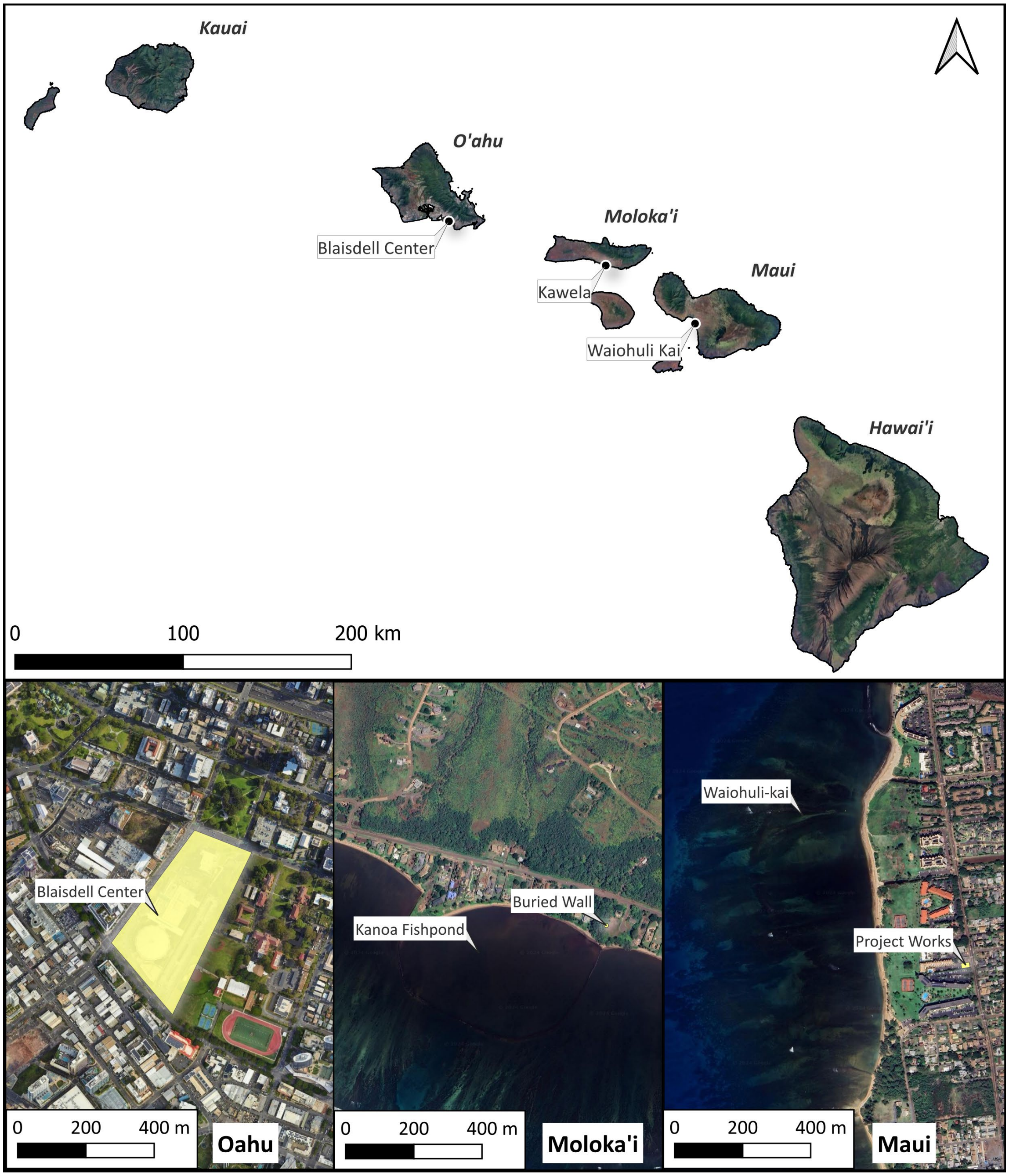

Figure 1: Location of the three project areas: O'ahu, Moloka'i, and Maui, Hawaiian Islands (Satellite imagery Google Satellite Imagery)

Eight samples (1, 2, 5, and 7-11) were selected from several of the core layers for microfossil analysis, as follows:

1 (Layer I), 0-4 cm, terrestrial silt loam

2 (Layer I), 0-4 cm, terrestrial silt loam

5 (Layer II), 4-26 cm, marine sandy loam

7 (Layer III, 26-30 cm, clay
8 (Layer IV), 30.0-31.5 cm, sandy clay loam
9 (Layer V), 31.5-33.5, clay
10 (Layer VI). 33.5-35.0, clay silt loam with fine lamina and one sand lens
11 (Layer VII), 35-38, silt clay

2.2. Blaisdell Center, O'ahu

Athens *et al.*'s (2000) Oʻahu fishpond pollen study sites are Loko Hanaloa, Loko Kuhia, and Loko Paʻiaiau, all in Pearl Harbor. Athens' (2002) study site, also in the harbor, is an unnamed fishpond at the Abrasive Blast Facility in the Navy's shipyard. Although indicating floristic differences in different parts of the study, the records are generally consistent with previous studies on Oʻahu (Athens 1997). Loko Paʻiaiau provided the longest sequence, dating from c. 8500-9000 cal. BP, showing a diverse pre-settlement indigenous forest, dominated by pollen of *Pritchardia*, *Dodonaea*, *Kanaloa*, and Cheno-Am (probably *Chenopodium oahuense*). Polynesian settlement is marked by major vegetation changes, with clearance of lowland forest resulting in increases in herbs, e.g., Cyperaceae and in ground ferns. Other Polynesian effects are evidenced by pollen of the cultigens *Aleurites moluccana* and *Cordyline fruticosa* in all four and three of the records, respectively, and increased microscopic charcoal particles.

A recent archaeological inventory survey within the Neal S. Blaisdell Center in Honolulu, situated approximately 600 m inland from the coast, investigated the buried remnants of inland, spring-fed fishponds (Sroat *et al.* 2023) (Fig. 2). Prior to a succession of late 19th and early-20th-century land reclamation projects, which infilled the patchwork of natural wetlands and marshes stretching between Honolulu and Waikīkī, the study area consisted of spring-fed marshland (the Kewalo Wetlands) and an inland dryland plain. A study of mid-19th century land use records indicated that by this time period, if not earlier, the study area portion of the Kewalo Wetlands had been converted by Hawaiians into a mosaic of fishponds and associated ʻauwai (water channels), as well as salt pans and *Colocasia esculenta* pond fields.

Thirteen test trenches were placed within the Kewalo Wetlands area targeting aquatic cultural resources (e.g., fishponds, berms, ʻauwai) and based on georeferencing of 1848 and 1870 land award survey maps (Fig. 2). Buried natural marsh deposits and/or modified deposits were identified within 11 of the test trenches, including fishpond sediments (five trenches), man-made berms associated with fishpond edges or ʻauwai (four trenches), salt pan deposits (two trenches), and agricultural soil (one trench).

Eight soil column samples were collected for microfossil analysis. These included two samples from a fishpond identified as "Kalaau's Fish Pond" on the 1848 survey map (T-02: Sample 1 from 93-95 cmbs; Sample 2 from 96-100 cmbs), two samples from a salt pan basin and the marsh soil substrate (T-10: Sample 3 from 194-217 cmbs; Sample 4 from 217-240 cmbs), two samples from the agricultural deposit (T-32: Sample 5 from 125-140 cmbs; Sample 6 from 140-154 cmbs), and two samples from a fishpond identified as "Piikoi's Fish Ponds," one of which consisted of the interpreted marsh soil substrate (T-33: Sample 7 from 122-124 cmbs; Sample 8 from 136-138 cmbs) (Fig. 2).

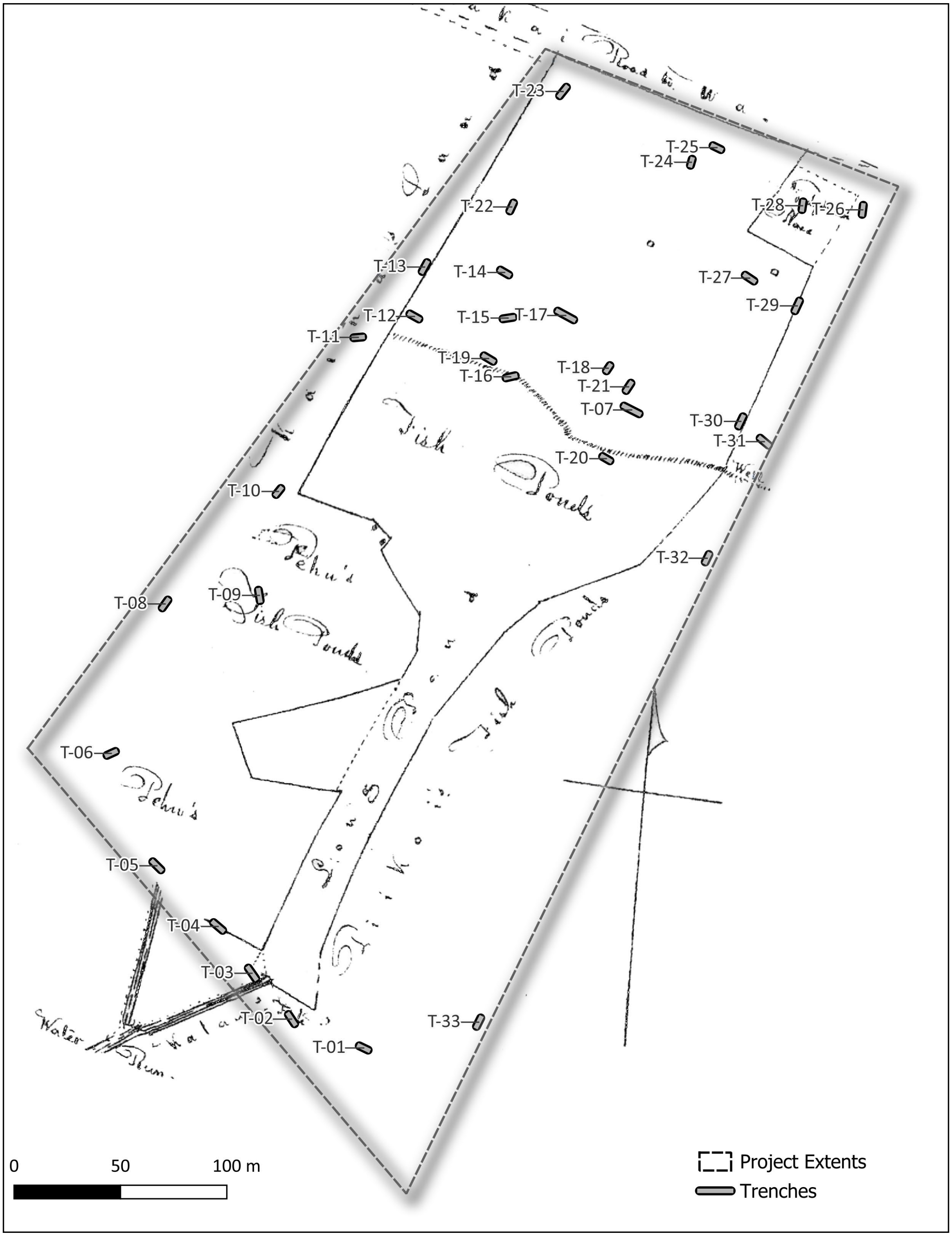

Figure 2: Location map of Blaisdell Center, Oʻahu (Source: LCA 274, map awarded to Joseph Booth) showing overlay of excavated trenches.

2.3. Kawela, Molokaʻi

Molokaʻi's south coast has expansive offshore shallows that in most places was formerly bordered by an accessible fringing reef, ideal for the construction of fishponds (Handy *et al.* 1991). The reef is approximately 30 miles long and deemed the longest continuous reef system in the United States (Nature Conservancy and East Molokaʻi Watershed Partnership 2019). Because of this configuration, this portion of the island's south shore contains the highest concentration of saltwater fishponds of any coast in the Hawaiian Islands (Handy *et al.* 1991). Kanoa Fishpond in Kawela was once one of the largest fishponds on the island (Estioko-Griffin 1987). The coastline in this region could have changed majorly over time due to sedimentation, as alluvial processes washed soils down the slopes above the coastal flats. At least one historic map shows a buried segment of the Kanoa Fishpond wall extending inland, suggesting that the coastline was further inland than it is today (Howell 1936).

A recent archaeological inventory survey of a residential property in Kawela, on the southern coast of Molokaʻi, was carried out just inland of the visible portion of Kanoa Fishpond (McElroy & McElroy 2023) (Fig. 1). While no surface remains of Kanoa Fishpond were found on the property during this survey, the fishpond is still extant offshore. What is thought to be the buried fishpond wall was identified within one of four excavated trenches during the survey. The wall consists of 10-40 cm diameter basalt cobbles and stones forming a flat surface at 120 cm below the current ground surface. The buried wall crossed the trench and likely continues beneath the surface, connecting to the visible portion of the fishpond in the ocean. The wall exposure in the trench was 2.1 m wide, approximately the same as that of the extant fishpond wall off the coast.

Stratigraphy in the trench differed on either side of the buried wall. The east side, outside the fishpond wall, was characterised by alluvial layers with intrusive lenses above a natural beach deposit. Charcoal flecking was observed in the upper lens, although no fragments were large enough to collect for 14C analysis. The west side of the trench, inside the wall, exposed alluvial layers above a possible fishpond deposit. The sample analysed for this study was collected from 130 cm below the current ground surface from the possible fishpond deposit, which could have formerly been located on the interior of Kanoa Fishpond.

3. Materials and methods

Samples were prepared for pollen analysis by the standard acetolysis method (Moore *et al.* 1991, Horrocks 2020). The preparations were stained with basic fuchsin and slides were mounted on glycerol jelly. For Waiohuli Kai and Blaisdell Center, where possible, a sum of at least 100 pollen grains and spores was counted. Palynomorphs were sparse in several Waiohuli Kai samples, with Samples 7, 9, and 10, giving counts of 25, 77, and almost zero, respectively. Microscopic charcoal fragments (not analysed) were extracted, along with pollen.

Phytoliths were separated from the sediment samples by density separation (2.3 specific gravity) with sodium polytungstate (Horrocks 2020; Pearsall 2015). Slides were mounted on Canada balsam. For all sites, where possible a sum of at least 100 phytoliths was counted for each sample, and slides were scanned for types not found during the counts. Slides with insufficient phytoliths for meaningful counting were still scanned for occasional palynomorph types. Other biosiolicates were not included in the sum from which the percentage frequencies were calculated.

Starch and associated material were separated from the sediment samples by density separation (1.8 specific gravity) with sodium polytungstate (Horrocks 2020; Pearsall 2015) and presence/absence noted. Slides were mounted on glycerol jelly. These remains can often be found in pollen preparations, despite the harsh chemicals used in that treatment.

Identification of pollen, phytoliths, starch, xylem, phenolic inclusions, and other microfossils found in this study was aided using a modern reference collection of specimens of species cultivated by Polynesians. The collection is housed at Microfossil Research Ltd., Auckland. Descriptions and photomicrographs of modern reference of material identified are given in the works of Reichert (1913), Cranwell (1942), Selling (1947), Seidemann (1966), Loy *et al.* (1992), Horrocks *et al.* (2012a, 2012b, 2017, 2023, 2024), Horrocks & Thomas (2022), and Horrocks and Weisler (2006). The software package Tilia 2.6.1 was used to construct the graphical diagrams. Photomicrographs of cultigen microfossils were taken with a Canon EOS 600D camera mounted on a Nikon 400E microscope. Measurements were made using a calibration slide.

4. Results

Results are presented graphically in Figures 3-5 and photomicrographs of selected microfossils are shown in Figure 6.

4.1. Waiohuli Kai, Maui

All samples from this site contained microscopic charcoal fragments. All samples except Sample 10 contained sufficient pollen and spores for meaningful counting. The lowermost core sample was dominated by fern spores, with a small amount of Poaceae pollen (Fig. 3A). Poaceae pollen then increased majorly, followed by peaks in Cheno-Am and cf. *Morinda trimera* pollen. Several introduced pollen types were found, namely *Aleurites moluccana* (Fig. 6A), *Casuarina equisetifolia*, *Cichorieae*, *Pinus* (pine), *Plantago lanceolata*, *Podocarpaceae*, and *Zea mays* (maize) (Fig. 6B). The latter five are modern introductions, and first appear in the core in Sample 5, with *Pinus* dominating the assemblages thereafter.

The phytolith assemblages were overwhelmingly dominated by several types of Poaceae leaf phytolith (Fig. 3B). Other biosilicates comprised very small, insignificant amounts of diatom tissue fragments in two samples (one fragment each per slide preparation).

Two types of starch were identified in this study. The first type, identified in all samples, comprised degraded amyloplast (sub-cellular units that synthesise and store starch grains) fragments of the corms of cf. *Colocasia esculenta* (Fig. 3B). In addition, xylem cell (tracheary tissue) fragments (Fig. 6G) consistent with this species were observed in several samples. The other type of starch, found in Sample 10, comprised clumps of degraded starch grains, some composite, and much larger in size and different in shape than the cf. *C. esculenta* starch grains.

4.2. Blaisdell Center, Oʻahu

The pollen assemblages of Sample 4 from T-10 and Samples 5-8 from T-32 and T-33 were dominated by Cyperaceae (sedges) pollen (Figure 4A). Small to moderate amounts of Poaceae and Cheno-Am pollen and small amounts of *Potamogeton* and *Ruppia* pollen were also observed. The remaining two samples, 1 and 2, differed from the other samples by having much larger amounts of *Cibotium* tree fern spores and monolete fern spores. Pollen of several introduced taxa was noted, namely Cichorieae and *Cocos nucifera* (coconut) (Fig. 6C) in several samples. *Pandanus tectorius* (screwpine) pollen (Fig. 6D) was found in Sample 7. A small number of marine dinoflagellate cysts was observed in Sample 8.

Samples 4-6 and 8 contained insufficient phytoliths for meaningful counting. The phytolith assemblages of the remaining samples were dominated by Arecaceae (palms) and Poaceae. In Sample 5, a "ruffle-top" rondel phytolith from the cob of *Zea mays* (maize) (Fig. 6E), was identified (Piperno 2006) (Fig. 4B). Other biosilicate material, identified in almost all samples, comprised diatom and sponge spicule fragments.

One type of starch was identified at this site. This type comprised small amounts of degraded amyloplast remains of the corm of introduced cf. *Colocasia esculenta* (Fig. 6F). In addition, a large amount of cf. phenolic inclusions of the skin of the corm of this species was observed in Sample 7 (Fig. 6H). Other plant material identified in this analysis included cell sheets of cf. *Freycinetia* in Samples 4-8.

Non-marine snails were found within all wetland, fishpond, and agricultural soils (Fig. 4A, B). These were dominated by two species, *Tryonia* sp. cf. *porrecta* and *Terebria granifera*, with a third, *Physa* sp. cf. *acuta*, also well-represented. *Assiminea parvula* and *Pomacea canaliculata* (apple snail) were each present in a singular context. *Tryonia porrecta* is an indigenous fresh or brackish water snail which is often found in fishpond and *Colocasia esculenta* field soils. *Tarebia granifera* is introduced to the Hawaiian Islands, possibly by Polynesians; it is a freshwater snail that can tolerate brackish water (Smithsonian Environmental Research Center 2022). *Physa acuta* is an introduced fresh-brackish water species from North America. It was first noted in the islands in 1905 within the Kewalo Wetlands by C. M. Cooke, Jr. (Christensen 2013). *Assiminea parvula* is a fresh-brackish indigenous snail that inhabits the shoreline on rubble. *Pomacea canaliculata* is an invasive fresh-water species from South America, tolerant of relatively low salinity levels (Department of Land and Natural Resources 2022). The snails cause serious damage to *C. esculenta* and *Oryza sativa* (rice) plants. Notably, *P. canaliculata* was found solely within interpreted *C. esculenta* agricultural soils (T-32).

4.3. Kawela, Molokaʻi

The sample from this site contained an extremely low concentration of organic material, including microscopic charcoal fragments. Pollen and spore analysis yielded only a single spore, of *Lycopodium cernuum* (Fig. 5). This analysis also yielded a single foraminiferal organic lining.

Sufficient phytoliths were preserved in the sampled deposit to allow meaningful counting. The assemblage was dominated almost entirely by Poaceae leaf phytoliths, with a negligible amount of non-Poaceae phytoliths (Fig. 5). A large amount of other biosilicates, in this case fragments of diatoms and sponge spicules, were also observed in the sample.

Starch analysis did not provide any evidence of horticulture in the area. This analysis also yielded a single foraminiferal organic lining (Fig. 5).

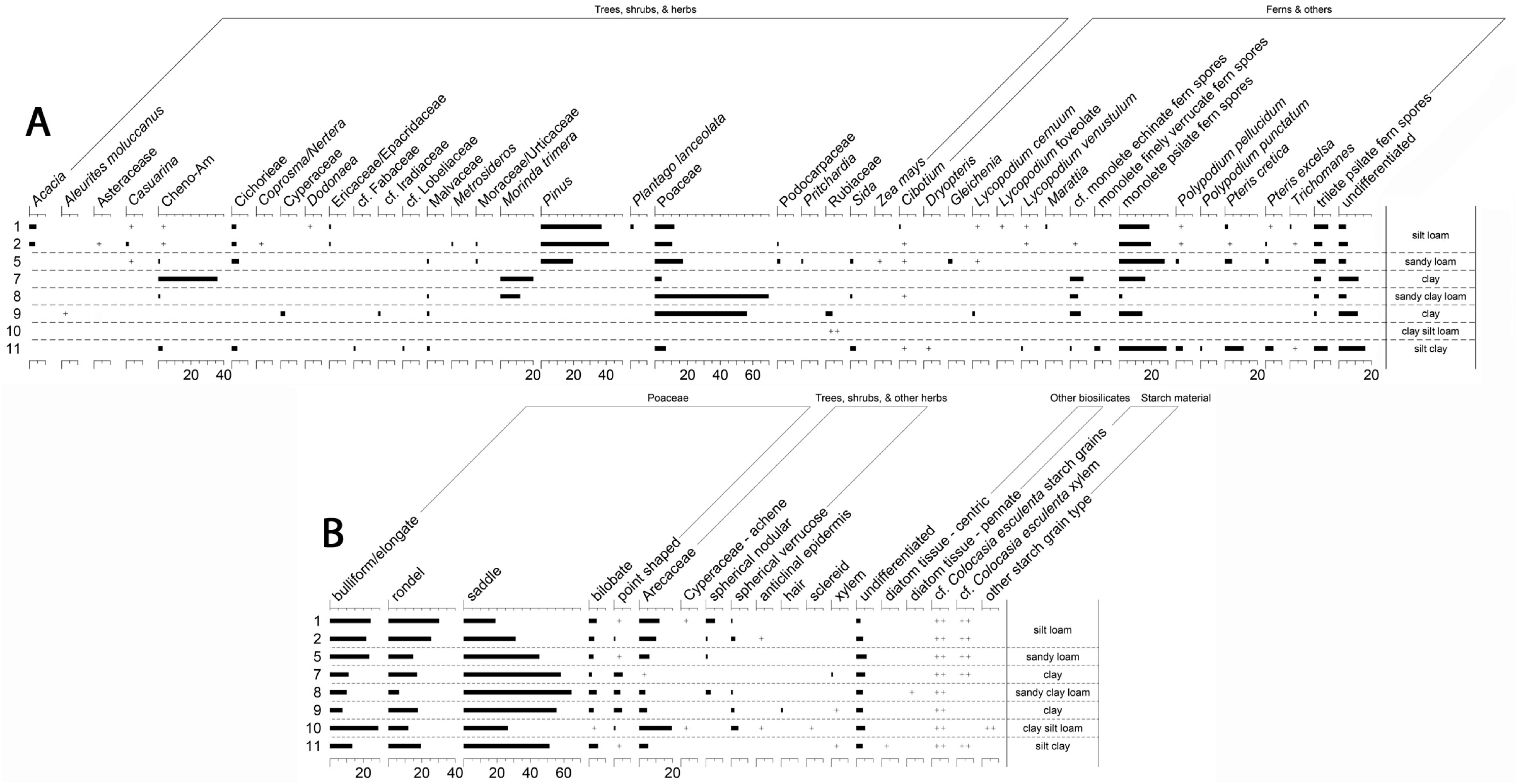

Figure 3: (A) Palynomorph and (B) phytolith percentage diagrams from Waiohuli Kai (+ = found after count, ++ = present).

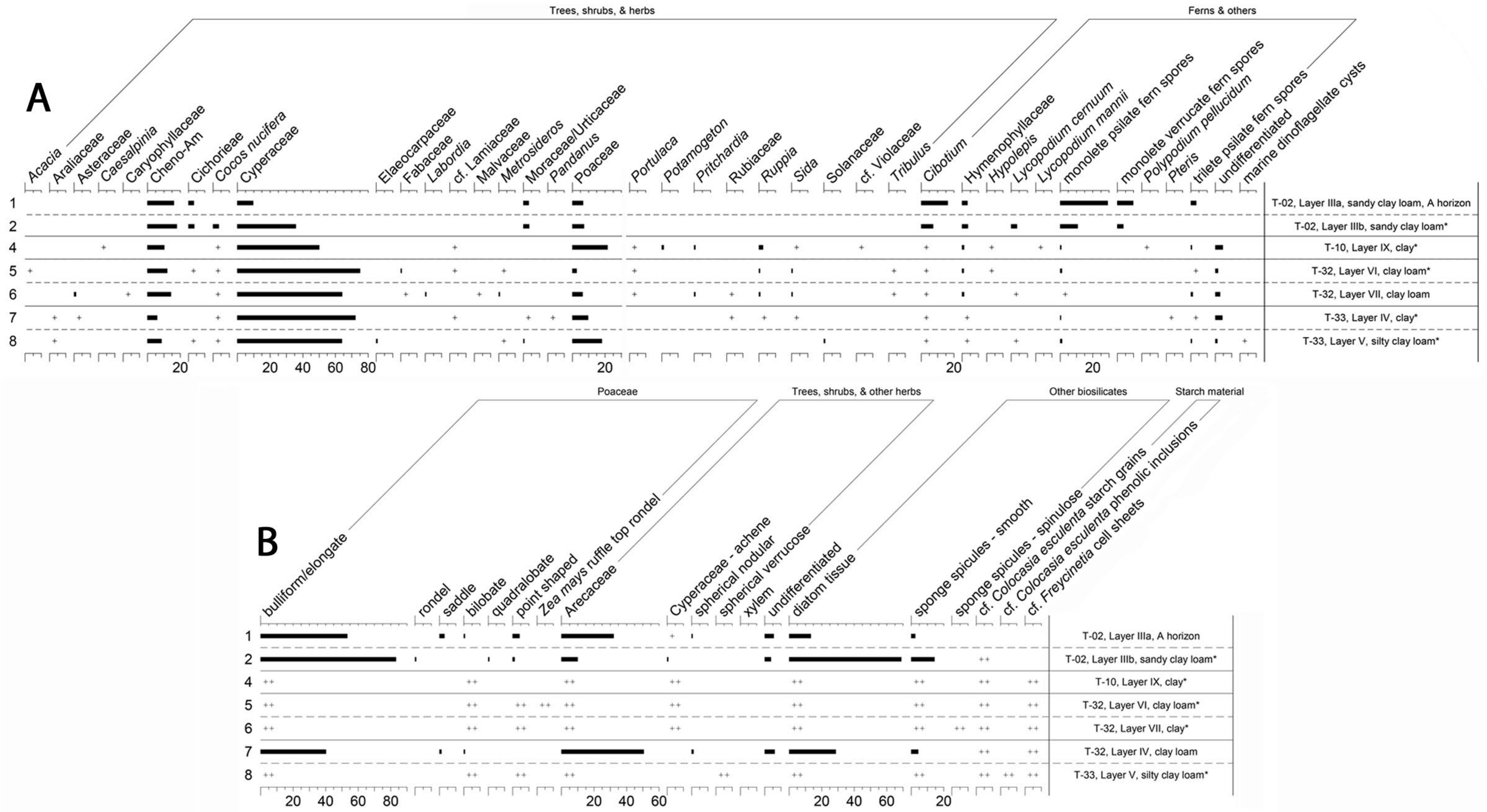

Figure 4: (A) Palynomorph and (B) phytolith percentage diagrams from Blaisdell Center (+ = found after count, ++ = present, *brackish water gastropods).

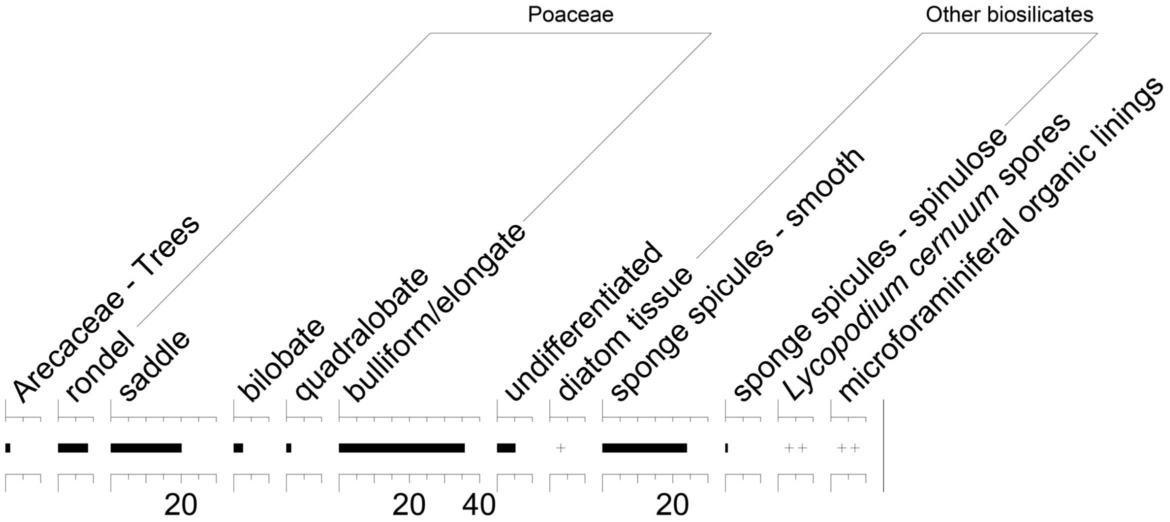

Figure 5: Palynomorph percentage diagram from Kawela (+ = found after count, ++ = present).

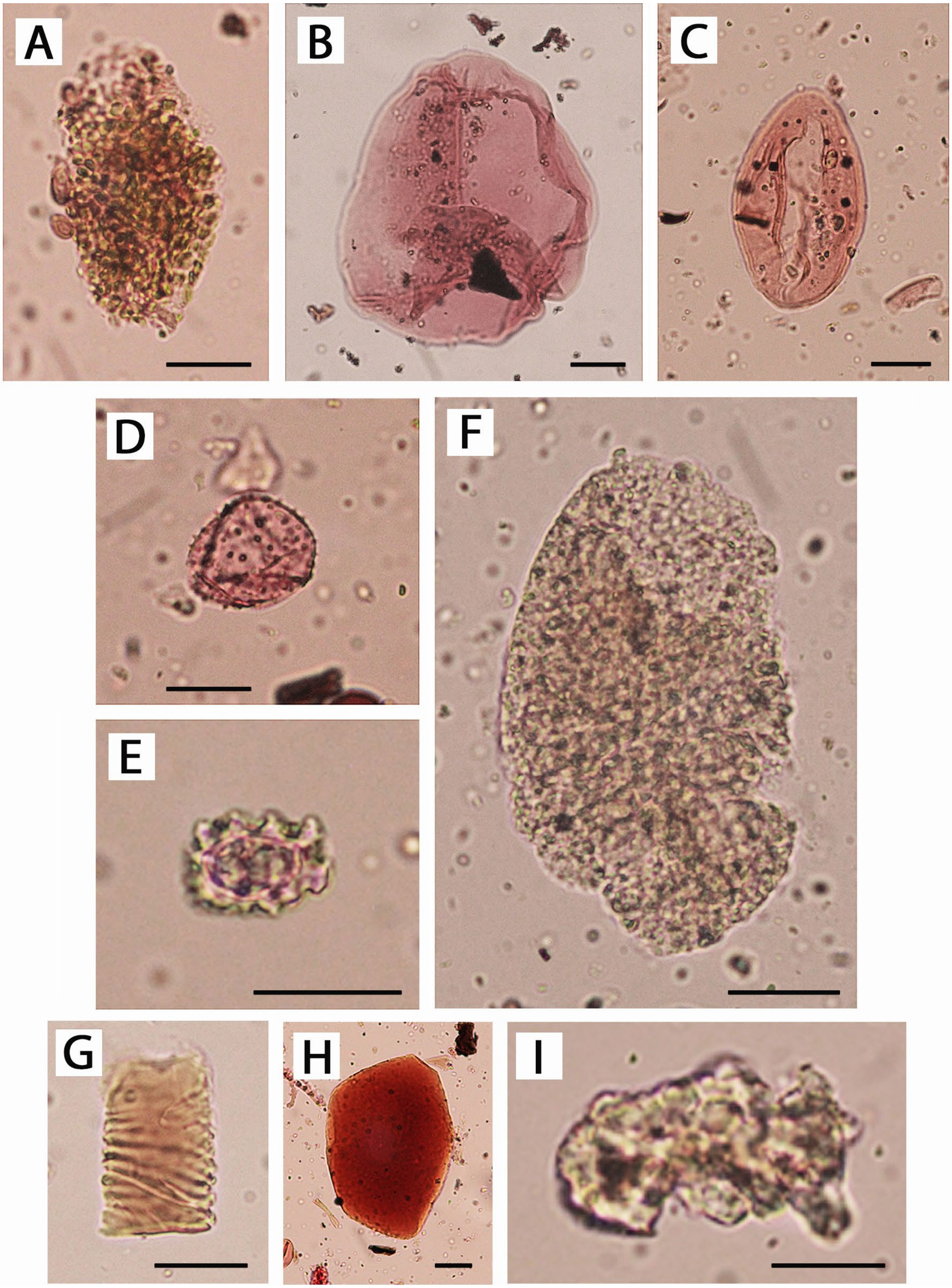

Figure 6: Cultigen microfossils from sites. Sample labels in brackets; 600x; scale bars: 20 µm. (A) (Waiohuli Kai 9) Damaged *Aluerites moluccanus* pollen grain, showing characteristic brown color,

described by Cranwell (1942) as having crowded blunt spines, and by Selling (1947) as having free, rodlike projections forming an apparent reticulum of minute lumina. (B) (Waiohuli Kai 5) *Zea mays* pollen grain, with pore shown near upper left edge. (C) (Blaisdell 8) *Cocos nucifera* pollen grain. (D) (Blaisdell 7) *Pandanus tectorius* pollen grain. € (Blaisdell 5) *Zea mays* ruffle-top rondel phytolith. (F) (Blaisdell 6) Degraded amyloplast of cf. *Colocasia esculenta* corm, showing characteristic densely packed, tiny, sharply angular starch grains (100s). Central grain vacuole typically seen as a dark grey or black dot. (G) (Waiohuli Kai 2) Xylem vessel fragment cf. *Colocasia esculenta* corm, showing characteristic helical wall thickening. (H) (Blaisdell 8) Phenolic inclusion of cf. *Colocasia esculenta* corm. (I) (Waiohuli Kai 10) Clump of other, unidentified starch type, showing relatively larger starch grains, with facets visible on the two grains upper centre.

5. Discussion

5.1. Waiohuli Kai, Maui

The Poaceae pollen and monolete psilate fern spores, coincident with the Cichorieae pollen and charcoal fragments to the full depth of the core, indicate open vegetation disturbed by people (Fig. 3A). Monolete fern spores, bean-shaped and difficult to differentiate, are produced by numerous indigenous ground fern species (Selling 1948). The Cheno-Am pollen type is from the Chenopodiaceae and Amaranthaceae, both comprising small trees, shrubs, and herbs, pollen of which is difficult to differentiate. The tree/shrub *Chenopodium oahuense* is a likely candidate (Athens *et al.* 2002).

Aleurites moluccana is a Polynesian introduction to the Hawaiian Islands. The Cichorieae is a plant tribe comprising many invasive species following disturbance. As the Hawaiian Islands have no indigenous members of the Cichorieae, this pollen type is presumably of the *Sonchus* genus, a probable accidental Polynesian introduction, and in Sample 5 when the first European effects are observed (*Casuarina*, *Pinus*, *Plantago*, *Podocarpaceae*, and *Zea*), and in overlying samples, could also be European-introduced *Taraxacum officinale* (dandelion) (Arthur Whistler, pers. comm.) (Fig. 3A).

Although the Poaceae tends to be over-represented in phytolith spectra, the phytolith evidence supports the pollen and spore evidence of vegetation disturbance (Fig. 3A, B). The lack of other biosilicates in the core, notably diatoms and sponge spicules, strongly suggest little, if any, direct association with marine environments. This does not necessarily preclude a location directly adjacent to such an environment, however.

The evidence thus suggests a transition in the area from fernland with grasses, to mostly grassland, with a mid-core change to shrubby (Cheno-Am and Morinda trimera) vegetation (Fig. 3A). After European contact, there appears to have been a return to fernland with grasses, along with Pinus plantings in the region.

The presence of Polynesian-introduced cf. Colocasia esculenta starch throughout the core reflects the importance of this crop in Hawaiian agriculture, from precontact times and continuing after European contact (Fig. 3A). Microfossils of this cultigen, including starch, and pollen of several other cultigens have been identified at one other Hawaiian Island site, namely Hālawa Valley, Molokaʻi (Kirch *et al.* 2024).

The other type of starch, in Sample 10, could be from several other possible starch-rich, cultigen candidates, including *Alocasia mycorrhiza*, *Ipomoea batatas*, *Piper methysticum,* and *Tacca leontepaloides*. While well-preserved starch grains of these three species can show features allowing differentiation, decay, as in this case, can blur such differences. The presence of *Zea mays* pollen in Sample 5 marks the start of inclusion of European-introduced cropping in the catchment.

5.2. Blaisdell Center, Oʻahu

The dominance of Cyperaceae pollen and presence of pollen of the aquatics Potamogeton and Ruppia in the lower part of the profile (Samples 4-8) reflects local wetland conditions (Fig. 4A). The major increase in Poaceae pollen in Sample 3, immediately followed by a decline in Cyperaceae pollen and increase in Cibotium tree fern spores and monolete fern spores, indicates a change to drier conditions. Most pollen grains from the Poaceae are difficult to differentiate because of their general morphological similarity, although in this case, based on size, exine pattern, and pore characteristics, the grains appear to be of one type, suggesting a single species. The Cibotium tree fern spores and monolete fern spores in the uppermost two samples also reflect drier conditions.

The cultigen *Cocos nucifera* is a Polynesian introduction to the Hawaiian Islands (Whistler 2009). Some of the Cheno-Am and Poaceae pollen could be from modern introductions. The cultigen *Pandanus tectorius* is indigenous (Whistler 2009).

This poor phytolith preservation in some of the samples is presumably due to the high alkalinity of the sampled substrates. Phytoliths tend to be poorly preserved in alkaline environments (Piperno 2006). The *Zea mays* cob phytolith in Sample 5 reflects introduced European cropping (Fig. 4B).

The other biosilicate material identified at this site, namely fragments of diatoms and sponge spicules (along with the marine dinoflagellate cyst in Sample 8) reflect the local coastal environment (Fig. 4A, B). The fragmentation is a result of physical damage during redeposition. Most of the diatoms were the aquatics Campylodiscus and Hyalodiscus. The former genus is epipelic (grows on mud), while the latter is epiphytic (grows on objects).

The cf. *Colocasia esculenta* starch type identified in most of the samples reflects introduced Polynesian cropping (Fig. 4B). The cf. Freycinetia cell sheets are consistent with those of the adventitious roots of this genus of woody climbers indigenous to much of the Pacific region (Flexner *et al.* 2024) (Fig. 4B). The inner portion of the often-wiry roots, adapted for attaching the climber to tree trunks, was utilised by ancient people for a variety of purposes (Whistler 2009).

5.3. Kawela, Molokaʻi

Although the pollen and spore assemblage of the sample from this site comprised only a single *Lycopodium cernuum* spore, this species tends to reflect disturbed, open vegetation (Fig. 5). The overwhelming dominance of Poaceae leaf phytoliths in the sample certainly indicates such an environment.

The large amount of the other type of biosilicate found in the sample, namely sponge spicules, reflects an aquatic environment (Fig. 5). Although sponges are found in both salt and freshwater environments, the coincident foraminiferal (exclusively estuarine/marine environments) evidence very strongly suggests a saline source.

6. Conclusion

The pollen records in this study are generally consistent with those of the Polynesian period in previous fishpond pollen studies of the Hawaiian Islands. The presence of Polynesian-introduced Cichorieae pollen in the lowermost sample of the Waiohuli Kai, Maui and in the natural marshland deposits at the Blaisdell Center, Oʻahu indicates that those analysed substrates are of post-settlement age. Lack of pollen or any other dating data in the Kawela, Molokaʻi sample precludes any age determination.

The large amounts of Arecaceae and Poaceae phytoliths in the results are partly because of over-representation in Hawaiian Island (and elsewhere) phytolith spectra due to very high phytolith production (mostly in their fronds and leaves) compared with most other families. In a Hawaiian Island context, the Arecaceae phytoliths are from *Pritchardia* spp. or *Cocos nucifera*.

The foraminiferal, dinoflagellate, diatom, sponge spicule, and snail remains from the Blaisdell Center and Kawela sites show a strong aquatic/brackish environment, most likely a direct fishpond association. Lack of these types of remains in the Waiohuli Kai samples indicates that the immediate core site was in proximity, rather than part of, the local fishpond.

The study identifies a range of different crops, indigenous and Polynesian and European introduced, including *Aleurites moluccana*, *Cocos nucifera*, *Colocasia esculenta*, *Pandanus tectorius*, and *Zea mays*, indicating multi-cropping in the vicinity of the ponds or elsewhere in the associated catchments. The fishponds on Oʻahu, Molokaʻi, and Maui mirror the development of large fishponds on Hawaiʻi Island in the centuries before European contact. Elaboration of kapu (tapu) practices associated with the management of these ponds shows how valuable they were as a source of both food and prestige (e.g., Kirch 2000:298ff). The possible use of animal and human waste and food scraps used as fishpond fertiliser as a source of the microfossils can probably be ruled out (but not disproven) due to the chiefly prohibition against this (Wilder 1923, Titcomb 1952, Kikuchi 1976). The continuing use of the fishponds after European arrival and recording as part of land commission awards from the 19th century onwards (e.g., Fig 2), emphasises their integral function within Hawaiian social organisation, even as new crops were being grown across the islands.

The results show that surviving fishponds and their surrounds represent a useful sink of bio-archaeological evidence of Hawaiian aqua-agricultural activity. As plant species differ considerably in their production and preservation of tissues, results also show the value of the combined microfossil approach in increasing the range of identified environments and cultigen species.

Funding

This research received no external funding

Data Availability Statement

Data available on request from the authors

Partnerships

This research did not use any primary data from Indigenous contexts

Conflicts of Interest

The authors declare no conflicts of interest

Author Contributions

Conceptualization, M.H.; methodology, M.H.; formal analysis, M.H.; investigation, E.S., J.S., M.M., W.M., and T.L.-G.; writing—original draft preparation, M.H., E.S., J.S., M.M., W.M., T.L.-G., and S.B.; writing—review and editing, M.H. and S.B.; All authors have read and agreed to the published version of the manuscript.

Acknowledgements

The coring study for Waiohuli Kai was completed as a part of a native plant restoration project. We acknowledge ʻĀinakūkoʻa O Waiohuli Kai and the cultural descendants of Waiohuli Kai, Kawela, and Honolulu. We thank the Paragas ʻOhana (the Kawela landowner), the Blaisdell Center landowner, and the City and County of Honolulu for supporting this project.

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