MICROFOSSIL ANALYSIS OF TERRESTRIAL SEDIMENTS FROM AN AGRICULTURAL SITE IN THE QARAQARA DRAINAGE, VITI LEVU, FIJI: DEFORESTATION AND EARLY AGRICULTURE IN THE SIGATOKA VALLEY

by

Rebecca E. Hazard

A thesis
submitted in partial fulfillment
of the requirements for the degree of
Master of Science in the Department of Anthropology
Idaho State University
December 2017

Acknowledgements

This research was supported by NSF Award # 1216330 as part of the collaborative proposal “Investigating the Subsistence Transition in Post-Lapita Fiji (2500-1500 BP)” (PIs Julie Field, Chris Roos, John Dudgeon), as well as NSF Awards 1216310 and 1523409, the Idaho State University Career Center, and the Idaho State University Office for Research.

I would first like to thank my advisor, Dr. John Dudgeon, for introducing me to and encouraging my interest in archaeological laboratory analysis. His enthusiasm for scientific research and desire for continuous improvement has been a constant source of inspiration during my time at ISU. I am extremely grateful for Dr. Julie Field’s guidance during two field seasons in Fiji and for her helpful editorial advice on this thesis. I am also grateful for the very helpful editorial assistance and comments of Dr. Katherine Reedy and Dr. Leif Tapanila. Many thanks go to Dr. Christopher Roos for providing the core sediment and supporting data used in this thesis, and to Amy Commendador for the direction she provided with modern plant sample collection. I would also like to acknowledge the valuable assistance provided by The Fiji Museum, the Nadroga/Navosa Provincial Office, and the many Fijian people who made my time in Fiji a joyful and unforgettable experience.

Finally, I am forever grateful for the love and support of my family and friends: Lisa, David, Daniel, Bryan, Caitlin, Amanda, Alan, and Dane. I could not have done this without you.

Table of Contents

List of Figures

List of Tables

Abstract

MICROFOSSIL ANALYSIS OF TERRESTRIAL SEDIMENTS FROM AN AGRICULTURAL SITE IN THE QARAQARA DRAINAGE, VITI LEVU, FIJI: DEFORESTATION AND EARLY AGRICULTURE IN THE SIGATOKA VALLEY

Thesis Abstract – Idaho State University (2017)

Sediment analysis can provide a wide range of data from archaeological contexts. This thesis uses silica phytoliths extracted from sediment sampled from a terrestrial core collected at an agricultural site in the Qaraqara drainage of the Sigatoka Valley, Viti Levu, Fiji, in order to address questions surrounding the Post-Lapita period subsistence transition from foraging to food production (1500-2500 BP). Over time, an increase in *Poaceae* (grass) phytoliths and a decrease in tree and shrub taxa phytoliths was observed, indicating an event of deforestation taking place. While there appears to be some low-level deforestation occurring before the arrival of humans, approximately 2800 to 3000 years BP, the process becomes much more intense around the time the first non-native taxa, *Musaceae* (banana), is detected in the record. As edible banana species require humans for propagation, its occurrence provides evidence for cultivation in the Sigatoka Valley soon after the first people colonized Fiji.

Chapter 1. Introduction

Sediment Analysis – Landscape Change and Use Over Time

Sediment from archaeological contexts can provide a wide range of data with the ability to inform on landscape change over time, whether it be natural or the result of human activities. Through the analysis of sediment, researchers can infer how a site has been altered or what types of human activities, like agriculture or the domestic processing of material (e.g. food preparation or item construction), have taken place at specific points in time. The benefits of using sediment, which is part of the geomorphic landscape, as the source of data are numerous, especially as it is considered to be "the platform on which all biological organisms… have evolved, lived, and interacted through time," (Waters 1992:12). In an anthropological and archaeological context, sediment is in many cases not considered to be sensitive material and is not as closely controlled as artifacts or human remains. Extensive columns of sediment can be obtained without the need for a full-scale excavation; for example, terrestrial cores are a low-impact strategy for sample collection. Extending several meters in depth, they produce a large volume of material for sampling. Analyses can be performed at several points of a site if necessary. Finally, contained within just a few grams of sediment is a great variety of material available to aid in answering a wide range of questions, like those related to the reconstruction of a dynamic environment and the natural and cultural processes

that contributed to the formation of a site. Archaeologically significant materials available for analyses include: micro and macro-botanical remains; faunal remains; the carbon derived from micro and macro-botanical remains in sediment, which is valuable for stable isotope analysis to determine the fluctuations in the abundances of C3 and C4 plants over time and thus, general environmental conditions (Roos et al. 2016); and the geologically-derived portion of sediment. Geoarchaeological and micromorphological analysis of sediment is another strategy for landscape reconstruction by determining site formation processes, both natural and cultural. Using stratigraphic principles, the vertical sedimentary context of a site can be placed within a temporal context through the application of absolute and relative dating techniques (Waters 1992; Weiner 2010).

Ecofacts, biologically-derived material that remains after the decomposition of plants or animals, can be extracted from sediment and used to reconstruct the past ecological conditions of a site. Micro and macro-botanical remains can be used to determine the presence and changing frequencies of specific plant taxa, which can be useful for determining season of occupation (Weiner 2010:41), agricultural activity (Prebble et al. 2012), and environmental changes (Lentfer et al. 2002). Carbonized plant material charcoal can be used to derive radiocarbon dates, in addition to providing fire histories (Roos et al. 2016; Whitlock and Larsen 2001). Several types of micro-botanical remains, also referred to as plant microfossils, such as silica phytoliths (Bremond et al. 2005; Horrocks 2005; Iriarte and Paz 2009), diatoms (Dudgeon and Tromp 2012; Weiner 2010), starches (Lentfer et al. 2002;

Tromp 2012), pollens (Hope et al. 2009; Fall 2010), calcium oxalates (Crowther 2009) have been used for plant taxa identification. For this thesis, I have chosen to utilize silica phytoliths in order to reconstruct the patterns of landscape change over time at an agricultural site in Fiji. Silica phytoliths are microscopic biogenic opal particles produced in the tissues of many different plant taxa. There are many benefits to targeting phytoliths for analysis. Silica phytoliths are not as mobile as pollen grains, which are easily dispersed over great distances by wind, and therefore have the ability to provide a more site-specific dataset. Calcium oxalates and starches, found in tubers and some fruits, are highly susceptible to degradation in conditions where silica phytoliths have the ability to survive. The identification and quantification of phytoliths for paleoenvironmental reconstruction has proven to be valuable at archaeological sites all over the world, including, but not limited to, Hawai'i (Pearsall and Trimble 1984), Vanuatu (Horrocks and Bedford 2004), New Zealand (Horrocks et al. 2003), Easter Island (Horrocks et al. 2012), Cameroon (Bremond et al. 2005), and Uruguay (Iriarte and Paz 2009).

Post-Lapita Subsistence Transition in Fiji's Sigatoka Valley

One of the primary goals of this project, and the larger project it is a part of, is to understand the nature of the Post-Lapita-era subsistence transition that took place in Fiji's Sigatoka Valley between 1500 and 2500 years BP. When and how did agriculture become the main mode of subsistence in the centuries following initial colonization? What were the driving forces behind this major cultural change? While a significant amount of research has been done on the transition period and the

resulting changes in material culture and settlement patterns (Burley 2005; Burley and Edinborough 2014; Clark 2000; Field 2002; Field 2003a; Field 2003b; Field 2005; Field 2008b), this period is still not as well defined or understood as is the case for the Lapita phenomenon and its associated cultural complex (Clark and Anderson 2009; Green 2003; Kirch 2000; Spriggs 1984).

Fiji was colonized by humans approximately 2800 to 3000 years BP, with some of the earliest evidence for settlements at Bourewa (2950-3050 cal. BP) and in the Lau Group (2850-2900 cal. BP) (Clark and Anderson 2009). As the Lapita people are recognized as the first to colonize Fiji, it is important to understand who they were and where they came from. The Lapita people are believed to be descendants of a ceramic-making people who lived on the island of Taiwan approximately 5000 years BP, who eventually dispersed southward through southeast Asia during the "Austronesian Expansion". Pottery that is very similar in style to Lapita plainware, dated to around 3000 to 3300 years BP, has been found on Kayoa Island (see Figure 1.1) in eastern Indonesia. Early Lapita sites in the Bismarck Archipelago (see Figure 1.2) suggest that the distinctive Lapita "culture complex" emerged out of the Bismarcks as a fusion between Austronesian immigrants and indigenous Papuan cultures. This cultural fusion may be explained by the hypothesis that Lapita settlement was restricted to the Bismarcks for several centuries before the outward expansion (Clark and Anderson 2001). Between 2800 and 3300 years BP, the Lapita people expanded rapidly across Near and Remote Oceania (Kirch 2000:91-98). The Lapita are most commonly defined by their seafaring adaptations, coastal

settlements, reliance on marine resources, and dentate-stamped ceramics (Anderson et al. 2000; Spriggs 1984). Green (2003:110) explains that the "Lapita Cultural Complex" is defined by more than just a ceramic style. Other core components include: long-distance exchange networks; an adze kit; fishing gear; shell "ornaments" or functional items constructed primarily of *Conus* species shell; a tattooing complex, evidenced by an archaeological flying fox wing bone that appears to have served as a tattoo needle; and houses, which were ground-level and rectangle-shaped in Near and Remote Oceania, with stilt-style houses built over water in Near Oceania (Green 2003:110).

Figure 1.1. Map showing the geographic locations of Taiwan, Kayoa Island, and the Bismarck Archipelago (image from Google Earth).

With regard to Lapita subsistence strategies, as explained above, they are usually recognized primarily as foragers who relied on marine plants (e.g. sea grapes) and proteins (e.g. fish). Groube (1971) suggested that the Lapita colonizers were "strandloopers" who had an economy restricted to marine resources with negligible contributions from terrestrial flora and fauna; however, additional evidence has since replaced and reformulated Groube's hypothesis (Hunt 1981; Davidson and Leach 2001). Kirch (2000) has argued that the existence of evidence for permanent settlements and at least low-level horticulture has effectively disproved the strandlooper hypothesis. Evidence for horticulture suggests that Lapita colonizers traveled with "transported landscapes" that would have included familiar domestic animals and economically significant plant cultigens. Linguistic reconstructions of Proto-Oceanic words for crop plants and other words associated with horticulture have provided further evidence in support of the idea that the Lapita were more than mere foragers (Davidson and Leach 2001; Kirch 2000). Microfossil analysis on Lapita-era (3050 to 2500 cal. BP) deposits from Bourewa in Fiji identified introduced *Colocasia esculenta* (taro) and *Dioscorea esculenta* (yam) (Horrocks and Nunn 2007). Banana (*Musa*) phytoliths from Lapita-era deposits in Vanuatu further support the hypothesis that the Lapita did actively cultivate some food crops, as all banana in Remote Oceania are human introductions and require special care for propagation (Horrocks et al. 2009). Another study performed on Lapita-era deposits in Vanuatu used stable isotope analysis to determine that the subsistence strategies were likely mixed, with both terrestrial and marine dietary

contributions, as well as some from small-scale food production (Valentin et al. 2010). A stable isotope analysis done on Lapita burials on Watom Island in Papua New Guinea had similar results, indicating that terrestrial foods made up a high percentage of prehistoric diets at that site as well (Leach et al. 2000). Some studies suggest that subsistence strategies became more variable in the centuries following colonization, but remained largely dependent on geography when it came to utilizing marine and terrestrial resources. It has been determined that on small islands, like Waya in northwestern Fiji, diets remained predominantly focused on marine resources even as more terrestrial sources became incorporated into the food base (Field et al. 2009).

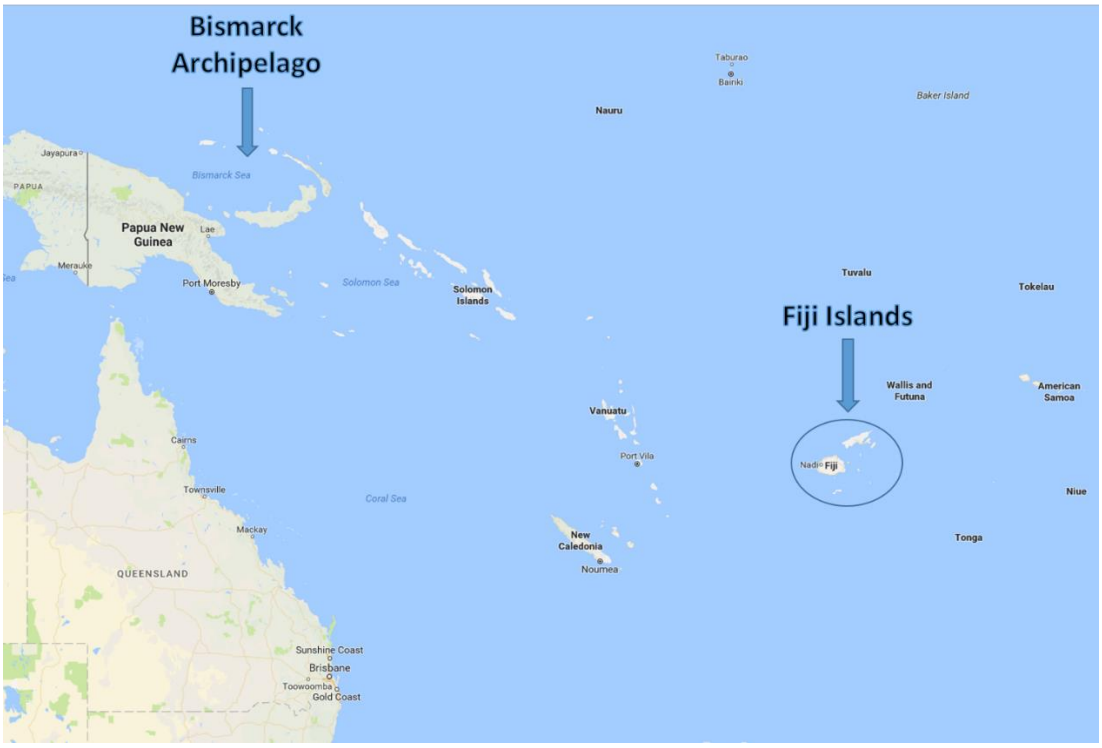

Figure 1.2. Geographic location of the Fiji Islands in relation to the Bismarck Archipelago (image from Google Earth).

The Post-Lapita period in Fiji is not yet as well-defined as the Lapita era, but is typically marked throughout the Pacific by the point in time at which ceramic styles begin to diverge and the dentate-stamped style associated with Lapita is no longer being produced. Throughout Near and Remote Oceania (i.e. the western and eastern regions of Oceania, respectively) this change generally occurs after 2500 years BP (Clark and Anderson 2009; Kirch 1984). In Fiji this era is referred to as the "Mid-Sequence" period and spans from 2500 to 1000 BP (Clark 2000). It has been viewed by some researchers as being the result of internal cultural processes and may have been the result of the end of long-term communication networks sustained during the Lapita period (Reepmeyer and Clark 2010; Spriggs 2003), possibly indicative of transformed religious practices or an economic response manifesting in material culture change (Burley and Dickinson 2004). Of these internal processes, a change in subsistence strategies has been acknowledged as a potentially significant influence for the role it may have played in the transformation of material culture. The shift from a primarily marine foraging adaptation to one focused on terrestrial resources and agricultural production may explain the observed changes in ceramic styles with relation to form and function. This hypothesis is further supported by a change in settlement patterns that led colonists to move inland in the following centuries, resulting in a rich archaeological record of agricultural and defensive features throughout the Sigatoka Valley (Clark 2000; Clark 2009; Field 2002; Field 2003a; Field 2004; Field 2005; Hunt 1986; Rechtman 1992).

Others view the mid-sequence change to have occurred far too rapidly to be the result of strictly internal processes; rather, they attribute it with demographic and social change caused by the arrival of new populations into Fiji (Best 2002; Burley 2005; Burley and Edinborough 2014). Burley's excavations at the Sigatoka Sand Dunes on Viti Levu revealed two distinct ceramic styles separated only by a thin layer of sand. The lower level was termed Fijian plainware (dated 1335-1516 cal. BP) while the ceramic in the upper layer has been termed Navatu-phase style (dated 1275-1340 cal. BP). It is argued that the close age ranges suggest a rapid transmission of the newer Navatu-phase ceramic style (Burley 2003; Burley 2005; Clark and Anderson 2009). Either way, the current research in progress, here and elsewhere, will hopefully provide more insight into the mechanisms responsible for these significant cultural changes.

Another still poorly understood feature attending the observed cultural change in Post-Lapita Fiji is the shift in diet and subsistence strategies. While the Lapita were originally accepted as having focused primarily on marine resources, new evidence now supports the idea that their subsistence economy was probably also characterized by variable amounts of terrestrial contributions from foraging, and possibly small-scale levels of horticulture (Davidson and Leach 2001; Field et al. 2009; Horrocks et al. 2009; Horrocks and Nunn 2007; Kirch 2000; Leach et al. 2000; Valentin et al. 2010). Post-Lapita dated materials indicate that as later populations moved inland they relied more heavily on terrestrial resources, and probably cultivated domesticates in permanent settlements, as evidenced by the presence of

archaeological agricultural and defensive features in the Sigatoka Valley (Field 2002; Field 2003a; Field 2004) and stable isotope analyses of Post-Lapita human and pig remains (Field et al. 2009). Stable isotope analysis on mid-sequence (1435-1300 cal BP) human burials from the Sigatoka Sand Dunes excavations revealed a mixed diet, with both marine and terrestrial dietary contributions (Phaff et al. 2016), further supporting the idea that geography is going to play a major role in subsistence strategies, like what has been observed on Waya (Field et al. 2009).

Yet to be determined is the precise nature of this subsistence transition; how, when, and why did it happen? What was the driving force, or forces, behind the change in subsistence from hunting and gathering to food production? One possible explanation is climate change and instability, especially in relation to the "1300 AD Event", or "Little Ice Age", as this phenomenon appears to correspond with subsequent dates of inland settlement throughout the Pacific (Kumar et al. 2006; Nunn 2007). In Fiji, this period of dramatic climate instability and sea-level change may have been the impetus for the significant human-societal changes that resulted in the abandonment of coastal settlements, the establishment of inland settlements (Kumar et al. 2006), and a diversification of diet based on more sustainable subsistence strategies in the event of resource depletion (Jones and Quinn 2009). As the inland settlements were often accompanied or identified by defensive features, we must also consider what the role of conflict and competition was in the Post-Lapita period (Field 2003a; Field 2008a), and what the implications may be for a subsistence economy now based primarily on agriculture.

A common agricultural technique used throughout the Pacific is swidden cultivation, or slash and burn. In order for land to remain viable, it must be allowed to lay fallow for as long as possible between growing seasons. In areas with small populations, finding a new section of land to cultivate while letting others lay fallow for the season is a common strategy to preserve land and maintain good standards of agricultural practice. In the lower Sigatoka Valley, however, there is evidence for an intense period of swidden cultivation that coincides with the appearance of defensive structures. The resulting erosion and deterioration of the land from shortened fallow periods remains evident today, where the lower valley hillslopes have since degraded into *talasiga* ("sun-burnt land") grassland. The establishment of fortifications, along with the shorter fallow periods, suggest that there may have been some level of demographic pressure influencing settlement patterns and agricultural practices at this time (Field 2004; Field 2005; Roos et al. 2016).

Among the literature currently published about Fiji's vegetation history, there seems to be a common finding, which is that Fiji was once much more forested than it is today. On the eve of the arrival of humans, approximately 3000 years ago, Fiji appears to have been a mix of dry forest and rainforest with some patches of naturally occurring grassland (Ash 1992; Hope et al. 2009). The decline and extinction of palm tree taxa specifically has also been correlated with the arrival of humans across the Pacific islands, including Fiji (Prebble and Dowe 2008). Today, only about 45% of the main islands are forested (Watling 2005). According to palynological data, the *talasiqa* grassland that now covers a major swath of the dry

side of Viti Levu was probably forested before the arrival of people; it is most likely the result of erosion induced by the over-use of fire for cultivation (Roos et al. 2016). A distinct change in vegetation around 2700 to 3100 years ago along with an increased and sustained signal of fire suggests humans quickly started to have a major impact on the landscape (Hope et al. 2009; Keppel and Tuiwawa 2007). Since the arrival of humans, Fiji's diversity of flora appears to have increased by about 50%, with most of the introductions being grasses and weeds (Ash 1992). This thesis seeks to use silica phytolith analysis to determine the nature of landscape vegetation change in the centuries following the initial period of colonization, especially at the advent of agriculture, at a site in the middle Sigatoka Valley.

The setting: Qaraqara Drainage Terrace Site (Lolevu)

The site that is the subject of this thesis, known as Lolevu or Qaraqara, is located near the middle Sigatoka Valley of Viti Levu, Fiji, Nadroga Province; it is named after the local drainage and creek and is comprised of an upper and a lower terrace which are both actively cultivated today. Naihehe Cave is approximately 500 meters to the south of the coring site and adjacent excavation unit; a small freshwater spring flows through this cave and across the northern half of the site. Geographic coordinates for the coring site are 17º 58' 57.26" S, 177º 37' 42.64" E (see Figure 1.). The lower terrace is the former site of Sautabu village, which was relocated in the 1920s due to seasonal flooding. The western half of this site was

converted to farmland in the 1970s, with the eastern half also being converted to farmland a decade later in the early 1980s. Today, the upper terrace, and site of the 2014/2015 excavation, is used primarily for the cultivation of *Manihot esculenta* (cassava) along with an assortment of other modern introductions, such as green beans and cucumbers, a large portion of which are sold at the weekly local market.

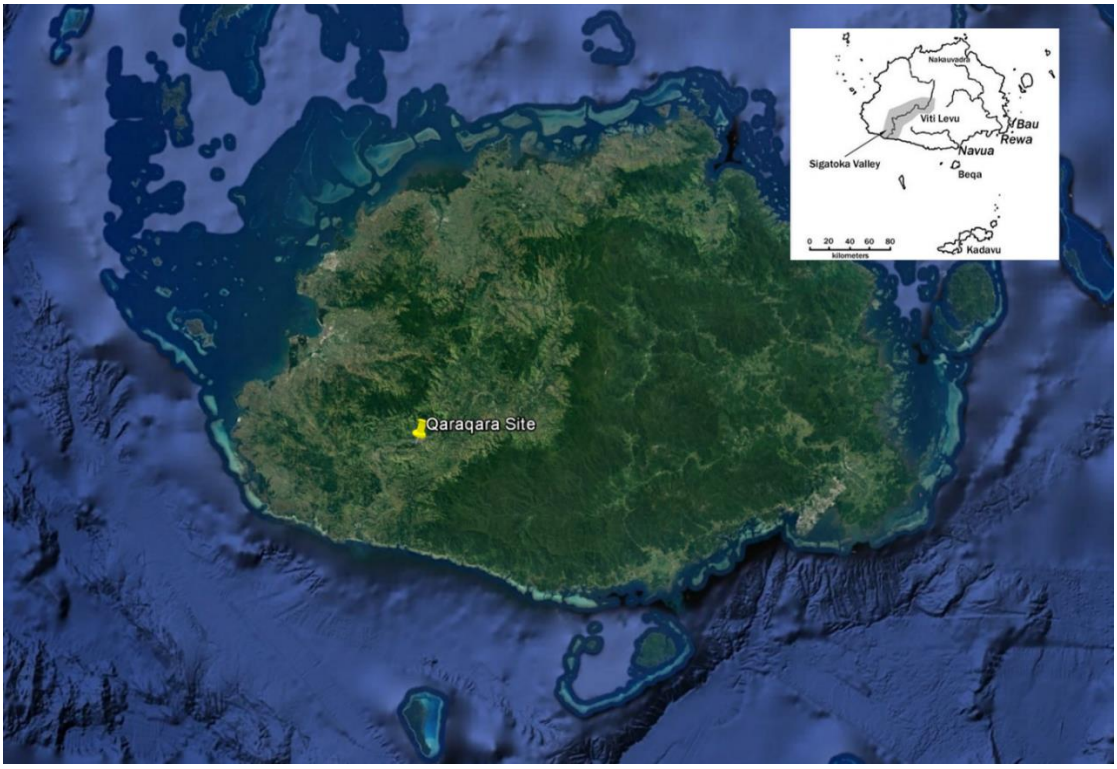

Figure 1.3. Location of the Qaraqara drainage excavation site (Image from Google Earth; inset from Field (2004)).

Microfossils

Microfossils in archaeology are defined as the floral and faunal-derived microscopic biogenic particles that preserve long after the original organism has

died and decayed (Piperno 2006). Some such examples of microfossils that have been analyzed from archaeological contexts are silica phytoliths (Dudgeon and Tromp 2012; Iriarte and Paz 2009; Lentfer and Boyd 2000; Piperno 2006), starches (Hardy et al. 2009; Henry and Piperno 2008; Lentfer et al. 2002; Piperno 2009; Tromp 2012; Tromp and Dudgeon 2015), pollens and spores (Hope 2000; Hope 2009; Horrocks et al. 2003; Prebble 2012), calcium oxalates (Crowther 2009; Sunell and Healey 1979), plant cellular tissue like trichomes and stomata (Piperno 2006), charcoal and carbon particles (Roos et al. 2016; Winterhalder and Kennett 2006), faunal spherulites, diatoms (Horrocks et al. 2003; Prebble et al. 2005; Tromp 2012), and sponge spicules (Tromp 2012). The absence or presence of certain microfossil taxa in sediment can be used to reconstruct paleo-climates and inform on if and when humans began altering the landscape through burning, agricultural activity, or processing of materials in domestic settings (Horrocks, Bulmer et al. 2008). Microfossil analysis provides a valuable proxy for inferring prehistoric environmental conditions as well as direct evidence for the presence of agricultural domesticates and other important subsistence cultigens (Horrocks, Smith et al. 2008; Iriarte and Paz 2009; Prebble et al. 2005).

This thesis uses silica phytoliths to provide vegetation-based evidence surrounding prehistoric landscape change and the Post-Lapita subsistence transition from foraging and small-scale horticulture to agriculture in the Sigatoka Valley during the period dating from 2500 to 1500 BP. Silica phytoliths, also commonly referred to as opal phytoliths, are composed of non-crystalline silicon dioxide (SiO_2)

and are produced by many plant species when amorphous silicic acid is deposited into a plant's epidermal tissues (Coil et al. 2003). The silicic acid solidifies into a variety of shapes and orientations, providing rigidity and strength to plant cell walls of leaves, bark/stalks, fruits, and seeds. The resulting morphological shapes that tend to survive even after the rest of a plant has completely decomposed can be diagnostic, allowing for the identification of specific plant taxa (Piperno 2006; Runge 1999).

Of course, there are some limitations to be aware of with this approach. First, not all plants produce microfossils and not all microfossils are diagnostic to specific taxa. It is very difficult, and impossible in some cases, to distinguish below the family level of many taxa; although, being able to identify down to this level is often more than sufficient to answer research questions, especially with regard to the process of deforestation where a researcher may only be interested in the changing frequencies of grasses versus trees (Bremond et al. 2005). Second, depending on the depositional context and taphonomic conditions of preservation, archaeological microfossils can be highly fragmentary or become lost to complete deterioration if exposed to high pH levels for extended periods of time (Coil et al. 2003; Jenkins 2009; Osterrieth et al. 2009). Finally, phytolith frequencies can vary not only between taxa but also within species, depending on the amount of available soluble silica (silicic acid) and moisture in the soil they were grown in (Piperno 2006). Despite these considerations, phytolith analysis has proven to be a valuable and reliable strategy for reconstructing archaeological diets, environment,

domestic activity, and landscape change over time (Bremond et al. 2005; Dudgeon and Tromp 2012; Henry et al. 2011; Horrocks and Rechtman 2009; Horrocks and Wozniak 2008; Horrocks et al. 2003; Iriarte and Paz 2009; Lentfer and Green 2004; Pearsall and Trimble 1984; Piperno 2006; Runge 1999; Tromp 2012).

Scanning Electron Microscopy Energy Dispersive X-ray Spectroscopy

The standard method of visualization in microfossil studies has been by optical light microscopy due to its low associated costs and the user's ability to manipulate particles in real time (Bremond et al. 2005; Fenwick et al. 2011; Horrocks 2005; Horrocks and Rechtman 2009; Horrocks and Weisler 2006; Iriarte and Paz 2009; Lentfer and Green 2004; Piperno 2009). For the imaging of the silica phytoliths analyzed for this thesis I opted to utilize scanning electron microscopy equipped with energy dispersive x-ray spectroscopy (SEM-EDS), due to its ability to better visualize topographic and morphological features beyond the practical limits imposed by optical light microscopy. There are several benefits to this visualization method, which has been employed in only a small number of studies to date (Dudgeon and Tromp 2012; Runge 1999; Tromp 2012). Scanning electron microscopy does not suffer from errors associated with other visualization methods, like chromatic aberration. It is especially useful for discerning minute topographic features because, unlike with light microscopy, silica phytoliths are opaque when visualized by SEM and topographical detail over a wider focal length is possible. The SEM-EDS computer user-interface simplifies navigation around the complete expanse of a sample with the creation of maps and reference points. Additional

software packages can be applied to help automate morphological analysis and data collection of microfossil assemblages (Ball et al. 2016). SEM equipped with EDS gives the user the ability to determine elemental chemistries of different particles in a sample, making it a more straightforward process to distinguish between different classes of microfossils, like silica phytoliths and calcium oxalates, and any organic or geologic detritus that may also be present in a sample. The SEM-EDS analysis used in this thesis was performed on the FEI Quanta 200 FEG with a Bruker Quantax 200 SDD-EDS X-ray detector (Figure 1.4) housed Idaho State University's Center for Archaeology, Materials, and Applied Spectroscopy (CAMAS).

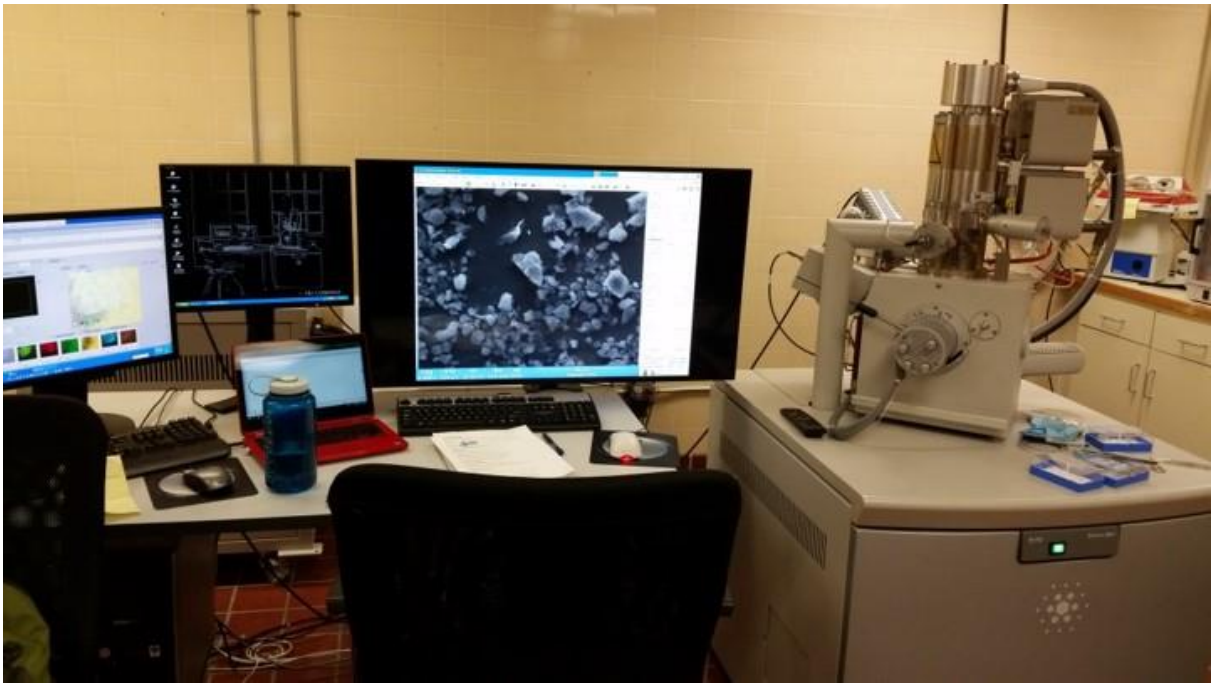

Figure 1.4. FEI Quanta 200 FEG with a Bruker Quantax 200 SDD-EDS X-ray detector.

Summary and Hypotheses

Sediment from archaeological contexts can be used to address a wide variety of questions surrounding paleo-environmental reconstruction, landscape vegetation change over time, fire history, and human activity. This thesis uses silica phytoliths extracted from sediment collected via a terrestrial coring from a site of interest in the middle Sigatoka Valley on Viti Levu, Fiji, with the hope of answering questions related to the Post-Lapita subsistence transition to agriculture. The Lapita are commonly portrayed as a seafaring people who lived in coastal settlements and relied primarily on foraged marine resources, with low levels of terrestrial resources contributing to their diets. In the centuries following the first colonization of Fiji by the Lapita, however, people began to move inland and incorporate more terrestrial resources into their diets. Evidence for the intensification of swidden cultivation has left a record that indicates an increased reliance on agricultural activity to produce a major portion of these resources. Based on this evidence, along with other vegetation histories for Fiji reconstructed by pollen analyses, I hypothesize that 1) I will be able to detect a signal of deforestation over time through a decrease in tree taxa and an increase in grass taxa phytolith morphologies; 2) human activity, especially agriculture, will be evident by the presence of non-native plant cultivars; and 3) the types of non-native plant cultivars discovered will be those associated with small-scale gardening that is considered by some to be a part of the Lapita Cultural Complex.

Chapter 2. Materials and Methods

Materials

Modern Herbarium Reference Specimens

In order to familiarize myself with different morphological types and potential for variation within taxa, modern plant samples were collected in order to develop a reference collection. While there is sometimes a low level of morphological variation between cultivars that is likely to also be present in modern versus archaeological specimens, the general shapes and features of different morphotypes tend to remain consistent and diagnostic within plant families (Piperno 2006). The construction of a modern plant reference collection also provided an opportunity to examine and image known specimens via SEM-EDS, the main tool utilized for this thesis, as a valuable resource for the future identification of unknowns, in addition to the more commonly available, but less detailed, light microscope images.

During the 2014 field season in Fiji, 62 modern plant samples were collected from various locations on the island of Viti Levu. Among these 62 specimens, 34 different taxa were sampled. In some cases, multiple samples were taken from different parts of the same plant (e.g., leaf, stalk, trunk husk, etc.) in order to determine whether morphological differences would be observed within a single plant. Both native and introduced species were sampled. Specimen collection sites include Kula Ecopark, Garden of the Sleeping Giant, Sigatoka Market, the Tubakula

Beach Bungalows grounds, and Lolevu (Qaraqara drainage), the site where terrestrial core was taken and where the excavation was carried out. Many plants sampled were accompanied by identification placards that listed genus and species; plants without placards were identified via local plant guides (Thaman et al. 2012; Whistler 2009; Watling 2005) and with the help of local Fijians knowledgeable about traditional plant species.

Terrestrial Core Sediment

A series of terrestrial cores were collected by Dr. Christopher Roos (Southern Methodist University) during the 2013 field season in Fiji. The core from which the sediment came that is used in this thesis was collected adjacent to the location of the 2014/2015 excavation at a site known as Lolevu, or the Qaraqara drainage, located in the middle Sigatoka Valley, on the south side of the Sigatoka River near Sautabu Village in the Nadroga-Navosa province. The geographic coordinates for the coring site are 17º 58' 57.26" S, 177º 37' 42.64" E. Coring was performed by Dr. Roos and his assistants with a percussion hammered 3-centimeter diameter JMC ESP subsoil corer. The corer extracted subsurface samples in 90 centimeter increments to a final depth of approximately 5.5 meters. The cores were later split longitudinally and subsamples were collected in approximately 5-centimeter intervals, dried, ground, and sieved to <2 millimeters. Geoarchaeological analysis was performed by Dr. Roos at SMU, while subsamples were sent to ISU's CAMAS laboratory for stable isotope and microfossil analysis.

Methods

Microfossil Extraction from Modern Reference Specimens

To prepare the collected plant specimens for shipping to ISU and subsequent microfossil extraction, the plant tissues were photographed and then dried while in Fiji using steel mesh over an electric skillet on low heat. Once thoroughly dried, the plant tissues were ground via mortar and pestle or with an electric coffee grinder. These samples were then carefully packaged and shipped to ISU's CAMAS laboratory for further processing and analysis. Figure 2.1 shows the dried and powdered plant samples.

Figure 2.1. Modern plant specimens after being dried and ground.

The extraction of microfossils (phytoliths and calcium oxalate crystals) from the modern plant specimens used a modified version of the dry ashing method for phytolith extraction from plants described by Piperno (2006). Approximately 50 milligrams of each dried and powdered plant sample was dry ashed in a furnace at 550 degrees Celsius for 2 hours. Once cooled, the samples were suspended in 3 to 4 milliliters of ultrapure water or denatured alcohol. 100 microliter aliquots of each suspension were placed on polished aluminum stubs, dried, and carbon coated to prevent charging of particles during visualization by SEM. Starches were extracted from fruits and tubers using a simple hydration protocol, then visualized by light microscope. See Appendix A for a detailed protocol.

Microfossil Extraction from Sediment

Starting at about 5 meters below the surface of the terrestrial core, sediment samples were selected at approximately every 10 centimeters to undergo microfossil extraction. For each sample 1 milligram was weighed into a 15-milliliter tube for processing. The microfossil extraction from sediment protocol used is a modified version of the protocol described by Piperno (2006). Preliminary versions of this protocol used centrifugation and heavy liquid to expedite particle separation, but for consistency and precision purposes particles were settled on the benchtop at 0 RPM following the guidelines for the Stokes equation outline in Lentfer et al. (2003). The Stokes equation models settling times based on a particle's specific gravity and diameter, the viscosity of the fluid medium, and the distance being settled from (Lentfer et al. 2003). Samples were placed on a nutator tray overnight

in a 5% Calgon (sodium metaphosphate) solution to deflocculate particles that might be bound together and interfere with subsequent processing. See figure 2.3, which shows progress during the first sodium metaphosphate wash step.

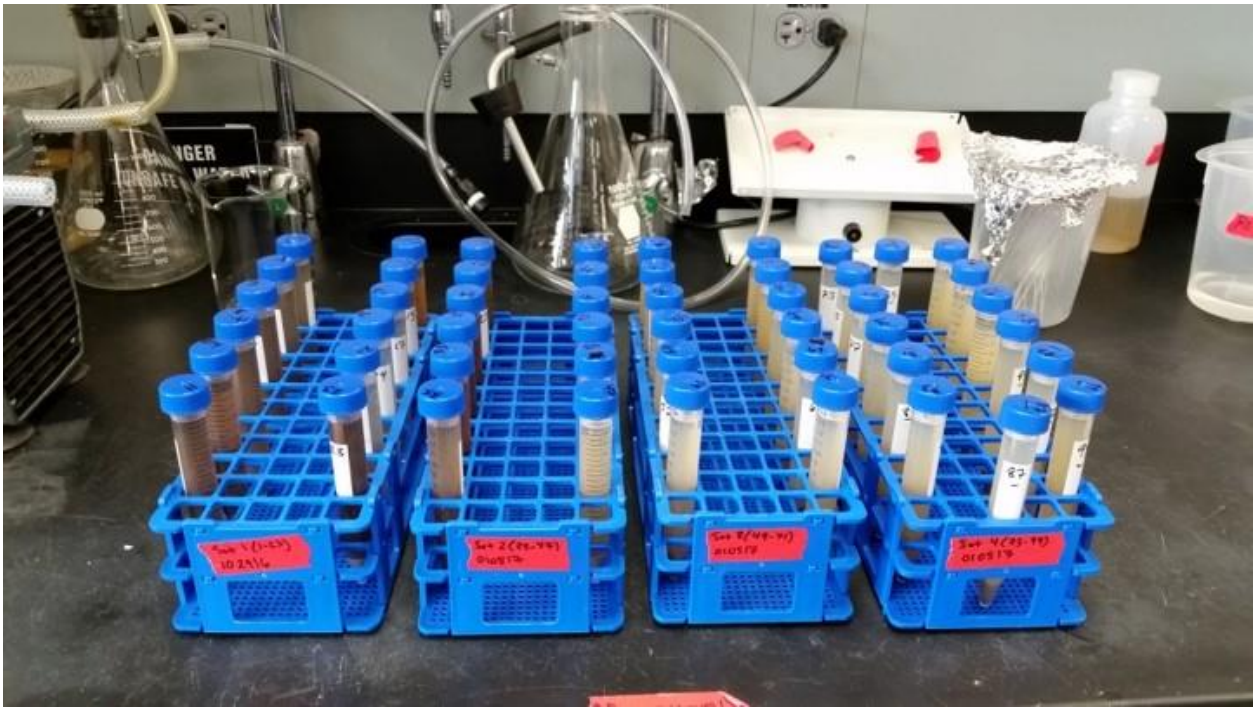

Figure 2.2. Sediment samples after the first sodium metaphosphate wash and settle period.

Information provided by Lentfer et al. (2003), was used to determine the settling times for particles based on diameter, specific gravity (g/cc), centrifuge revolutions per minute (RPM), and viscosity of the fluid being used. Phytoliths range in size from 2 to 250 microns, and have a specific gravity that ranges from 1.5 to 2.3. (Lentfer et al. 2003). Based on a survey of the modern reference collection and preliminary analyses of microfossil extractions from subsamples of excavation and core sediments, it was likely that the majority of target particles would fall between

5 and 100 microns in size. As these sediments were particularly rich in clay, and disaggregated clay particles measure about 2 microns and smaller, measures were taken to reduce the amount of residual clay as much as possible, as it interferes with the efficiency of analysis during data collection. In early experiments settled particles of 3.9 microns and larger, but this resulted in the retention of too many clay particles and other mineral detritus that made microfossil identification difficult. For these reasons, settling times were adjusted so that particles 5 microns and larger would be settled and retained, with particles smaller than 5 microns in size being discarded in each wash step. This step was repeated at least three times per sample. Progress was monitored by keeping track of how clear the supernatant was at the end of each settling time; some samples had a higher percentage of particles smaller than 5 microns and had to undergo additional settling steps. To verify that no target particles were being lost during settling, aliquots of the supernatant were viewed by light microscope at each wash step. Light microscopy was also used to monitor progress in removing all particles below the target size range. Once all non-target particles were removed, an aliquot was taken of the suspensions and diluted five times in a 50:50 mixture of RO H_2O and 99% ethanol (EtOH). Aliquots of the diluted suspensions were placed onto a polished 25.4-millimeter aluminum specimen mount, dried, and carbon coated for subsequent visualization by SEM. See Appendix A for a detailed protocol.

Visualization and Analysis by Scanning Electron Microscope (SEM)

Scanning electron microscopy analysis was performed at ISU's CAMAS facility on a FEI Quanta 200 FEG with a Bruker Quantax 200 SDD-EDS X-ray detector. Aliquots of the diluted suspensions were placed onto polished 25.4-millimeter aluminum specimen mounts, dried, and carbon coated for subsequent visualization by SEM. Aluminum mounts were chosen for this project due to the high proportion of residual geologic aluminosilicates that remained in the final sample suspensions. These particles are similar to silica microfossils in size and specific gravity, so no number of washes could effectively remove them. Placing sample aliquots on an aluminum background made distinguishing target silica phytoliths (SiO_2) from aluminosilicates (Al_5SiO_5), other geologic minerals, and organic detritus simple and streamlined. By utilizing the EDS attachment on the SEM, I was easily able to identify which particles contained aluminum or other elements not associated with phytoliths and exclude them from further analyses. This feature was particularly useful in identifying previously unidentified or otherwise unknown silica phytoliths, especially during the construction of the modern plant reference collection and preliminary analyses of sediments during protocol development. The EDS attachment was used throughout the data collection step to verify particles as phytoliths that appeared ambiguous due to degradation or fracturing.

Morphological Type Categorization

Instead of recording microfossil data by taxa, it is more common practice to record particles as they fit into previously defined morphological categories based

on their observed physical characteristics. The microfossil morphological types used in this thesis were defined according to the *International Code for Phytolith Nomenclature 1.0* (Madella et al. 2005). This is a useful strategy for recording microfossil data because certain suites of physical characteristics, like general shape and texture and/or ornamentation, can be diagnostic of certain plant taxa. Some plant taxa, such as the grasses (Poaceae), are characterized by a wide variety of morphological types that have the potential to further narrow down a taxonomic classification. By recording each microfossil in as much detail as is realistically possible in a project of this scope, the ability to make additional observations after the fact is preserved. As more research is conducted on plant microfossils (ancient and modern), more reference materials on variation within families and even genera are likely to become available. To see the morphological types used in this thesis, see Figure 2.3 and Table 2.1.

Globular (spherical)	Morphological Structure	Family
GE	Globular echinate (pointy)	Palmae
GEL	Globular echinate pitted	
GEO	Globular echinate oblong	
GG	Globular granulate (knobby)	Trees & Shrubs
GV	Globular verrucate (irregular/lumpy surface)	
GS	Globular smooth (no surface texture)	
Lobate (lobed)		
B	Bilobate (2 rounded lobes)	Poaceae
P	Polylobate (many lobes in linear arrangement)	
Q	Quadra-lobate (4 lobes, x-shaped)	
EQ	Elongated quadra-lobate (extended 4-lobes, dog bone)	
CB	Cuneiform bulliform (single lobe, fan-shaped)	
PP	Propeller polylobate (mirrored propeller-shape)	
IP	Irregular polylobate (asymmetrical lobes)	
Elongate (rectangular)		
EE	Elongate echinate (pointy protrusions)	Poaceae
ET	Elongate tuberculate (knob-like protrusions)	
ES	Elongate sinuate (uneven, alternating concavities/convexities)	
EP	Elongate pilate (facets)	
EF	Elongate flat (smooth)	
Others:		
R	Rondel (lampshade)	Poaceae
S	Saddle	
SC	Scutiform (thorn)	
T	Trapeziform (3D trapezoid)	
V	Volcaniform (volcano with jigsaw puzzle-shaped base)	Musaceae
X	Degraded beyond identification	Unknown

Table 2.1. Morphological classifications and their associated family designation.

At some points in the column of sediment used in this thesis, however, there are high levels of degradation of diagnostic phytolith types observed. While diagnostic features of some of these phytoliths could be determined, others were too poorly preserved to be accurately identified. In some cases, all traces of identifiable phytoliths were absent. While this was slightly discouraging at first, I decided to take advantage of these differing levels of preservation as a potentially informative data point about taphonomic processes that have taken place.

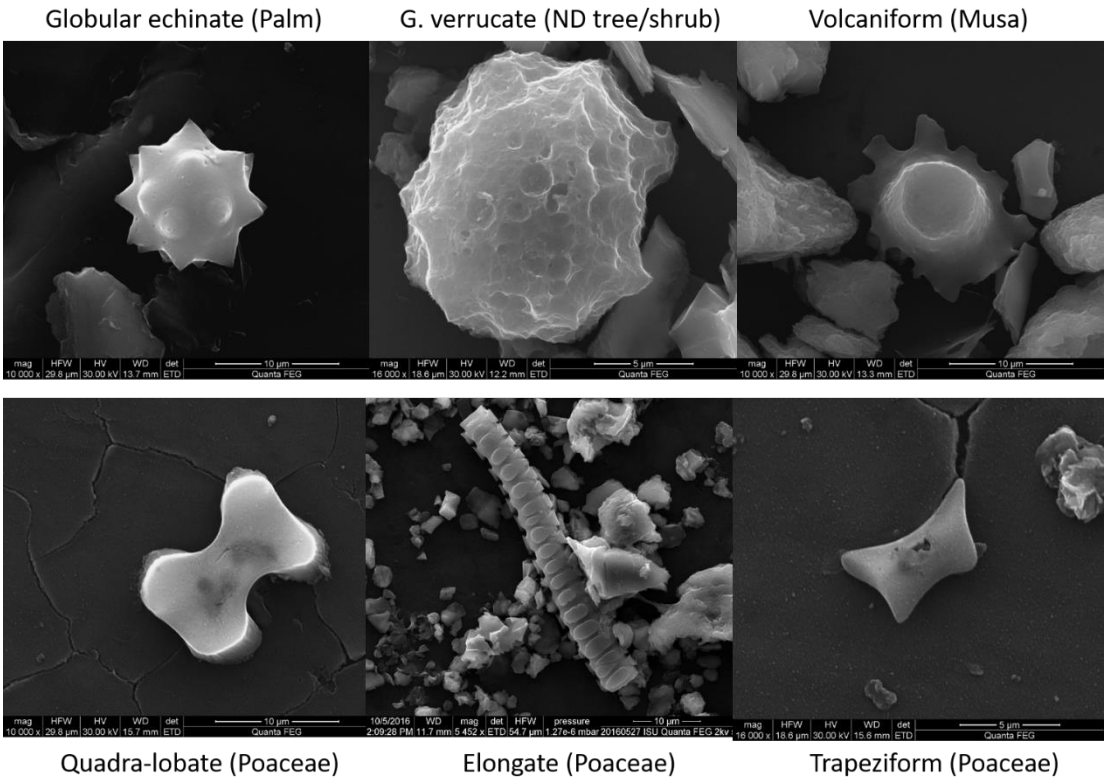

Figure 2.3. Exemplars of silica phytolith morphotypes.

Data Collection

Using abbreviations of each morphological type, 200 phytoliths were recorded per 100 microliter sample, except where poor levels of preservation prevented this target from being reached. The decision to forgo additional analysis of these samples was based on my determination to avoid introducing any form of bias and to maintain as much consistency between all samples as possible. The target of 200 phytoliths was set according to current published standards for studies of this nature (Horrocks et al. 2012; Piperno 2006; Stromberg 2009). Data collection proceeded in a raster-like pattern across each sample area, beginning at the top of the sample drop as it was oriented at the top of the SEM computer monitor. Each

morphological type was recorded on a Microsoft Excel spreadsheet on a laptop computer along with general observations about the level of preservation of each sample. The presence of diatoms was noted, and some images were collected for identification, but they are not being considered in any further detail at this time. See Figure 2.4 for diatom exemplars extracted from the core sediment.

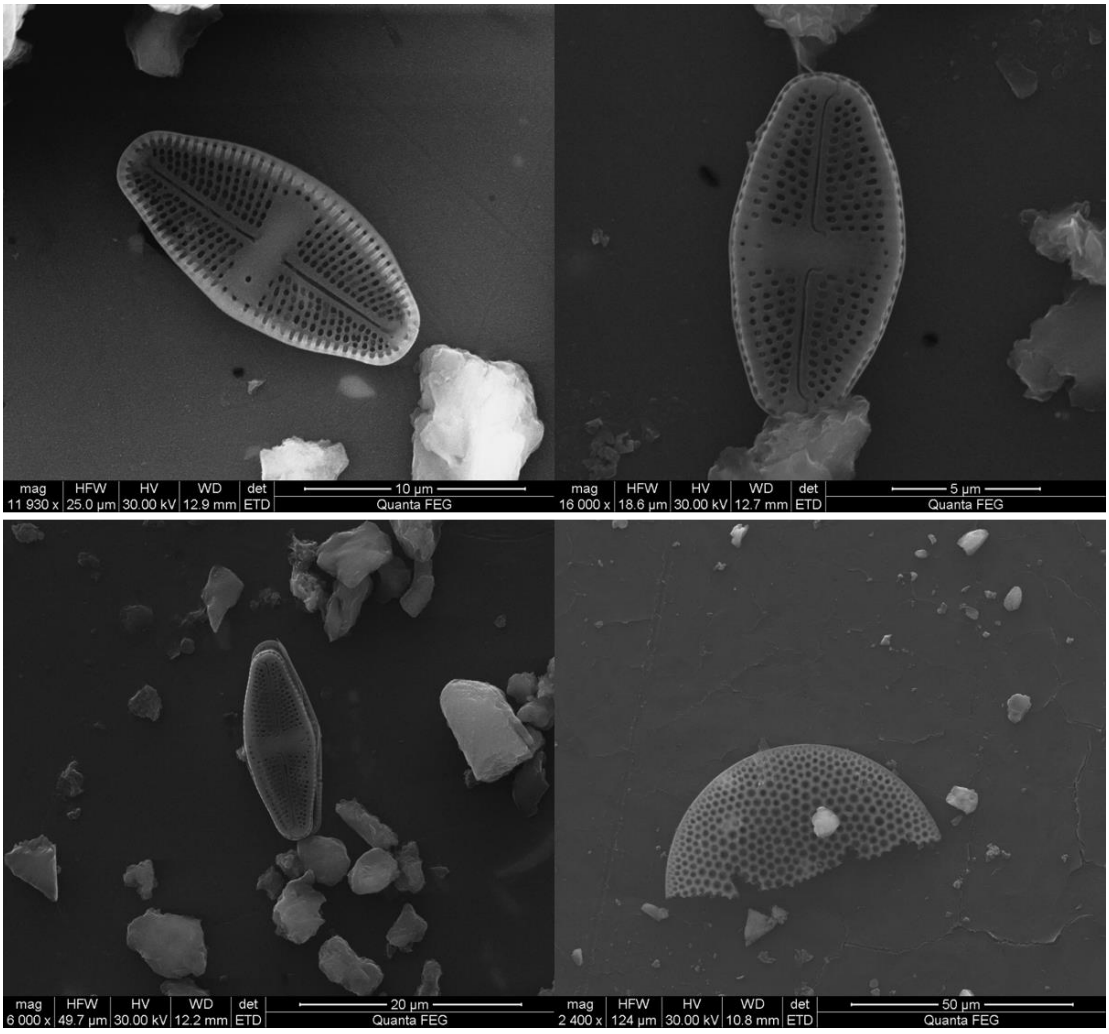

Figure 2.4. Diatom morphotypes observed in core sediment.

Where preservation was extremely poor, the EDS attachment was used to identify the highly degraded remains of phytoliths. For a small subset of samples

there were not enough surviving diagnostic phytoliths to reach the target of 200; some samples contained no identifiable phytoliths at all.

Chapter 3. Results

At each step of protocol development and data collection, it became apparent that methods must be continuously optimized and that no pre-existing protocol could be applied without modification. There are several variables that will affect the efficiency and outcome of microfossil analyses that need to be taken into consideration during research development phases. First, microfossil extraction and data collection protocols should be tailored to each project based on the geologic composition of the sediment being analyzed. Unfortunately, there was a large proportion of particles present in the sediment used in this thesis that had similar physical-chemical properties (specific gravity and size) to the target particles, silica phytoliths. This resulted in a high amount of geologic detritus that had to be visually screened during the data collection step, which greatly increased the time required to accomplish my goal of counting 200 phytoliths per sample.

Next is the issue of microfossil preservation. Madella and Lancelotti (2012) address the potential biases, along with proposed methodological adjustments, that may be introduced during phytolith analysis. Taphonomic processes have the ability to alter the morphological appearance of phytoliths to varying degrees, ranging from slight pitting on a phytolith's surface to the complete disintegration of target particles. Clearly, this presents a host of challenges when attempting to identify and quantify phytoliths present in an assemblage. The absence of identifiable phytoliths when a sample is visualized does not necessarily mean the extraction protocol is

flawed – they may simply have completely degraded over time and are not representative of the original phytolith input. Some morphotypes are more susceptible to chemical and physical degradation than others; long cell morphotypes are more fragile than short cell types (Madella and Lancelotti 2012). Because of this, it is important to remark on the overall level of preservation observed during analysis, along with whether the diversity of expected morphotypes (long and short) was present. Highly degraded phytoliths, identified with the SEM's EDS attachment, were included in the counts for this thesis, as they have the potential to provide additional insight into landscape character and change over time.

Modern Herbarium Specimens

Using my simplified dry-ashing protocol, I was able to co-extract several different types of microfossil from each sample, including stomata, trichomes, calcium oxalate raphides and druses, and silica phytoliths (Figure 3.1). While excluding oxidization and acid wash steps resulted in more organic detritus than is ideal, it also allowed me to view several types of microfossils *in situ*, as they would be oriented in the living plant, articulated within epidermal tissues. Starches (Figure 3.2) were extracted separately through a simple hydration step followed by air drying on a slide and re-suspending in immersion oil for visualization through cross-polarized light on a Leica DM2500 M light microscope. Visualization under cross-polarized light allows us to analyze the grain's overall shape and the orientation of the distinctive Maltese, or extinction, cross. While not utilized in this thesis, a

reference collection of high quality starch images will be useful for future projects of this nature.

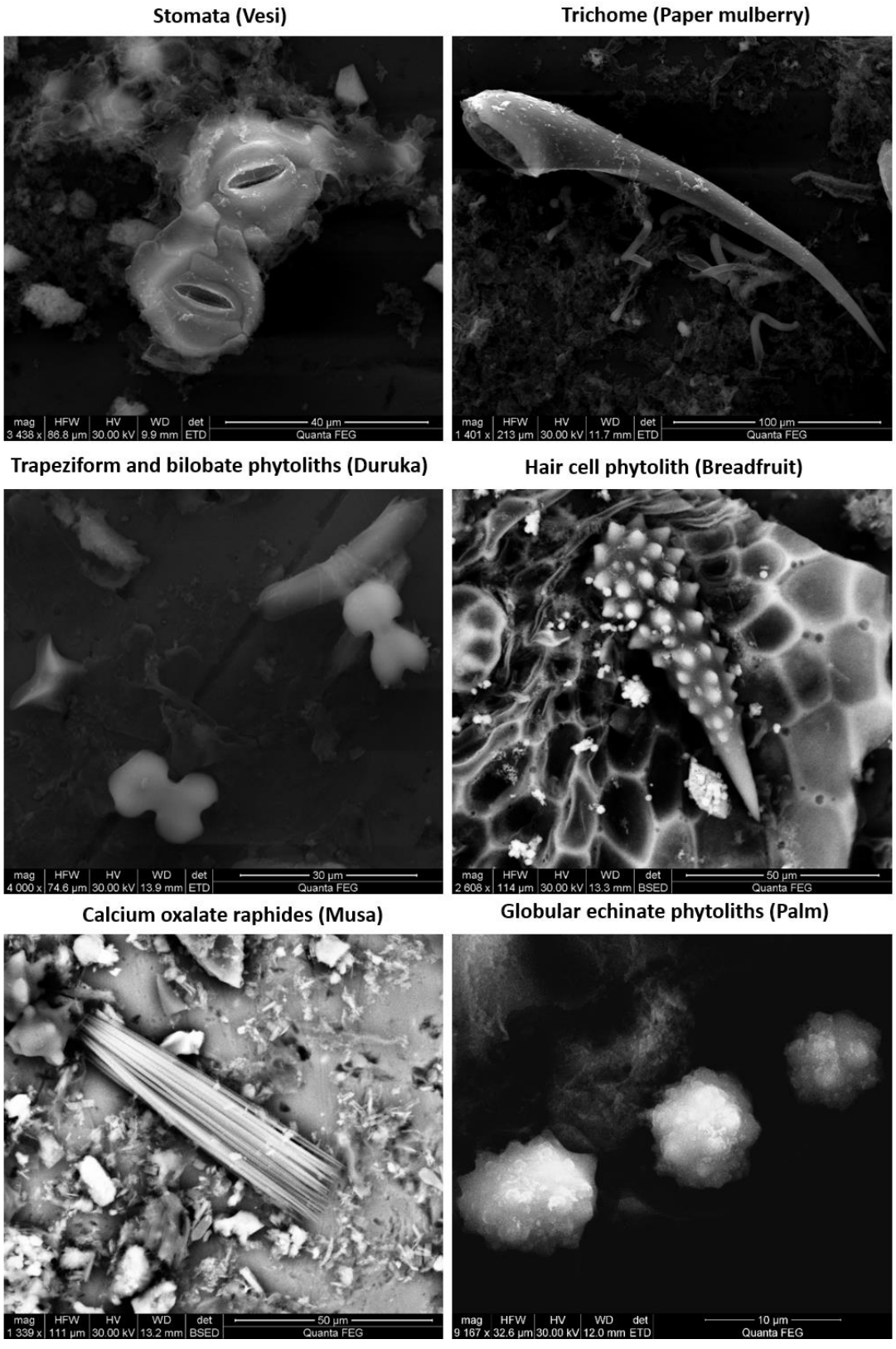

Figure 3.1. Microfossils extracted from modern herbarium specimens.

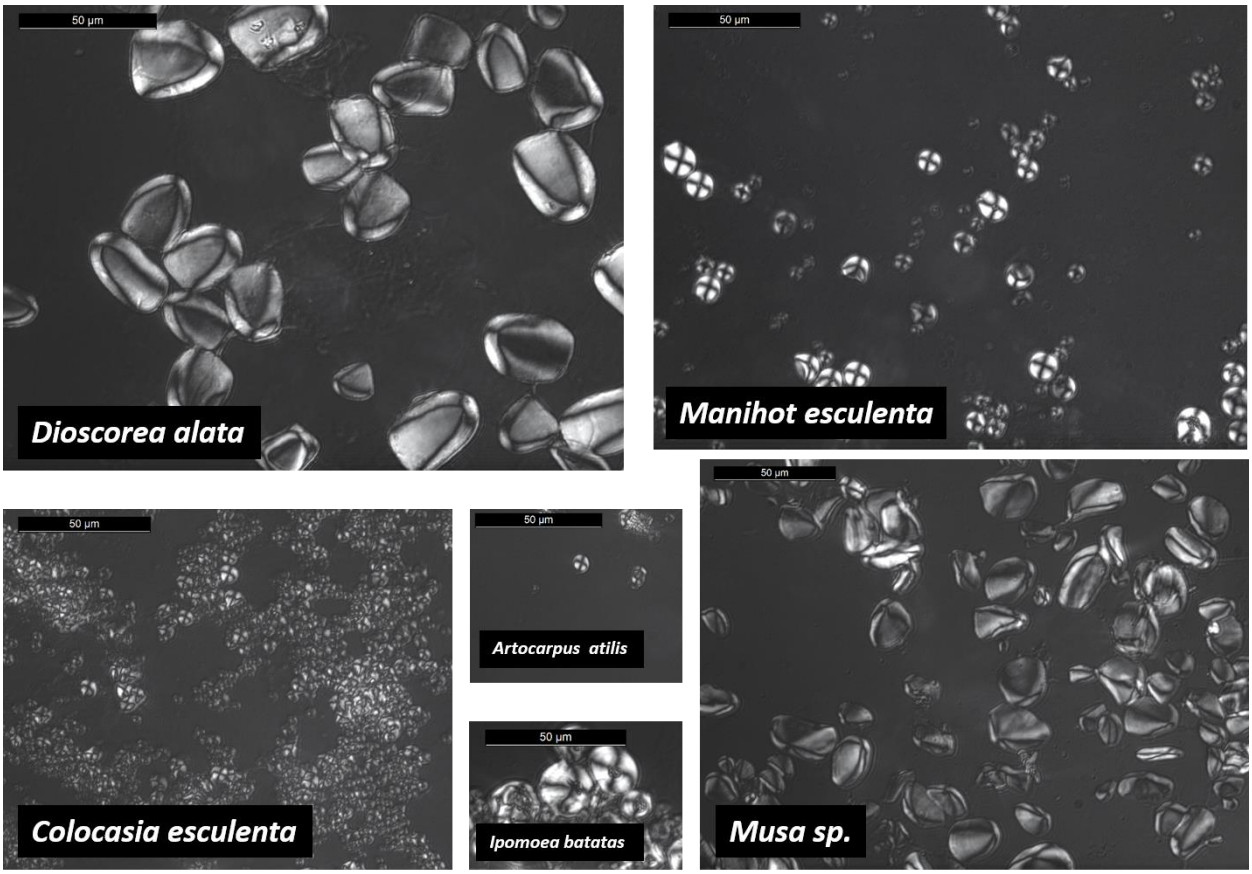

Figure 3.2. Starch grains extracted from modern plant specimens. Note all starch grains are reproduced at the same scale in this composite image.

Terrestrial Core Sediment

Preservation of Microfossils

As explained above, the preservation of microfossils is an important variable to consider with this type of project. The level of preservation of silica phytoliths in the sediments analyzed in this thesis ranged from good to extremely poor. See Figure 3.3 for examples of the varying levels of degradation demonstrated by silica phytoliths extracted from sediment. Samples that qualified as "good" contained phytoliths with no or minimal surface pitting that were completely or nearly intact.

Those that qualified as “extremely poor” had no phytoliths that could be confidently identified, or the majority of phytoliths that could be identified were heavily pitted and/or fractured. Of the 48 samples prepared and analyzed, 10 were rated as “extremely poor” for preservation quality; 3 of these samples yielded no identifiable phytoliths.

Silica Phytoliths

A total of 8244 phytoliths were counted between 495 and 20 centimeters below the modern surface; the top 20 centimeters were excluded from analysis as this portion of the sediment core falls within the plow zone, which was still being actively worked by residents of Sautabu village at the time of collection. My selection of morphotypes to be analyzed for this thesis was guided by the phytolith morphologies I found in preliminary screenings of sediment collected from the excavation, by my experience during the construction of the reference library, and by previous microfossil studies in the region (Horrocks and Rechtman 2009; Horrocks et al. 2003; Horrocks and Wozniak 2008; Horrocks et al. 2012; Tromp 2012). See Table 3.1 for an overview of the phytolith morphologies and their associated taxonomic families. Each 100-microliter sample area was also scanned exhaustively for rare phytolith morphotypes not included in this table. Any particles that appeared ambiguous and could not be confidently identified were analyzed with the EDS attachment to verify that their chemical signatures corresponded to those of silica phytoliths.

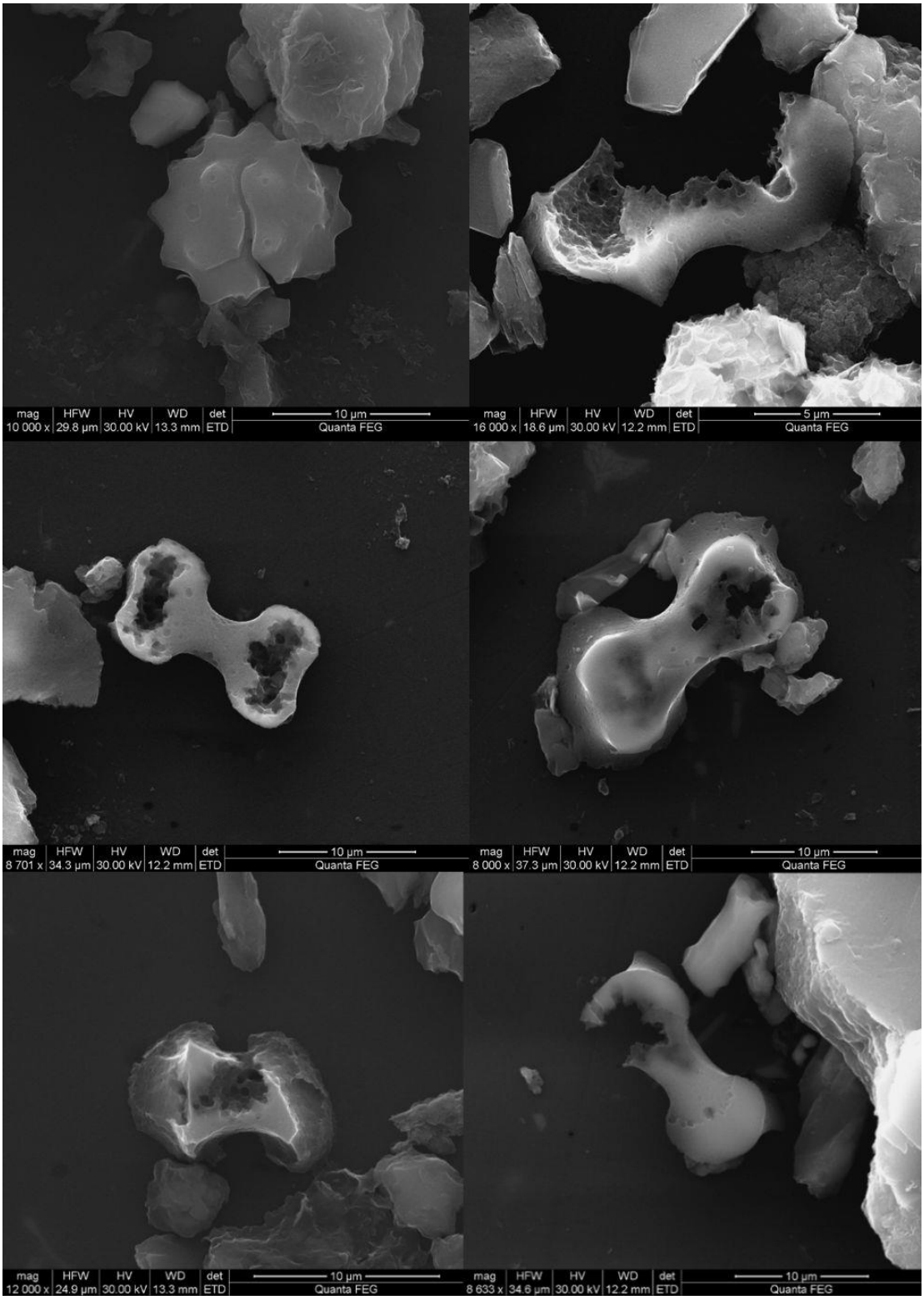

Figure 3.3. Silica phytoliths extracted from sediment, demonstrating varying levels of diagenetic alteration.

Globular (spherical)	Morphological Structure	Family
GE	Globular echinate (pointy)	Palmae
GEL	Globular echinate pitted	
GEO	Globular echinate oblong	
GG	Globular granulate (knobby)	Trees & Shrubs
GV	Globular verrucate (irregular/lumpy surface)	
GS	Globular smooth (no surface texture)	
Lobate (lobed)		
B	Bilobate (2 rounded lobes)	Poaceae
P	Polylobate (many lobes in linear arrangement)	
Q	Quadra-lobate (4 lobes, x-shaped)	
EQ	Elongated quadra-lobate (extended 4-lobes, dog bone)	
CB	Cuneiform bulliform (single lobe, fan-shaped)	
PP	Propeller polylobate (mirrored propeller-shape)	
IP	Irregular polylobate (asymmetrical lobes)	
Elongate (rectangular)		
EE	Elongate echinate (pointy protrusions)	Poaceae
ET	Elongate tuberculate (knob-like protrusions)	
ES	Elongate sinuate (uneven, alternating concavities/convexities)	
EP	Elongate pilate (facets)	
EF	Elongate flat (smooth)	
Others:		
R	Rondel (lampshade)	Poaceae
S	Saddle	
SC	Scutiform (thorn)	
T	Trapeziform (3D trapezoid)	
V	Volcaniform (volcano with jigsaw puzzle-shaped base)	Musaceae
X	Degraded beyond identification	Unknown

Table 3.1. Phytolith morphotypes recorded for this thesis, with their associated taxonomic families.

Ligneous Plants (Trees & Shrubs)

The globular-shaped morphologies are associated with ligneous (woody-stemmed) trees and shrubs (Piperno 2006; Bremond et al. 2005; Horrocks and Rechtman 2009; Horrocks et al. 2003). These types of phytoliths made up the majority of particles counted, with 75 percent of all phytoliths recorded belonging to

this morphotype. This category encompasses six distinct globular morphotypes: echinate (spherical), echinate oblong (ellipsoidal), echinate lacunose (pitted), granulate, lacunose, cavate, and verrucate. The echinate morphotype was recorded with two additional descriptors (oblong/ellipsoidal and lacunose) to record as much data on potentially significant variation as possible. Some species of palm have demonstrated multiple variations of the globular echinate phytolith (Fenwick et al. 2011). Globular verrucate, which includes all spherical phytoliths with irregular surfaces, accounted for approximately 84 percent of this category. Globular echinate phytoliths, which are associated specifically with palm trees (Piperno 2006; Bremond et al. 2005; Fenwick et al. 2011; Tromp 2012), accounted for 15 percent of all globular types counted. Globular cavate and globular granulate each made up less than 1 percent of the total. Over time, from the bottom of the sediment column moving up toward the modern surface, there is an overall reduction in the proportion of globular morphotypes. See Figure 3.4 for a graphical representation of this trend.

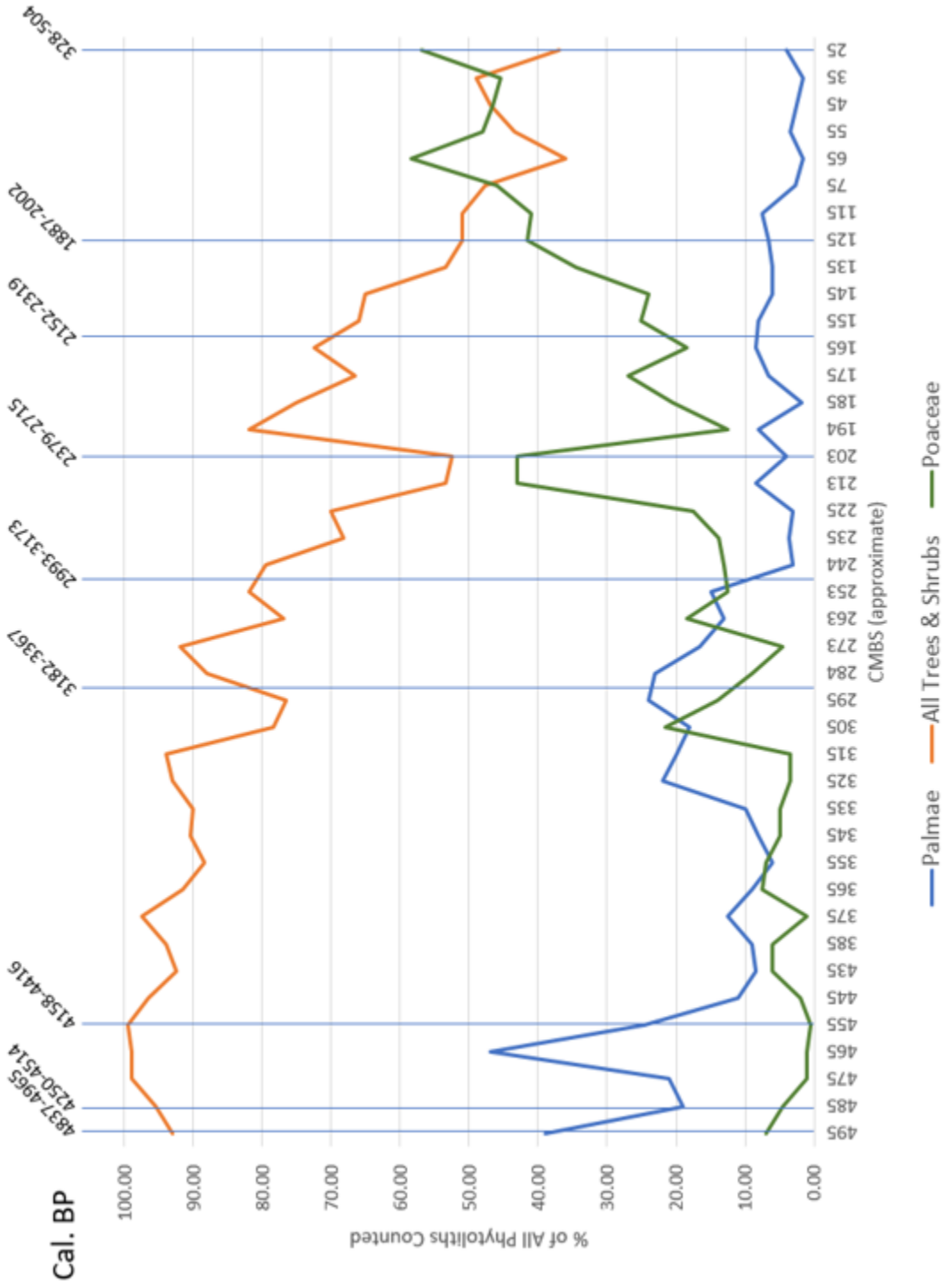

Figure 3.4. All recorded plant taxa percentages.

Palms (Palmae)

The three globular echinate morphologies recorded are associated with plants in the Palmae family. The general shape of globular echinate phytoliths that are associated with palms can range from spherical to ellipsoidal, and may also curve slightly in a reniform (kidney) shape (Fenwick et al. 2011; Piperno 2006; Bremond et al. 2005). Those recorded as "globular echinate" are spherical with spike-shaped protrusions; "globular echinate oblong" are ellipsoidal with spike-shaped protrusions; and "globular echinate lacunose" is spherical with spike-shaped protrusions and pitting on the surface. This last morphological type, globular echinate lacunose, may be the result of taphonomic degradation or it may be a distinct class that is yet to be determined. A total of 957 globular echinate phytoliths were recorded. The spherical globular echinate morphotype accounts for 66 percent of all phytoliths counted in this category; the ellipsoidal globular echinate morphotype is 34 percent of the total. The proportion of globular echinate morphotypes fluctuates over time, but the overall trend (see Figure 3.4) is a reduction in the total number of phytoliths in this category.

Grasses (Poaceae)

Phytolith morphotypes associated with the grasses are the most diverse. Grasses tend to be among the most prolific producers of phytoliths, so they typically make up a large part of microfossil datasets (Bremond et al. 2005; Horrocks and Bedford 2004; Horrocks and Lawlor 2006; Horrocks and Nunn 2007; Horrocks et al. 2003; Piperno 2006; Piperno 2009). For this project, 15 distinct shapes were

recorded that include both long and short-cell types. In total, 1625 grass phytoliths were recorded; 994 were short-cell and 631 were long-cell. The most common types of grass morphotypes were bilobate (221), elongate flat (401), elongated quadra-lobate (282), elongate sinuate (193), and quadra-lobate (341). Over time and from the bottom of the sediment column, there is a clear increase in the proportion of grasses compared to other taxa, peaking near the modern surface where they account for approximately 57% of the total phytoliths counted. There are some apparent spikes in this trendline, with the first major event appearing around 305 centimeters below the modern surface. A second spike is present around 253 with a third around 225 to 203. When plotted against C4 plant proportions calculated by Dr. Christopher Roos (SMU) from δ13C stable isotope values using a conservative mass balance equation, the major spike in grass phytolith types around 203 CMBS appears to correlate with a major increase in C4 plants. This spike is followed by a slight decrease in and then another increase in both datasets. See Figure 3.5.

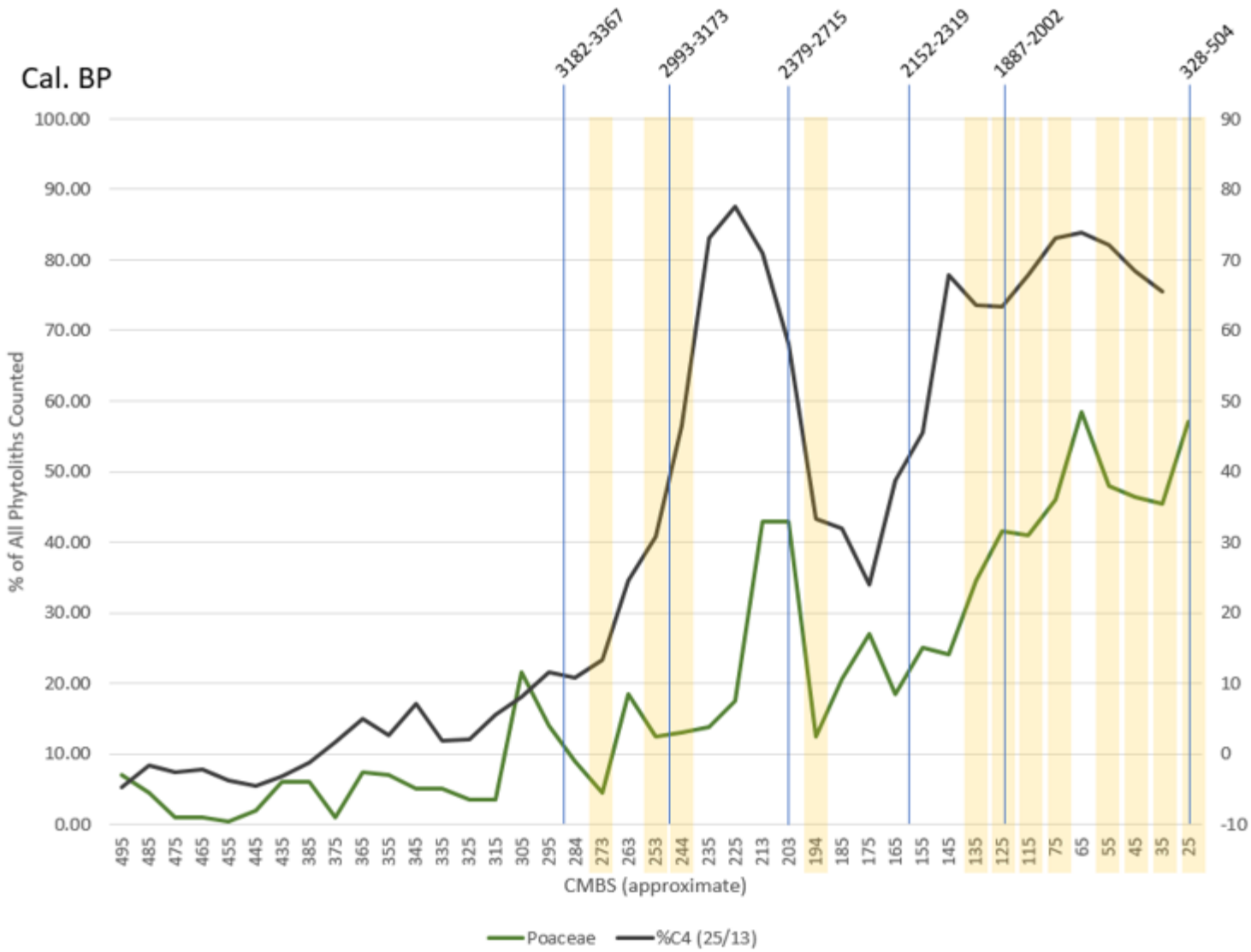

Figure 3.5. Percentages of grass phytoliths, plotted with percent of C4 grasses. Presence of volcaniform (*Musa*) phytoliths highlighted in yellow.

Banana (Musaceae)

The morphological phytolith type associated with banana is referred to as volcaniform (Figure 3.6), which appears as a flattened cone with a circular pit or crater at its tip and a square to rectangular sinuate border around its base (Horrocks and Rechtman 2009; Horrocks et al. 2009; Lentfer and Green 2004; Piperno 2006; Vrydaghs et al. 2009). In this core, 18 volcaniform phytoliths were recorded, with the earliest occurring at level 55 (268 to 273 CMBS). Volcaniform phytoliths were among the rarest types counted, with the total number making up less than 1% of all phytoliths. The highest number of volcaniform phytoliths occurs at level 23 (110 to 115 CMBS) with a total of 4 recorded. See Figure 3.7 for the presence and distribution of volcaniform phytoliths.

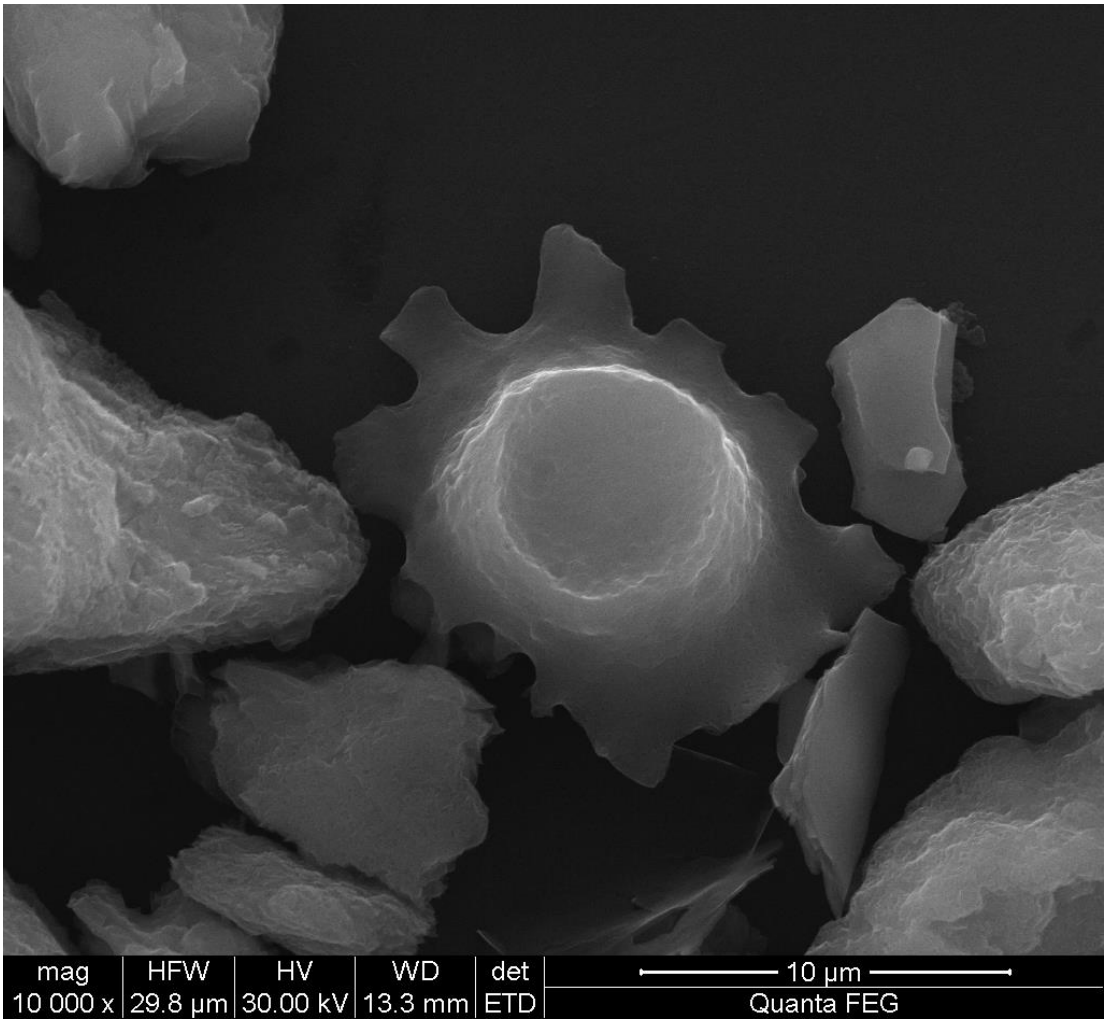

Figure 3.6. Example of volcaniform banana silica phytolith.

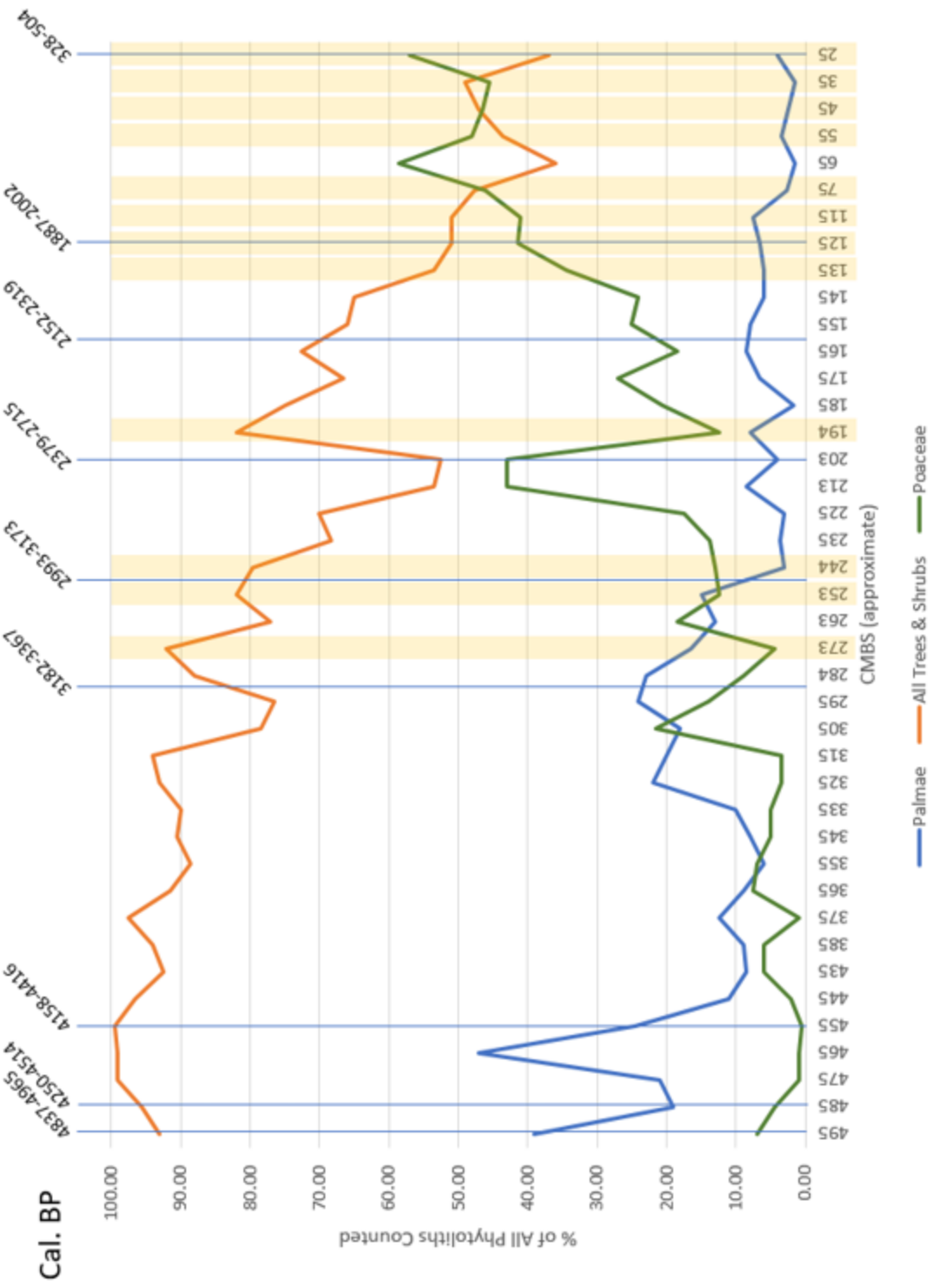

Figure 3.7. Percentages of all plant taxa. Volcaniform phytolith (*Musa*) presence is highlighted in yellow.

Diatoms

Diatom morphologies were not recorded, only the presence or absence of diatoms within each sample was noted. Sample fields were scanned for diatoms even after the target count number was achieved for each specimen. Most diatoms observed were highly fragmented. There does not appear to be any specific pattern to diatom distribution within the column, nor do they appear to correspond to the frequencies of silica phytoliths recorded. The quality score assigned to each sample also does not seem to correlate with diatom distribution. Out of a total of 42 samples analyzed, diatoms were present in 16. See Figure 3.8 for the distribution of diatoms within the core.

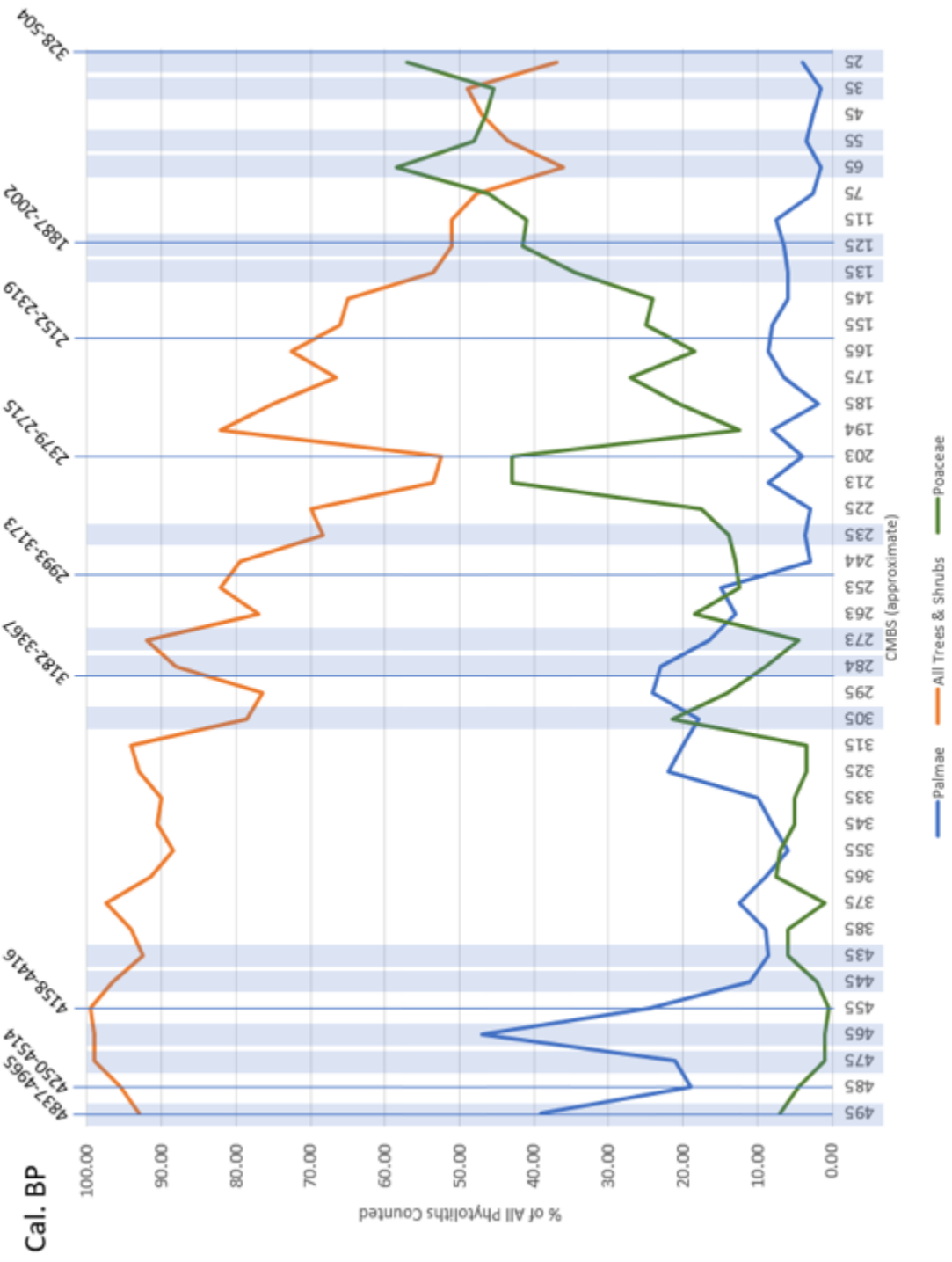

Figure 3.8. Percentages of all plant taxa recorded. Diatom presence is highlighted in blue.

Chapter 4. Discussion

The method and research design used in this thesis for silica phytolith extraction from sediment and subsequent analysis is the product of many iterations of trial, error, and improvement. They have been adapted from several published protocols (Bremond et al. 2005; Horrocks 2005; Lentfer et al. 2003; Piperno 2006; Tromp 2012). As explained by Coil and colleagues (2003), there is no single ideal microfossil extraction protocol for every archaeological site. Based on the geologic character of archaeological sites, as well as specific research questions, a protocol should be carefully tailored. The construction and analysis of the modern plant reference collection proved to be extremely valuable for the experience it provided during the extraction steps, and then for imaging silica phytoliths by SEM-EDS. Going through that process definitely helped to streamline the counting and analysis of phytoliths extracted from the sediment core. While the final protocol developed for this thesis could certainly use some refinement, especially with regard to efficiency, the resulting data aligns with previous observations made about Fiji's vegetation history (Ash 1992; Hope et al. 2009; Keppel and Tuiwawa 2007; Prebble and Dowe 2008; Watling 2005), conforms to the overarching methodological goals of microfossil extraction and analysis (Coil et al. 2003), and provides support for my hypotheses.

Deforestation in the Sigatoka Valley, Viti Levu, Fiji

My first hypothesis stated that I would be able to detect a signal of deforestation over time through a decrease in tree taxa and an increase in grass taxa phytolith morphologies. Previous research indicates that Fiji was much more forested during the mid-Holocene (Ash 1992; Hope et al. 2009), and only about 45% of the main islands remain forested today (Watling 2005). Before the arrival of the first humans approximately 3000 years ago, the landscape was a mix of dry forest and rainforest, with some patches of natural savannah grassland (Ash 1992; Hope et al. 2009). According to palynological data, the *talasiqa* grassland that now covers a major swath of the dry side of Viti Levu was probably forested before the arrival of people; it is most likely the result of erosion induced by the over-use of fire for cultivation (Hope et al. 2009; Keppel and Tuiwawa 2007). While globular-type phytoliths associated with ligneous trees and shrubs made up the overwhelming majority of the final count for the Qaraqara site, there is a definite decrease in this type over time. The gradual reduction of tree and shrub morphotypes over time is mirrored by an increase in grass-type phytoliths. The loss of trees and shrubs, with an influx of grasses, certainly reflects the process of deforestation (Bremond et al. 2005); however, if the current radiocarbon dates from the core are accurate, the data suggest that this process was taking place at least 1000 years before there is evidence of humans in Fiji. The decline in trees and shrubs with an increase in grasses is very subtle prior to colonization, as can be seen in Figure 4.1. The exact cause of this period of small-scale pre-colonization deforestation has yet to be

determined, but may be related to climate change and the occurrence of natural wildfire cycles at this site (Roos et al. 2017). This process also appears to be reflected by stable isotope analysis performed on sediment from the same terrestrial core, where there is a gradual increase in C4 plant contributions prior to the period human settlement (Roos, personal communication 2017). Deforestation is also evident in the reduction of globular echinate phytoliths associated with trees in the *Palmae* family. Palm-type phytoliths made a smaller contribution to the overall count than other tree and shrub types, suggesting that palms probably did not constitute as much of the forest as other taxa at this site. While the contribution of palm phytoliths is somewhat sporadic in the lower sediment levels, there is a sudden drop just prior to the increase in grasses and decrease in other tree and shrub taxa at the time when humans probably began affecting local vegetation. These results are consistent with observations made elsewhere on Fiji, as well as on other islands across the Pacific, where the decline and extinction of palm tree taxa has been correlated with the arrival of humans (Prebble and Dowe 2008).

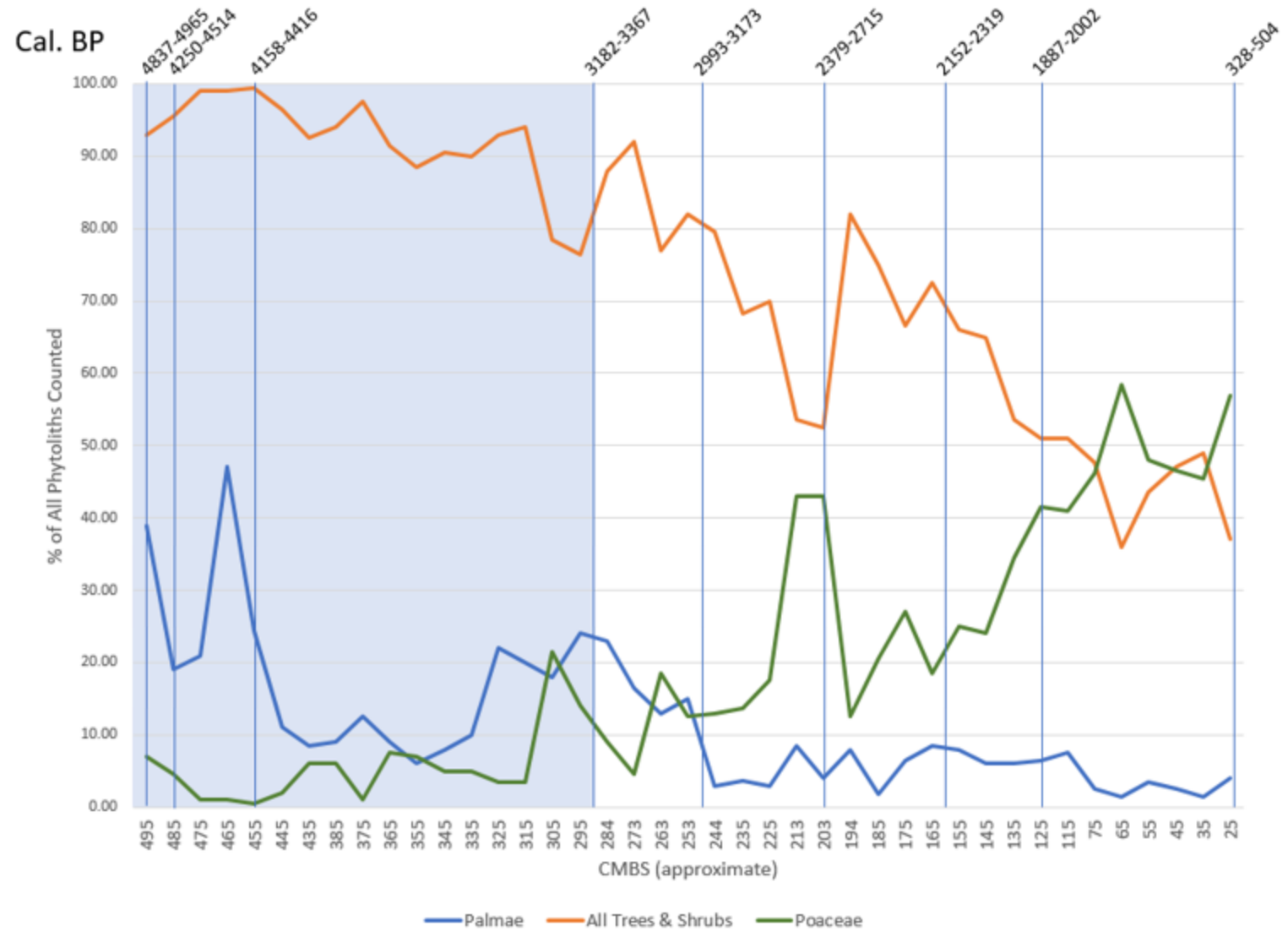

Figure 4.1. Percentages of all taxa; hypothesized pre-colonization period is highlighted in blue.

An event of large-scale deforestation appears to occur in the centuries following 3182 to 3367 cal. BP. A major decrease in tree and shrub phytolith morphotypes, including palm taxa, is paired at this time with a major increase in grass-type phytoliths, as well as an increase in C4 plants. This event occurs around the time period 2700 to 3100 years ago, when other researchers have noted a distinct change in vegetation along with an increased and sustained signal of fire in the region (Hope et al. 2009; Keppel and Tuiwawa 2007; Roos et al. 2016). This sudden change in vegetation suggests it was around this time that human activity began to have lasting effects on the native landscape, probably through the use of swidden cultivation.

Evidence for Agricultural Activity at Qaraqara Drainage Site

My second and third hypotheses stated that human activity, especially agriculture, would be evidenced by the presence of non-native cultivars, and that the types of non-native plant cultivars discovered would be those thought to characterize the small-scale gardening practices of the Lapita people. The results of my phytolith analysis provide evidence in support of both hypotheses. Non-native *Musa* (banana) phytoliths were identified at several key points in the core; edible banana cultivars are acknowledged as being among the plants likely transported by Lapita people during migration, and have been recovered from Lapita-era deposits elsewhere in the Pacific (Horrocks et al. 2009).

Despite some persisting theories that Lapita colonists were exclusively marine foragers, or "strandloopers" (Groube 1971), a wealth of new research casts doubt on Groube's Lapita subsistence model and now supports the idea that they actually relied on a mix of foraging and small-scale horticulture (Davidson and Leach 2001; Horrocks et al. 2009; Horrocks and Nunn 2007; Kirch 2000). Linguistic reconstructions of Proto-Oceanic words for crop plants and other words associated with horticulture have provided further evidence in support of the idea that the Lapita were more than mere foragers (Davidson and Leach 2001; Kirch 2000). Additional evidence in favor of small-scale horticulture practiced by Lapita colonists suggests they probably would have traveled with "transported landscapes" or "portable economies," made up of familiar domestic animals and economically significant plants, like taro, yam, and banana (Kirch 2000). Microfossil analysis on Lapita-era (3050 to 2500 cal. BP) deposits from Bourewa in Fiji identified introduced *Colocasia esculenta* (taro) and *Dioscorea esculenta* (yam) (Horrocks and Nunn 2007). At the Qaraqara site there is evidence for land clearance and possible cultivation as early as about 3000 years ago, around 250 CMBS in the sediment column analyzed for this thesis. Here, the first occurrence of banana-type phytoliths is accompanied by enriched δ13C values indicating a higher contribution of C4 pathway plants (e.g. tropical grasses), and an increase in grass-type phytoliths, another proxy for identifying cultivation (Pearsall and Trimble 1984; Roos et al. 2016). This could imply that early colonizers moved inland and began cultivating the land centuries earlier than previously thought.

Musa (banana) phytoliths from Lapita-era deposits in Vanuatu further support the hypothesis that Lapita did travel with and actively cultivate some food crops, as all banana in Remote Oceania are human introductions (Horrocks et al. 2009). Further, domesticated edible banana types are seedless and must be propagated and cultivated by humans for dispersal, making them an extremely valuable proxy for identifying human agricultural activity in the archaeological record (Vrydaghs et al. 2009). Banana is first present in the core at approximately 273 CMBS, with more banana phytoliths being recovered sporadically at 253, 244, and 194 CMBS. Around 135 CMBS, banana phytoliths are recovered consistently in each level, up to the modern surface. Considering the observed evidence for increased rates of deforestation, a higher contribution of grass phytoliths, enriched δ13C values (Roos, personal communication), and the presence of banana phytoliths, the earliest evidence for an environmental impact of human activity at the Qaraqara site appears to set the date for cultivation through swidden practices, and likely an increased reliance on terrestrial resources, to as early as 2993 to 3173 cal. BP, and almost certainly no later than 2379 to 2319 cal. BP where all evidence supports an event of intensified cultivation.

These findings, along with other studies of this nature, do conform to the idea that subsistence strategies became more variable in the centuries following the initial colonization of Fiji. The results also support previous research that found Late-Lapita and Post-Lapita dated materials which indicated that as later populations moved inland they relied more heavily on terrestrial resources, probably with a high

contribution of cultivated domesticates. These previous studies are based on the presence of archaeological agricultural and defensive features in the Sigatoka Valley, as well as stable isotope analyses performed on Post-Lapita era humans and pig (Field 2002; Field 2003; Field 2004; Field 2009). However, the dates from this study suggest that people may have begun establishing settlements in the Sigatoka Valley centuries earlier than previously thought. If this suite of data and the accompanying dates from the Qaraqara site is correct, it carries with it some significant implications for the prehistory of Fiji, and possibly for the Lapita Cultural Complex. First, the earliest evidence for cultivation at this site suggests that it coincides temporally with the initial colonization of Fiji, approximately 3000 years ago. This might lend further evidence in support of a Lapita Cultural Complex characterized to some extent by reliance on small-scale horticulture. It also implies that people began moving inland and establishing settlements almost immediately, rather than lingering on the coast until forced inland by unknown forces. There is currently, however, a lack of Lapita-style ceramics from archaeological contexts in the Sigatoka Valley to further support this hypothesis. This certainly does not mean they do not exist, as evidence for Lapita presence has been found in at least one inland site, 4 km from the coast, by Anderson, Clark, and Worthy (2000) in the form of a dentate-stamped ceramic rim sherd. They believe this evidence suggests more inland Lapita sites will be found in Fiji, and possibly elsewhere in the Pacific. Considering that the majority of archaeological excavation in the Pacific has taken place on coasts, this is not

surprising, but should act as an impetus for more researchers to pursue archaeological projects in the interior of islands.

The relationship between agriculture as a subsistence strategy and conflict is also important to consider. Excavations at an inland site in Fiji's Sigatoka Valley, Tatuba Cave, 20 km northeast of the Qaraqara site, determined it was likely occupied by people around 2000 years ago; however, the first fortified settlements were established only about 1500 years ago (Field 2008b; Kumar et al. 2006). Population growth and climate change may have contributed to conflict and competition, implied by the presence of hilltop forts in the valley several centuries later, especially around AD 1300. This appears to be a common pattern across the Pacific, where the majority of fortifications appear between AD 1300 and 1800 (Field and Lape 2010). During the AD 1300 event, the falling of sea-level would have resulted in a lowering of the water-table in the interior, amplifying the effects of climate instability, and resulting in the loss of arable land and a reduction of agricultural productivity (Field 2004; Kumar et al. 2006); a fall in average regional temperatures and changes in precipitation would have further stressed local ecosystems (Nunn 2000). Nunn (2003) suggests that even if population growth was not a factor at this time, the loss of resource productivity would have effectively lowered an island's carrying capacity, resulting in higher rates of conflict and competition. As more people moved inland at this time, previous sustainability strategies for swidden cultivation, like allowing land of already marginal quality to lay fallow between growing seasons, may not have remained practical options. The

new suite of problems presented by this event were likely exacerbated by the Sigatoka Valley's landscape already being highly variable in terms of agricultural productivity and predictability (Field 2003a). It is possible that the early age for cultivation at the Qaraqara site, along with a lack of similarly-aged defensive features in the valley, indicates a period relatively free of demographic and/or environmental pressures and conflict in the early centuries following colonization.

Chapter 5. Conclusion and Future Directions

Conclusion

The nature of life in Fiji in the centuries following colonization by Lapita people is yet to be fully characterized, but it is a work in progress. This thesis seeks to help illuminate at least one small aspect related to the Post-Lapita subsistence transition, from 2500 to 1500 years BP. It sought to accomplish this through the analysis of silica phytoliths extracted from terrestrial core sediment, sampled from an agricultural site in the Qaraqara drainage of the middle Sigatoka Valley. By limiting analysis to a small subset of types within one class of microfossil, diagnostic silica phytoliths, a dataset capable of directly addressing my three hypotheses was produced. Based on other studies on the vegetation history of Fiji (Ash 1992; Hope et al. 2009; Keppel and Tuiwawa 2007; Prebble and Dowe 2008; Watling 2005), the first hypothesis stated that a signal of deforestation would be detected around the time when colonization began, approximately 3000 years ago. The second hypothesized stated that the phytolith data would indicate human activity at this site; specifically, that cultivation would be indicated through the presence of non-native plant taxa. The final hypothesis stated that the non-native plant taxa identified would be associated with the Lapita Cultural Complex, as small-scale horticulture has demonstrated to be a part of it by previous research of Lapita and Late-Lapita contexts (Davidson and Leach 2001; Horrocks et al. 2009; Horrocks and Nunn 2007; Kirch 2000).

A strength of this thesis and the resulting data, as a small part of a much larger project, is in the ability to integrate many different types of data in order to make observations about prehistoric human-environment interactions in Fiji's Sigatoka Valley. My results have some interesting and possibly controversial implications for Fijian prehistory. This research is valuable for the contributions it may make toward the development of a model for human subsistence strategy transformation in response to environmental and demographic pressures. So far, I think we are on our way to a satisfactory and well-grounded synthesis that will hopefully help to elucidate previously unknown aspects of the Post-Lapita subsistence transition in Fiji's Sigatoka Valley.

Future Directions

Refine Phytolith Extraction Protocol

One goal for the future is to further refine the microfossil extraction protocol used here. The method developed for use in this thesis to extract and analyze silica phytoliths from terrestrial sediment has proven to be effective at addressing the stated hypotheses. The resulting data has made it possible to characterize deforestation over time through the analysis of changing frequencies of tree and grass phytoliths; and it allowed for the detection of the presence of significant non-native plant taxa. Its application to future projects is uncertain, however, as it did prove to be inefficient with regard to the amount of time required for particle separation. A benefit of settling particles at 0 RPM on the benchtop, rather than in a

centrifuge, is that it eliminates the ambiguities and other uncontrollable variables associated with centrifugation. Lentfer and colleagues (2003) do provide a set of guidelines based on the Stokes equation for particle settling times at various speeds using a centrifuge, but the imprecise nature of centrifuge start-up and stopping times is not addressed. The method employed in this study required suspensions to settle on the bench without the aid of a centrifuge in an effort to maintain as much uniformity between samples as possible. A more time-efficient protocol, one that also maintains a high level of precision and consistency between samples, should be developed for future projects of this nature. There are a wide range of extraction methods in publication (Horrocks 2005; Lentfer and Boyd 2000; Piperno 2006) that provide good starting points; however, the protocol employed should be tailored to each specific set of research questions as well as to the geomorphological characteristics of the sediment being analyzed. This is especially important if the sediment has a large proportion of particles similar in size and specific gravity to the microfossils of interest.

Analyzing Microfossils from Excavation Sediment

The dataset produced in this thesis could be greatly expanded by performing a similar analysis on sediment recovered from the adjacent excavation unit. Not only would this put the present results into a more cultural context, but the ceramic sherds excavated from the unit could be an additional source of microfossils.

Extract and Analyze Starches

A shortfall of phytolith analysis is that it is not going to be fully representative of plants that may have contributed to the archaeological record. Not all plants produce phytoliths, so it is important to include additional classes of microfossils if the goal is to acquire a record that is as complete as possible. Archaeological starch analysis can be used in place of or as a supplement to silica phytolith analysis to infer prehistoric human diets (Henry and Piperno 2008; Horrocks, Grant-Mackie et al. 2008; Tromp and Dudgeon 2015) and evidence for cultivation (Horrocks et al. 2004; Horrocks and Nunn 2007; Horrocks and Rechtman 2009; Horrocks and Weisler 2006;). Previous attempts to recover starches from pottery sherds excavated from Qaraqara were unsuccessful (Hernandez 2015). These preliminary analyses of Qaraqara sediment also failed to recover starches, and further efforts to identify them were excluded. While starches have been successfully recovered from archaeological contexts, they are not as robust as silica phytoliths and more susceptible to degradation over time. It would be worthwhile, however, to pursue the development of a protocol to extract and visualize any starches that might be present in these sediments.

References

Anderson, A. J., S. Bedford, G. R. Clark, I. Lilley, C. Sand, G. Summerhayes and R. Torrence

2000 An inventory of Lapita sites containing dentate-stamped pottery. In *The Archaeology of Lapita Dispersal in Oceania*, edited by G. R. Clark, A. J. Anderson and T. S. Vunidilo, pp. 1-14. Pandanus Books, Canberra.

Anderson, A., G. Clark, and T. Worthy

2000 An Inland Lapita Site in Fiji. *The Journal of the Polynesian Society* 103(3): 311-316.

Ash, J.

1992 Vegetation Ecology of Fiji: Past, Present, and Future Perspectives. *Pacific Science* 46(2): 111-127.

Ball, T.B., A.D. Davis, R.R. Evett, J.L. Ladwig, M. Tromp, W. Out, and M. Portillo

2016 Morphometric Analysis of Phytoliths: Recommendations towards Standardization from the International Committee for Phytolith Morphometrics. *Journal of Archaeological Science* 68: 106-111.

Bremond, L., A. Alexandre, C. Hely, and J. Guiot

2005 A phytolith index as a proxy of tree cover density in tropical areas: Calibration with Leaf Area Index along a forest-savanna transect in southeastern Cameroon. *Global and Planetary Change* 45: 277-293.

Burley, D.

2005 Mid-sequence archaeology at the Sigatoka Sand Dunes with interpretive implications for Fijian and Oceanic culture history. *Asian Perspectives* 44(2):320-348.

Burley, D. and W. R. Dickinson

2004 Late Lapita occupation and its ceramic assemblage at the Sigatoka Sand Dune site, Fiji, and their place in Oceanic prehistory. *Archaeology in Oceania* 39:12-25.

Burley, D.V. and K. Edinborough

2014 Discontinuity in the Fijian Archaeological Record Supported by a Bayesian Radiocarbon Model. *Radiocarbon* 56(1): 295-303.

Clark, G. R.

2000 Mid sequence isolation in Fiji 2500-1000 BP. In Indo-Pacific Prehistory: The Melaka Papers, edited by P. S. Bellwood, pp. 152-158. vol. 19. Indo-Pacific Prehistory Association, Canberra.

Clark, G. and A. Anderson

2001 The Pattern of Lapita Settlement in Fiji. *Archaeology in Oceania* 36(2): 77-88.

2009 Site chronology and a review of radiocarbon dates from Fiji. In *The Early Prehistory of Fiji*, edited by G. Clark and A. Anderson. ANU E Press, Canberra.

Coil, J., M.A. Korstanje, S. Archer, and C.A. Hastorf

2003 Laboratory goals and considerations for multiple microfossil extraction in archaeology. *Journal of Archaeological Science* 30: 991-1008.

Crowther, A.

2009 Morphometric Analysis of Calcium Oxalate Raphides and Assessment of Their Taxonomic Value for Archaeological Microfossil Studies. In *Archaeological science under a microscope: studies in residue and ancient DNA analysis in honour of Thomas H. Loy*, edited by M. Haslam, G. Robertson, A. Crowther, S. Nugent, and L. Kirkwood. ANU Press, Canberra.

Davidson and Leach

2001 The Strandlooper concept and economic naivety. In *The Archaeology of Lapita Dispersal in Oceania*, edited by G.R. Clark, A.J. Anderson, and T. Vunidilo. ANU Press, Canberra.

Dudgeon, J. V., M. Tromp

2012 Diet, geography and drinking water in Polynesia: Microfossil research from archaeological human dental calculus, Rapa Nui (Easter Island). *International Journal of Osteoarchaeology* 24(5): 634-648.

Fall, P.

2010 Pollen evidence for plant introductions in a Polynesian tropical island ecosystem, Kingdom of Tonga. In *Altered Ecologies: Fire, Climate and Human Influence on Terrestrial Landscapes*, edited by S. Haberle, J. Stevenson and M. Prebble, pp. 253-271. Terra Australis 32, ANU Press, Canberra.

Fenwick, R. S. H., C. J. Lentfer and M. I. Weisler

2011 Palm reading: a pilot study to discriminate phytoliths of four Arecaceae (Palmae) taxa. *Journal of Archaeological Science* 38(9):2190-2199.

Field, J. S.

2002 GIS-based analyses of agricultural production and habitation in the Sigatoka Valley, Fiji. In *Pacific Landscapes: Archaeological Approaches*, edited by T. N. Ladefoged and M. W. Graves, pp. 97-124. Easter Island Foundation Press, Los Osos.

2003a *The Evolution of Competition and Cooperation in Fijian Prehistory: Archaeological Research in the Sigatoka Valley, Fiji.* Unpublished PhD dissertation, University of Hawai‘ i Manoa.

2003b *Archaeological Investigations of the Sigatoka Valley, 2001-2002, Nadroga and Navosa Provinces, Fiji Islands.* Report produced for the Dept. of Immigration, Republic of Fiji.

2004 Environmental and climatic considerations: A hypothesis for conflict and the emergence
of social complexity in Fijian prehistory. *Journal of Anthropological Archaeology* 23:79-99.

2005 Land tenure, competition, and ecology in Fijian prehistory. *Antiquity* 79:586-600.

2008a Explaining Fortifications in Indo-Pacific Prehistory. *Archaeology in Oceania* 43: 1-10.

2008b Natural and Cultural Deposits in Tatuba Cave, Fiji Islands: 1972 and 2002 Investigations. In *Recent Advances in the Archaeology of the Fiji/West-Polynesia Region*, edited by D.J. Addison and C. Sand. University of Otago Studies in Prehistoric Anthropology, Dunedin.

Field, J.S. and P.V. Lape

2010 Paleoclimates and the emergence of fortifications in the tropical Pacific islands. Journal of Anthropological Archaeology 29: 113-124.

Field, J. S., E. E. Cochrane and D. M. Greenlee

2009 Dietary change in Fijian prehistory: Isotopic analyses of human and animal skeletal material. *Journal of Archaeological Science* 36:1547-1556.

Green, R.C.
2003 The Lapita horizon and traditions--Signature for one set of Oceanic migrations. In *Pacific Archaeology: Assessments and prospects. Proceedings of the International Conference for the 50th Anniversary of the First Lapita Excavation*, edited by C. Sand, pp. 95-120. Les Cahiers de l'Archaéologie en Nouvelle Calédonie. vol. 15. Service des Musées et du Patrimonie de Nouvelle-Calédonie, Nouméa.

Groube, L.
1971 Tonga, Lapita pottery, and Polynesian origins. *Journal of the Polynesian Society* 80:278-316.

Hardy, K., T. Blakeney, L. Copeland, J. Kirkham, R. Wrangham and M. Collins
2009 Starch granules, dental calculus and new perspectives on ancient diet. *Journal of Archaeological Science* 36:248-255.

Henry, A. G. and D. R. Piperno
2008 Using plant microfossils from dental calculus to recover human diet: a case study from Tell al-Raqa'i, Syria. *Journal of Archaeological Science* 35:1943-1950.

Henry, A. G., A. S. Brooks and D. R. Piperno
2011 Microfossils in calculus demonstrate consumption of plants and cooked foods in Neanderthal diets (Shanidar III, Iraq; Spy I and II, Belgium). *Proceedings of the National Academy of Sciences* 108:486-491.

Hernandez, M.M.
2015 Archaeological Starch Preservation and Methodological Parameters: Where Does Qaraqara Fit? Unpublished MS thesis, The Ohio State University, Columbus.

Hope, G.
2009 Vegetation histories from the Fijian Islands: Alternative records of human impact. In *The Early Prehistory of Fiji*, edited by G. Clark and A. Anderson., pp. 63-86.ANU E Press, Canberra.

Horrocks, M.
2005 A combined procedure for recovering phytoliths and starch residues from soils, sedimentary deposits and similar materials. *Journal of Archaeological Science* 32(8):1169-1175.

Horrocks, M. and S. Bedford
2005 Microfossil analysis of Lapita deposits in Vanuatu reveals introduced Araceae (aroids). Archaeology in Oceania 40(2):67-74.

Horrocks, M. and I. Lawlor
2006 Plant microfossil analysis of soils from Polynesian stonefields in South Auckland, New Zealand. *Journal of Archaeological Science* 33:200-217.

Horrocks, M. and P. D. Nunn
2007 Evidence for introduced taro (*Colocasia esculenta*) and lesser yam (*Dioscorea esculenta*) in Lapita-era (c. 3050-2500 cal. yr BP) deposits from Bourewa, southwest Viti Levu Island, Fiji. *Journal of Archaeological Science* 34(5):739-748.

Horrocks, M. and R. B. Rechtman
2009 Sweet potato (*Ipomoea batatas*) and banana (*Musa* sp.) microfossils in deposits from the Kona Field System, Island of Hawaii. *Journal of Archaeological Science* 36(5):1115-1126.

Horrocks, M. and M. I. Weisler
2006 Analysis of plant macrofossils in archaeological deposits from two remote archipelagos: The Marshall Islands, Eastern Micronesia and the Pitcairn Group, Southeast Polynesia. *Pacific Science* 60(2):261-280.

Horrocks, M. and J. A. Wozniak
2008 Plant microfossil analysis reveals disturbed forest and a mixed-crop, dryland production system at Te Niu, Easter Island. *Journal of Archaeological Science* 35(1):126-142.

Horrocks, M., G.J. Irwin, M.S. McGlone, S.L. Nichol, and L.J. Williams
2003 Pollen, Phytoliths and Diatoms in Prehistoric Coprolites from Kohika, Bay of Plenty, New Zealand. *Journal of Archaeological Science* 30: 13-20.

Horrocks, M., G. Irwin, M. Jones and D. Sutton
2004 Starch grains and xylem cells of sweet potato (Ipomoea batatas) and bracken (Pteridium esculentum) in archaeological deposits from northern New Zealand. *Journal of Archaeological Science* 31:251-258.

Horrocks, M., J. Grant-Mackie and E. Matisoo-Smith

2008 Introduced taro (*Colocasia esculenta*) and yams (*Dioscorea* spp.) in Podtanean (2700-1800 years BP) deposits from Me Aure Cave (WMD007), Moindou, New Caledonia. *Journal of Archaeological Science* 35(1):169-180.

Horrocks, M., S. Bulmer and R. O. Gardner
2008 Plant microfossils in prehistoric archaeological deposits from Yuku rock shelter, Western Highlands, Papua New Guinea. *Journal of Archaeological Science* 35(2):290-301.

Horrocks, M., I. W. G. Smith, S. L. Nichol and R. Wallace
2008 Sediment, soil and plant microfossil analysis of Maori gardens at Anaura Bay, eastern North Island, New Zealand: comparison with descriptions made in 1769 by Captain Cook's expedition. *Journal of Archaeological Science* 35(9):2446-2464.

Horrocks, M., S. Bedford and M. Spriggs
2009 A short note on banana (*Musa*) phytoliths in Lapita, immediately post-Lapita and modern period archaeological deposits from Vanuatu. *Journal of Archaeological Science* 36:2048-2054.

Horrocks, M., W. T. Baisden, M. K. Nieuwoudt, J. Flenley, D. Feek, L. González Nualart, S. Haoa-Cardinali, and T. Edmunds Gorman
2012 Microfossils of Polynesian cultigens in lake sediment cores from Rano Kau, Easter Island. *Journal of Paleolimnology* 47(2): 185-204.

Hunt, T.L.
1981 New Evidence for Early Horticulture in Fiji. The Journal of the Polynesian Society 90(2): 259-266.

Iriarte, J. and E. A. Paz
2009 Phytolith analysis of selected native plants and modern soils from southeastern Uruguay and its implications for paleoenvironmental and archeological reconstruction. *Quaternary International* 193(1-2):99-123.

Jenkins, E.
2009 Phytolith taphonomy: a comparison of dry ashing and acid extraction on the breakdown of conjoined phytoliths formed in Triticum durum. *Journal of Archaeological Science* 36:2402-2407.

Jones, S. and R. Quinn

2009 Prehistoric Fijian diet and subsistence: Integration of faunal, ethnographic, and stable isotopic evidence from the Lau Island Group. *Journal of Archaeological Science* 36:2742-2754.

Keppel, G. and M.V. Tuiwawa
2007 Dry zone forests of Fiji: species composition, life history traits, and conservation. *New Zealand Journal of Botany* 45: 545-563.

Kirch, P.V.
2000 *On the Road of the Winds: An Archaeological History of the Pacific Islands before European Contact*. University of California Press, Berkley.

Kumar, R., P.D. Nunn, J.S. Field, and A. de Biran
2006 Human responses to climate change around AD 1300: A case study of the Sigatoka Valley, Viti Levu Island, Fiji. *Quaternary International* 151: 133-143.

Leach, B. F., C. J. Quinn, G. L. Lyon, A. Haystead and D. B. Myers
2000 Evidence of prehistoric Lapita diet at Watom Island, Papua New Guinea, using stable isotopes. *New Zealand Journal of Archaeology* 20(149-159).

Lentfer, C. J. and W. E. Boyd
2000 Simultaneous Extraction of Phytoliths, Pollen and Spores from Sediments. *Journal of Archaeological Science* 27(5):363-372.

Lentfer, C. J. and R. C. Green
2004 *Phytoliths and the Evidence for Banana Cultivation at the Lapita Reber-Rakival Site on Watom Island, Papua New Guinea*. Records of the Australian Museum 29.

Lentfer, C., M. Therin and R. Torrence
2002 Starch Grains and Environmental Reconstruction: a Modern Test Case from West New Britain, Papua New Guinea. *Journal of Archaeological Science* 29:687-698.

Lentfer, C.J., M.M. Cotter, and W.E. Boyd
2003 Particle Settling Times for Gravity Sedimentation and Centrifugation: A Practical Guide for Palynologists. Journal of Archaeological Science 30: 149-168.

Madella, M., A. Alexandre and T. Ball
2005 International Code for Phytolith Nomenclature 1.0. *Annals of Botany* 96:253–260.

Madella, M. and C. Lancelotti
2012 Taphonomy and phytoliths: A user manual. *Quaternary International* 275: 76-83.

Nunn, P.D.
2000 Environmental Catastrophe in the Pacific Islands around A.D. 1300. *Geoarchaeology* 15(7): 715-740.

2003 Revising ideas about environmental determinism: Human-environment relations in the Pacific Islands. *Asia Pacific Viewpoint* 44(1): 63-72.

2007 The A.D. 1300 Event in the Pacific Basin. *The Geographical Review* 97(1): 1-23.

Osterrieth, M., M. Madella, D. Zurro and M. Fernanda Alvarez
2009 Taphonomical aspects of silica phytoliths in the loess sediments of the Argentinean Pampas. *Quaternary International* 193(1-2):70-79.

Pearsall, D. M.
2009 Investigating the transition to agriculture. *Current Anthropology* 50(5):609-613.

Pearsall, D. M. and M. K. Trimble
1984 Identifying past agricultural activity through soil phytolith analysis: a case study from the Hawaiian Islands. *Journal of Archaeological Science* 11:119-133.

Phaff, B., D.V. Burley, and M. Richards
2016 Dietary isotope patterns and their social implications in a prehistoric human population from Sigatoka, Fiji. *Journal of Archaeological Science: Reports* 5: 680-688.

Piperno, D. R.
2006 *Phytoliths: A Comprehensive Guide for Archaeologists and Paleoecologists*. AltaMira Press, Lanham.

2009 Identifying crop plants with phytoliths (and starch grains) in Central and

South America- A review and an update of the evidence. *Quaternary International* 193:146-159.

Prebble, M. and J.L. Dowe
2008 The late Quaternary decline and extinction of palms on oceanic Pacific islands. *Quaternary Science Reviews* 27: 2546-2567.

Prebble, M., R. Sim, J. Finn, and D. Fink
2005 A Holocene pollen and diatom record from Vanderlin Island, Gulf of Carpentaria, lowland tropical Australia. *Quaternary Research* 64: 357-371.

Prebble, M., A. Anderson, and D.J. Kennett
2012 Forest clearance and agricultural expansion on Rapa, Austral archipelago, French Polynesia. *The Holocene* 23(2): 179-196.

Reepmeyer, C. and G. Clark
2010 Post-colonization interaction between Vanuatu and Fiji reconsidered: the re-analysis of obsidian from Lakeba Island, Fiji. *Archaeometry* 52(1): 1-18.

Roos, C., J. Field, J. Dudgeon
2017 Variability in the Onset and Intensification of Swidden Cultivation on Viti Levu, Fiji. Paper presented at the 82nd Annual Meeting of the Society for American Archaeology, Vancouver, British Columbia.

Roos, C.I., J.S. Field, and J.V. Dudgeon
2016 Anthropogenic Burning, Agricultural Intensification, and Landscape Transformation in Post-Lapita Fiji. *Journal of Ethnobiology* 36(3): 535-553.

Runge, F.
1999 The opal phytolith inventory of soils in central Africa - quantities, shapes, classification, and spectra. *Review of Palaeobotany and Palynology* 107:23-53.

Spriggs, M.
1984 The Lapita Cultural Complex: Origins, distribution, contemporaries, and successors. *Journal of Pacific History* 19:202-223.

2003 Post-Lapita evolutions in Island Melanesia. In *Pacific Archaeology: Assessments and Prospects. Proceedings of the International Conference for the 50th Anniversary of the First Lapita Excavation*, edited by C. Sand, pp.

205-212. Les Cahiers de l'Archaéologie en Nouvelle Calédonie. vol. 15. Service des Musées et du Patrimonie de Nouvelle- Calédonie, Nouméa.

Strömberg, C. A. E.
2009 Methodological concerns for analysis of phytolith assemblages: Does count size matter? *Quaternary International* 193(1-2):124-140.

Sunell, L. A. and P. L. Healey
1979 Distribution of Calcium Oxalate Crystal Idioblasts in Corms of Taro (Colocasia esculenta). *American Journal of Botany* 66(9):1029-1032.

Thaman, R., M. Gregory, and S. Takeda
2011 *Trees of Life: A Guide to Trees and Shrubs of The University of the South Pacific*. The University of the South Pacific Press, Suva.

Tromp, M.
2012 Large-scale analysis of microfossils extracted from human Rapanui dental calculus: a dual-method approach using SEM-EDS and light microscopy to address ancient dietary hypotheses. *Unpublished MS thesis*, Idaho State University, Pocatello.

Tromp, M. and J.V. Dudgeon
2015 Differentiating dietary and non-dietary microfossils extracted from human dental calculus: the importance of sweet potato to ancient diet on Rapa Nui. *Journal of Archaeological Science* 54: 54-63.

Valentin, F., H. R. Buckley, E. Herrscher, R. Kinaston, S. Bedford, M. Spriggs, S. Hawkins, K. Neal
2010 Lapita subsistence strategies and food consumption patterns in the community of Teouma (Efate, Vanuatu). *Journal of Archaeological Science* 37:1820-1829.

Vrydaghs, L., T. Ball, H. Volkaert, I. van den Houwe, J. Manwaring and E. De Langhe
2009 Differentiating the Volcaniform Phytoliths of Bananas: Musa acuminata. *Ethnobotany Research and Applications* 7:239-246.

Waters, M.R.
1992 *Principles of Geoarchaeology: A North American perspective.* The University of Arizona Press, Tucson.

Watling, D.
2005 *Palms of the Fiji Islands*. Environmental Consultants Fiji, Suva.

Whitlock, C. and C. P. S. Larsen
2001 Charcoal as a fire proxy. In *Tracking Environmental Change Using Lake Sediments*, edited by J. P. Smol, H. J. B. Birks and W. M. Last, pp. 75-97. vol. 3. Terrestrial, Algal, and Siliceous Indicators. Kluwer Academic Publishers, Dordrecht.

Weiner, S.
2010 *Microarchaeology: Beyond the Visible Archaeological Record*. Cambridge University Press, New York.

Whistler, W.A.
2009 *Plants of the Canoe People: An Ethnobotanical Voyage through Polynesia*. National Tropical Botanical Garden, Kalaheo.

Appendix A

Microfossil Extraction from Modern Reference Plant Specimens

Silica phytolith and calcium oxalate extraction

1. Weigh approximately 50 mg of dried and ground plant tissue into clean borosilicate glass tube, labeled with wax pencil
2. Loosely cover each tube with a small square of aluminum foil
3. Place tubes in furnace and set temperature to 550°C
4. Set timer for 2 hours
5. Allow furnace to cool completely before removing tubes
6. Add 4 mL 18 MΩ water to each tube
7. Seal each tube with parafilm and vortex carefully for 30 seconds
8. Aliquot 100 µL from each tube onto a polished aluminum stub
9. Visualize with SEM-EDS or a light microscope

Starch extraction

1. Weigh approximately 1 gram of ground tuber/fruit into a weigh boat
2. Add 500 µL 18 MΩ water to each sample
3. Cover loosely with aluminum foil and allow to soak for at least 24 hours
4. Spread approximately 100 µL of mixture onto glass slide in as thin a layer as possible
5. Allow to dry at room temperature for 15 minutes before placing immersion oil and slip cover
6. Visualize with light microscope

Silica Phytolith Extraction from Sediment

1. Weigh out approximately 1 gram of sediment into a 15 mL tube, avoiding gravel and other macro-remains
2. Dry completely at room temperature or in a drying oven

3. Fill with 5% sodium metaphosphate solution, up to 13.5 mL mark on tube and vortex
4. Place on nutator tray overnight to thoroughly deflocculate particles
5. The following day, place tubes upright in a rack and settle overnight on bench top, at least 12 hours
6. Use vacuum with glass pipette tips (a clean tip for each sample) to remove supernatant, being careful not to disturb settled particles
7. Fill with 5% sodium metaphosphate solution, up to 13.5 mL mark on tube and vortex
8. Settle overnight on bench top, at least 12 hours
9. Use vacuum with glass pipette tips (a clean tip for each sample) to remove supernatant, being careful not to disturb settled particles
10. Repeat steps 7-9 at least one time, until supernatant appears mostly clear
    a. At each wash step, examine an aliquot of the supernatant to verify no target particles are being discarded
11. Add RO water up to 13.5 mL mark on the tube and vortex
12. Centrifuge at 2000 RPM for 5 minutes to pellet all material
13. Carefully remove water with clean glass pipette tips and vacuum
14. Repeat steps 7-9 two times to remove all residual sodium metaphosphate
    a. At each wash step, examine an aliquot of the supernatant to verify no target particles are being discarded
15. Add RO water up to the 13.5 mL mark on the tube and vortex
16. To settle target particles ≥5 µm in diameter with ≥1.5 specific gravity, settle on the benchtop at 0 RPM for 4.08 hours (approx. 4 hours and 5 minutes)
17. Repeat 3 times, or as needed

    a. Check progress between washes by placing a small aliquot (~10 µL) of the target fraction in solution and checking particle size distributions by light microscope

    b. At each wash step, examine an aliquot of the supernatant to verify no target particles are being discarded
18. After the final wash, refill tube to 13.5 mL with RO water

19. Vortex and let sit on bench at 0 RPM for 45 seconds
20. Aliquot 100 µL from top half of 15 mL tube into a new 2.0 mL tube
21. Dilute by adding 200 µL RO water and 200 µL EtOH (99%) to each sample tube and vortex
22. Use 10 µL aliquots on a polished aluminum stub for visualization with SEM-EDS